Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Allen, Wychmere and Saquatucket Harbor Embayment Systems, Harwich, Massachusetts

University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

FINAL REPORT – May 2010

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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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor embayment systems, a series of coastal embayments within the Town of Harwich, Massachusetts. Analyses of the three harbors was performed to assist the Town of Harwich with on-going nitrogen management decisions associated with the Towns' current and future wastewater planning efforts, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and river/harbor maintenance programs. As part of the MEP approach, habitat assessment was conducted on the embayments based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Town of Harwich 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor embayments, (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 Town) for the restoration of the three individual embayment systems.

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 three harbor embayment systems within the Town of Harwich are at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater from the increasingly developed watershed to these coastal systems. Eutrophication is a process that occurs naturally and gradually over a period of tens or hundreds of years. However, human-related (anthropogenic) sources of nitrogen may be introduced into ecosystems at an accelerated rate that cannot be easily absorbed, resulting in a phenomenon known as cultural eutrophication. In both marine and freshwater systems, cultural eutrophication results in degraded water quality, adverse impacts to ecosystems, and limits on the use of water resources.

The Town of Harwich has recognized the severity of the problem of eutrophication and the need for watershed nutrient management and is currently developing a Comprehensive Wastewater Management Plan which it plans to rapidly implement. The Town of Harwich is also completing wastewater planning in other regions of the Town not associated with the Allen, Wychmere and Saquatucket Harbor embayment systems, specifically those areas of the Town affecting Pleasant Bay. The Town of Harwich and work groups/committees 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 Town. 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 a given 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor embayment systems by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Town of Harwich, 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 Harwich Planning Department, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the three harbor embayment systems 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 these tidally influenced estuaries included a thorough evaluation of the hydrodynamics of each of the estuarine systems. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of a given system was quantified, transport of nitrogen was evaluated from tidal current information developed by the embayment specific numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for evaluation of each of the three harbors. Once the hydrodynamic properties of the estuarine systems 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 the type represented by the three harbors, 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 for each harbor. The distributions of nitrogen loads from watershed sources were determined from land-use analysis. Boundary nutrient concentrations in Nantucket Sound source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the three harbor systems was used to calibrate each of the water quality models, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model for each system 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 (as appropriate) and infaunal habitats in the three harbor systems. 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 (1 sentinel station per 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 , such as may be the case for the Saquatucket Harbor system relative to the Bank Street Bogs. 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 these nitrogen impaired embayments.

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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor embayment systems in the Town of Harwich. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the individual embayments. 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 septic system nitrogen loads generally represent 80% - 85% of the controllable watershed load to the three harbor systems and are more manageable than other of the nitrogen sources, the ability to achieve needed reductions through this source is a good gage of the feasibility for restoration of these systems.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Allen, Wychmere and Saquatucket Harbor systems based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. At present, each of the three harbors is showing similar levels of nitrogen enrichment and habitat quality. Allen Harbor, Wychmere Harbor and Saquatucket Harbor are presently supporting moderately to significantly impaired habitat quality throughout the open water basins (refer to Table VIII-1). Impairment is indicated by the absence of eelgrass, the structure of the benthic communities, periodic oxygen depletion and high levels of chlorophyll a and typical concentrations of total nitrogen of 0.65-0.82 mg N L^{-1} in the basin waters.

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). Overall, the dissolved oxygen records clearly show oxygen depletion and elevated chlorophyll *a* levels in each of the basins of the three harbors at levels that stress benthic animal communities and therefore cause impaired habitat quality (refer to Table VII-1 and VII-2). The MEP measurements are fully consistent with the observed extent of oxygen depletion in each estuary as measured through traditional surveys by the Harwich Water Quality Monitoring Program. The basins of Allen Harbor, Wychmere Harbor and Saquatucket Harbor each showed periodic oxygen depletions to levels less than 4 mg L^{-1}, however, the minima varied between basins, between 2 and 3 mg L^{-1} (Section VII.2)..

The main basin of Saquatucket Harbor exhibited frequent oxygen depletions to < 4 mg L^{-1} and periodic oxygen depletion to <3 mg L^{-1}, indicative of a moderate to significantly impaired system. Some values were in excess of air equilibration in day time, but the bottom water rarely reached air equilibration throughout the MEP deployment period. The main basin of Wychmere Harbor had periodic depletion of bottom water oxygen to < 4 mg L^{-1}, but levels did not go below 3 mg L^{-1}, indicative of a moderately impaired system. Oxygen levels in excess of air equilibration in day time were observed, but were not the norm. The bottom water remained below air equilibration for the first half of the deployment period. Allen Harbor differs from Saquatucket and Wychmere Harbors in that it has a tributary open water basin off the main basin. Both basins have periodic depletion of bottom water oxygen levels to < 4 mg L^{-1}, but depletion was significantly greater in Allen Creek when compared to the main basin. Main basin bottom water oxygen showed periodic levels of bottom water oxygen in the 3-4 mg L^{-1} range, indicative of a moderately impaired system. The Creek had greater oxygen declines into the 2-3 mg L^{-1} range, indicative of a significantly impaired system. Oxygen levels in excess of air equilibration in day time were observed, but were not the norm. The bottom water generally remained below air equilibration at both sites.

The absence of eelgrass throughout Allen Harbor, Wychmere Harbor and Saquatucket Harbor is consistent with the observed nitrogen and the chlorophyll levels and the structure of the basins comprising these estuaries. Equally important, all of the available information on eelgrass relative to these three systems indicates that they have not supported eelgrass over the past half century (MassDEP maps) and likely longer. Saquatucket Harbor was originally a tidal river salt marsh system, Andrews River, until it was dredged to create the present harbor in 1968-69 (Chapter I). As such, it has never supported eelgrass beds.

It should be noted that the absence of eelgrass within these basins is consistent with their present total nitrogen levels (>0.65 mg N L^{-1}; Chapter VI) which are much higher than found to be supportive of eelgrass habitat in similarly configured basins on Cape Cod. As eelgrass habitat could not be documented to exist, either historically or presently, within Allen, Wychmere or Saquatucket Harbors (Section VII.3), the thresholds analysis for these systems necessarily focuses on restoration of each systems impaired infaunal animal habitats. However, it is likely that nitrogen management within these three systems will improve eelgrass and infaunal habitat within the down-gradient nearshore waters of Nantucket Sound.

The infaunal study indicated that the basins comprising Allen, Wychmere and Saquatucket Harbors are presently supporting impaired benthic habitat and that there is little variation within each estuary and even between the estuaries. This latter observation likely stems from their similar configuration, single tidal inlet and developed watersheds. The benthic animal habitat assessment is consistent with the present absence of eelgrass and the levels of oxygen depletion and chlorophyll a in the waters of each harbor and observations of the sediments themselves (Section VII.4).

Each of the basins of the three harbors is dominated by a gammarid amphipod community, comprised primarily of *Ampelisca abdita* and *Microdeutopus anomalus*. Dominance of the benthic community by amphipods is indicative of nitrogen and organic enrichment, but is "transitional", i.e. usually associated with a shift from low enrichment to high enrichment or high enrichment to low enrichment and is therefore not indicative of severe degradation, rather intermediate stress. In addition, the main basins had moderate numbers of species with very high numbers of individuals and moderate diversity and low-moderate evenness indicative of habitat impairment. The predominance of these communities and structure throughout the main basins of Allen, Wychmere and Saquatucket Harbors is indicative of moderate to significant levels of impairment of benthic habitat. However, these communities will be replaced by deep burrowing large forms as nitrogen enrichment is reduced. While much of the benthic habitat within the three harbors was dominated by amphipods, the small tributary in Allen Harbor, Allen Creek, also supported benthic communities with less species at lower densities than the main basins and in some areas were dominated by stress indicators, e.g. C*apitella capitata*. The dominance of this species in some areas indicates a lower level of habitat quality (i.e. significant impairment), than indicated for the main basins. The observed benthic habitat quality is completely consistent with the observed levels of oxygen depletion, chlorophyll a and macroalgal accumulations (only found in Allen Creek).

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 these embayment systems were developed to restore or maintain SA waters or high habitat quality. In these systems, given their structural characteristics and the lack of historical eelgrass, 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 Harwich Allen Harbor, Wychmere Harbor and Saquatucket Harbor embayment systems were comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 80% - 85% 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 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.

The threshold nitrogen levels for the three harbor embayment systems in Harwich were determined as follows:

Allen Harbor, Wychmere Harbor and Saquatucket Harbor Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Allen, Wychmere and Saquatucket Harbor systems should reflect both recent pre-degradation habitat quality and be reasonably achievable. Based upon the assessment data (Chapter VII), at present the monitoring data indicates total nitrogen levels of 0.65-0.82 mg N L^{-1}, levels higher than found by the MEP to be supportive of "healthy" benthic communities. Based upon the observations in each of the three harbors and threshold analyses completed by the MEP in 30+ estuaries throughout the MEP project region, 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 each of the basins of the three harbors

- The sentinel stations for each of the three estuaries are located within the main basin at the long-term water quality monitoring stations: Saquatucket Harbor (HAR-2), Wychmere (HAR-3) and Allen Harbor (HAR-4). However, given the potential for tidal restriction to Allen Creek, it is necessary to include a secondary "check" station specific to that basin (HAR-5). The sentinel stations are situated (as originally were the monitoring stations) such that achieving the nitrogen threshold target at each sentinel station should restore benthic animal habitat throughout the associated estuary. The secondary check station in Allen Creek is to merely provide a check on the acceptability of conditions within the tributary basin at the point that the threshold level is attained at the sentinel station and to control for potential tidal restriction between this tributary basin and the main basin.

- The nitrogen load reductions within the Allen Harbor watersheds necessary to achieve the threshold nitrogen concentrations required a 55% reduction in the total septic watershed nitrogen load for all the sub-watersheds flowing into Allen Pond Stream, as well as removing 80% of total septic watershed nitrogen load associated with Watershed #3 which directly contributes groundwater to Allen Harbor.

- Wychmere Harbor required nitrogen load reductions within all the sub-watershed to achieve the threshold nitrogen concentrations. To achieve the threshold, a 100% reduction in the total septic watershed nitrogen load was required for all the sub-watersheds flowing into Wychmere Harbor.

- The nitrogen load reductions within the Saquatucket Harbor watersheds necessary to achieve the threshold nitrogen concentrations required a 55% reduction in the total septic watershed nitrogen load for the sub-watersheds flowing into Cold Spring Brook and East Saquatucket Stream, as well as removing 80% of total septic watershed nitrogen load within Watershed #16 which directly contributes groundwater to Saquatucket Harbor.

- 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 to enhance nitrogen attenuation associated with restored wetlands or ecologically engineered ponds/wetlands. 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 the quality of associated aquatic resources within the watershed and upper estuarine reaches.

It is important to note that the analysis of loading reductions provided above is but one approach to meeting threshold nitrogen concentrations in each of the harbors evaluated in this report. Using the MEP developed embayment specific modeling tools allows the Town of Harwich to explore a wide range of implementation alternatives. Additionally, the analysis of future nitrogen loading to the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems 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 (presently less than half of the parcels use lawn 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 three harbor estuarine systems is that restoration will necessitate a reduction in the present (2006) 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations.										
Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. (mg/L)
SYSTEMS										
Allen Harbor	0.063	0.550	4.214	--	4.764	0.227	13.109	18.1	0.673-0.819	--
Wychmere Harbor	0.047	0.592	3.208	0.066	3.866	0.195	13.865	17.926	0.530-0.812	--
Saquatucket Harbor	0.038	0.250	2.545	--	2.795	0.151	15.285	18.231	0.658	--
Surface Water Sources										
Allen Pond Stream	0.052	0.412	1.426	--	1.838	--	--	1.838	--	--
Cold Spring Brook	0.337	2.726	7.775	--	10.501	--	--	10.501	--	--
East Saquatucket Stream	0.225	1.022	2.926	--	3.948	--	--	3.948	--	--
System Total	**0.762**	**5.552**	**22.094**	**0.066**	**27.712**	**0.573**	**42.259**	**70.544**	**--**	**0.50[8]**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings
[5] atmospheric deposition to embayment surface only
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 2001 – 2008 data, ranges show the upper to lower regions (highest-lowest) of an sub-embayment. Individual yearly means and standard deviations in Table VI-1.
[8] Threshold for sentinel sites located in Saquatucket Harbor at water quality station HAR-2, Wychmere Harbor at water quality station HAR-3, and Allen Harbor at water station HAR-4.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems , Town of Harwich, Massachusetts.

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
SYSTEMS						
Allen Harbor	4.764	1.392	0.227	8.216	9.835	-70.78%
Wychmere Harbor	3.866	0.66	0.195	6.03	6.885	-82.93%
Saquatucket Harbor	2.795	0.756	0.151	10.67	11.577	-72.95%
Surface Water Sources						
Allen Pond Stream	1.838	1.055	--	-	1.055	-42.60%
Cold Spring Brook	10.501	6.225	--	-	6.225	-40.72%
East Saquatucket Stream	3.948	2.296	--	-	2.296	-41.84%
System Total	**27.712**	**12.384**	**0.573**	**24.916**	**37.873**	**-55.31%**

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

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The Massachusetts Estuaries Project Technical Team would like to acknowledge the contributions of the many individuals who have worked tirelessly for the restoration and protection of the critical coastal resources of the Town of Harwich and Cape Cod. Over the years their efforts have brought focus on the declining quality of Cape Cod's estuaries and freshwater ponds and has been essential in advancing restoration efforts. Over the years, these individuals and the Town have collected various datasets and other information that was integrated into the MEP's application of the Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor Embayment Systems.

Without these stewards and their continuing efforts, the present analysis would not be available for these systems.

First and foremost we would like to recognize the significant time and effort taken to gather the baseline water quality data on each of the Town's estuaries by by members of the Town of Harwich Water Quality Monitoring Program directed by Heinz Proft. Similarly, the Harwich volunteers participating in the SMAST/CCC Ponds and Lakes Stewardship project, which provided the fresh pond data. All of these individuals gave of their time to collect nutrient related water quality measurements related to these estuaries and their associated upland freshwater resources. These data are essential to the validation of the MEP approach and the determination of natural attenuation rates of nitrogen during transport.

Of particular note are Frank Sampson, Chairman of the Town-wide Water Quality Management Task Force and Heinz Proft, Coordinator of the Town of Harwich Monitoring Program. Similarly, many in the Town of Harwich helped in this effort, the Harwich Department of Public Works, Planning Department (David Spitz, Sue Leven, Elizabeth Hude) and the Harwich Shellfish Department. In addition to local contributions, technical, policy and regulatory support has been freely and graciously provided by Paul Nezwicki and Tom Cambareri of the Cape Cod Commission, who also continue to provide GIS support to the MEP effort. Also, Brian Dudley, MassDEP for providing information on groundwater discharges and Sue Rask, BCDHE, for providing information from the County's alternative septic system database associated with the Town of Harwich. We are also thankful for the long hours in the field and laboratory spent by the technical staff (Jen Antosca, Michael Bartlett, Sara Sampieri and Dahlia Medieros), interns and students within the Coastal Systems Program at SMAST-UMD.

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PROPER CITATION

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I. INTRODUCTION

The Allen Harbor, Wychmere Harbor and Saquatucket Harbor Embayment Systems are small, simple estuaries located within the Town of Harwich on Cape Cod, Massachusetts with southern shores bounded by barrier beaches fronting Nantucket Sound (Figure I-1,2,3). These three embayments are situated on the coast between the larger estuarine systems of Herring River (also located in the Town of Harwich) and Stage Harbor in the Town of Chatham. The watersheds to Allen Harbor, Wychmere Harbor and Saquatucket Harbor are fully within the Town of Harwich, making Harwich the sole municipal steward of these small estuarine systems. Going forward in this report, MEP staff have tried to establish a consistent naming convention for places mentioned in this report, but there may be some references where locations are referred to by different names. These differences may be somewhat unavoidable given that some of the places listed in the report have numerous names, including different ones on more conventional sources, such as US Geological Survey quadrangles and Google Earth, and in local references and discussions.

Virtually all watershed freshwater and nutrients enter these three estuaries via either groundwater or surface water to varying degrees depending on the system, and all three systems contain marine waters diluted by these freshwater inflows. In the case of Saquatucket Harbor, there are two significant surface water inflows (Carding Machine Brook from the northwest and Cold Brook from the northeast) that discharge to the headwaters with additional freshwater inflow entering through groundwater discharge directly to the harbor perimeter. In contrast, all the freshwater entering the Wychmere Harbor system is via direct groundwater seepage, as there are no significant surface inflows to this system. Allen Harbor shows an intermediate condition, with a relatively small surface water inflow, an un-named creek passing under Kildee Road, but with most freshwater entering the system directly via groundwater discharge. As a result of their freshwater inflows, Saquatucket and Allen Harbor, may have opportunities for nitrogen removal via enhanced natural nitrogen attenuation, as nitrogen is transported from watershed sources to estuarine waters.

Allen Harbor, Wychmere Harbor and Saquatucket Harbor are all relatively simple estuaries that have each been anthropogenically altered over time to varying degrees. All three have a single tidal outlet through which tidal exchange with Nantucket Sound occurs. With the exception of Allen Harbor that has a small tributary basin near the inlet and a salt marsh at the head, the other two systems are comprised of a single basin.

Historically, these systems were structured differently than today. Wychmere Harbor was formed as a Cape Cod great salt pond" (Woodworth and Wigglesworth 1934) and had a small island or emergent bar within the tidal inlet (1890 Atlas of Barnstable County). Salt marsh does not appear to have been prevalent in Wychmere Harbor, which is consistent with the observed present day shoreline topography. In contrast, Allen Pond and Saquatucket Harbor contained significant salt marsh areas.

Josiah Paine, a prominent character in the history of the Town of Harwich wrote in *Paine's History of Harwich, Mass published 1937* that the Town of Harwich had no natural harbors. Wychmere, previously known as “Salt Pond” was still a salt pond with a small tidal brook that would not be made navigable until 1887. Similarly, Allen Harbor, historically known as Oyster pond or Gray's pond or even Gray's harbor, was a shallow, muddy-bottomed pond with a narrow outlet to Nantucket Sound and a narrow stream that flowed into the system from lowlands to the east. Allen Harbor has also been (and continues to be) modified to support navigation.

Saquatucket Harbor was originally a salt marsh formed by the flooding, by sea-level rise, of the valley created by present-day Carding Machine Brook from Grassy Pond and Cold Brook. The tidal channels filled with salt marsh until the system was dredged to form the present harbor basin. The tidal river was commonly referred to as Andrews River. The dredging of Saquatucket Harbor was to accommodate a burgeoning fishing fleet and commerce in Harwichport. Saquatucket harbor was dredged from the broad marshes surrounding Andrews River beginning in 1968, and was completed as the Town's municipal marina in 1969 to open in 1970. At present each of the basins is primarily open water.

Figure I-1. Study region for the Massachusetts Estuaries Project analysis of the Saquatucket Harbor System. Tidal waters enter the system from Nantucket Sound. Freshwater enters from the watershed through a combination of direct groundwater discharge, direct precipitation and stream flow from Carding Machine Brook (northwest stream) and Cold Brook (northeast stream). Note the remnants of what was historically the Andrews River, in the wetlands, particularly along the western shore.

Figure I-2. Study region for the Massachusetts Estuaries Project analysis of the Wychmere Harbor System. Tidal waters enter the system from Nantucket Sound. Freshwater enters from the watershed primarily through direct groundwater discharge and direct precipitation.

Figure I-3. Study area for the Massachusetts Estuaries Project analysis of the Allen Harbor System. Tidal waters enter the system from Nantucket Sound. Freshwaters enter from the watershed primarily through direct groundwater discharge, precipitation and a small creek entering from the northeast.

While the open water area of these systems make them look like harbors presently, in recent history Allen and Saquatucket Harbors supported salt marsh and tidal basins similar to lower Taylors Pond, Cockle Cove and lower Parkers River/Lewis Pond. As a result of the importance of navigation, these and many other salt marsh basins were "opened", see also Rock Harbor and Ellisville Harbor. In addition to anthropogenic alterations, natural processes continue to alter the configuration of these systems. The southern coast of Cape Cod in the vicinity of Allen Harbor, Wychmere Harbor and Saquatucket Harbor is a moderately dynamic region, where natural wave and tidal forces continue to reshape the shoreline (see Chapters II and V). In addition, these systems are both relatively young geologically (<10,000 yrs), with the salt marshes likely forming ~4,000 years ago.

Though the Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems presently show a moderate nitrogen load from their associated watersheds, they still appear impaired by nitrogen enrichment. This results from the interplay between nitrogen loading rates from the watershed, the relatively small size of the basins as receptors of the nutrient load and tidal exchange rates that are defined by the inlet channels that must be regularly maintained through dredging. This dredging also helps to sustain tidal exchange, which is critical to nitrogen management in these systems. It should be noted, however, that as nutrient loading increases with development or should tidal flushing be reduced, the relatively small size of these systems makes them sensitive to changes in nitrogen inputs.

While the nitrogen loads to the Wychmere, Allen, and Saquatucket Harbor systems are presently causing moderate impairments, nitrogen management planning is being presently undertaken by the Town of Harwich for the restoration of water quality and habitat within these estuaries. The Town of Harwich, along with other Cape Cod municipalities, has been among the fastest growing towns in the Commonwealth over the past two decades and does not have a centralized wastewater treatment system located within the town boundaries. As such, little to none of the land area contributing nitrogen to these three estuaries is presently serviced by municipal sewers. Wastewater treatment is almost entirely via privately maintained septic systems with the exception of facilities that hold discharge permits with the State. As existing and probable increasing levels of nutrients impact the coastal embayments of the Town of Harwich, water quality degradation will accelerate, with further harm to invaluable environmental resources.

As the stakeholder to the Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems, the Town of Harwich and its citizens have been active in promoting restoration of these systems. This local concern also led to the conduct of several studies (see Chapter II) to support management and restoration. The Town is presently undertaking the development of a Comprehensive Wastewater Master Plan in order to implement a unified nitrogen management program for the town that will restore its coastal resources impaired by watershed nitrogen inputs. An essential part of this effort by the Town, through the Harbormaster Office, has been the development and conduct of a Town-wide estuarine water quality monitoring program. As a result of this monitoring effort, the needed water quality baseline data required for entry into the Massachusetts Estuaries Project has been developed. In 2001, the nitrogen related water quality monitoring program was established throughout the coastal embayments of the Town of Harwich. The Town managed "Harwich Water Quality Monitoring Program" was provided technical assistance by the Coastal Systems Program at SMAST-UMD and has continued over the past several years to increase the accuracy of the MEP water quality module. This water quality monitoring effort provides the quantitative watercolumn nitrogen data (2001-2008) required for the implementation and validation of the MEP's Linked Watershed-Embayment Approach used in the present study.

The common focus of the Harwich effort over the past eight years has been to gather site-specific data on the current nitrogen related water quality throughout each of the Town's estuarine systems, including the three systems that are the focus of this investigation. The data collection was undertaken specifically to support quantitative determination of the relationship of water quality to tidal flushing and watershed nitrogen loads. This multi-year effort has provided the baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. The MEP effort builds upon the Water Quality Monitoring Program, and previous hydrodynamic and water quality analyses, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for each of the three embayments.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to develop and implement management alternatives needed by the Town of Harwich for estuarine restoration/protection. 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, the Water Quality Task Force and volunteers over many years, most notably within the Natural Resources Department. The modeling tools developed as part of this program provide the quantitative information necessary for the Town of Harwich to develop and evaluate the most cost effective management alternatives to restore and maintain its coastal resources.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

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

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

The Massachusetts Estuaries Project represents the next generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (MA 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 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 MassDEP and municipalities with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety (explicit and implicit conservatism) and seasonal variations. In addition, each TMDL must contain an outline of an implementation plan. For this project, the MassDEP recognizes that there are likely to be multiple ways to achieve the desired goals, some of which are more cost effective than others and therefore, it is extremely important for the Town of Harwich to further evaluate potential options suitable to its community. As such, MassDEP will likely be recommending that specific activities and timelines be further evaluated and developed by the Town through the Comprehensive Wastewater Management Planning process.

In appropriate estuaries, TMDLs for bacterial contamination have also been conducted in concert with the nutrient effort (particularly if there is a 303d listing). In these cases, the MEP (through SMAST) has produced a Technical Analysis and Report to support a bacterial TMDL for the system from which MassDEP develops the TMDL. The goal of the bacterial program is to provide information to guide targeted sampling for specific source identification and remediation.

In contrast to the bacterial program, the MEP nitrogen program also 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 70 out of 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 33 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-4). This methodology integrates a variety of field data and models, specifically:

- Watercolumn Monitoring - multi-year embayment nutrient sampling

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

I.2 SITE DESCRIPTION

Wychmere, Allen and Saquatucket Harbors are simple estuaries, each essentially comprised of a single embayment basin and tidal inlet. The open water area of these estuaries is <20 acres in all cases (Wychmere, 16ac; Allen,19ac; Saquatucket, 12ac) placing them among the smaller embayments of southeastern. Massachusetts. Each estuary exchanges tidal waters with Nantucket Sound through inlets that have been "fixed" by jetties, although maintenance dredging is required to maintain the inlets. Allen and Saquatucket Harbors were formed by tidal flooding of channels formed within the outwash deposits of Cape Cod by streams, while Wychmere Harbor formed as a salt pond.

All three estuaries are sited in the Chatham Outwash Plain, comprised of sands and gravels, chiefly pre-Wisconsin deposits. The result is permeable soils with little runoff and a permeable groundwater aquifer, with aerobic waters. Between each estuarine basin and the Sound, a barrier beach has developed from deposited sands and gravels. For the MEP analysis, the open water basin of each system is the principal estuarine basin in the modeling and thresholds analysis, as it is the main receptor of watershed inputs and supports the major estuarine habitats.

The (Wychmere, Allen, and Saquatucket Harbors are shallow, ~3m, ~2m and ~3m respectively and tend to be vertically well mixed, with only periodic stratification. Salt marsh is presently mainly found within Allen and Saquatucket Harbors, but historically the basins supported a much greater emergent marsh area. As indicated above, Saquatucket Harbor was functionally a tidal salt marsh with a central tidal river until 1968 when it was dredged to create the present harbor basin. The remnant salt marsh can still be seen along the eastern and western shores of the mid region of the basin (Figure I-1). Allen Harbor still supports a moderately sized and relatively healthy salt marsh in its northern reach, which exchanges waters with the main basin.

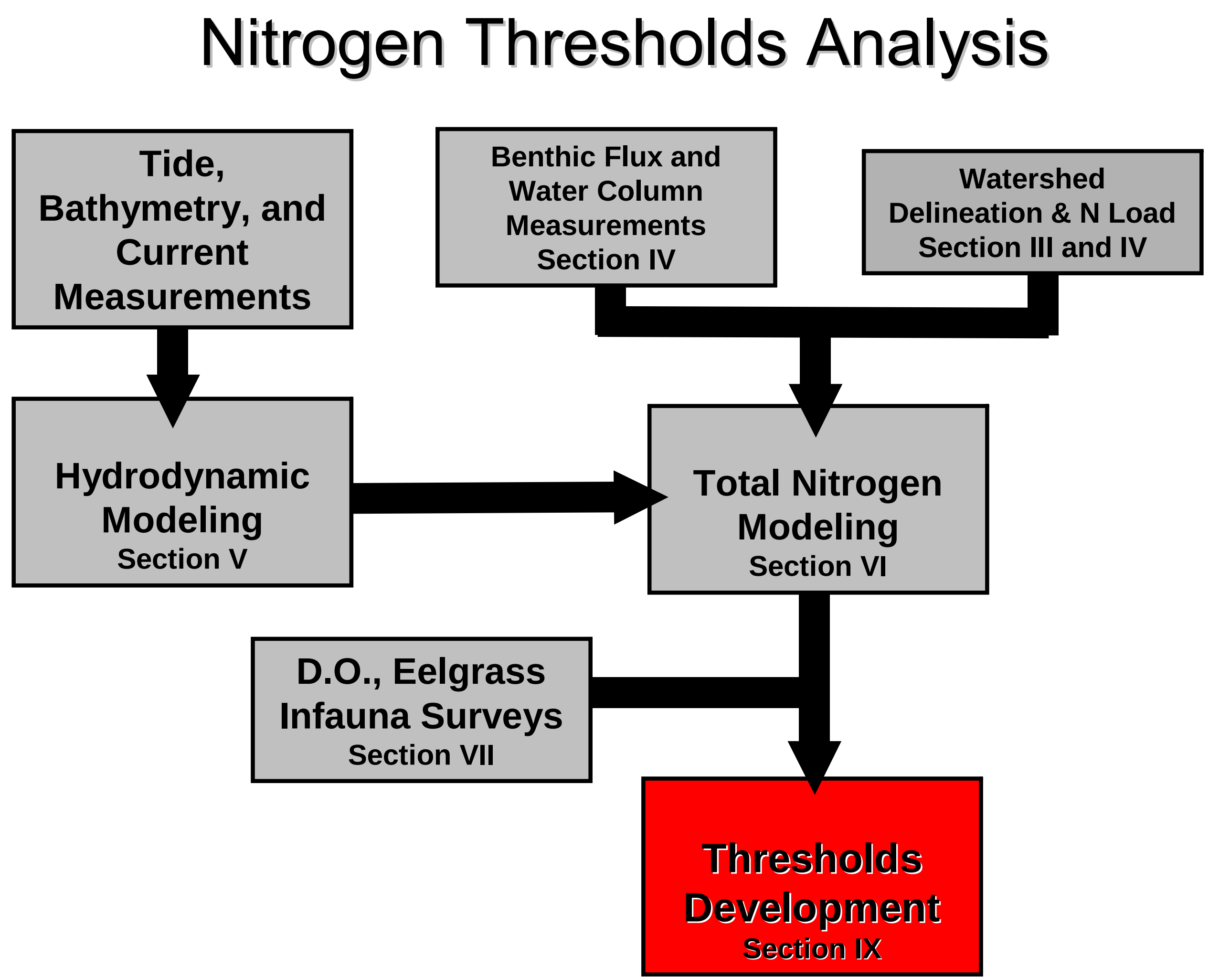


Figure I-4. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

At present, each of the estuaries is showing impairment by nitrogen enrichment, associated with watershed inputs. Each system is characterized by periodic summer phytoplankton blooms and depleted bottom water oxygen (hypoxia). The result, as observed in MEP surveys, are sediments consistent with nitrogen enrichment, with regions of soft organic/sulfidic muds and benthic animal communities dominated by transition and stress indicator species, although the organism numbers were high.

As management alternatives are being developed and evaluated, it is important to note that these systems are highly man-altered and in the case of Saquatucket Harbor and to a lesser extent Allen Harbor, are composed of "constructed" basins. However, all of these estuaries are fully functioning as estuarine basins at present and must be managed as such to attain the “maximum level of sustainable environmental health”, which should focus on restoring benthic animal habitats throughout.

While the nutrient related health of the these three estuaries as they exist today is linked to changes wrought by natural processes and human activities, it is the physical structure of the system laid down by the retreat of the Laurentide Ice Sheet that still controls much of the Systems’ tolerance to nutrient inputs. The physical structure (naturally or anthropogenically determined as the case may be), shape and depth of a coastal embayment plays a major role in its susceptibility to ecological impacts from nutrient loading. Physical structure (geomorphology), which includes embayment bathymetry, inlet configuration and saltwater reaches, when coupled with the tidal range of the adjacent open waters, determines the system’s rate of flushing. System flushing rate is generally the primary factor for removing nutrients from active cycling within coastal bays and harbors like Allen Harbor, Wychmere Harbor and Saquatucket Harbor. As a result maintaining or maximizing system flushing is one of the standard approaches for controlling the nutrient related health of coastal embayments, but not at the exclusion of nutrient management in the associated watersheds as appropriate.

By far the greatest changes to the watersheds of these three Harwich systems have also occurred during the last 100 years. The most obvious change has been the dramatic shift in land-use to residential housing during the last half of the 1900's. With this shift and the advent of fertilized lawns, has come an increase in the amount of nitrogen, which enters the estuary and is resulting in nutrient related habitat declines, such as loss of eelgrass and benthic animal communities. The previous large shifts in land-use, primarily from forest to agriculture did not have the same resultant enhancement in nitrogen loading, as agriculture generally recycled nitrogen (as opposed to commercial fertilizers) and the population was <10% of today.

The MEP analysis focused on determining the extent to which the environmental health of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor Systems will be enhanced by management of tidal exchange with the high quality waters of Nantucket Sound, relative to the potential need to manage watershed nutrient loading. The goal of the MEP and the local stakeholders is to restore the estuarine habitats within these harbor/estuarine systems to meet the high level of quality designated by the State Water Quality Standards for the benefit of both present and future generations.

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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems, 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 1996, 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 these three estuaries presently 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems monitored by the Town of Harwich Water Quality Monitoring Program, with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) utilized to "tune" general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately and to varying degrees, Allen Harbor, Wychmere Harbor and Saquatucket Harbor are presently beyond their ability to assimilate additional nutrients without impacting their ecological health. This is in significant part due to the increased development in the watersheds to each of these systems over the past 50 years. This increase in external nitrogen input has increased the phytoplankton production of these systems with consequent increases in rates of oxygen uptake and summertime nitrogen release from their sediments. The result is that today nitrogen levels are moderately elevated, benthic animal communities are representative of moderate system impairment and there are large summer phytoplankton blooms and periodic low oxygen conditions (hypoxia) in bottom waters. The result is that nitrogen management of these three estuarine systems should be aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed “eutrophication” and when the nutrient loading is primarily from human activities, “cultural eutrophication”. Although the influence of human-induced changes has increased nitrogen loading to the systems and contributed to the degradation in ecological health, it is sometimes possible that natural processes associated with the Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems could increase the effective level of nitrogen enrichment and must be considered in the nutrient threshold analysis, particularly in basins that are dominated by salt marsh. 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 into a “pristine” system, but in the case of the three small Harwich estuaries, it is clear that restoration of presently impaired habitat is the goal.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading and water quality data provide important “boundary conditions” (e.g. watershed derived and offshore nutrient inputs) for water quality modeling of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems; however, a thorough understanding of hydrodynamics is required to accurately project nitrogen concentrations within each system. Therefore, water quality modeling of tidally dominated 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 these three Harwich systems under a variety of nitrogen input (loading) and hydrodynamic conditions. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed. Once the hydrodynamic properties of each of the estuarine systems 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 nitrogen entering these systems is transported by freshwater, primarily through groundwater. Concentrations of total nitrogen and salinity of Nantucket Sound source waters and throughout Allen Harbor, Wychmere Harbor and

Saquatucket Harbor were taken from the Town of Harwich Water Quality Monitoring Program (a coordinated effort between the Town of Harwich and the Coastal Systems Program at SMAST, with additional Nantucket Sound data from the Nantucket Sound Monitoring Program[1]). Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of the Systems (2002-2008) 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems for the Town of Harwich. 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). 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. 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. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of the component sub-embayments was performed that included a review of existing water quality information and the results of a benthic analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of the Estuary in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined nitrogen threshold for restoration. This latter assessment represents only one of many solutions and is produced to assist the Town in developing a variety of alternative restoration options for this system. Finally, analyses of the three systems were relative to potential alterations of circulation and flushing, including an analysis of varying nitrogen loading alternatives developed by the Town of Harwich and its wastewater engineer. The results of the nitrogen modeling for each scenario have been presented (Section IX).

[1] A Nantucket Sound-wide water quality monitoring program conducted as a collaborative effort by Cape and Island Towns and NGO's and overseen by SMAST.

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 necessarily a part of the natural evolution of a system.

In most marine and estuarine systems, such as the Allen Harbor, Wychmere Harbor and Saquatucket Harbor Systems, 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor Systems. 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor Systems over the past decade.

Allen Harbor Dredging Project (completed November 2004) – As described by the Harwich Natural Resources Department, the Allen Harbor Dredging project for 2004 was completed November 4, 2004 by the Barnstable County Dredging Department. The County dredge team deepened the Allen Harbor entrance channel to its permit control depth of 6' at 100' width over 2800' by pumping 12,000 cubic yards of sand to nearby public and private beaches as determined by the Board of Selectmen. The Harbormaster allowed an additional 2,000 yards of material to be taken to reach the controlling depth. Material in this project had not been placed on the beaches east of Allen Harbor since 1998 when 2,417 cubic yards was placed at Wah Wah Taysee Road beach. While the inlet to Allen Harbor is armored to both the east and the west, the dynamic nature of the beach necessitates periodic dredging to maintain the navigability of the inlet channel to Allen Harbor in addition to the flushing of the system in general. Maintaining effective flushing of the estuarine system will have to be considered an integral part of the nutrient management plan for Allen Harbor, as well as for other of the Town's estuaries.

Along those lines, in 2008 the Town of Harwich received approvals from both the Army Corps of Engineers and the state of Massachusetts giving approvals for the town’s dredge and beach nourishment comprehensive permit. This permit was intended to facilitate the dredging of the Town of Harwich harbor channels in a unified manner and placing spoils on both public and private beaches. Prior to a comprehensive permit approach the town had several permits which expired at different times and were cumbersome for addressing immediate dredging needs. The comprehensive permit allows removal of up to 20,000 cubic yards of material from each of the four channels along Nantucket Sound (Saquatucket Harbor, Wychmere Harbor, Allen Harbor and the Herring River) and allows the dredge spoil to be utilized as beach nourishment. The permit allows dredging of channels to a maximum depth of eight feet.

Bacteria Study - While not generally linked to nitrogen loading, bacterial contamination is an issue in Cape Cod estuaries to the extent that it prevents shellfish harvest or cause closure of swimming beaches. As Harbors with active moorings and in some cases marinas, each of the three estuaries has shellfish harvest closures either for management purposes or conditionally based upon bacterial levels. As a result, an effort to identify bacteria sources is periodically undertaken. A detailed investigation of Allen Harbor was undertaken circa 2001 to support mitigation planning for the Allen Harbor watershed (Sterns & Wheler 2002). The study focused on identification of the most likely sources of fecal coliform in the watershed and made recommendations as to mitigation of those sources. The goal was the reduction in shellfish harvest closures and to enhance water recreation within the Harbor.

Water Quality Monitoring - The Town of Harwich, while 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 as Harwich also shares a common embayment, Pleasant Bay, with the Towns of Orleans and Chatham. While all the towns collaborate on sampling of Pleasant Bay via the Pleasant Bay Alliance, each Town operates a Water Quality Monitoring Program collecting water quality data on all of that town’s embayment systems, as is the case with Allen Harbor, Wychmere Harbor and Saquatucket Harbor. For Harwich and these three systems specifically, 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor Systems has been a coordinated effort between the Town of Harwich Natural Resources Department and the Coastal Systems Program at SMAST-UMD. The water quality monitoring program was initiated in 2001 with support from the Town of Harwich and has continued uninterrupted through the summer of 2009. While other monitoring programs in the study region shifted to a reduced sampling effort after three years of baseline water quality data were captured, the sampling program in Harwich has continued un-altered since inception and thus has developed an extremely robust water quality database which increases the certainty in the calibration and validation of the MEP water quality model. The Harwich Water Quality Monitoring Program for Allen Harbor, Wychmere Harbor and

Saquatucket Harbor developed the baseline data from sampling stations distributed throughout the main basins in each of the systems (Figures II-1, II-2).

Figure II-1. Town of Harwich Water Quality Monitoring Program for Saquatucket and Wychmere Harbors. Estuarine water quality monitoring stations sampled by the Town and volunteers. Stream water quality stations depicted in Chapter 4 sampled weekly by the MEP.

Figure II-2. Town of Harwich Water Quality Monitoring Program for Allen Harbor. Estuarine water quality monitoring stations sampled by the Town and volunteers. Stream water quality stations depicted in Chapter 4 sampled weekly by the MEP.

The water quality study also provided site-specific information indicating that each estuary is nitrogen limited, i.e. nitrogen is the nutrient that produces eutrophic conditions and is the nutrient that needs to be targeted for management. The analysis was based upon the Redfield ratio which is a general ratio developed for marine phytoplankton that indicates nitrogen limitation at molar ratios less than 16 (Redfield, 1934). The N/P molar ratio across all of the monitoring stations was less than 6.5, consistent with nitrogen as the target nutrient and similar to findings from all other similar estuaries throughout the MEP region. The Harwich Water

Quality Monitoring Program has documented periodic low oxygen events and phytoplankton blooms, which were also observed in the MEP surveys. One such phytoplankton bloom was observed in August 2001, where a dense marine euglena bloom occurred in Saquatucket Harbor. Similar blooms have been reported for Wychmere and Allen Harbors, as well as other estuaries on Nantucket Sound. They are typically found in nutrient enriched waters.

In addition to nutrients, the Town's program includes toxic phytoplankton monitoring through a partnership with the Massachusetts Phytoplankton Monitoring Program (coordinated with MassDMF). This program covers most state waters and is linked to a regional program within the Gulf of Maine. It is important for protection of public health related to shellfish harvest, but like bacterial monitoring, it addresses a public health issue rather than an environmental or habitat issue.

The "Three Harbors" of the Town of Harwich are a focal point of marine activity, evidence of the continuing ties of Harwich residents to their coastal resources. The Town relies on high quality waters of its estuaries for shellfishing and recreation. The Shellfish Laboratory has been operational for the past 17 years raising quahog seed for grow-out in Town waters and to support aquaculture programs. It is both an educational asset to the Town and attracts thousands of visitors each year.

As future remediation plans for these three harbor systems are implemented by the Town of Harwich, the Water Quality Monitoring Program will shift its focus to documenting improvements relative to meeting the targets set under the Federal Clean Water Act (TMDL's) and supporting adaptive management options. The Monitoring Program linked to some simple additional habitat measures is needed to indicate when restoration is complete and to track unanticipated changes in these dynamic coastal systems.

The Town of Harwich Water Quality Monitoring Program provided the quantitative water column nitrogen data (2001-2008) 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 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor Estuarine Systems. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for these three systems and to reduce costs to the Town of Harwich.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). The 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 to organize and analyze the available data use 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 Allen Harbor, Saquatucket Harbor, and Wychmere Harbor in the Town of Harwich. These estuaries are situated along the southern edge of Cape Cod and are bounded by Nantucket Sound. MEP staff have tried to establish a consistent naming convention for places mentioned in this report, but there may be some references where locations are referred to by different names. These differences may be somewhat unavoidable given that some of the places listed in the report have numerous names, including different ones on more conventional sources, such as US Geological Survey quadrangles and Google Earth, and in local references and discussions.

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 Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuary systems under evaluation by the Project Team. Further modeling of the estuary watersheds was undertaken to sub-divide the overall watersheds 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 gage 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 overall Monomoy groundwater flow cell. Model assumptions for calibration were matched to surface water inputs and flows from the most current stream gage information (2002-2004).

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 the stream and the portion of the groundwater system that discharges directly into the estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuary systems and their various subwatersheds, such as Cold Spring Brook and Paddocks Pond, were delineated using a regional model of the Monomoy 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. These modeled recharge areas are the primary basis for the estuary watersheds developed by the Massachusetts Estuaries Project. However, since the USGS uses regional models in the delineation process, the resulting recharge areas sometimes need to be adjusted to better reflect coastal and fresh pond shorelines and any new streamflow data collected since the development of the models. USGS and other MEP scientists work together to ensure that the final delineations are the best fit to all available data. This approach was used to determine the contributing areas to the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor systems and also to determine portions of recharged water that may flow through ponds and streams prior to discharging into the coastal water bodies.

The Monomoy Flow Model grid consists of 164 rows, 220 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 (Walter and Whealan, 2005). 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 525 feet below NGVD 29). 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. Since water elevations are less than +40 ft in the portion of the Monomoy Lens in which the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuaries reside, the three uppermost layers of the model are inactive.

The glacial sediments that comprise the aquifer of the Monomoy Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The sediments generally show a downwardly fining sequence 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 Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds are located in the Harwich Outwash Plain (Oldale 1992 or Chatham Plain by Woodsworth and Wigglesworth 1934), that were deposited as glacial ice lobes were retreating to positions near the current Cape Cod Bay shoreline and the barrier beach along the eastern edge of Pleasant Bay. The plains materials are generally composed of sand and gravel (Oldale, *et al*., 1971). Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from the USGS, local Town records and data from previous investigations. Final aquifer parameters 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 Town and water-level data.

The Monomoy Flow 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 municipal wastewater treatment facilities, water withdrawn from the modeled aquifer by public drinking water supply wells was evenly returned within designated residential areas utilizing on-site septic systems.

III.3 ALLEN HARBOR, SAQUATUCKET HARBOR, AND WYCHMERE HARBOR ESTUARY CONTRIBUTORY AREAS

Newly revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuarine systems (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 MEP Technical Team. The MEP sub-watershed delineations for these watersheds include selected 10 yr time of travel boundaries. Overall, Allen Harbor estuary watershed has three sub-watershed areas, Wychmere Harbor has one, and Saquatucket Harbor has nine, including Paddocks and Grass Ponds and Cold Spring Brook.

Table III-1 provides the daily freshwater discharge volumes for each of the subwatersheds as calculated by the groundwater model and these volumes were used to assist in the salinity calibration of the tidal hydrodynamic model and to determine hydrologic turnover in the lakes/ponds, as well as for comparison to measured surface water discharges. The overall estimated freshwater inflow into the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuaries from their respective MEP watersheds are: 2,129 m3/d, 13,302 m3/d, and 798 m3/d.

The delineations completed for this MEP analysis are the second watershed delineation completed in recent years for these estuaries. A pre-MEP delineation was completed by the Cape Cod Commission and was defined based on regional water table measurements collected from available wells over a number of years and normalized to average conditions (Eichner, *et al*., 1998). This analysis included data collected in Johnson and Davis (1988). The Commission's delineation was incorporated into the Commission's regulations through the three versions of the Regional Policy Plan (CCC, 1996, 2001, and 2009). Figure III-2 compares the Commission watershed delineation with the MEP delineation. The current revised watershed delineations add refined subwatershed delineations to the upgradient ponds (Paddock and Grass) and include subwatersheds to the streams entering Saquatucket Harbor, including Cold Spring Brook, and Allen Harbor.

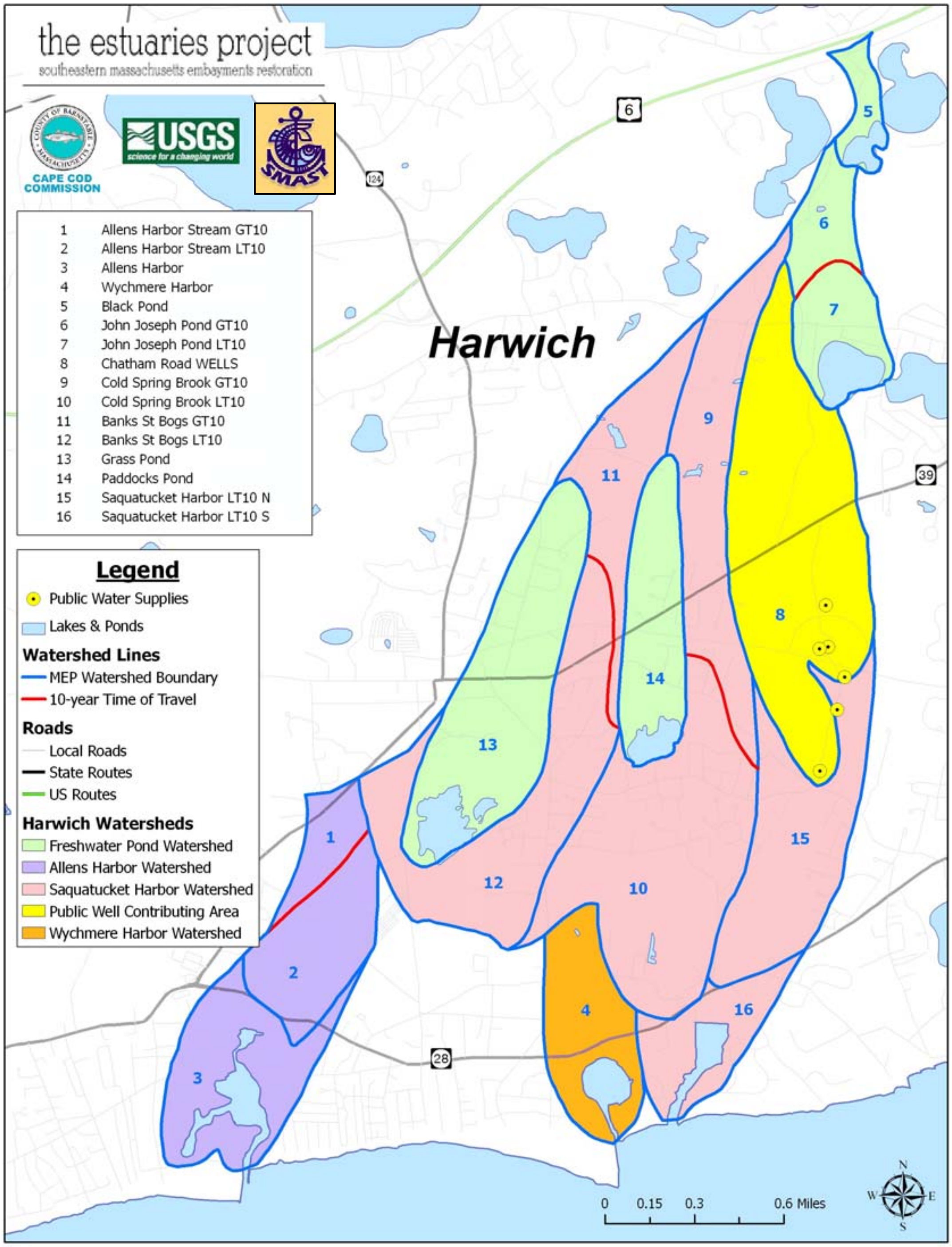


Figure III-1. Watershed delineations for Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuaries. Sub-watersheds were delineated based upon ponds, and stream, including gage locations, and the functional estuarine sub-units in the water quality model (see section VI).

Table III-1. Daily groundwater discharge to each of the sub-watersheds in the watersheds to Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuaries, as determined from the regional USGS groundwater model.

Watershed	#	Watershed Area (acres)	Discharge	
			m³/day	ft³/day
Allen Harbor Stream GT10	1	41	313	11,056
Allen Harbor Stream LT10	2	109	835	29,496
Allen Harbor	3	128	980	34,618
Wychmere Harbor	4	104	798	28,198
Black Pond	5	31	239	8,450
John Joseph Pond GT10	6	48	366	12,930
John Joseph Pond LT10	7	76	580	20,487
Chatham Road WELLS	8	334	2,561	90,435
Cold Spring Brook GT10	9	171	1,310	46,247
Cold Spring Brook LT10	10	308	2,366	83,556
Banks St Bogs GT10	11	110	848	29,936
Banks St Bogs LT10	12	233	1,785	63,046
Grass Pond	13	234	1,798	63,496
Paddocks Pond	14	116	889	31,391
Saquatucket Harbor GT10	15	182	1,398	49,383
Saquatucket Harbor LT10	16	78	597	21,069
Allen Harbor TOTAL			2,129	75,170
Wychmere Harbor TOTAL			798	28,198
Saquatucket Harbor TOTAL			13,302	469,747

Note: discharge volumes are based on 27.25 in of annual recharge over the watershed area; upgradient ponds often discharge to numerous downgradient subwatersheds, percentage of outflow is determined by length of downgradient shoreline going to each subwatershed. System totals will not be consistent with sum of subwatershed areas if portions of upgradient subwatersheds discharge outside of the overall system watershed.

Overall, the MEP contributing areas to the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuaries based upon the groundwater modeling effort are very different in area to the previous delineations based upon available well data and water table contours. These differences are largely due to incorporation of the measured streamflow information developed through the MEP. The watershed areas for the respective CCC delineations are 412 acres, 444 acres, and 462 acres for the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds and a total area among all three watersheds of 1,318 acres. In contrast, the watershed areas for the respective MEP delineations are 277 acres, 1,733 acres, and 104 acres for the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds and a total area among all three watersheds of 2,115 acres. The watersheds to all three systems are completely contained in Harwich and do not extend beyond town borders.

The large increase in the MEP watershed area is due to the better understanding of the Saquatucket Harbor watershed and the MEP streamflow measurements associated with the Cold Spring Brook system and the overall flows within this system taking into consideration ponds. The Cold Spring Brook watershed captures much of the recharge flow that was previously attributed to Wychmere Harbor, as well as the area between the CCC Wychmere

Harbor and Allen Harbor watersheds. Discussion of the streamflow information collected in Cold Spring Brook for the MEP is included in Chapter IV.2.

The evolution of the watershed delineations for the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuaries has allowed increasing accuracy as each new version adds new hydrologic data to that previously collected; the groundwater model allows all this data to be organized and to be brought into congruence with data from 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 downgradient estuary.

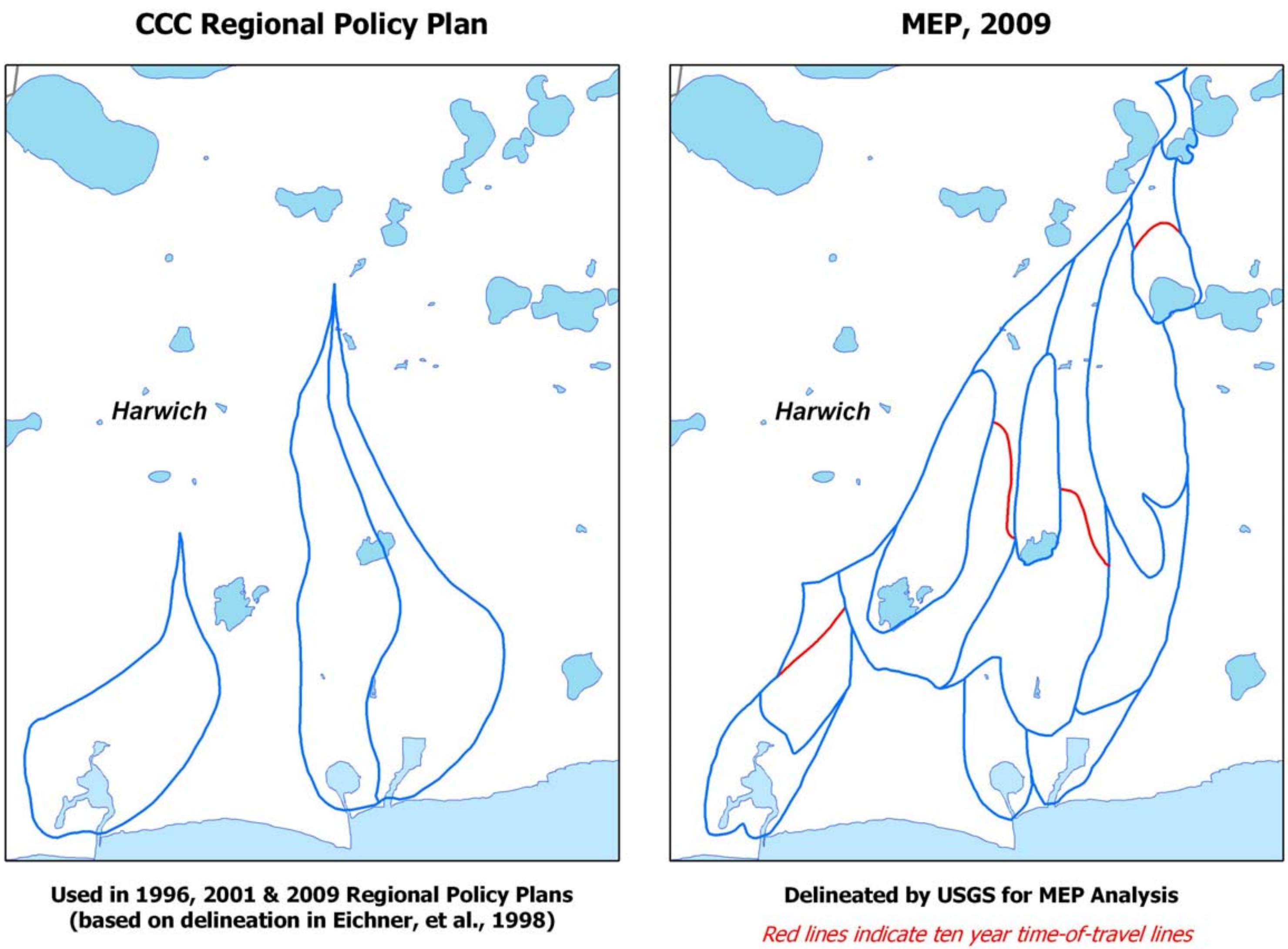


Figure III-2. Comparison of MEP watershed and subwatershed delineations used in the current analysis and the Cape Cod Commission delineation (Eichner, et al., 1998), which has been used in three Barnstable County Regional Policy Plans (CCC, 1996, 2001, and 2009). The major areal change stems from new data associated with the stream from Grassy Pond to Saquatucket Harbor.

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 Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuary systems. 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 effect results from biological processes that naturally occur within these 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.

In order to determine watershed nitrogen loading inputs to the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuary systems, the MEP Technical Team developed nitrogen-loading rates (Section IV.1) to each component of estuaries and their watersheds (Section III). This effort was completed with the assistance from staff from the Cape Cod Commission (CCC). The Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds were sub-divided to define contributing areas to each of the major inland freshwater systems and to each major sub-embayment. Further sub-divisions were made to identify watershed areas where a nitrogen discharge reaches estuary waters in less than 10 years or greater than 10 years. A total of 16 sub-watersheds were delineated for all three systems with three in the Allen Harbor estuary watershed, one in the Wychmere Harbor watershed, and twelve in the Saquatucket Harbor watershed, inclusive of the watersheds to Paddocks and Grass Ponds and Cold Spring Brook. 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 collections points, such as streams and ponds. Evaluation and delineation of ten-year time of travel zones are a regular part of the watershed analysis. Allen Harbor has one ten-year time of travel subwatershed, while Wychmere Harbor watershed is all within the ten-year groundwater travel time. Time of travel within the watershed to Saquatucket Harbor is a bit more complicated because the watershed contains multiple ponds and streams, Grass Pond and Paddocks Pond, Cold Spring Brook and the Chatham Road public water supply wells. Grass Pond and Paddocks Pond do not have ten-year time of travel subwatersheds meaning it takes ten years or less for groundwater in these watersheds to reach the ponds. Since the ponds themselves are within the less than ten-year time of travel watersheds to the Bank Street Bogs and Cold Spring Brook, respectively, nitrogen loads from the ponds reaches the estuaries in less than ten years. The public water supply capture area is more complex because it is removing some water and based on the development pattern, most likely redistributing it to subwatersheds with less than ten years time-of-travel to the estuaries. More refined modeling and data collection would be required to better ascertain flow times within the more complicated Saquatucket Harbor watershed system, however, in order to conservatively assess the groundwater flow within the public water supply capture area, project staff assumed that the area is a greater than ten year time-of-travel watershed. MEP staff also reviewed land use development records for the age of developed properties in the watersheds. Synthesis of this information indicates that Allen Harbor, Saquatucket Harbor, and Wychmere Harbor are currently in balance with their watershed load, and that 91%, 79%, and 100% of their respective unattenuated watershed nitrogen loads are within 10 years of groundwater time of travel to the estuaries (Table IV-1). The overall result of the timing of development relative to groundwater travel times is that the present watershed nitrogen load within the watershed to each estuary is an accurate representation of what is presently being discharged to estuarine waters (after accounting for natural attenuation, see below) and that the distinction between time of travel in the subwatersheds is not important for modeling existing conditions.

Table IV-1. Percentage of unattenuated nitrogen loads in less than 10 year time of travel subwatersheds to Allen Harbor, Saquatucket Harbor, and Wychmere Harbor. Based upon conservative assumptions (see text).

WATERSHED	LT10 kg/yr	GT10 kg/yr	TOTAL kg/yr	%LT10
Allen Harbor	2,454	243	2,696	91%
Wychmere Harbor	1,445	na	1,445	100%
Saquatucket Harbor	8,292	2,236	10,528	79%

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data are used for some portion of the loads, while information developed from other detailed studies is applied to other portions of the watersheds. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon subwatershed-specific land uses and pre-determined nitrogen loading rates. For the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuary systems, the model used Town of Harwich 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 alternative septic system monitoring). 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 Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds was determined based upon a site-specific study of streamflow and assumed attenuation in the up-gradient freshwater ponds. Streamflow was characterized in one stream discharging into Allen Harbor and two streams discharging into Saquatucket Harbor: Cold Spring Brook and another small stream discharge on the eastern edge, E. Saquatucket Stream. In contrast to Allen and Saquatucket Harbors, Wychmere Harbor receives all of its watershed freshwater discharge via direct groundwater discharge.

The unattenuated freshwater and nitrogen loads to the stream discharge points within Allen and Saquatucket Harbors based upon the nitrogen-loading sub-model were compared to direct measurements of freshwater flow and nitrogen transport at these sites over annual cycles (cf. Section IV.2). Attenuation of nitrogen during transport through the ponds was conservatively assumed to be 50% based on available monitoring of selected Cape Cod lakes; and was checked by calculations for the individual ponds based upon field data. Streamflow and N load 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, estimates of pond nitrogen attenuation were made in: Black Pond, Grass Pond, Paddocks Pond, and John Joseph Pond. If smaller aquatic features not 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 the evaluation of the watersheds, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the subwatersheds (1 per system) that discharge groundwater directly to the estuary without flowing through a pond, stream or well. Internal nitrogen recycling was also determined throughout the tidal reaches of the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor 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 digital parcel and tax assessor's data from the Town of Harwich. Digital parcels and land use/assessors data are from 2006. These land use databases contain traditional information regarding land use classifications (MassDOR, 2008) plus additional information developed by the town. 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 watersheds to Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuaries. Land uses in the study area are grouped into nine land use categories: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) recreational (golf course), 6) undeveloped, 7) agricultural, 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 (MassDOR, 2008). "Public service" in the MassDOR system is tax-exempt properties, including lands owned by government (*e.g.*, wellfields, schools, golf courses, open space, roads) and private non-profit groups like churches and colleges.

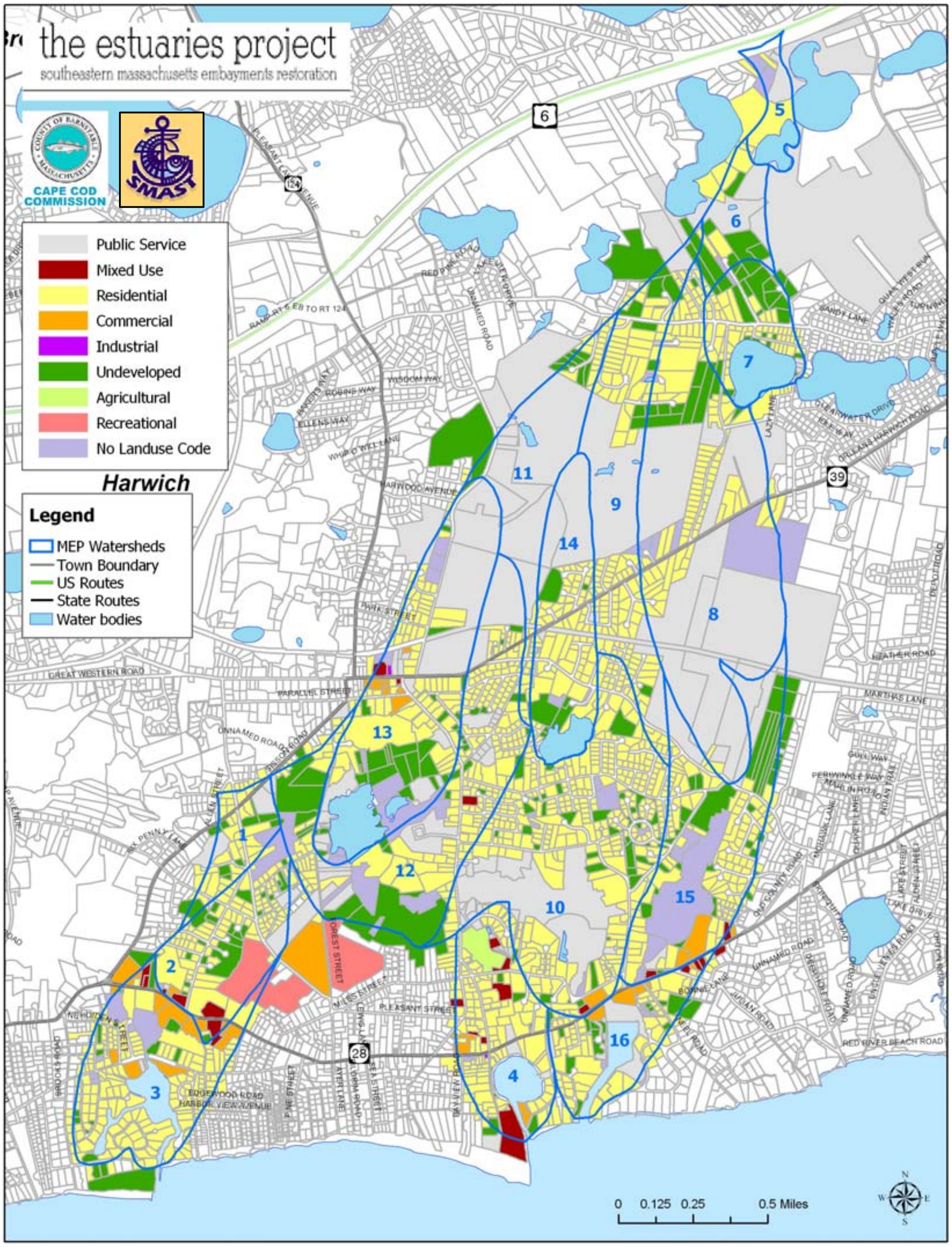


Figure IV-1. Land-use in the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds. All three watersheds are completely contained within the Town of Harwich. Land use classifications are based on 2006 assessors' records provided by the town.

The Allen Harbor and Wychmere Harbor watersheds have a similar land use breakdown, residential development is the predominant land use based on area in both watersheds. Residential parcels account for 54% of the Allen Harbor watershed area and 55% of the Wychmere Harbor watershed area (Figure IV-2). The second largest land use in both watersheds is public sector/right-of-way, which accounts for 15% and 16% of the overall watershed area, respectively. Mixed uses (*e.g.*, residential combined with commercial) also account for another 16% of the Wychmere Harbor watershed area. Other notable land use categories in the Allen Harbor watershed are undeveloped land (11%) and recreational (5%); the recreational land is a portion of the Harwichport Golf Course. Agricultural (9%) land uses is the other notable land use category in the Wychmere Harbor; this land use is a cranberry bog.

In the Allen Harbor and Wychmere Harbor watersheds, residential parcels are the predominant type of parcel. Residential parcels are 67% to 81% of all parcel types in the subwatersheds and account for 72% of the overall Wychmere Harbor watershed parcel count and 75% of the overall Allen Harbor watershed parcel count. Single family residences (MassDOR land use code 101) account for 85% and 94% of the residential parcels in the Wychmere Harbor and Allen Harbor watersheds, respectively. The next most frequent parcel type in the respective watersheds is undeveloped (12%) and mixed use (10%).

The land use pattern in the Saquatucket Harbor watershed presents a contrast to land use in the Allen Harbor and Wychmere Harbor watersheds. The predominant land use based on area is public service (41%), which is substantially due to the publicly-owned Cranberry Valley Golf Course, Town of Harwich lands preserved for public water supply wells and the protection of their water quality, and the former cranberry bog system on Cold Spring Brook, which is now owned by the Harwich Conservation Trust. The next largest percentage land use type is residential uses at 36%, followed by undeveloped land uses at 12%. Residential parcels are the most frequent parcel type in the watershed at 74%; undeveloped parcels are 13% of the total parcel count, while public service is 8%. Single-family residences (MassDOR land use code 101) are 97% of the residential parcels in the Saquatucket Harbor watershed.

In order to estimate wastewater flows within the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor study areas, MEP staff obtained four years of parcel-by-parcel water use information from the Town of Harwich Water Department (personal communication, Craig Weigand, Superintendent, 4/08). Water use from 2004 through 2007 was provided to the MEP and was linked to the parcel database by the Cape Cod Commission GIS Department staff. Measured water use is used to estimate wastewater-based nitrogen loading from the individual parcels; the final wastewater nitrogen load 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). All parcels are assumed to use on-site septic systems unless additional information is available.

MEP staff received state Groundwater Discharge Permit nitrogen effluent data from the MassDEP (personal communication, Brian Dudley, 2/09) and alternative, denitrifying septic system total nitrogen effluent data from the Barnstable County Department of Health and the Environment (personal communication, Sue Rask and Brian Baumgaertel, 2/09). Snow Inn, which is located adjacent to Wychmere Harbor, holds the only GWDP in the project study area. The BCDHE performance database shows 27 innovative/alternative septic systems for the Town of Harwich. Five IA systems are in the project study area; with four in the Saquatucket Harbor watershed and one in the Allen Harbor watershed. This data was used to develop wastewater nitrogen loads within the watersheds to the three harbors.

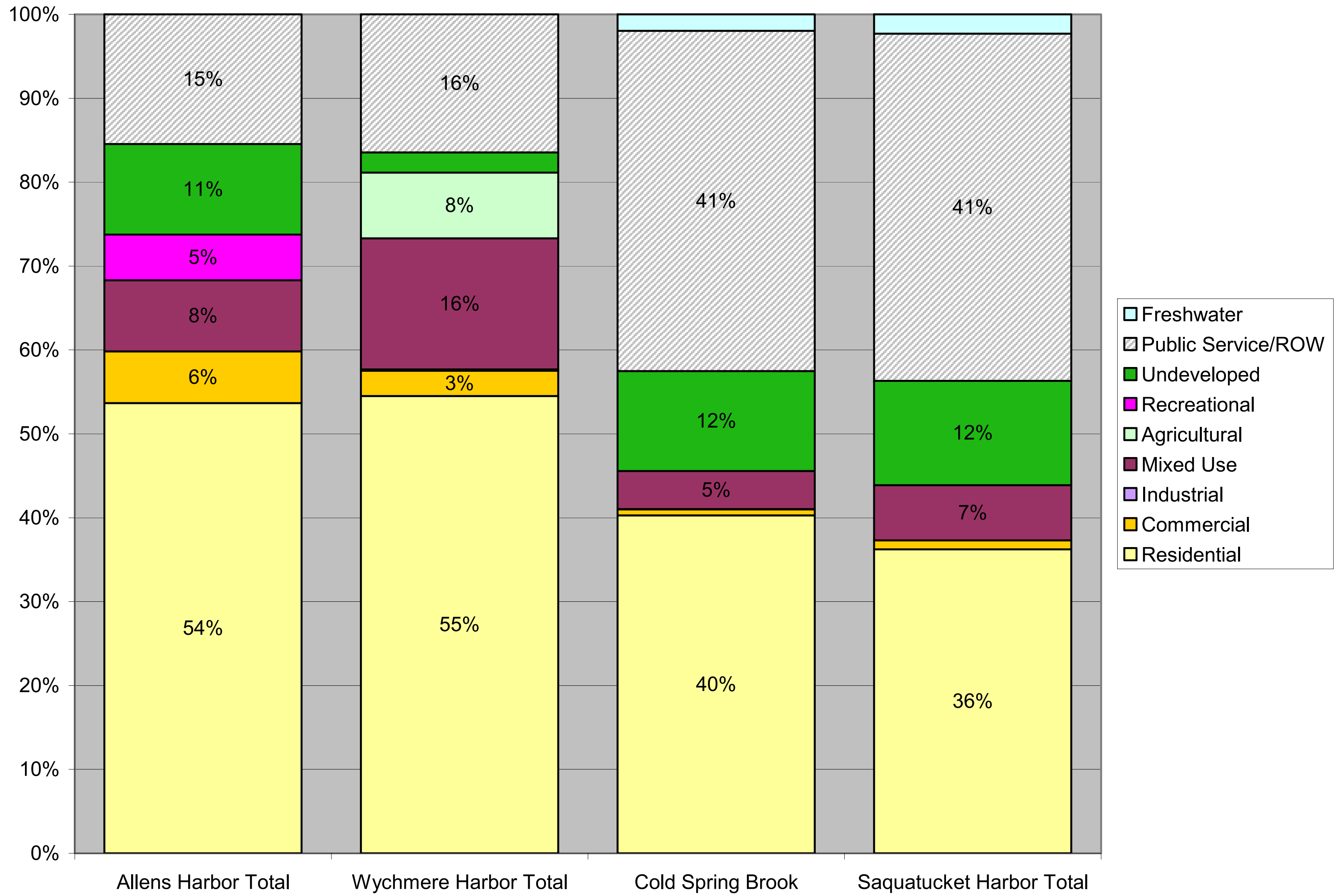


Figure IV-2. Distribution of land-uses by area within the Allen Harbor, Wychmere Harbor and Saquatucket Harbor, watersheds and the Cold Spring Brook subwatershed to Saquatucket Harbor. Only percentages greater than or equal to 3% are shown.

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 are linked to assessors parcel information using GIS techniques. The parcel specific water use data are converted to septic system nitrogen discharges (to the receiving aquatic systems) by adjusting for consumptive use (e.g. irrigation) and applying a wastewater nitrogen concentration. The water use approach focuses on the nitrogen load, which reaches the aquatic receptors down-gradient in the aquifer.

All nitrogen losses within the septic system are incorporated into the MEP analysis. For example, information developed at the 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).

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

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

While census based population data has limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water use based on average residential occupancy to measured average water uses. This is performed as a quality assurance check to increase certainty in the final results. This comparison has shown that the larger the watershed 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 are within 5% of that from the water use approach. This comparison matches some of the variability seen in census data itself. Census blocks, which are generally smaller areas of any given town, have shown up to a 13% difference in average occupancy 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 Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds, MEP staff reviewed US Census population values for the Town of Harwich. 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 Harwich is 2.26 people per housing unit with 58% of year-round occupancy of available housing units. Water records show average water use for single-family residences with municipal water accounts in the Harwich MEP study area to be 181 gpd. If this flow is multiplied by 0.9 to account for consumptive use, the study area average is 163 gpd. It is possible to develop a comparable residential wastewater production from the census data. If the state Title 5 estimate of 55 gpd per capita is multiplied by average Harwich occupancy (2.26 persons/residence), the average water use per residence would be estimated at 125 gpd. If it is assumed that seasonal properties are occupied at twice the year-round occupancy for three months, the average town-wide water use would be 156 gpd, which is approximately the same as that from the water use record.

At the outset of the MEP, project staff decided to utilize the water use approach for determining residential wastewater generation by septic systems because of the inherent difficulty in accurately gaging actual occupancy in areas impacted by seasonal population fluctuations such as most of Cape Cod. 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. This analysis suggests that water use, on average, is a reasonable estimate of wastewater generation within Harwich.

Although water use information exists for 98% of the 1,536 developed parcels in the combined Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds, there are 35 parcels that are assumed to utilize private wells for drinking water. Thirty-three of these are in the Saquatucket Harbor watershed. These are properties, that were classified with land use codes indicating development (*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 35 parcels, all but three of them are classified as single-family residences (land use code 101) and all of them are residential land uses. These parcels are assumed to utilize private wells and were assigned the Harwich study area average water use of 181 gpd in the watershed nitrogen loading modules.

Snow Inn Wastewater Treatment Facility

As mentioned previously, the Snow Inn maintains the only state-permitted wastewater treatment facility in the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor study area. The leach fields for the treatment facility are located within the watershed near the northern end of the channel connecting Wychmere Harbor to Nantucket Sound (personal communication, Paula Champagne, Town of Harwich Health Director, 1/09).

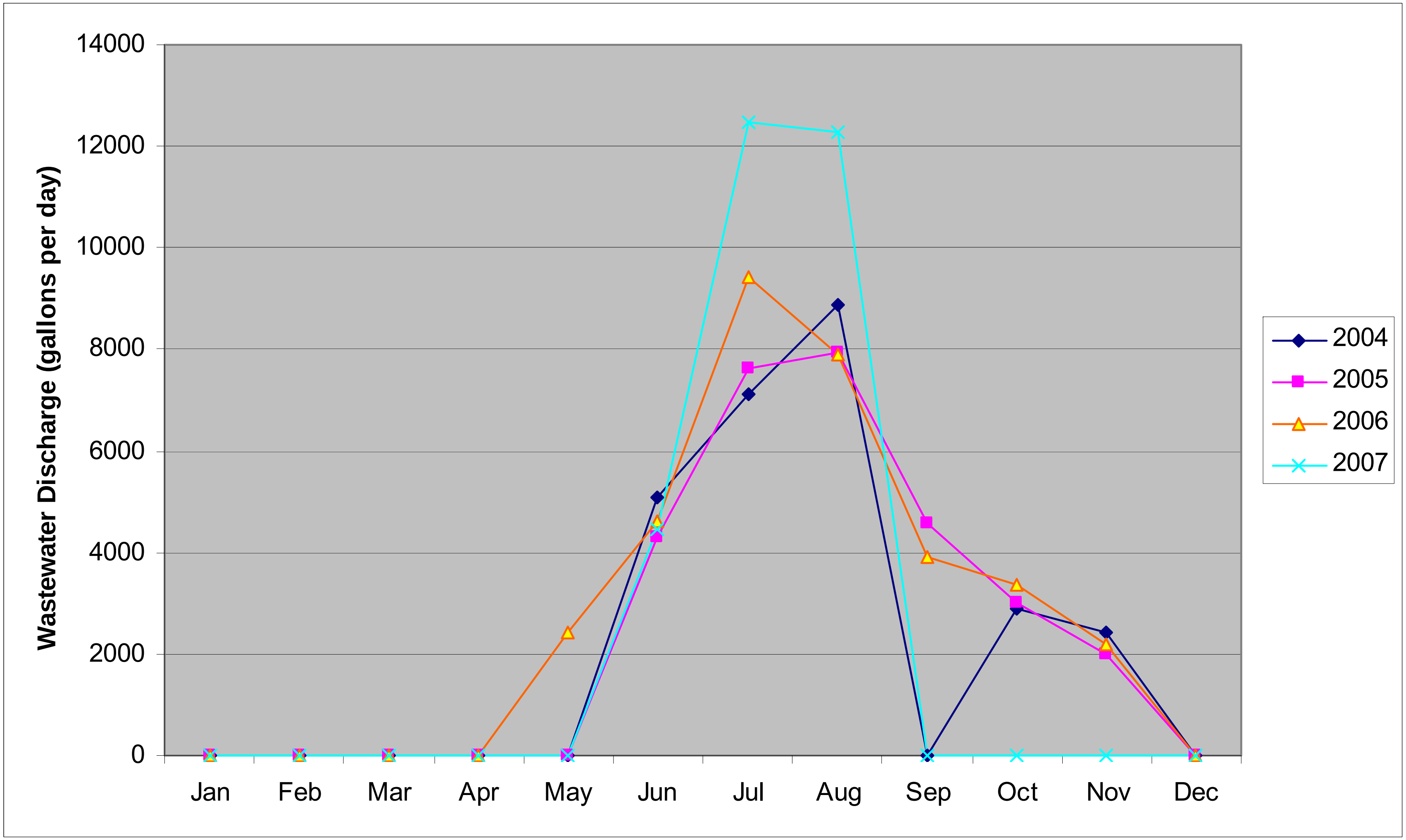


Figure IV-3. Total wastewater effluent discharge at the Snow Inn wastewater treatment facility (2004-2007). Original data provided by MassDEP (personal communication, B. Dudley, 2/09). The treatment facility is only used seasonally.

Effluent flow and total nitrogen concentration data were provided to MEP staff by MassDEP (personal communication, Brian Dudley, 2/09). This data covers the period from 2004 through 2007; most of the discharge occurs during June through November (Figure IV-3). Effluent total nitrogen concentrations range between 4.3 and 14.4 mg/l with a median concentration of 6.8 mg/l. The available dataset includes 21 monthly readings of effluent volume and total nitrogen concentrations recorded over the four year period. Conversion of monthly effluent flow to daily flow results in an average flow of 5,663 gallons per day when flow was recorded, an annual average of 2,478 gpd, and a range of 1,983 to 12,483 gpd. For the purposes of the watershed nitrogen loading modeling, MEP staff calculated monthly nitrogen loads and summed these to produce annual loads; these loads range between 21 (year 2004) and 28 kg/yr (year 2006). The average annual load over the four years is 24 kg/yr and this load is used in the annual watershed nitrogen loading estimates.

Alternative Septic Systems

As mentioned above, there are five innovative alternative, denitrifying septic systems in the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor study area that have total nitrogen effluent data in the Barnstable County Department of Health and the Environment database (personal communication, Sue Rask and Brian Baumgaertel, 2/09). Four of these systems are in the Saquatucket Harbor watershed and one is in the Allen Harbor watershed. These five systems have 5 to 16 effluent measurements each, showing average total nitrogen concentrations between 14.6 and 19.4 ppm except for one system (the FAST system owned by the Town of Harwich at Saquatucket Harbor) averaging 97 ppm. Project staff used these average measured effluent total nitrogen concentrations and the average measured water use from the town Water Department records to calculate average annual loads from each of these sites. These loads were incorporated into the nitrogen loading modules for Saquatucket and Allen Harbors.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and cranberry bogs, with residential lawns usually being the predominant source within this category. In order to add this source to the nitrogen loading model for the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor systems, MEP staff reviewed available regional information about residential lawn fertilizing practices and incorporated site-specific information for: 1) the portion of the Harwichport Golf Course in the Allen Harbor watershed, 2) the portion of the Cranberry Valley Golf Course in the Saquatucket Harbor watershed, and 3) the cranberry bogs in the Saquatucket and Wychmere Harbor watersheds. Cranberry bog nitrogen loading was determined based on previous studies conducted in southeastern Massachusetts, while MEP staff attempted to contact golf course superintendents to determine fertilizer application rates at the two golf courses.

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.

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 Sean Fernandez at the publicly-owned Cranberry Valley Golf Course to obtain current (2/09) information about fertilizer application rates. 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 Cranberry Valley Golf Course, Mr. Fernandez reported the following annual nitrogen application rates (lbs/1,000 ft^2) for the various turf areas: greens, 2.5; tees, 3.5; fairways, 3.5, and rough, 1.5. Numerous attempts to obtain similar information from a representative from the Harwichport Golf Course were unsuccessful. In the nitrogen loading calculations, MEP staff used average nitrogen application rates developed from 14 other golf courses (lbs/1,000 ft^2): greens, 3.8; tees, 3.5; fairways, 3.3, and rough, 2.5.

As has been done in all MEP assessments, MEP staff reviewed the layout of the two golf courses from aerial photographs, classified the turf types, and, using GIS, assigned these areas to the appropriate subwatersheds. The respective nitrogen application rates were then applied to these areas, a 20% leaching rate was applied, and annual load by subwatershed was calculated.

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 digitized 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 Saquatucket and Wychmere Harbor watersheds.

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 Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds are summarized in Table IV-2.

Road areas are based on MassHighway GIS information, which provides road width for various road segments. MEP staff utilized the Cape Cod Commission GIS to sum these segments and their various widths by subwatershed. Project staff also checked this information against parcel-based rights-of-way.

Table IV-2. Primary Nitrogen Loading Factors used in the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Harwich 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:	181 gpd
Wastewater Coefficient	23.63		
Snow Inn wastewater facility			
Average effluent Flow (gallons per day)	4,583		
Effluent Total Nitrogen concentration (mg/l)	6.8	Existing developed parcels w/water accounts:	Measured annual water use
Fertilizers:		Commercial and Industrial Buildings without/WU and buildout additions	
Average Residential Lawn Size (sq ft)*	5,000	Commercial	
Residential Watershed Nitrogen Rate (lbs/lawn)*	1.08	Wastewater flow (gpd/1,000 ft2 of building):	236
Cranberry Bogs nitrogen application (lbs/ac)	31	Building coverage:	13.2%
Cranberry Bogs nitrogen attenuation	34%	Industrial	
Nitrogen Fertilizer Rate for golf courses, cemeteries, and public parks determined from site-specific information		Wastewater flow (gpd/1,000 ft2 of building):	78
Average Single Family Residence Building Size from watershed data (sq ft)	1,216	Building coverage:	14.5%

In addition to these other factors, MEP staff also determined nitrogen loading estimates for farm animals. Project staff obtained locations of farms and counts of various animal species from the Town Health Director (personal communication, Paula Champagne, 3/08). Using nitrogen loading factors developed for individual farm animals in previous MEP analyses (Howes *et al.*, 2007) and GIS techniques, project staff determined nitrogen loading estimates for each farm and assigned the load to the appropriate subwatershed. Among Allen Harbor, Saquatucket Harbor, and Wychmere Harbor systems, only Saquatucket Harbor had farm animals within its watershed. Five animal types and a total of twenty animals are located in the Saquatucket Harbor watershed: 12 horses, 1 goat, 2 sheep, 3 rabbits, and 2 turkeys. The total unattenuated nitrogen load from all these animals is 166 kg/y.

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 subwatershed and the sum of the area of the parcels within each subwatershed. The resulting "parcelized" watersheds to Allen Harbor, Saquatucket Harbor, and Wychmere Harbor 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 Allen Harbor, Saquatucket Harbor, and Wychmere Harbor estuaries. The assignment effort was undertaken to better define sub-watershed loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Following the assignment of all parcels, subwatershed modules were generated for each of the 16 sub-watersheds in the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor study area. These subwatershed modules summarize, among other things: water use, parcel area, frequency, sewer connections, private wells, and road area. The individual sub-watershed modules were then integrated to create an Allen Harbor, Saquatucket Harbor, and Wychmere Harbor Watershed 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 Allen Harbor, Saquatucket Harbor, and Wychmere Harbor 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-c). 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.

One of these attenuation adjustments occurs in the freshwater ponds. 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. In the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor study area, this only occurs in John Joseph and Black ponds. At John Joseph, for example, the pond has a down-gradient shoreline of 1,121 feet; 27% of that shoreline discharges into the Chatham Road Well subwatershed (watershed 8 in Figure IV-1), while the remainder is discharged outside of the Saquatucket Harbor watershed. So the nitrogen load received in the Chatham Road Well subwatershed is 27% of the attenuated load that leaves John Joseph Pond.

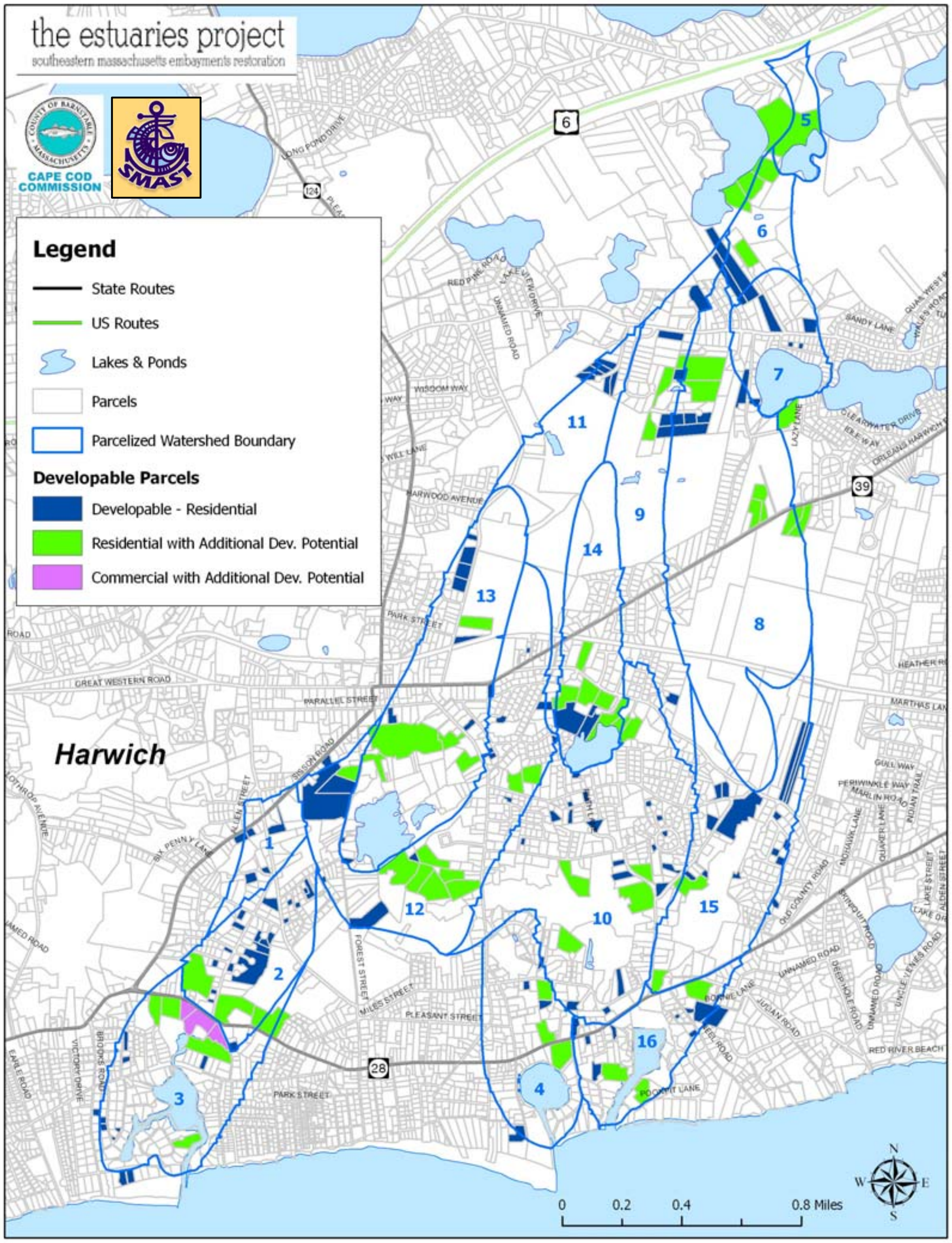
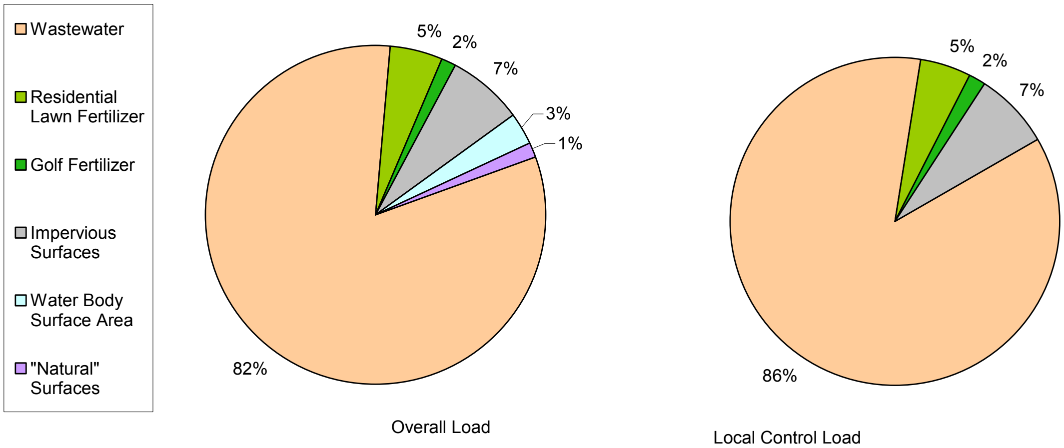


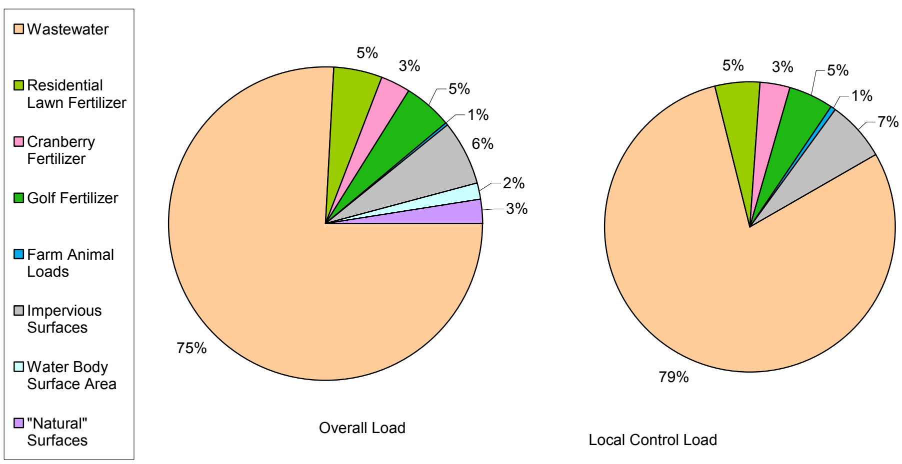
Figure IV-4. Parcels, Parcelized Watersheds, and Developable Parcels in the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds.

Table IV-3. Allen Harbor, Saquatucket Harbor, and Wychmere Harbor Watershed Nitrogen Loads. Attenuation of nitrogen loads occurs as nitrogen moves through up-gradient ponds, wetlands and streams during transport to the estuary in the Saquatucket and Allen Harbor watersheds. Attenuated loads in Saquatucket Harbor watershed include additional interim attenuation in up-gradient freshwater ponds. It should be noted that Cranberry and Golf Fertilizer totals are components of the Total Fertilizer Load. All values are kg N yr-1.

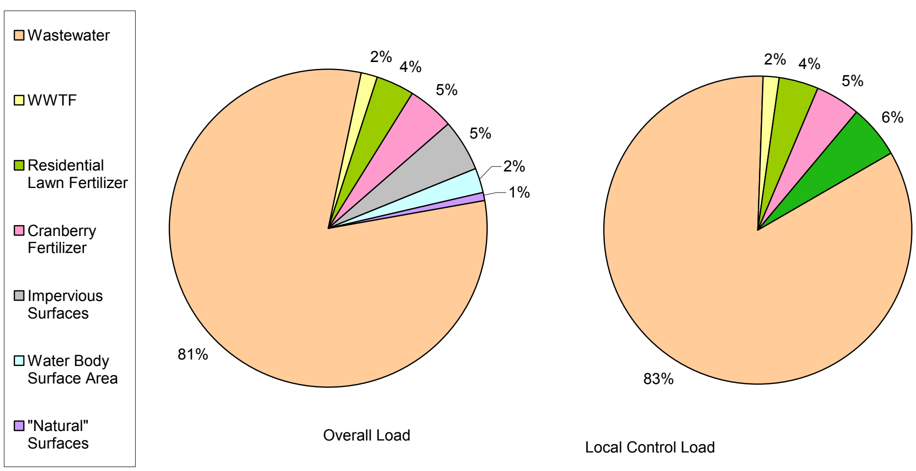
		Harwich N Loads by Input (kg/y):										***Present N Loads***			***Buildout N Loads***		
Name	**Watershed ID#**	**Wastewater**	**WWTF**	**Total Fertilizers**	**Cranberry Fertilizer**	**Golf Fertilizer**	**Farm Animal Loads**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Allens Harbor Total		**2281**	**0**	**179**	**0**	**44**	**0**	**197**	**83**	**40**	**514**	**2779**		**2492**	**3293**		**2929**
Allens Pond Stream Total		743	0	96	0	38	0	98	0	22	253	958	30%	671	1212	30%	848
Allens Harbor Estuary Surface									83			83		83	83		83
Wychmere Harbor Total		**1171**	**24**	**125**	**68**	**0**	**0**	**78**	**71**	**14**	**40**	**1483**		**1483**	**1523**		**1523**
Wychmere Harbor Estuary Surface									71			71		71	71		71
Saquatucket Harbor Total		**8039**	**0**	**1354**	**342**	**502**	**56**	**679**	**181**	**273**	**1378**	**10583**		**6349**	**11961**		**7117**
Cold Spring Brook Total		5753	0	1105	342	375	56	521	102	176	947	7713	35%	3833	8659	35%	4238
E Saquatucket Stream		1357	0	220	0	127	0	109	25	85	338	1796	15%	1441	2134	15%	1711
Saquatucket Harbor Estuary Surface									55			55		55	55		55



a. Allen Harbor



b. Saquatucket Harbor



c. Wychmere Harbor

Figure IV-5 (a-c). Land use-specific unattenuated nitrogen load (by percent) to the (a) Allen Harbor watershed, (b) Saquatucket Harbor subwatershed, and (c) Wychmere Harbor subwatershed. “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 subwatershed) and attenuated nitrogen loads.

Nitrogen attenuation in freshwater ponds has generally been found to be at least 50% in MEP analyses, so the watershed model assigns a conservative attenuation rate of 50% to all nitrogen from freshwater pond watersheds. 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 minimum 50% attenuation factor. However, in some cases, sufficient monitoring information is available, to develop a pond-specific attenuation rate for incorporation into the watershed nitrogen loading modeling (Howes, et al., 2006). In order to review whether a nitrogen attenuation rate higher than 50% should be used for a specific pond, the MEP Technical Team reviews the available data on each pond, including available nitrogen concentrations, impacts of sediment regeneration, temperature profiles, and bathymetric information.

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

In addition to bathymetry, temperature profiles are useful to help understand whether temperature stratification is occurring in a pond. If the pond has an epilimnion (*i.e.*, a well mixed, relatively isothermic, warm, upper portion of the water column) and a hypolimnion (i.e., a deeper, colder layer), the stability and volume of these two layers must be accounted for in the nitrogen attenuation calculations. Deep lakes with hypolimnions often also have significant sediment regeneration of nitrogen that should also be included in consideration of nitrogen attenuation.

Among the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds, only the Saquatucket Harbor watershed has ponds in it: John Joseph Pond, Black Pond, Paddocks Pond and Grass Pond. Of these ponds, only John Joseph has available both bathymetric information and water quality data. Available water quality monitoring data collected through 2008 by town volunteers, including laboratory samples analyzed through the annual Cape Cod Pond and Lake Stewards (PALS) Snapshots and town-funded activities, show that Black and Paddocks Ponds have not been sampled, while Grass Pond has only six samples. Fortunately, John Joseph Pond has been well sampled with over 60 samples collected at various depths for integration with the bathymetric information. PALS Snapshots are regional volunteer pond sampling supported for the last eight years by SMAST and the Cape Cod Commission, with free laboratory services provided by the Coastal Systems Analytical Laboratory at SMAST. After reviewing aerial photography of Black, Paddocks, and Grass Ponds, it appears that a high percentage of their surface area is covered with aquatic macrophytes. This condition suggests that these ponds are relatively shallow and are unlikely to have temperature stratification. For Grass, Black, and Paddocks ponds, the standard 50% pond attenuation rate has been assigned given the limited available information.

For John Joseph Pond, 31 surface water total nitrogen samples have been collected through town monitoring and various PALS Snapshots mostly between 2005 and 2008 with single readings collected between 2002 and 2004. Readings have been collected between June and September, but most of the data has been collected in July and August. Sampling runs have generally followed PALS protocols (Eichner *et al*., 2003), which means that sampling has included field collection of temperature and dissolved oxygen profiles and sampling has generally occurred at standardized depths that provide some evaluation of potential sediment nutrient regeneration. PALS water samples are analyzed at the SMAST analytical facility for total nitrogen, total phosphorus, chlorophyll *a*, alkalinity, and pH.

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.

Review of available data in John Joseph Pond shows sediment regeneration occurring, so for the purposes of calculating estimated nitrogen attenuation only surface total nitrogen concentrations were reviewed. Based on this analysis, John Joseph Pond removes 74% of the nitrogen entering it from its watershed and available information is sufficient to utilize this attenuation factor. Monitoring of other ponds within the Saquatucket Harbor watershed is insufficient to support use of a factor different than the MEP standard 50% attenuation. No ponds in the Allen Harbor or Wychmere Harbor watersheds have separate subwatersheds delineations. Table IV-4 presents the turnover times and attenuation factors for the ponds in the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds.

Table IV-4. Nitrogen attenuation by Freshwater Ponds in the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds based upon 2001 through 2008 town volunteer sampling and 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. All ponds in these watersheds are assigned the standard MEP nitrogen attenuation value of 50% except for John Joseph, which has sufficient information to utilize a pond-specific value of 74%.

Pond	PALS ID	Area acres	Estuary Watershed	Maximum Depth m	Upper volume turnover time yrs	# of TN samples for N Attenuation calculation	N Load Attenuation %
John Joseph	HA-416	20.6	Saquatucket	17	0.2	31	74%
Grass	HA-579	14.3	Saquatucket	0.5 est.	No Bathymetric Map	6	Not calculated due to lack of bathymetry
Paddocks	HA-569	8.4	Saquatucket	unknown		0	
Black	HA-364	9.2	Saquatucket			0	
						Mean	74%
						std dev	n/a

Data sources: all areas from CCC GIS; estimated Max Depth for Grass Pond based on sampling from Cape Cod PALS monitoring; TN concentrations for attenuation calculations are surface concentrations from town monitoring and annual PALS Snapshot provided by SMAST lab; John Joseph bathymetry from MassDFW bathymetric maps (www.mass.gov/dfwele/dfw/dfw_pond.htm

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development within the study area watersheds. The MEP buildout is relatively straightforward: residential parcels classified by the town assessor as developable are divided by minimum lot sizes specified in town zoning and the result is rounded down. For example, a 81,000 square foot lot classified by the town assessor as a developable residential lot (land use code 130) is divided by the 40,000 square foot minimum lot size specified in town zoning and the result is rounded down to two additional residential lots at buildout. Properties classified by the Town of Harwich assessors as “undevelopable” (*e.g.*, MassDOR codes 132, 392, and 442) are not assigned any development at buildout. Commercial and industrial properties classified as developable are not subdivided; the area of each parcel and the factors in Table IV-3 are used to determine a wastewater flow for these properties. Pre-existing lots classified by the town assessor as developable are also treated as developable even if they are less than the minimum lot size specified in zoning. Existing developed residential properties that are larger than zoning’s minimum lot sizes are also assigned additional development potential if enough area is available to accommodate at least one additional lot as specified by the zoning minimum. This buildout approach is the initial first step in a MEP buildout assessment; results from this analysis are then discussed with town planners and, occasionally, town planning boards and wastewater consultants.

Following the completion of the initial buildout assessment for the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds, MEP staff reviewed the results with Harwich officials. The majority of these discussions were with Sue Leven, the town planner at the time of their preparation, and Frank Sampson, Chair of the Town-Wide Water Quality Management Task Force. Buildout was also discussed with Elizabeth Hude as well as the previous town planner and David Spitz, the current town planner. The final MEP buildout analysis incorporates modifications to the standard MEP buildout stemming from these discussions. All the parcels included in the buildout assessment of the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds are shown in Figure IV-3.

Overall, each additional residential, commercial, or industrial property added at buildout is assigned nitrogen loads for wastewater and impervious surfaces. Residential additions also include lawn fertilizer additions. In Harwich, all wastewater loads are assumed to come from on-site septic systems. Cumulative unattenuated buildout loads are indicated in a separate column in Table IV-3. Buildout additions within the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor watersheds will increase the respective unattenuated loading rates by 18%, 13%, and 3%.

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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor Systems being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1).

If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such as the developed regions of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor watersheds). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. However, in most watersheds in southeastern Massachusetts, nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the watershed for these three embayment systems, a portion of the freshwater flow and transported nitrogen passes through several surface water systems (e.g. Cold Brook and Carding Machine Brook into Saquatucket Harbor and a small creek passing under Kildee Road discharging into Allen

Harbor) 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 in these three Town of Harwich embayment systems. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the perimeter of the embayment systems 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 3 major surface water flow systems in the respective watersheds, 1) Cold Spring Brook discharging to the western portion of the head of Saquatucket Harbor, 2) East Saquatucket Stream discharging to the eastern portion of the head of Saquatucket Harbor and 3) a small un-named creek passing under Kildee Road and discharging to the head of Allen Harbor and an associated salt marsh (Figures IV-6 and 7). Wychmere Harbor is devoid of any streams and therefore no stream gaging was undertaken in that embayment system.

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 gaging 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 gaging location (Figures IV-8 to IV-10). 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).

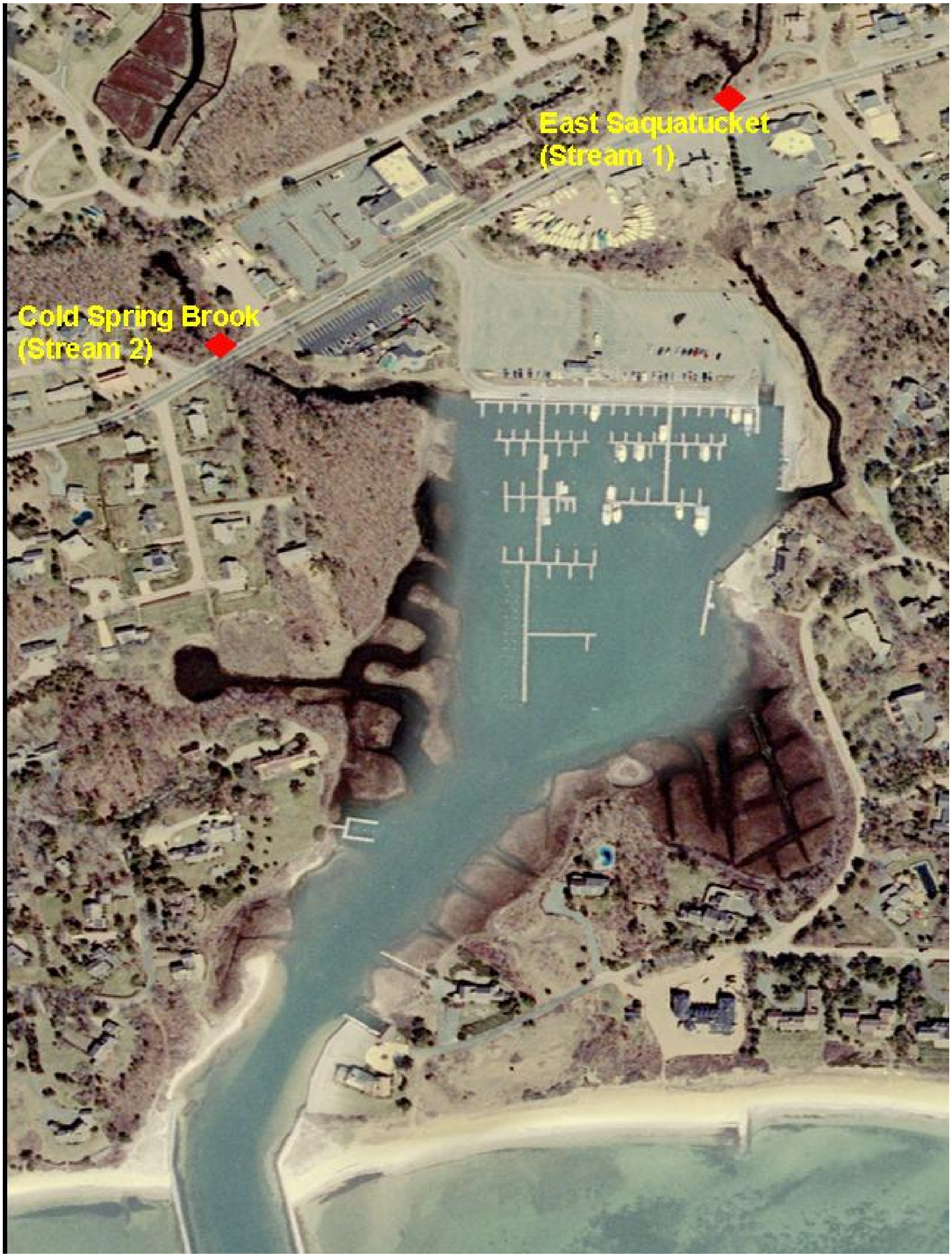


Figure IV-6. Location of Stream gages (red symbols) in the Saquatucket Harbor Estuarine System. Gages are placed as far down-gradient in the watershed as possible to capture watershed discharge, but be outside of tidal influence.

Figure IV-7. Location of Stream gage (red symbols) in the Allen Harbor Estuarine 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 were averaged to obtain hourly stages for a given river. These hourly stages values were then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. In the case of tidal influence on 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 Saquatucket and Allen Harbor embayment systems (Table IV-5 and summarized in Table IV-6).

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 head of the Saquatucket Harbor and Allen Harbor systems. 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 gaging 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 gaged stream currently reduces nitrogen loading (percent attenuation) to the overall embayment systems.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Cold Spring Brook (Stream 2) Discharge to Western Portion of Head of Saquatucket Harbor

Grass Pond, located up gradient of the Cold Spring Brook 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 (e.g. Paddocks Pond) along its down-gradient shore. This stream outflow, Cold Spring Brook, 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 Bogs, wetlands and streambed associated with Cold Spring 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 Cold Spring Brook above the gage site and the measured annual discharge of nitrogen to the tidal portion of the Saquatucket Harbor system, Figure IV-6.

At the Cold Spring Brook gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the freshwater portion of the Cold Spring Brook-Saquatucket Harbor estuarine system that carries the flows and associated nitrogen load to the near shore waters of Nantucket Sound. As portions of the lower portion of Cold Spring Brook is tidally influenced, the gage was located as far down gradient along the Cold Spring Brook reach such that freshwater flow could be measured at low tide. 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 Cold Spring Brook was installed on May 22, 2004 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 December 20, 2005 for a total deployment of 19 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 Cold Spring Brook 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 head of Saquatucket Harbor from Cold Spring Brook, reflective of the biological processes occurring in the up-gradient bogs contributing to nitrogen attenuation (Figure IV-8 and Table IV-5). 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 Cold Spring 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 Cold Spring Brook was 13% above 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 10,328 m^3/day compared to the long term average flows determined by the USGS modeling effort (8,995 m^3/day).

Table IV-5. Comparison of water flow and nitrogen discharges from Rivers and Streams (freshwater) discharging to estuarine systems of Harwich. The "Stream" data are from the MEP stream gaging effort. Watershed data are based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	(Stream 1) **E. Saquatucket Stream Discharge**[(a)] Saquatucket Hrb.	(Stream 2) **Cold Spring Brook Discharge**[(a)] Saquatucket Hrb.	**Un-named Crk. Discharge**[(a)] Allens Harbor	**Data Source**
Total Days of Record	365[(b)]	365[(b)]	365[(b)]	(1)
Flow Characteristics				
Stream Average Discharge (m3/day) **	3,929	10,328	1,905	(1)
Contributing Area Average Discharge (m3/day)	3710	8995	1148	(2)
Discharge Stream 2004-05 vs. Long-term Discharge	6%	13%	40%	
Nitrogen Characteristics				
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.63	0.672	0.505	(1)
Stream Average Total N Concentration (mg N/L)	0.987	0.961	0.938	(1)
Nitrate + Nitrite as Percent of Total N (%)	64%	70%	54%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	3.88	9.93	1.79	(1)
TN Average Contributing UN-attenuated Load (kg/day)	4.92	21.13	2.62	(3)
Attenuation of Nitrogen in Pond/Stream (%)	21%	53%	32%	(4)

(a) Flow and N load to streams discharging to Saquatucket and Allens Harbor includes apportionments of Pond contributing areas.
(b) September 1, 2004 to August 31, 2005.
** Flow is an average of annual flow for 2004-2005

(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 Saquatucket Harbor and Allens Harbor;
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.

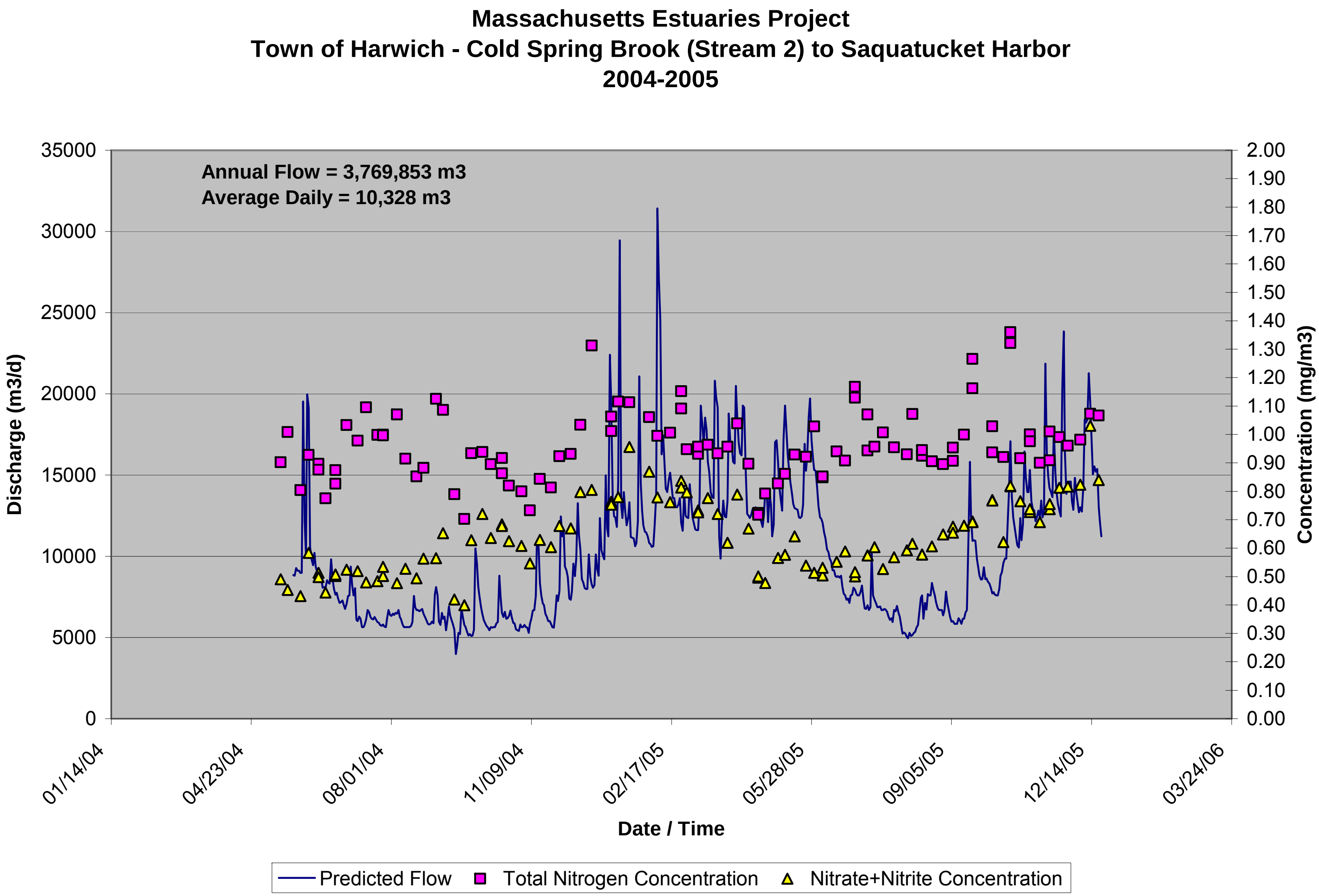


Figure IV-8. Cold Spring Brook (Stream 2) discharge (solid blue line), nitrate+nitrite (yellow triangle) and total nitrogen (pink square) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Saquatucket Harbor (Table IV-6).

The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Cold Spring Brook was considered to be negligible. The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Cold Spring Brook discharging from Grass Pond would indicate that the Brook is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Cold Spring Brook outflow were low to moderate for a developed watershed with wastewater treatment by on-site septic systems, 0.961 mg N L^{-1}. Combining the nitrogen concentrations with stream flow yielded an average daily total nitrogen discharge to the estuary of 9.93 kg/day and a total annual TN load of 3,623 kg/yr. In Cold Spring Brook, nitrate was the predominant form of nitrogen (70%), 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 watershed either within Grass Pond, the bogs between grass pond and the Cold Spring Brook discharge to Saquatucket Harbor or along the freshwater reach of Cold Spring Brook.

From the measured nitrogen load discharged by Cold Spring Brook to the Saquatucket Harbor 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 total nitrogen load (3,623 kg yr^{-1}) discharged from the freshwater Cold Spring Brook to the estuary compared to the nitrogen added by the various land-uses within the associated subwatersheds (7,712 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 53% (i.e. 53% 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: East Saquatucket Stream (Stream 1) Discharge Eastern Portion of Head of Saquatucket Harbor

Unlike Cold Spring Brook, the East Saquatucket Stream (referred to by the MEP as Stream 1) for the purpose of this analysis, does not have an up-gradient pond from which the stream discharges. Rather, this small stream appears to be groundwater fed and emanates from a wooded area up-gradient of Route 28. There may historically have been a small pond up-gradient of the stream, however, recent aerial photography indicates that whatever pond may have existed in the past is now grown over. The stream outflow leaving the wooded area travels through a small salt water marsh just prior to passing under Route 28 through a culvert under the roadway and discharging to the eastern portion of the head of Saquatucket Harbor. 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 the main basin of Saquatucket Harbor. 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 Saquatucket Harbor relative to the gage, Figure IV-6.

At the gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the stream discharge that carries nitrogen load from the watershed to the head of the Saquatucket Harbor system. As this Stream discharge is tidally influenced the gage was located as far above the saltwater reach such that freshwater flow could be measured at low tide in the harbor. 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 0.2 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 was installed on May 22, 2004 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 December 20, 2005 for a total deployment of 19 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 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 Saquatucket Harbor system (Figure IV-9 and Table IV-5). 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 the gage site.

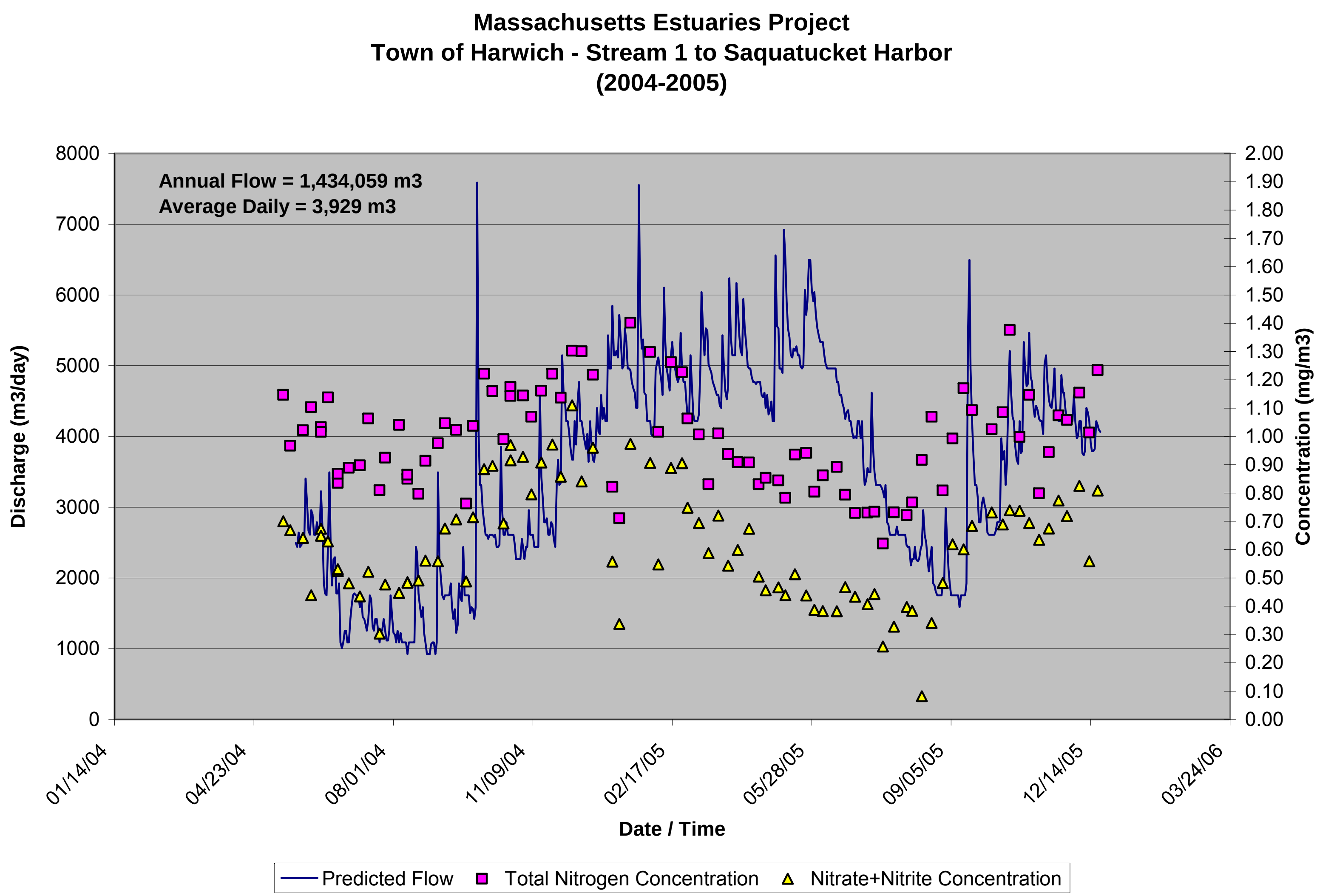


Figure IV-9. East Saquatucket Stream (Stream 1) discharge (solid blue line), nitrate+nitrite (yellow triangle) and total nitrogen (pink squares) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Saquatucket Harbor (Table IV-6).

Table IV-6. Summary of annual volumetric discharge and nitrogen load from the Creeks and Brook (freshwater) discharging to the Saquatucket Harbor and Allen Harbor embayment systems based upon the data presented in Figures IV-8 through IV-10 and Table IV-5.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Saquatucket Harbor East Saquatucket Stream (Stream 1) MEP	**September 1, 2004 to August 31, 2005**	**1,434,059**	**903**	**1415**
Saquatucket Harbor East Saquatucket Stream (Stream 1) CCC	Based on Watershed Area and Recharge	**1,354,150**	--	--
Saquatucket Harbor Cold Spring Brook (Stream 2) MEP	**September 1, 2004 to August 31, 2005**	**3,769,853**	**2533**	**3623**
Saquatucket Harbor Cold Spring Brook (Stream 2) CCC	Based on Watershed Area and Recharge	**3,283,175**	--	--
Allens Harbor Un-Named Creek @ Kildee Rd. (MEP)	**September 1, 2004 to August 31, 2005**	**695,319**	**351**	**652**
Allens Harbor Un-Named Creek @ Kildee Rd. (CCC)	Based on Watershed Area and Recharge	**507,715**	--	--

The annual freshwater flow record for the Stream (also referred by the MEP as Stream 1) 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 Stream was 6% above the long-term average modeled flows. Measured flow in the Stream was obtained for one hydrologic year (September 2003 to August 2004). The average daily flow based on the MEP measured flow data was 3,929 m^3/day compared to the long term average flows determined by the USGS modeling effort (3,710 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 Stream 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 flow in Stream discharging from the wooded portion of the watershed would indicate that the Stream is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Stream outflow were moderate, 0.987 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 3.88 kg/day and a measured total annual TN load of 1,415 kg/yr. In the Stream surface water system, nitrate was the predominant form of nitrogen (64%), 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 wooded areas and the few freshwater ecosystems is not nitrogen limited. In addition, the high nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished as appropriate.

From the measured nitrogen load discharged by the Stream to the head of the Saquatucket Harbor system 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 (1,415 kg yr^{-1}) discharged from the freshwater Stream compared to that added by the various land-uses to the associated watershed (1,795 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and wetland prior to discharge to the estuary is 21% (i.e. 21% 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 hydrologic characteristics of the up-gradient watershed that shows little potential for attenuation by ponds and wetlands that would have the requisite biological activity to yield nitrogen attenuation. The directly measured nitrogen loads from the Stream was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.2.4 Surface water Discharge and Attenuation of Watershed Nitrogen: Un-named Creek Discharge to the Head of Allen Harbor

Unlike the stream flowing out of the Grassy Pond / cranberry bog system into the nearby Saquatucket Harbor system, the un-named creek flowing into the head of Allen Harbor does not have an up-gradient pond from which the stream discharges. Rather, this small creek appears to be groundwater fed and emanates from a wooded / wetland area up-gradient of Route 28. There may historically have been a small pond up-gradient of the creek, however, recent aerial photography indicates that whatever pond may have existed in the past is now grown over. The creek outflow leaving the wooded area travels through a small marsh just prior to passing under Route 28 through a culvert under the roadway and continues through more marsh before passing through a second culvert under Kildee Road, finally discharging to the head of Allen Harbor. The creek outflow from the wooded / wetland area up gradient of the gage provides for a direct measurement of the nitrogen attenuation that may be occurring in this portion of the watershed. The combined rate of nitrogen attenuation by biological processes occurring in the undeveloped and wetland areas of the watershed to the creek was determined by comparing the present predicted nitrogen loading (based on land use) to the sub-watershed region contributing to the wetland above the gage site and the measured annual discharge of nitrogen to Allen Harbor relative to the gage, Figure IV-7.

At the Kildee Road 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 head of Allen Harbor. As the Creek discharge is tidally influenced the gage was located as far above the saltwater reach such that freshwater flow could be measured at low tide in Allen Harbor. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Low tide salinity ranged between 0.4 ppt and 8.2 ppt, indicating periodic tidal influence. Based on the salinity, a correction was made to the 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 on nearly a monthly basis. The gage on the Creek passing under Kildee Road was installed on May 22, 2004 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 December 20, 2005 for a total deployment of 19 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 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 head of Allen Harbor (Figure IV-10 and Table IV-5). 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 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 Creek was 40% above the long-term average modeled flows. Measured flow in the Creek was obtained for one hydrologic year (September 2004 to August 2005). The average daily flow based on the MEP measured flow data was 1,905 m^3/day compared to the long term average flows determined by the USGS modeling effort (1,148 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 Creek discharging to Allen Harbor was significant (40%) and is likely due to the fact that this is a small stream with relatively low flows that can easily be confounded due to the tidal influence, despite the salinity adjustment. Moreover, the flows are also likely high due to the above average precipitation in the previous hydrologic year. Whereas the average precipitation during a hydrologic year (low flow to low flow) was 39.04 inches over the period 1995 to 2005, the year leading into the deployment period experienced 54.07 inches of precipitation. The MEP Technical Team concurred that the flow was unusually high and that the modeled flow and load should be used in the water quality modeling to be more conservative.

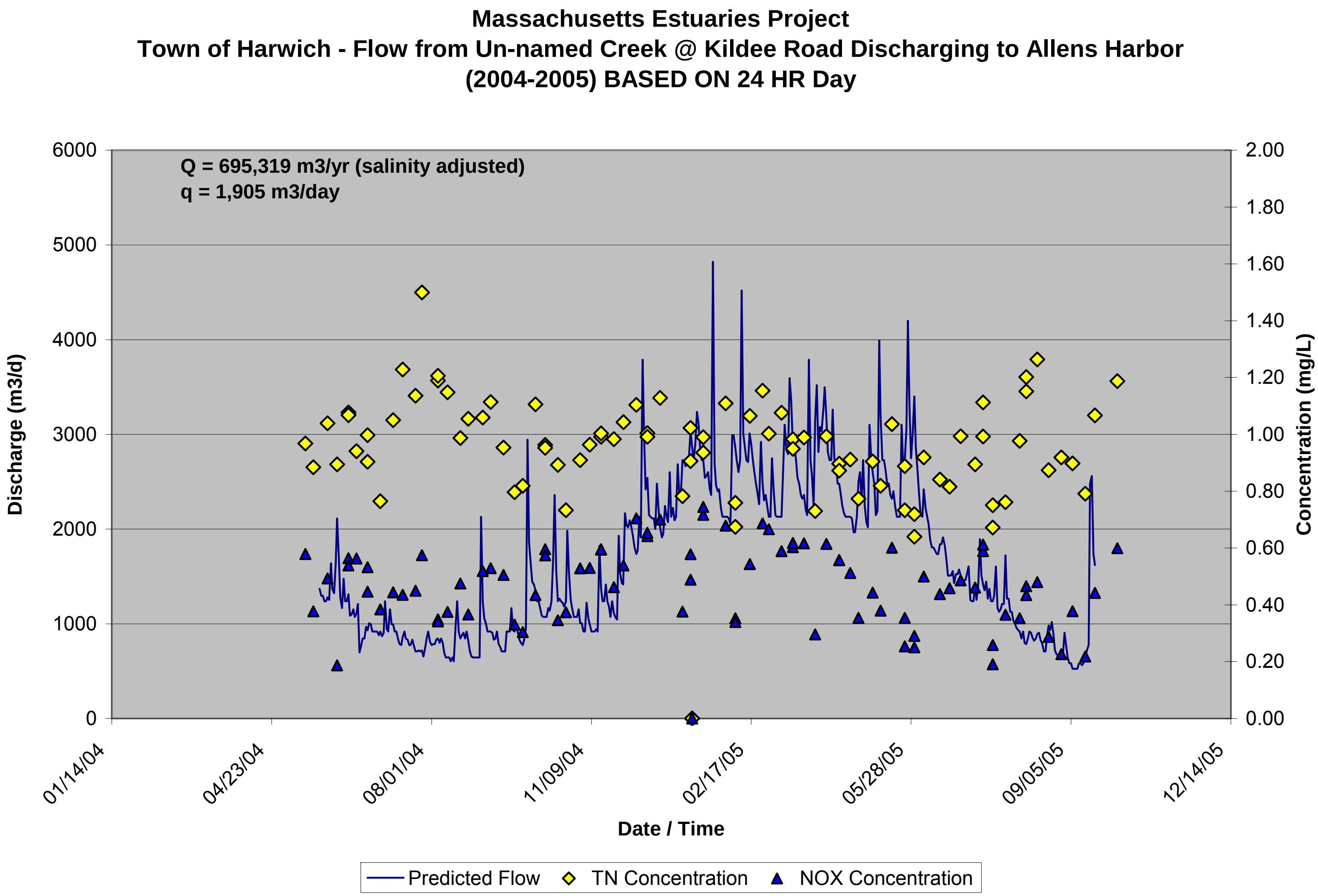


Figure IV-10. Discharge from Un-named Creek (solid blue line), nitrate+nitrite (blue symbols) and total nitrogen (yellow symbols) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to the head of Allen Harbor (Table IV-6).

Total nitrogen concentrations within the Creek outflow were moderate, 0.938 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 1.79 kg/day and a measured total annual TN load of 652 kg/yr. In the Creek surface water system, nitrate constituted just over half of the total nitrogen load (32%), 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 relatively high concentration of inorganic nitrogen in the out flowing stream waters also suggests that plant production within the up gradient wooded and wetland area is not nitrogen limited. In addition, the moderately 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 Creek gage.

From the measured nitrogen load discharged by the Creek to the Allen Harbor 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 (652 kg yr^{-1}) discharged from the freshwater Creek compared to that added by the various land-uses to the associated watershed (958 kg yr^{-1}), the integrated attenuation in passage through the wetland prior to discharge to Allen Harbor is 32% (i.e. 32% 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 hydrologic characteristics of the up gradient watershed that shows minimal ponds and wetlands that would have the requisite biological activity to yield nitrogen attenuation. However, due to the uncertainty in the high measured flows, the MEP Technical Team decided it would be more conservative to utilize the attenuated nitrogen loads based on the land use analysis for the Creek 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor embayment systems. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-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 three harbor systems predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like Nantucket Sound). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom sediments. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with associated nitrogen "load" become incorporated into the surficial sediments of the harbors.

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 salt marsh at the head of the Allen Harbor system may also function as such a salt marsh basin. To the extent that the role of the marshes at the head of Allen Harbor is better understood, its attenuation capacity might be "used" through siting of nitrogen sources. In West Falmouth Harbor the Town of Falmouth gets "credit" in its discharge permit for discharging through groundwater flow to a tidal salt marsh rather than directly to the harbor waters. In addition, to the extent that the removal capacity of the marsh has been impaired by alteration, it might be restored to maximum attenuation capacity. 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 similar to portions of these three harbors, typically support anoxic sediments with elevated rates of nitrogen release during summer months. The consequence of this deposition is that these basin sediments are unconsolidated, organic rich and sulfidic nature (MEP field observations).

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading to the three harbor systems. 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor embayment systems, 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 6 sites in Saquatucket Harbor, 7 sites within Wychmere Harbor and 7 sites in nearby Allen Harbor inclusive of the small tributary to the system (Figures IV-11-13). All the sediment cores for these three systems were collected in

July-August 2004. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Figure IV-11. Saquatucket Harbor embayment system sediment sampling sites (blue symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above.

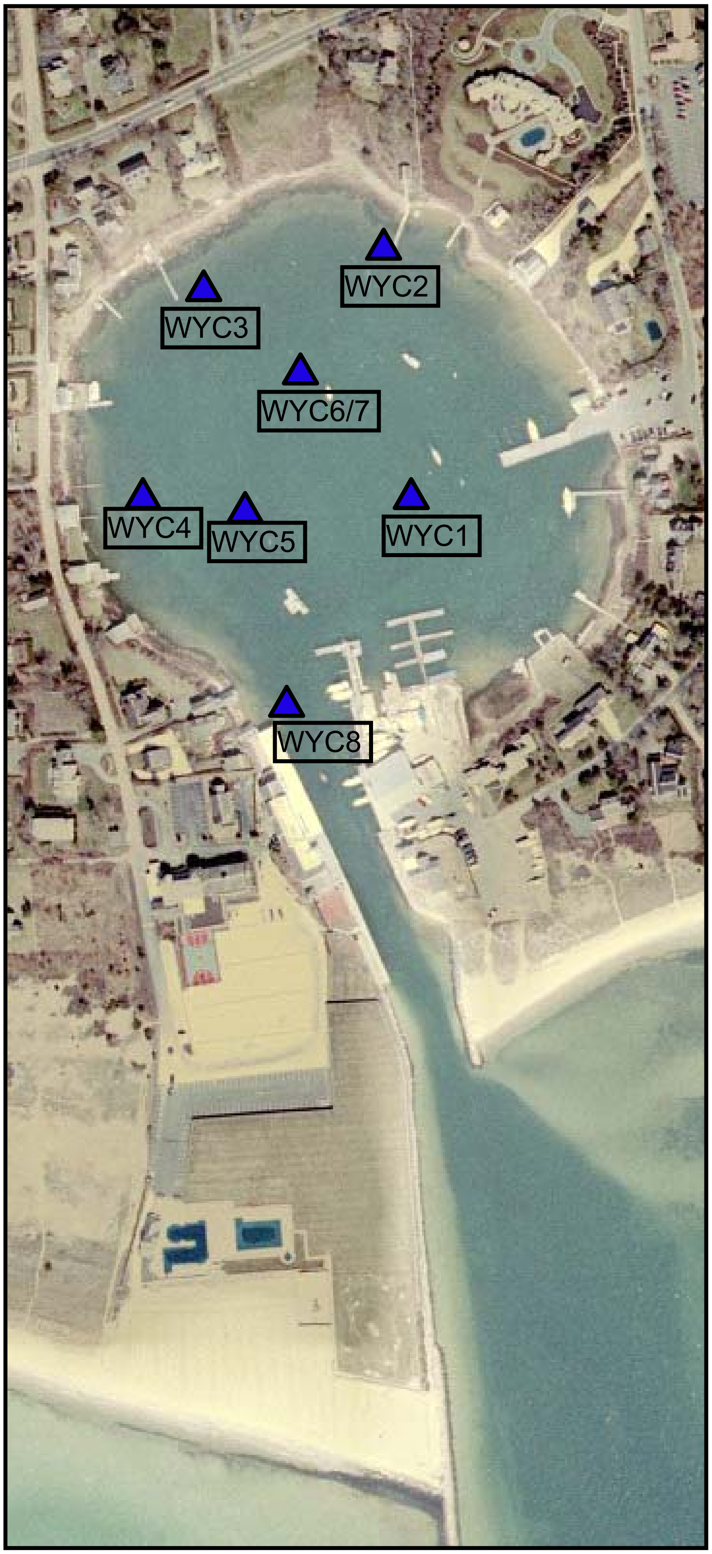


Figure IV-12. Wychmere Harbor embayment system sediment sampling sites (blue symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above.

Figure IV-13. Allen Harbor embayment system sediment sampling sites (blue symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above.

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 (Figures IV-11-13) per incubation are as follows:

Saquatucket Harbor Embayment System Benthic Nutrient Regeneration Cores

• SAQ-1	1 core	(Outer Basin)
• SAQ-2	1 core	(Outer Basin)
• SAQ-3	1 core	(Outer Basin)
• SAQ-4	1 core	(Inner Basin)
• SAQ-5/6	2 cores	(Inner Basin)
• SAQ-7/8	2 cores	(Inner Basin)

Wychmere Harbor Embayment System Benthic Nutrient Regeneration Cores

• WYC-1	1 core	(Center Basin)
• WYC-2	1 core	(Margin Basin)
• WYC-3	1 core	(Margin Basin)
• WYC-4	1 core	(Margin Basin)
• WYC-5	1 core	(Margin Basin)
• WYC-6/7	2 cores	(Center Basin)
• WYC-8	1 core	(Inlet)

Allen Harbor Benthic Nutrient Regeneration Cores

• ALN -1	1 core	(Tributary Creek)
• ALN -2	1 core	(Tributary Creek)
• ALN -3	1 core	(Main Basin)
• ALN -4	1 core	(Main Basin
• ALN-5/6	2 cores	(Main Basin)
• ALN-7	1 core	(Main Basin)
• ALN-8	1 core	(Main Basin)

Sampling was distributed throughout the primary embayment basins of each system 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 (Allen Harbor Marine) 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-14).

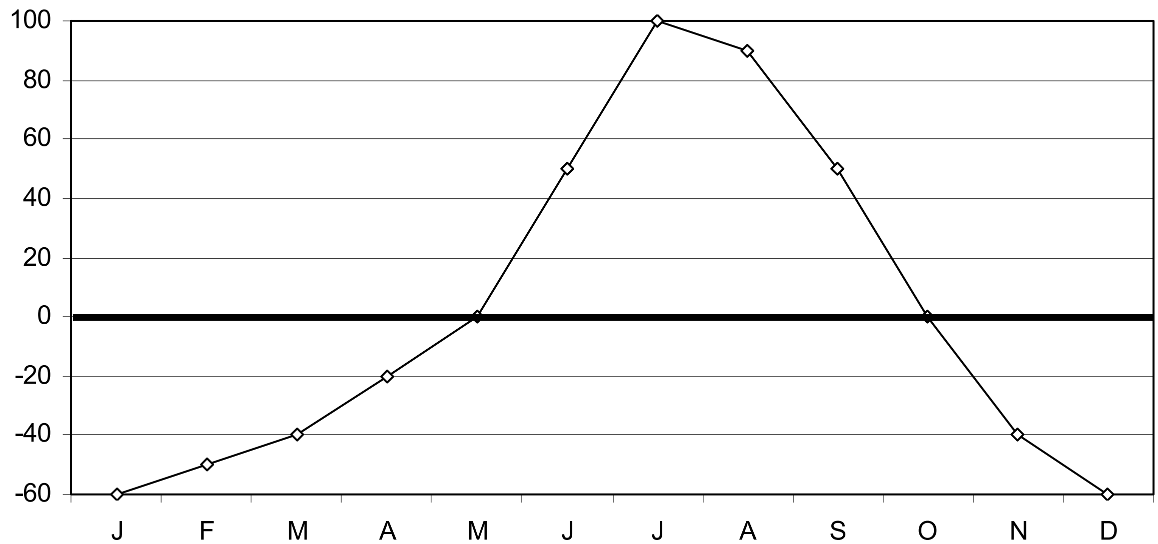


Figure IV-14. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

In order to determine the net nitrogen flux between water column and sediments, all of the above factors were taken into account. The net input or release of nitrogen within each of the three harbors 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 basins of each of the three systems in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores in each harbor was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (Chapter V). Two levels of settling 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor basins were comparable to other similar embayments with similar configuration and flushing rates in southeastern. Massachusetts. In addition the magnitude of nitrogen regenerated from the central portion of each of the main basins was also similar between Allen, Saquatucket and Wychmere Harbors with rates of 102, ~132 and 114 mg N $m^{-2}d^{-1}$, respectively (Table IV-7). Only the sediments at the margin of Wychmere Harbor showed nitrogen uptake, although the rates were generally low, -28 mg N $m^{-2}d^{-1}$. In addition, the pattern of sediment N release was also similar to other systems, with the creeks and channels showing lower nitrogen release than the central depositional basins. The main basins account for the bulk of the sediment nitrogen release, almost certainly due to their configuration as depositional basins, with long narrow inlet channels. However, the measured rates of nitrogen release are similar to other similarly sized enclosed basins such as the Pleasant Bay sub-basins of Meetinghouse Pond, Areys Pond, Paw Wah Pond and Round Cove, 79.5, 107.3, 120.7 and 139 mg N m^{-2} d^{-1}, respectively, while the upper and mid reaches of The River (12-14 mg N m^{-2} d^{-1}) had rates consistent with the Wychmere channel station, as might be expected from their analogous configurations and functions. The observed uptake at the margins of Wychmere Harbor were also observed in the similar setting of Farm Pond (Oak Bluffs, Martha's Vineyard), 6-26 mg N m^{-2} d^{-1} and in a variety of regions of basins with oxidized sediments, such as adjacent Strong Island and Bassing Harbor in Pleasant Bay.

Net nitrogen release rates for use in the water quality modeling effort for the main basins of Allen Harbor, Wychmere Harbor and Saquatucket Harbor (Chapter VI) are presented in Table IV-7. Overall, the absolute amounts and spatial distribution of sediment regeneration rates within the three harbors investigated in this report is consistent with most other systems assayed by the MEP throughout southeastern Massachusetts. Consistent with general nitrogen dynamics, depositional areas showed the highest rates of net nitrogen release, with lower rates in channels or shallow creeks and net uptake in oxidized sediments. The sediments within each of the three harbors in Harwich showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to these systems and their flushing rates (cf. Chapter VI).

Table IV-7. Rates of net nitrogen return from sediments to the overlying waters of the Allen Harbor, Saquatucket Harbor, and Wychmere Harbor Systems. 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.	N	
Allen Harbor Estuary				
Allen Creek	0.3	31.7	2	ALN 1,2
Allen Harbor Main Basin	102.4	46.7	6	ALN 3,4,5,6,7,8
Saquatucket Harbor Estuary				
Harbor - Inner	132.4	42.6	5	SAQ-4,5,6,7,8
Harbor - Outer	131.4	77.5	3	SAQ-1,2,3
Wychmere Harbor Estuary				
Main Basin - Margin	-28.4	7.8	4	WYC 2,3,4,5
Main Basin	113.6	38.5	5	WYC 1,6,7
Channel	15.5	1.5	1	WYC 8

* 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems (Figure V-1). For these systems, the final calibrated model offers an understanding of water movement through the estuaries, and provides the first step towards evaluating water quality, as well as being a tool for later determining nitrogen loading “thresholds”. Tidal flushing information is utilized as the basis for a quantitative evaluation of water quality. Nutrient loading data combined with measured environmental parameters within the various sub-embayments become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing estuarine water quality, as well as determining the likely positive impacts of various alternatives for improving overall estuarine health, enabling the bordering residences 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine 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 before being flushed out to adjacent open waters, and the shallow depths both decrease the systems 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.

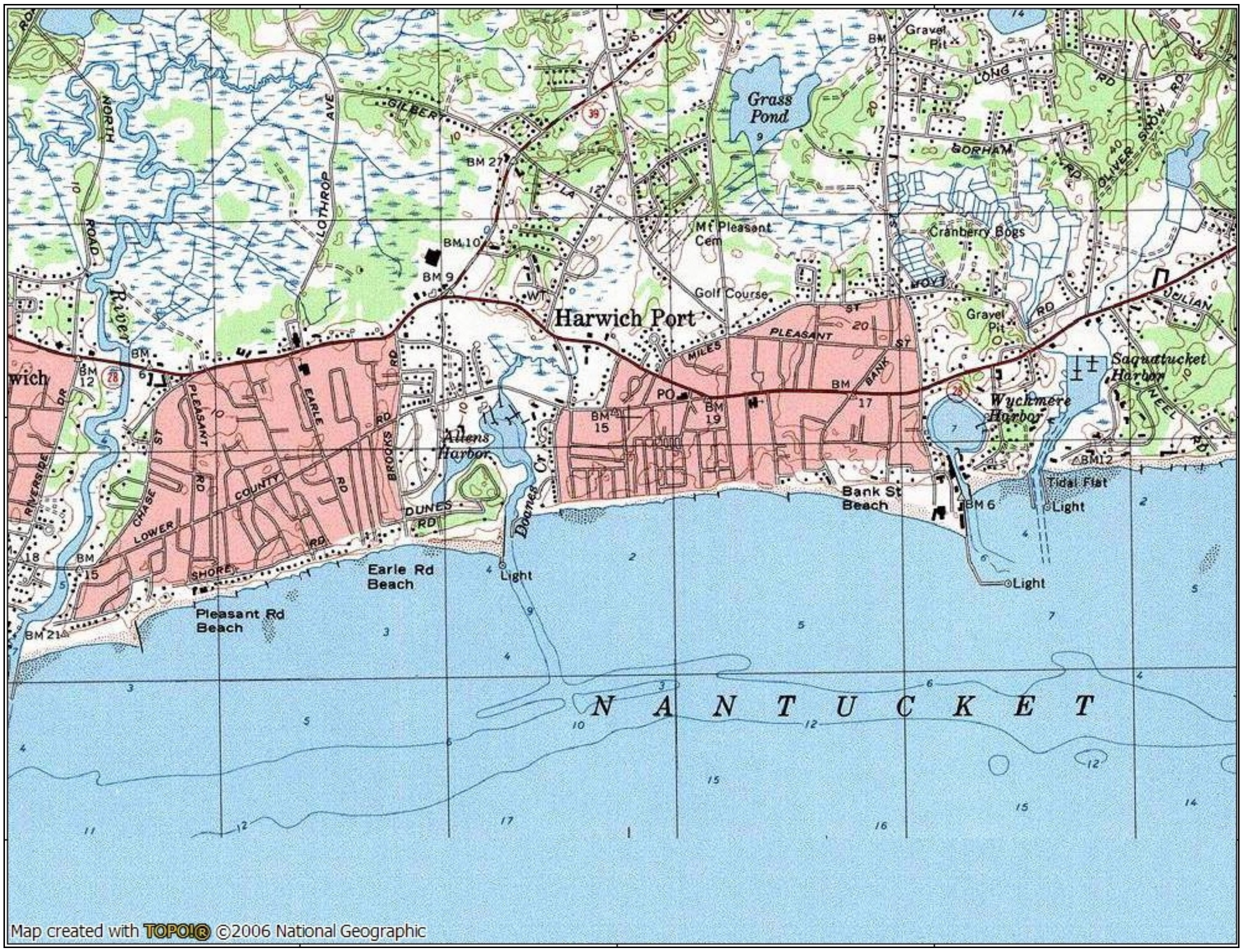


Figure V-1. Map of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems (from United States Geological Survey topographic maps).

To understand the dynamics of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems, a hydrodynamic study was performed. The systems are surrounded by the Town of Harwich along the south coast of Cape Cod, Massachusetts. A site map showing the study areas is shown in Figure V-1. Allen Harbor consists of the main harbor basin which is the entrance to the system from Nantucket Sound. The entrance is stabilized with jetties on the east and west sides of the inlet. There is a small basin extending to the west of the main harbor basin and a marsh area north of Lower County Road that is connected through a channel by a bridge/culvert under the roadway. The entrances to Wychmere and Saquatucket Harbors are protected by the long curving jetty that extends from the coastline west of Wychmere Harbor out into Nantucket Sound then curves to the east. Wychmere Harbor has a short channel leading from the coast to the main harbor basin which has a number of docks on the periphery. The Saquatucket Harbor system consists of jetties on each side of the inlet and the main basin which extends to the northeast. Saquatucket Harbor has fringing salt marshes along most of the coastline inside of the harbor. The approximate tidal range within the system is 5.0 feet, with Nantucket Sound tidal variations providing the hydraulic forcing that drives water movement throughout the system.

The Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems are shallow tidal estuaries. Salt marsh areas are contained on the margins of Allen Harbor and Saquatucket Harbor. The embayments contain approximately 14.3 acres of marsh (8.2 acres in Allen Harbor and 6.1 acres in Saquatucket Harbor), which accounts for 19 percent of the total estuary surface area for the three harbors.

Since the water elevation difference between Nantucket Sound and the inland reaches of the harbors 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 systems that flush efficiently. Any issues with water quality, therefore, would likely be due to other factors including nutrient loading conditions from the system's watersheds, and the tide range in Nantucket Sound.

Circulation in Allen Harbor, Wychmere Harbor and Saquatucket Harbor was simulated using the RMA-2 numerical hydrodynamic model. To calibrate the model, field measurements of water elevations and bathymetry were required for each system. Tide data were acquired within Nantucket Sound at a gage station installed offshore of the coastline, and also at three stations located within Allen Harbor and a gage in each of Wychmere and Saquatucket Harbors (Figure V-2). All temperature-depth recorders (TDRs or tide gages) were installed for a 30-day period to measure tidal variations through one spring-neap tidal cycle. In this manner, attenuation of the tidal signal as it propagates through the various sub-embayments was evaluated accurately.

V.2 FIELD DATA COLLECTION AND ANALYSIS

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

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

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

Boundary conditions for the numerical model consist of variations of water surface elevations measured in 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 (gaging locations are shown in Figure V-2). These measurements were used to calibrate and verify the model results, and to assure that the dynamics of the physical system were properly simulated.

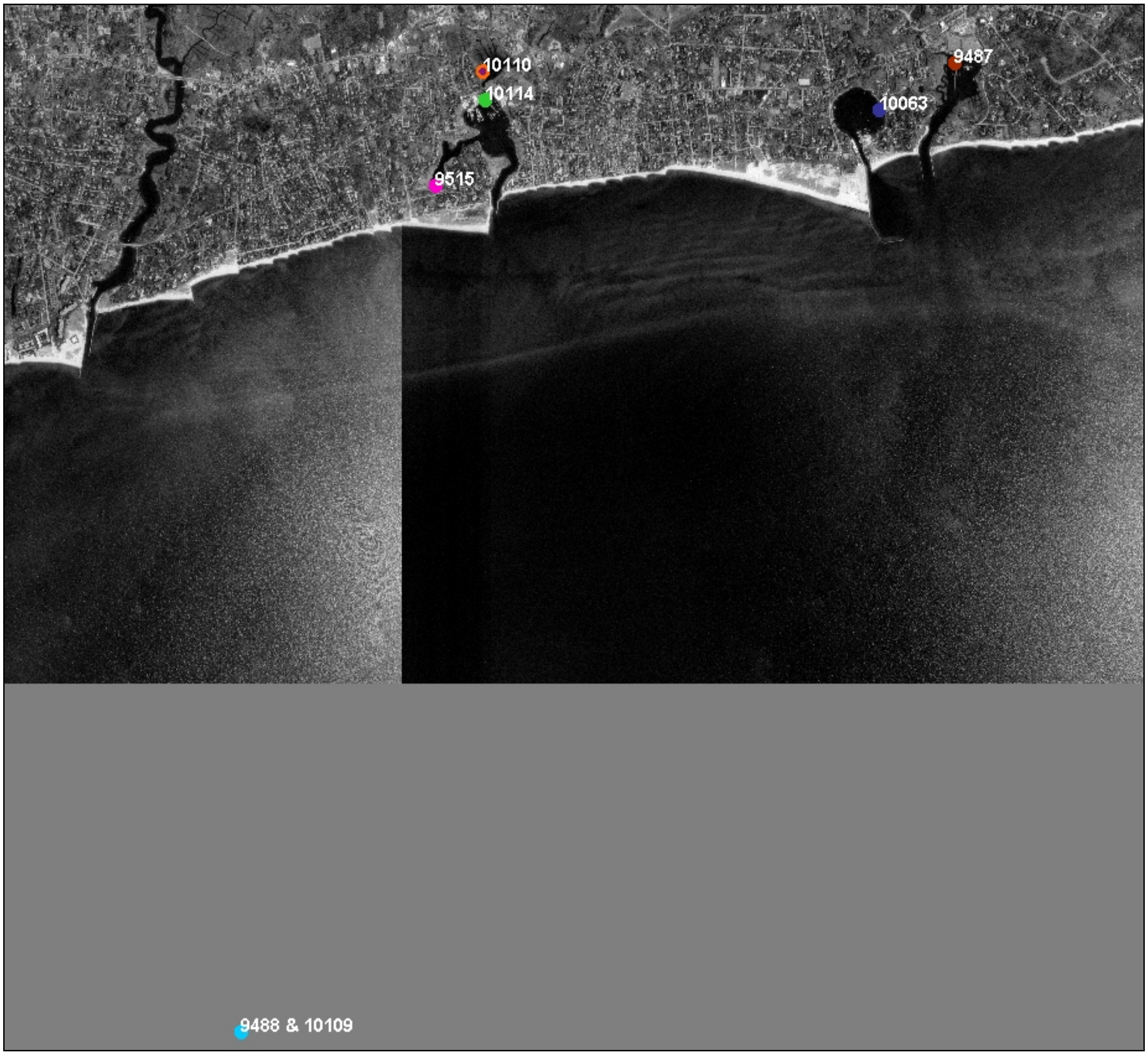


Figure V-2. Map of the study region identifying locations of the tide gages used to measure water level variations throughout the system. Six (6) gages were deployed for the 30-day period between June 1, and July 1, 2005. The colored circles represents the approximate locations of the tide gages: (9488 & 10109) represents the gage in Nantucket Sound (Offshore), (9515) inside the Allen Harbor, (10114) in Allen Harbor below Lower County Road, (10110) in Allen Harbor above Lower County Road, (10063) in Wychmere Harbor, and (9487) in Saquatucket Harbor.

V.2.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems was assembled from a hydrographic survey performed specifically for this study and historical NOS survey data. The NOS data were used for areas in Nantucket Sound that were not covered by the more recent survey.

The hydrographic survey was conducted in June of 2005. The survey was designed to collect coverage of the harbors and entrance channels. The survey transects were most dense in the vicinity of the inlets, where the greatest variability in bottom bathymetry was expected. Bathymetry in the inlet is important from the standpoint that it has the most influence on tidal circulation in and out of the estuary. The survey was conducted from 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. The digital output produced a single data set consisting of water depth as a function of geographic position (Massachusetts State Plane). The tide gages used to collect water surface elevation in the various embayments were used to correct bathymetry data to NGVD 1929.

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to the NGVD 1929 vertical datum. Once rectified, the finished processed data were archived as 'xyz' files containing x-y horizontal position (in Massachusetts State Plan 1983 coordinates) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The final processed bathymetric data from the survey are presented in Figure V-3.

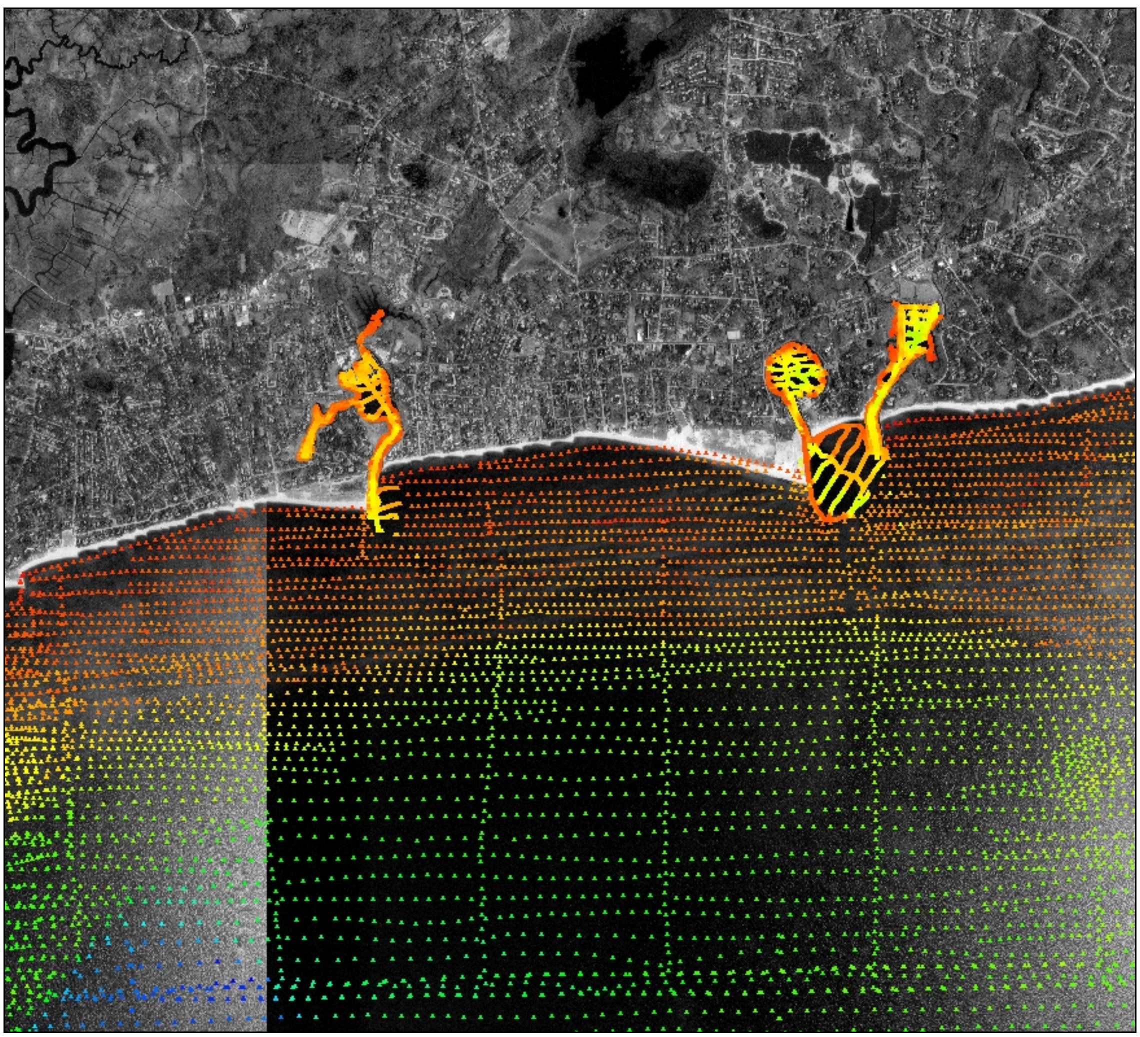


Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

V.2.2 Tide Data Collection and Analysis

Variations in water surface elevation were measured at one station at each of three locations in Allen Harbor. Water surface elevations were also measured at one station in each of Wychmere and Saquatucket Harbors, and a single station in Nantucket Sound. Stations within the Allen Harbor were located inside the main harbor basin (10114), north of Lower County Road (10110), and at the head of the cove that extends to the west of Allen Harbors main basin (9515). Wychmere Harbor (10063) and Saquatucket Harbor (9487) each had a tide gage located on a dock in the main harbor basin. These six gages were deployed for the 30-day period between June 1, and July 1, 2005. The duration of the TDR deployments allowed time to conduct the bathymetric survey, as well as sufficient data to perform a thorough analysis of the tides in these systems.

The tide records 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-4, for the complete 30-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 an 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 the three harbors, a visual comparison in Figure V-5 between tide elevations at six stations along the system demonstrates how little change there is between the tide range and timing from Nantucket Sound to the inside of the harbor basins. This provides an initial indication that flushing conditions in each of the three systems are ideal, with minimal loss of tidal energy along the length of any given system.

To better quantify the changes to the tide from the inlet to inside a 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 Allen, Wychmere and Saquatucket Harbors 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 NAVD88).

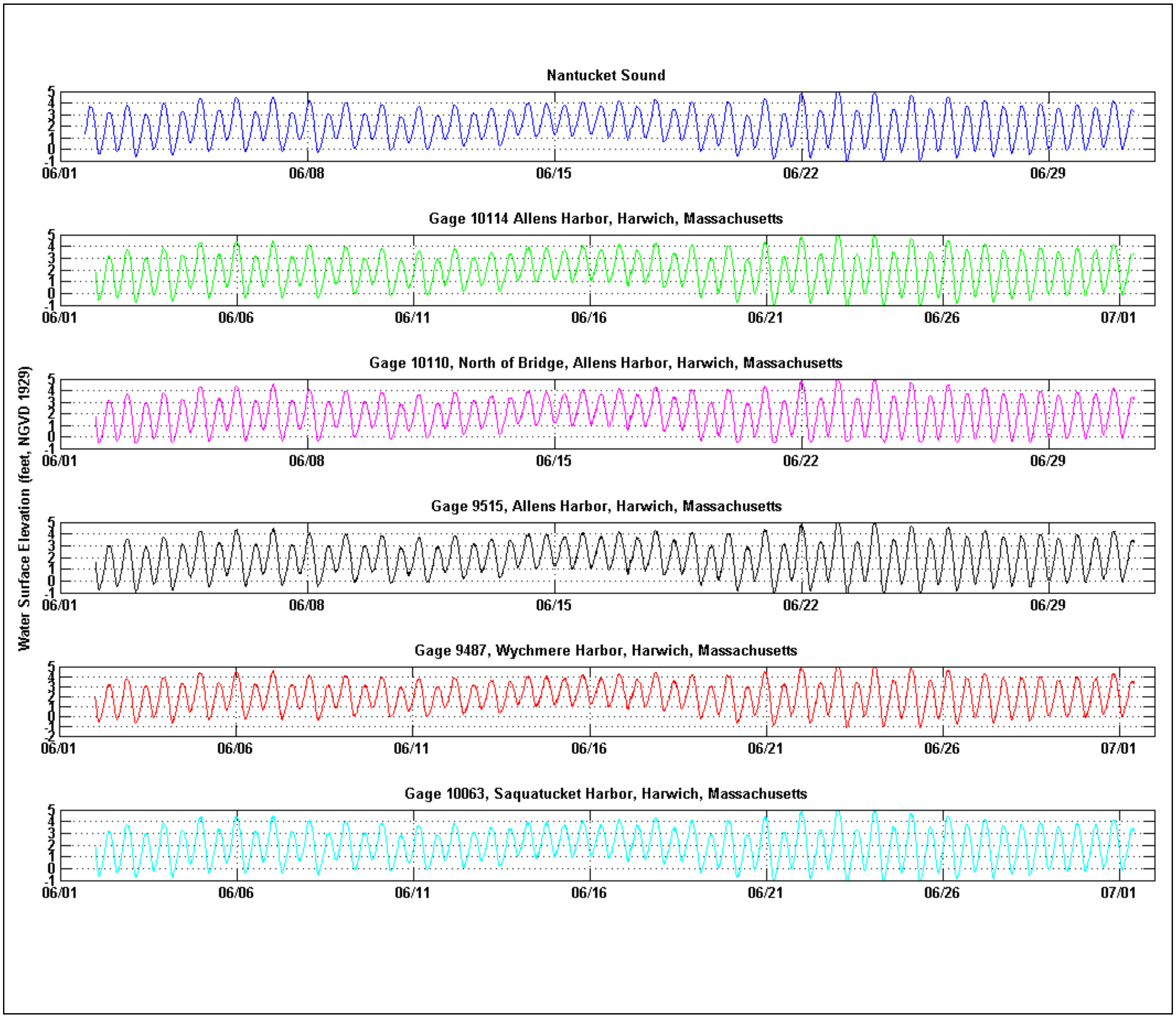


Figure V-4. Water elevation variations as measured in Nantucket Sound and within the harbor systems, between June 1 and July 1, 2005.

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 systems. From the computed datums, it is further apparent that there is little tide damping throughout the systems. Again, the absence of tide damping exhibited in Allen, Saquatucket, and Wychmere Harbors indicates that they flush efficiently.

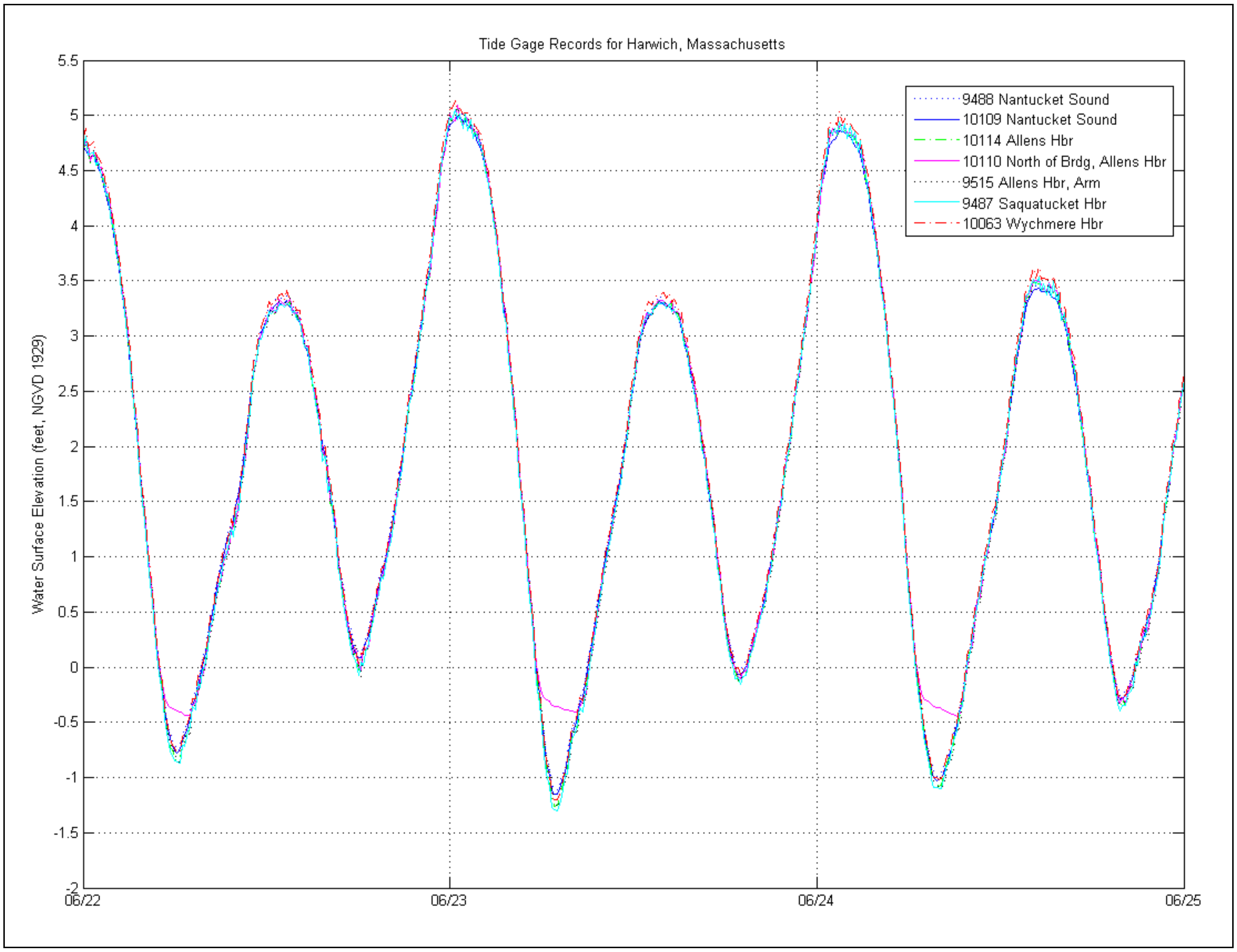


Figure V-5 Plot showing two tide cycles tides at seven stations in the Allen, Saquatucket, and Wychmere Harbors plotted together.

A more thorough harmonic analysis was also performed on the time series data from each gaging 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 estuaries. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 tidal constituents, with periods between 4 hours and 2 weeks, result from this procedure. The observed tide is therefore the sum of an astronomical tide component and a residual atmospheric component. The astronomical tide in turn is the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-6.

Table V-2 presents the amplitudes of 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 1.7 feet in Nantucket Sound. The range of the M_2 tide is twice the amplitude, or about 3.4 feet. The diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar), possess amplitudes of approximately 0.46 and 0.37 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 0.43 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-1. Tide datums computed from records collected in the Allen, Saquatucket, and Wychmere Harbor systems June 1 - July 1, 2005. Datum elevations are given in feet relative to NGVD 29.

Tide Datum	Nantucket Sound 9488	Allen Harbor 10114	Allen Harbor 10110	Allen Harbor 9515	Saquatucket Harbor 9487	Wychmere Harbor 10063
Maximum Tide	5.03	5.07	5.09	5.08	5.05	5.13
MHHW	4.16	4.20	4.22	4.22	4.22	4.29
MHW	3.77	3.74	3.75	3.76	3.75	3.83
MTL	1.95	1.87	1.92	1.87	1.86	1.94
MLW	0.14	0.00	0.09	-0.02	-0.04	0.06
MLLW	-0.17	-0.30	-0.13	-0.32	-0.35	-0.25
Minimum Tide	-1.11	-1.26	-0.51	-1.27	-1.30	-1.20

Table V-2. Tidal Constituents for each gaging station, June 1 - July 1, 2005

	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, 9488	1.73	0.13	0.08	0.12	0.43	0.46	0.37	0.11
Allen Harbor, 10114	1.76	0.14	0.09	0.12	0.44	0.46	0.37	0.11
Allen Harbor, 10110	1.75	0.13	0.08	0.11	0.42	0.45	0.36	0.11
Allen Harbor, 9515	1.77	0.13	0.08	0.12	0.45	0.48	0.37	0.14
Saquatucket Harbor, 9487	1.78	0.14	0.09	0.12	0.44	0.47	0.37	0.11
Wychmere Harbor, 10063	1.77	0.14	0.09	0.12	0.44	0.47	0.37	0.12

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 gage locations inside the estuaries. The greatest delay occurs between the Nantucket Sound and Allen Harbor gaging station 9515. However, all the gages reflect that there is only a minor phase delay of the tide inside the estuaries. There is a slight increase in the delay in Allen Harbor between the main bay and the smaller fringing embayments to the west and north of Lower County Road. 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.

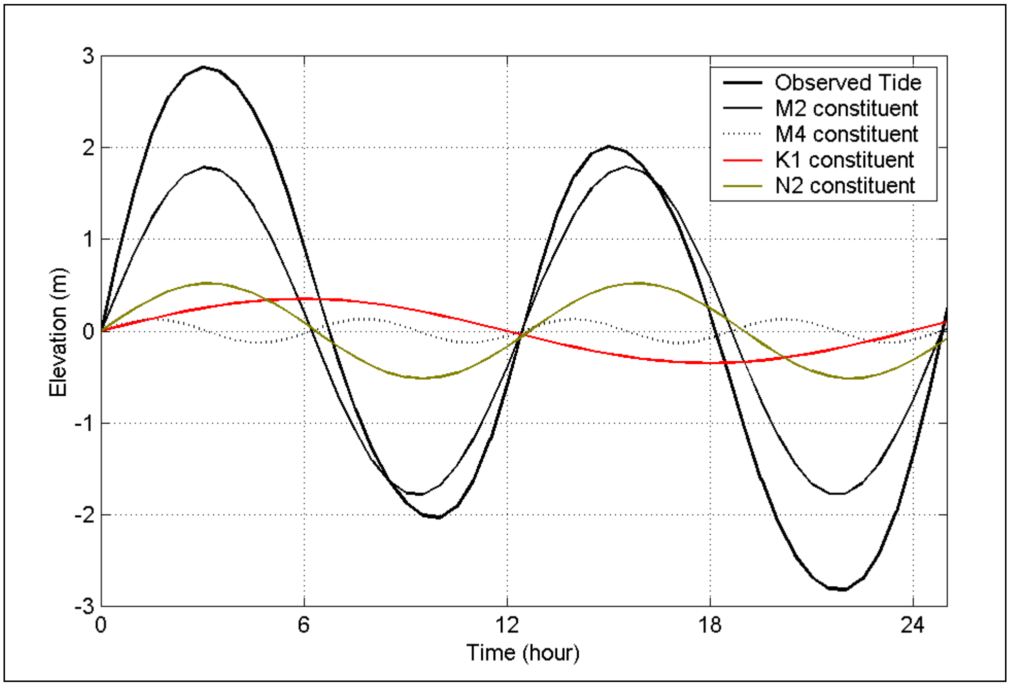


Figure V-6. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-3. M_2 Tidal Attenuation, Harwich, MA.	
June 1 – July 1 2005 (Delay in hours relative to Nantucket Sound Gage)	
Location	Delay (hours)
Allen Harbor, 10114	5.42
Allen Harbor, 10110	5.44
Allen Harbor, 9515	5.46
Saquatucket Harbor, 9487	5.40
Wychmere Harbor, 10063	5.41

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 the non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes are relative to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from 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 96% of the water level changes in the three estuary systems. The remaining 4% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of Nantucket Sound and the estuaries. The total energy content of the tide signal from each gaging station does not change significantly, nor does the relative contribution of tidal vs. non-tidal forces along the estuary system within the three estuaries. This is further indication that tide attenuation across the inlets and through the systems 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 systems (e.g., from wind set-up of the estuary surface).

The results from Table V-4 indicate that hydrodynamic circulation throughout Allen, Saquatucket, and Wychmere Harbor systems 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, Allen, Saquatucket, and Wychmere Harbor systems, June 1 – July 1, 2005.

	Total Variance	Total	Tidal	Non-tidal
Unit	(ft^2)	(%)	(%)	(%)
Nantucket Sound, 9488	1.88	100	96.3	3.7
Allen Harbor, 10114	1.93	100	96.6	3.4
Allen Harbor, 10110	1.90	100	96.5	3.5
Allen Harbor, 9515	1.98	100	95.9	4.1
Saquatucket Harbor, 9487	1.97	100	96.5	3.5
Wychmere Harbor, 10063	1.97	100	96.5	3.5

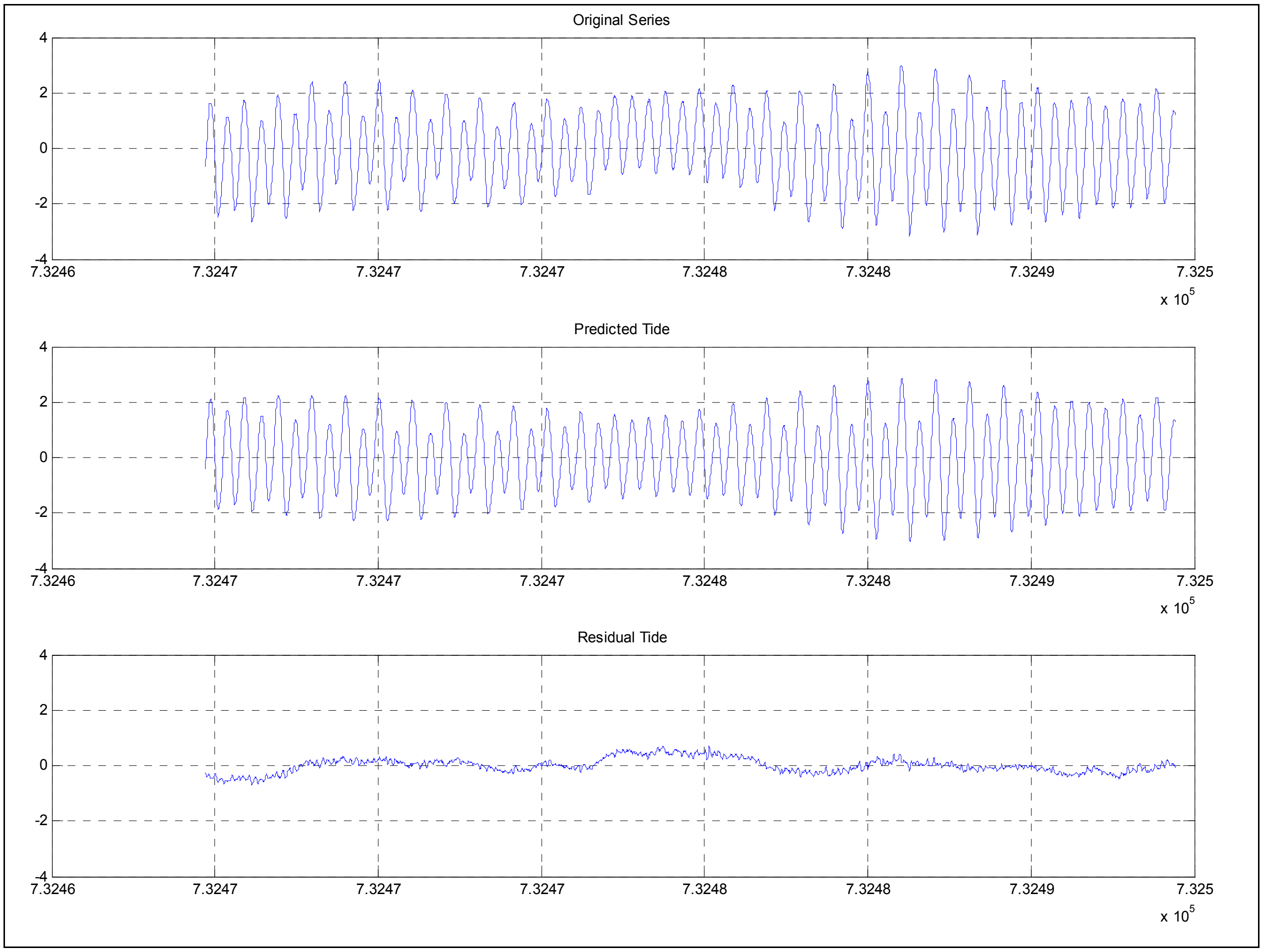


Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured in Nantucket Sound (Gage 9488).

V.3 HYDRODYNAMIC MODELING

The focus of this study was the development of a numerical model capable of accurately simulating hydrodynamic circulation within the Allen, Saquatucket, and Wychmere Harbor systems. Once calibrated, the model was used to calculate water volumes for sub-embayments as well as determine the volumes of water exchanged during each tidal cycle. These parameters are used to calculate system residence times, or flushing rates. The ultimate utility of the hydrodynamic model is to supply required input data for the water quality modeling effort described in Chapter VI.

V.3.1 Model Theory

This study of the Allen, Saquatucket, and Wychmere Harbor systems 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 Centerville River, Lewis Bay, and Pleasant 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 the finite element grid was generated using digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) based on the tide gage data collected in Nantucket Sound was specified along the offshore boundary to the model which spanned the entrances of the three systems. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several model calibration simulations for each system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid Generation

The grid generation process for the model was assisted through the use of the SMS package. The digital shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary with 1682 elements and 4063 nodes. All regions in the systems were represented by two-dimensional (depth-averaged) elements. The finite element grid for the systems provided the detail necessary to evaluate accurately the variation in hydrodynamic properties within the estuaries (Figure V-8). Fine resolution was required to simulate the numerous channel constrictions (e.g., entrance to Allen Harbor) that impact the estuarine hydrodynamics. The completed grid is made up of quadrilateral and triangular two-dimensional elements. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the recent field surveys and the NOS data archive. The final interpolated grid bathymetry is shown in Figure V-9. The model computed water elevation and velocity at each node in the model domain.

Grid resolution is governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each region. Smaller cross channel node spacing in the 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.

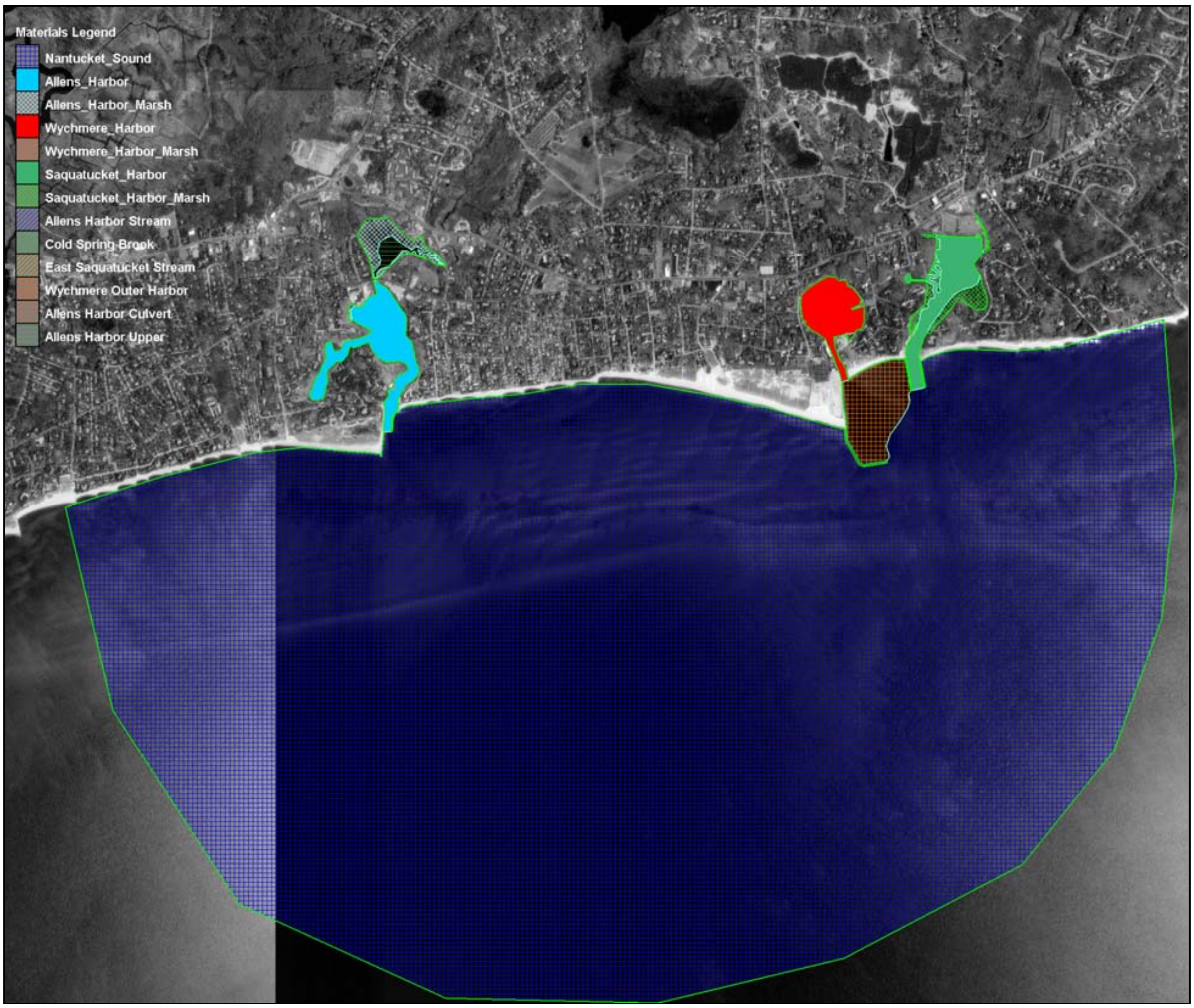


Figure V-8. The model finite element mesh developed for Allen, Saquatucket, and Wychmere Harbor systems. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained in Nantucket Sound.

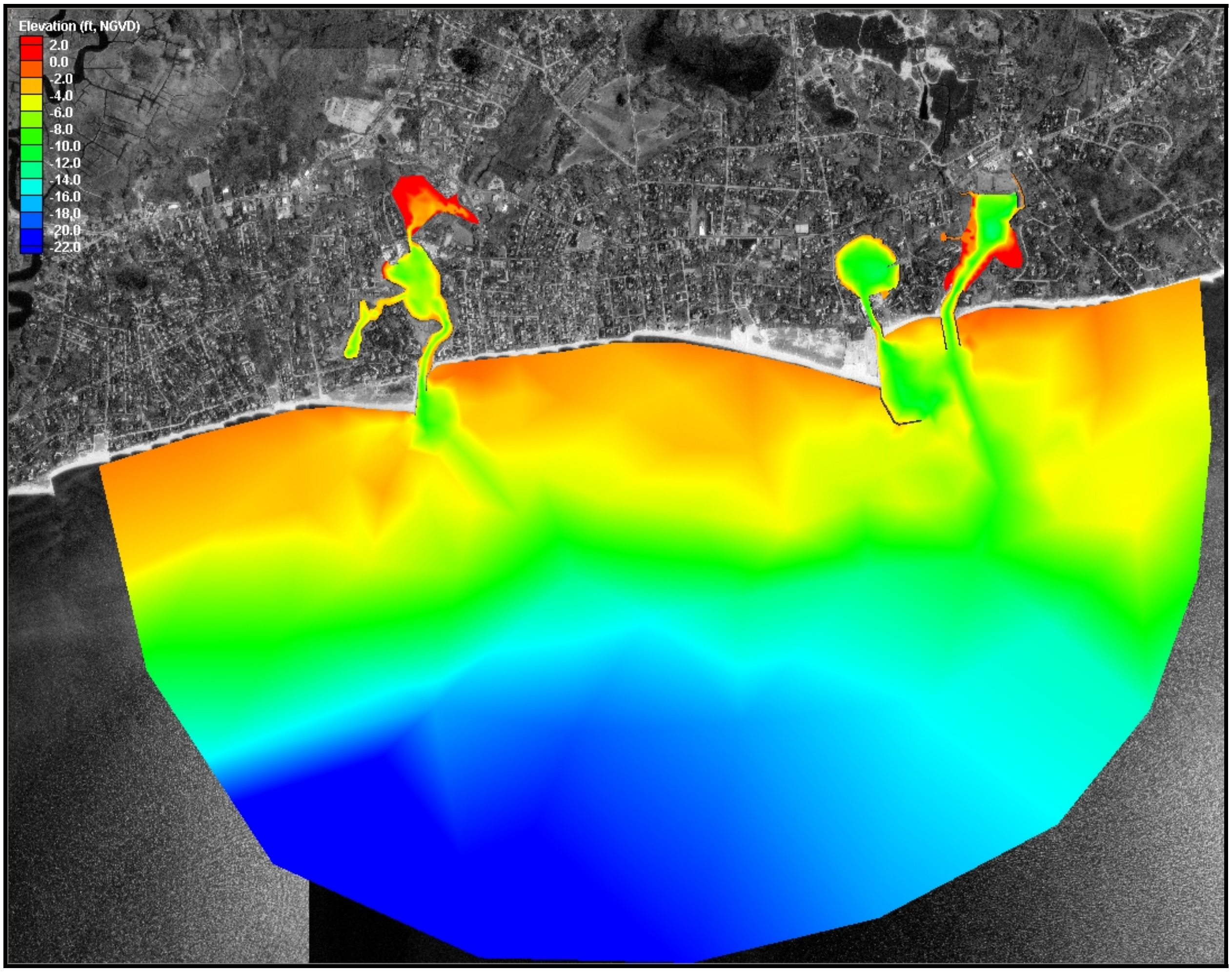


Figure V-9. Depth contours of the completed Allen, Saquatucket, and Wychmere Harbor systems finite element mesh.

V.3.2.2 Boundary Condition Specification

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

V.3.3 Calibration

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

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

The calibration was performed for an approximate eight-day period, beginning 4:00 hours EDT June 11, 2005 and ending 4:00 EDT June 19, 2005. This time period included a 12-hour model spin-up period, and a 15-tide cycle period used for calibration. This representative time period was selected because it included tidal conditions where the wind-induced portion of the signals (i.e. the residual) was minimal, hence more typical of tidal circulation within the estuary. The selected time period also spanned the spring (bi-monthly maximum) tide. Throughout the selected 7.75 day period, the tide ranged approximately 5.8 feet from minimum low to maximum high tides. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. Modeled tides were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.3.3.1 Friction Coefficients

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

Table V-5. Manning's Roughness coefficients used in simulations of modeled embayments.	
Embayment	Bottom Friction
Nantucket Sound	0.025
Allen Harbor	0.025
Allen Harbor Marsh	0.035
Allen Harbor Culvert	0.025
Allen Harbor Upper Marsh	0.025
Saquatucket Harbor	0.025
Saquatucket Harbor Marsh	0.035
Wychmere Harbor	0.025
Wychmere Harbor Marsh	0.035
Wychmere Outer Harbor	0.025

V.3.3.2 Turbulent Exchange Coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swift, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). The model was mildly sensitive to turbulent exchange coefficients, with areas of marsh plain being most sensitive. In other regions where the flow gradients were not as strong, the model was much less sensitive to changes in the turbulent exchange coefficients. Typically, model turbulence coefficients (D) are set between 50 and 150 lb-sec/ft^2 (as listed in Table V-6). Higher values (up to 500 lb-sec/ft^2) are typically used on the marsh plain, to ensure solution stability.

Table V-6. Turbulence exchange coefficients (D) used in simulations of modeled embayment system.	
Embayment	D (lb-sec/ft$^{2)}$
Nantucket Sound	50
Allen Harbor	50
Allen Harbor Marsh	150
Allen Harbor Culvert	100
Allen Harbor Upper Marsh	50
Saquatucket Harbor	50
Saquatucket Harbor Marsh	150
Wychmere Harbor	50
Wychmere Harbor Marsh	100
Wychmere Outer Harbor	50

V.3.3.3 Wetting and Drying/Marsh Porosity Processes

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

V.3.3.4 Comparison of Modeled Tides and Measured Tide Data

Several calibration model runs were performed to determine how changes to various parameters (e.g. friction and turbulent exchange coefficients) affected the model results. These trial runs achieved excellent agreement between the model simulations and the field data. Comparison plots of modeled versus measured water levels at the eight gage locations is presented in Figures V-10 through V-14. At all gaging stations RMS errors were less than 0.10 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 a half inch for all locations, suggesting the model accurately predicts tidal hydrodynamics within the Allen, Saquatucket, and Wychmere Harbors. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the calibration time period are shown in Table V-7. The constituent values in for the calibration time period differ from those in Tables V-2.

Because constituents were computed for only 7.75 days, rather than the entire 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 gages (±0.12 ft). Time lag errors were less than the time increment resolved by the model and measured tide data (1/6 hours or 10 minutes), indicating good agreement between the model and data.

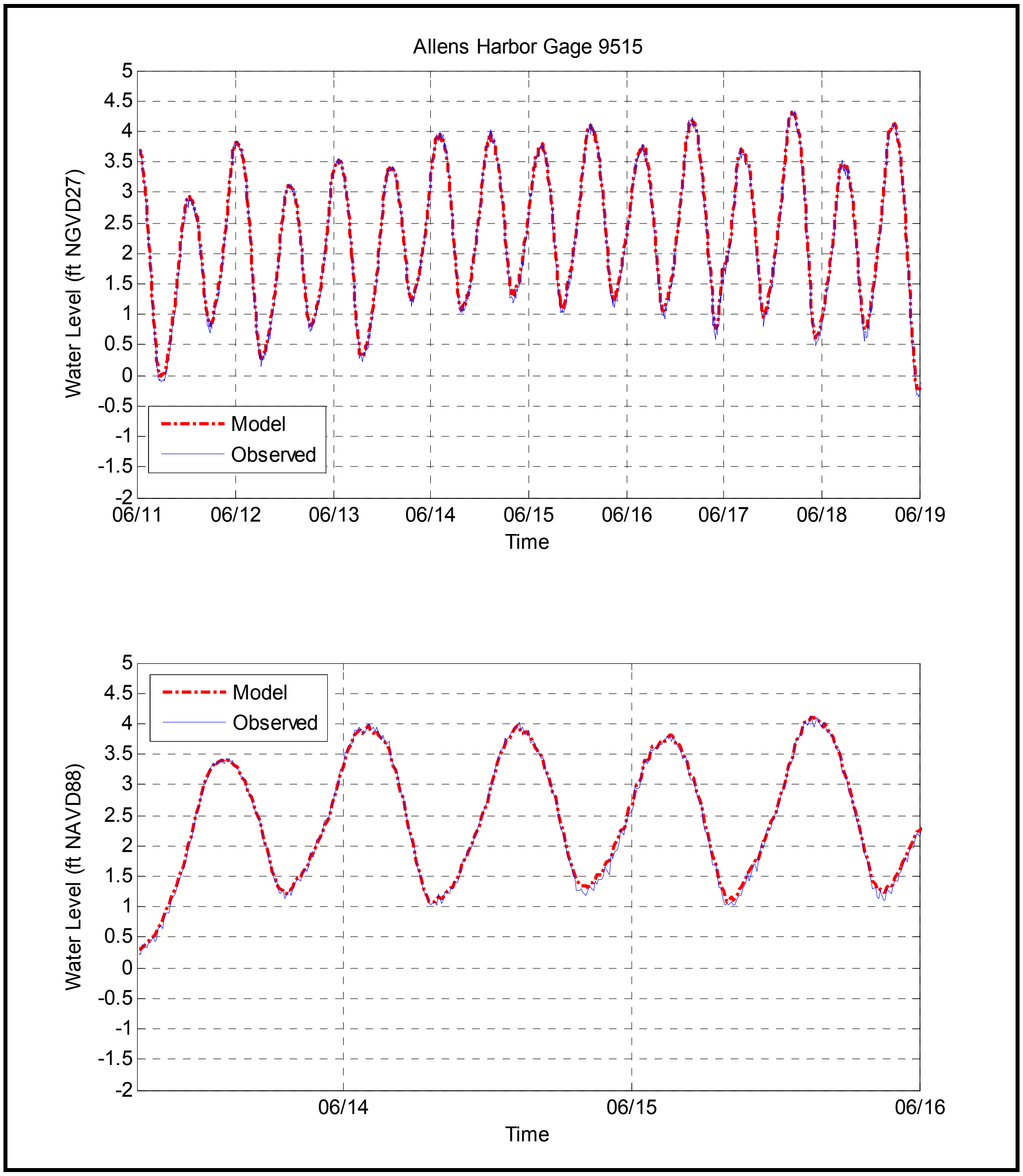


Figure V-10. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the calibration time period, for the western basin within Allen Harbor, gaging station 9515. The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

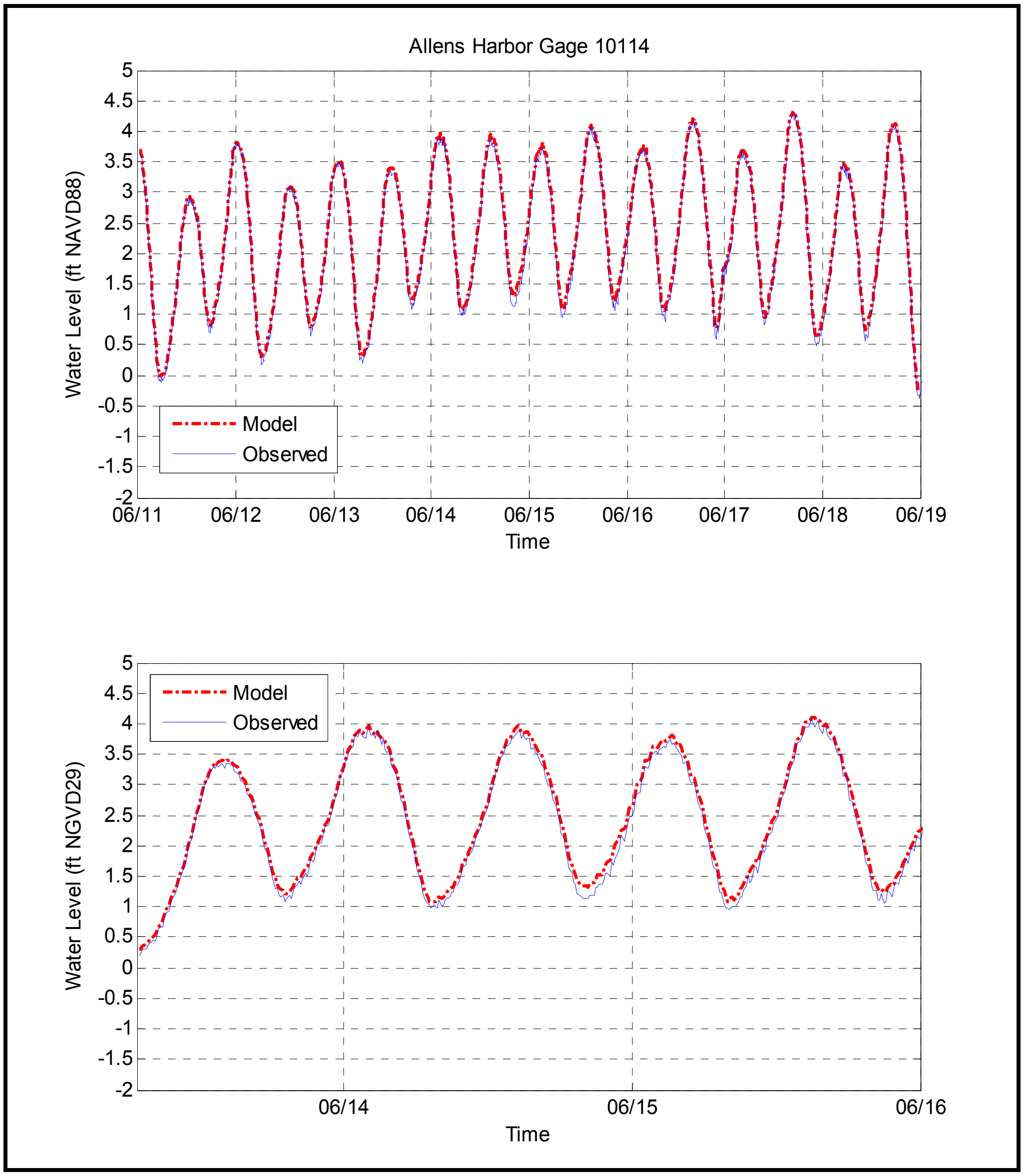


Figure V-11. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period for Allen Harbor main basin, gaging station 10114. The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

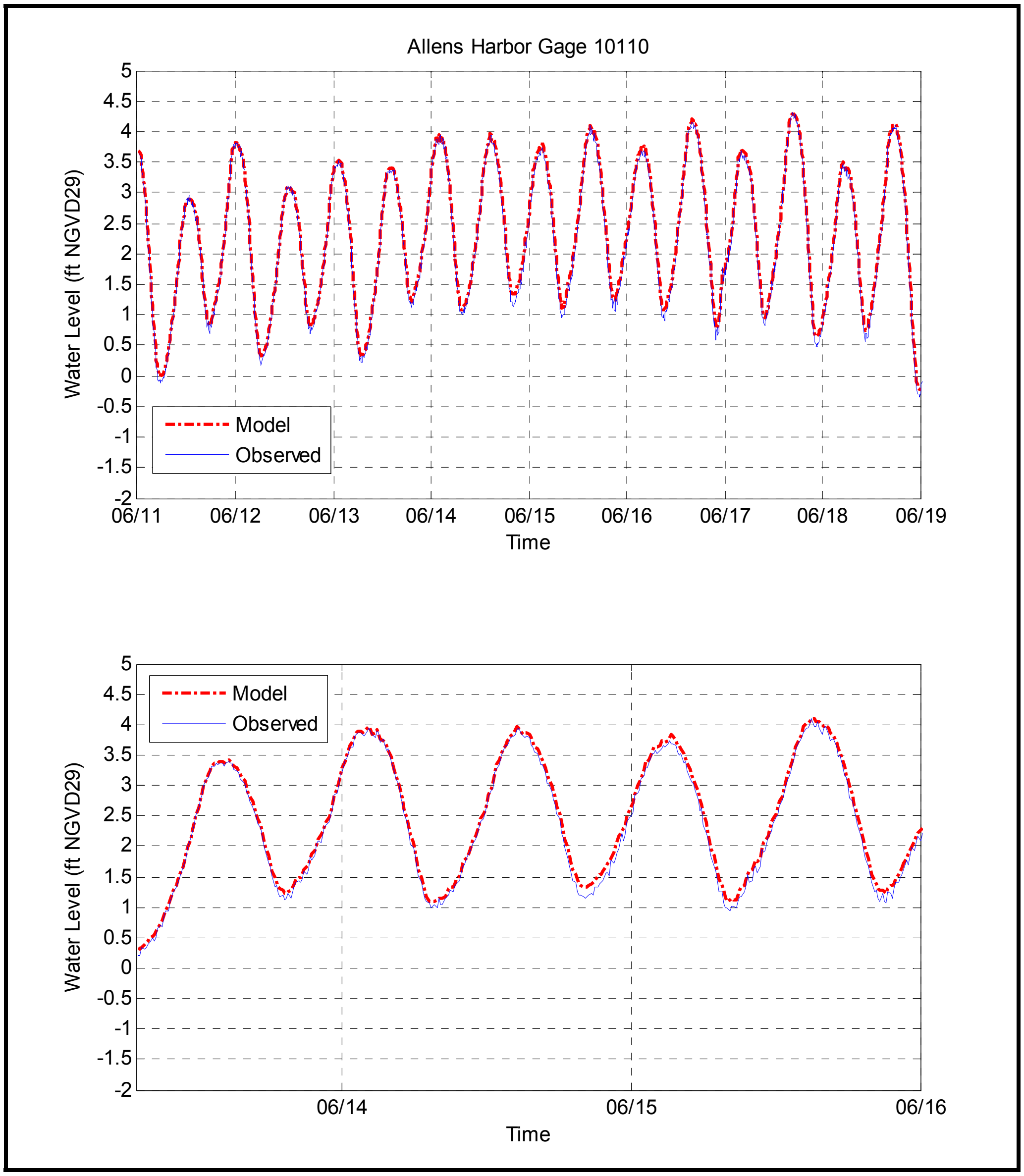


Figure V-12. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period for Allen Harbor northern basin, gaging station 10110. The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

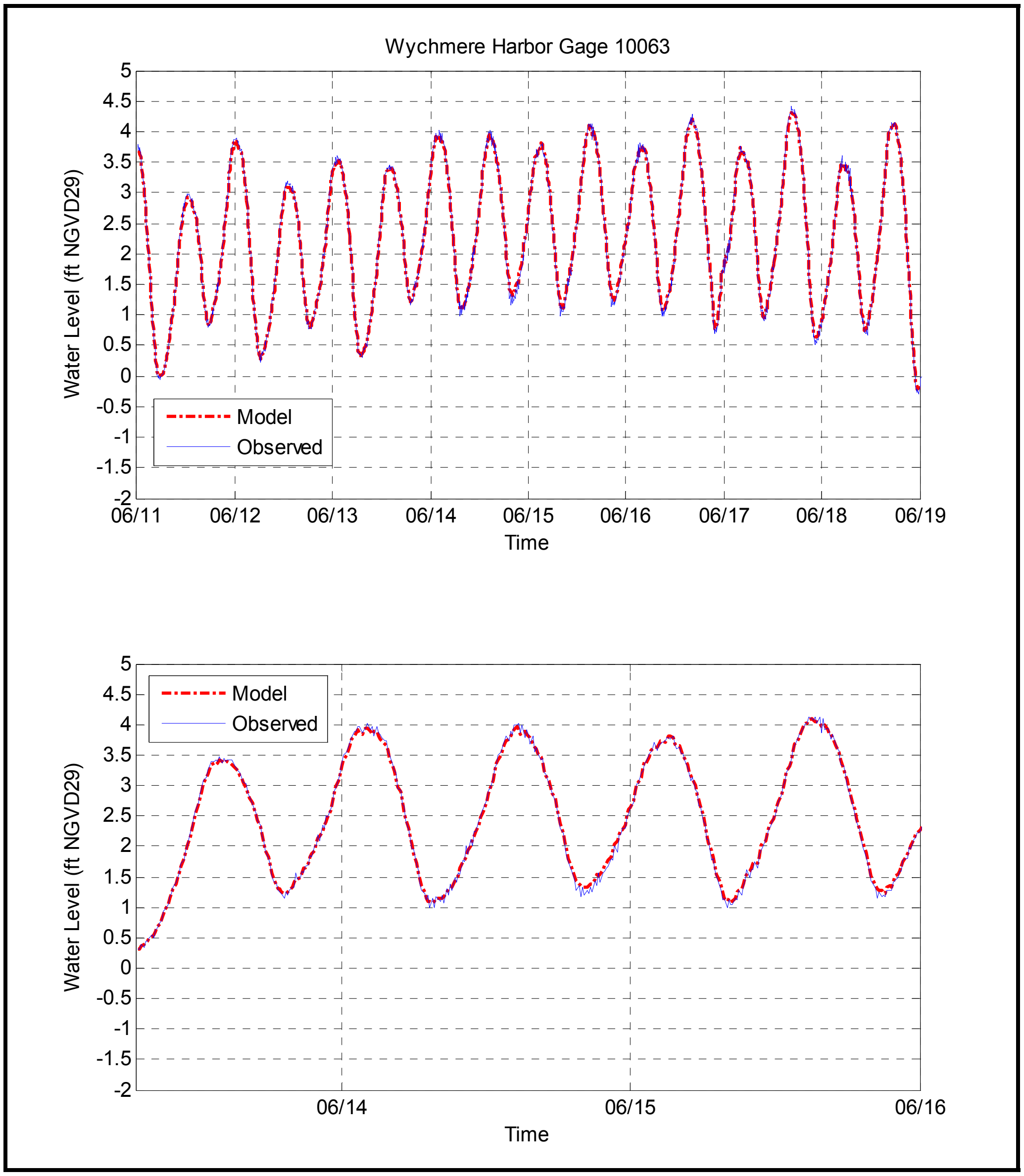


Figure V-13. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period For Wychmere Harbor, gaging station 10063. The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

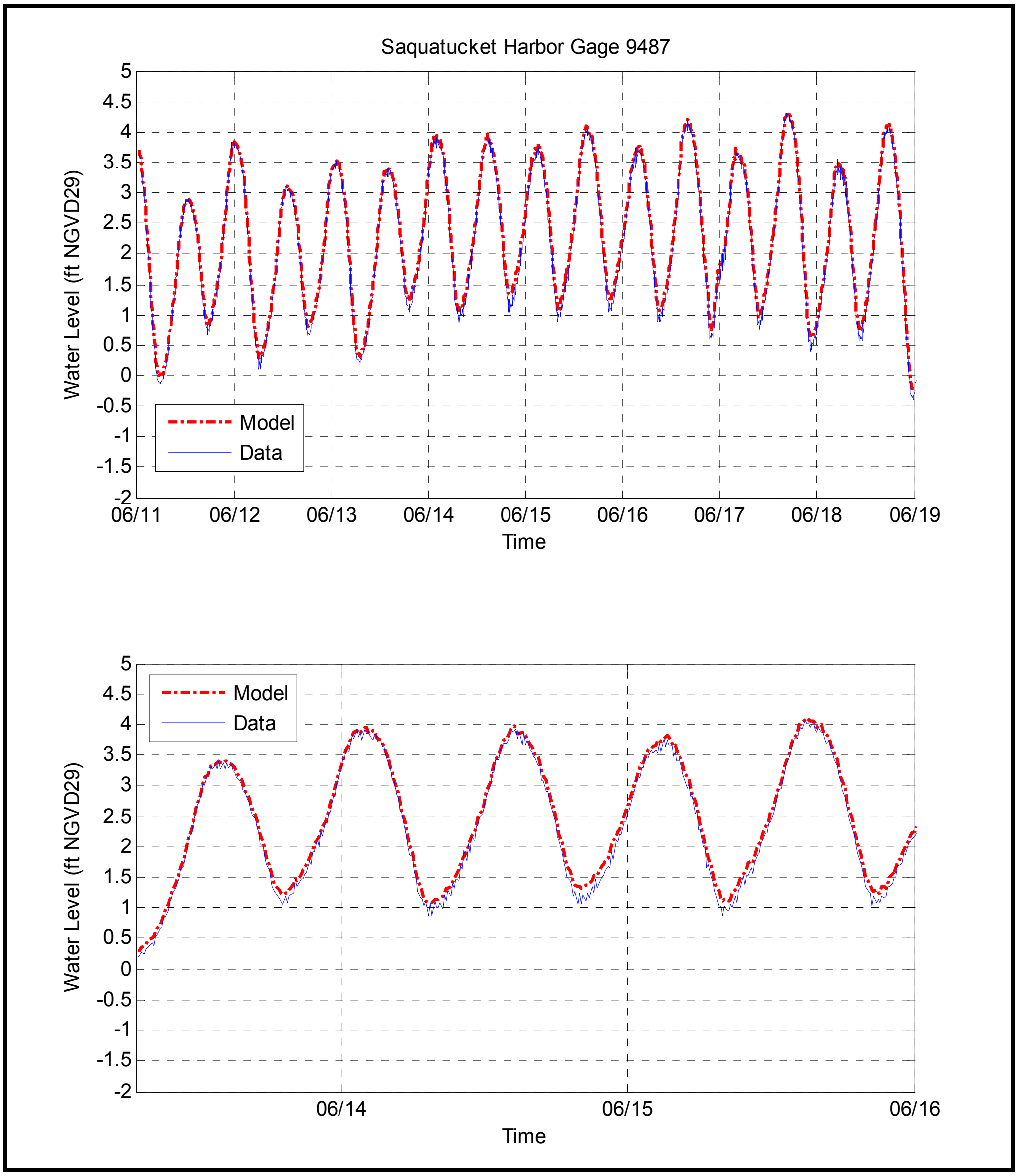


Figure V-14. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period for Saquatucket Harbor, gaging station 9487. The bottom plot is a 65-hour sub-section of the total modeled time period, shown in the top plot.

Table V-7. Comparison of Tidal Constituents calibrated RMA2 model versus measured tidal data for the period June 11 to June 19, 2005.

Model Verification Run						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Allen Harbor, 10114	0.26	1.42	0.12	0.09	174.74	82.06
Allen Harbor, 10110	0.26	1.42	0.12	0.09	175.70	83.98
Allen Harbor, 9515	0.26	1.42	0.12	0.09	174.82	82.35
Saquatucket Harbor, 9487	0.26	1.42	0.12	0.09	174.36	81.27
Wychmere Harbor, 10063	0.26	1.42	0.12	0.09	174.32	81.18
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Allen Harbor, 10114	0.25	1.44	0.13	0.1	173.48	74.27
Allen Harbor, 10110	0.25	1.45	0.13	0.09	173.81	78.37
Allen Harbor, 9515	0.26	1.45	0.12	0.09	174.25	77.97
Saquatucket Harbor, 9487	0.25	1.46	0.13	0.10	172.92	77.26
Wychmere Harbor, 10063	0.25	1.45	0.13	0.10	173.08	77.60
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Allen Harbor, 10114	-0.01	0.02	0.00	0.01	-2.61	-8.06
Allen Harbor, 10110	-0.01	0.03	0.01	0.01	-3.92	-5.81
Allen Harbor, 9515	0.00	0.03	0.00	0.00	-1.19	-4.53
Saquatucket Harbor, 9487	-0.01	0.04	0.00	0.01	-2.97	-4.15
Wychmere Harbor, 10063	-0.01	0.03	0.00	0.01	-2.56	-3.70

V.3.4 Model Circulation Characteristics

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

Overall, the velocity magnitudes throughout Allen, Saquatucket, and Wychmere Harbor systems are very low compared to other systems along the south coast of Cape Cod. The maximum ebb velocity recorded during the simulations was within the inlet to Allen Harbor during an ebb cycle, where the velocity peaked at 0.60 ft/s. The low velocity magnitudes result from the limited volume of the systems and relatively wide entrance channels allowing the water to enter and exit efficiently as the tide raises and falls in Nantucket Sound. A close-up of the model output is presented in Figure V-15, which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow, for a single model time-step, at the portion of the tide where maximum ebb velocities occur at the inlet.

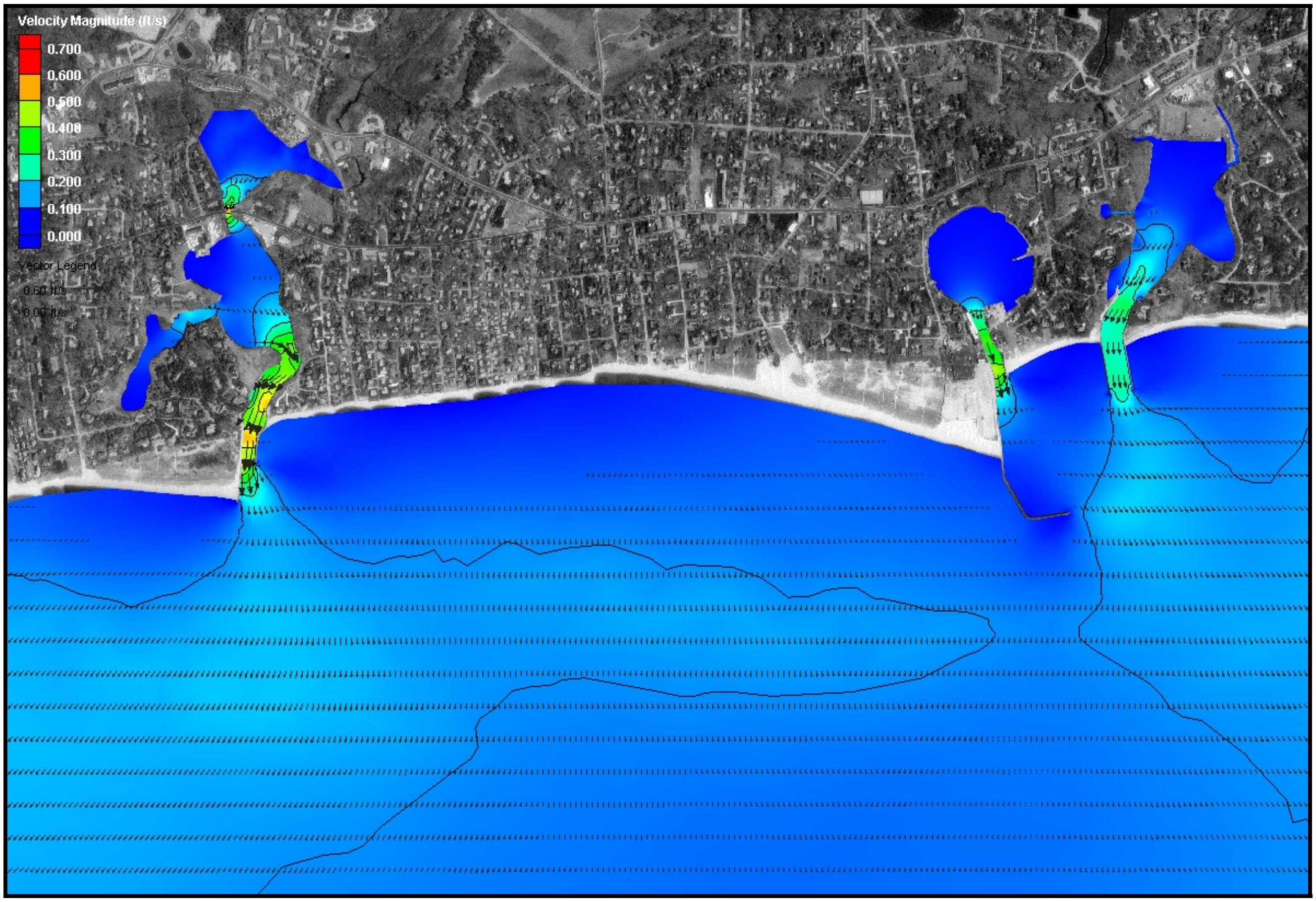


Figure V-15. Example of hydrodynamic model output in Allen, Saquatucket, and Wychmere Harbors for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

V.4 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 Allen, Saquatucket, and Wychmere Harbors 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 systems. Similarly, the estuaries drain 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.

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 will be obtained from the calibrated hydrodynamic model by extending the model to include a total nitrogen dispersion model (Section VI). The water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Allen, Saquatucket, and Wychmere Harbors.

The volume of the each embayment, as well as their respective tidal prisms, were computed as cubic feet (Table V-8). The model computed total volume of each embayment (using the divisions shown in Figure V-8), at every time step, and this output was used to calculate mean embayment volume and average tide prism. Since the 7.75-day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system embayments.

Table V-8. Embayment mean volumes and average tidal prism of the Allen, Saquatucket, and Wychmere Harbor estuary systems during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Allen Harbor	8,204,817	4,325,916
Saquatucket Harbor	7,033,798	2,680,660
Wychmere Harbor	6,654,311	2,292,460

Residence times were averaged for the tidal cycles comprising a representative 7.75 day period (15 tide cycles), and are listed in Table V-9. Residence times were computed for the entire estuaries. 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 embayment over a flood tidal cycle (tidal prism). Units then were converted to days.

Table V-9. Computed System residence times for Allen, Saquatucket, and Wychmere Harbor estuary systems.

Embayment	System Residence Time (days)
Allen Harbor	0.98
Saquatucket Harbor	1.36
Wychmere Harbor	1.51

The Allen, Saquatucket, and Wychmere Harbor estuarine systems have low residence times showing that the systems have good flushing conditions. All three harbors flush within approximately two tidal cycles. 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 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 marsh areas within the systems.

Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary 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.

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems. These include the output from the hydrodynamics model, calculations of external nitrogen loads and freshwater inflows from the watersheds and atmosphere, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen and salinity in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayment

Extensive field measurements and hydrodynamic modeling of the embayments were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated model output representing the transport of water within the three embayment systems. 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. The period of hydrodynamic output for the water quality model calibration was an 11-tidal cycle period in June 2005. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic "steady state", and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayment

Three primary nitrogen loads to each 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine 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 grid.

VI.1.3 Measured Nitrogen Concentrations in the Embayment

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in Figure VI-1. The multi-year averages present the "best" comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. The periods of data collected in each system varied with a maximum of eight years of data (collected between 2001 and 2008) for stations monitored in Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems by the Town of Harwich Water Quality Monitoring Program in collaboration with the Coastal Systems Program at SMAST.

Table VI-1. Measured data, and modeled Total Nitrogen concentrations for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems used in the model calibration plots of Figure VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data are provided courtesy of the Coastal Systems Program at SMAST.						
Sub-Embayment	Saquatucket Harbor	Wychmere Harbor: Outer	Wychmere Harbor	Allen Harbor Marina	Allen Harbor Hulse Pt	Allen Harbor Creek
Monitoring station	HAR-2	HAR-2A	HAR-3	HAR-4	HAR-4A	HAR-5
2001 mean	0.669	--	0.658	1.135	--	1.187
2002 mean	0.546	0.470	0.712	0.689	0.516	0.679
2003 mean	0.643	0.506	0.887	0.481	0.534	0.525
2004 mean	0.584	0.533	0.847	0.484	0.538	0.576
2005 mean	0.587	0.505	0.639	0.488	0.473	0.482
2006 mean	0.720	0.588	0.875	1.130	1.144	1.141
2007 mean	0.698	0.551	0.956	0.697	0.939	1.415
2008 mean	0.819	0.542	0.892	0.902	0.794	0.977
mean	0.658	0.530	0.812	0.747	0.673	0.819
s.d. all data	0.169	0.128	0.254	0.323	0.252	0.400
N	76	34	77	43	34	38
model min	0.627	0.409	0.763	0.592	0.335	0.794
model max	0.680	0.558	0.846	0.749	0.675	0.825
model average	0.652	0.453	0.813	0.679	0.451	0.808

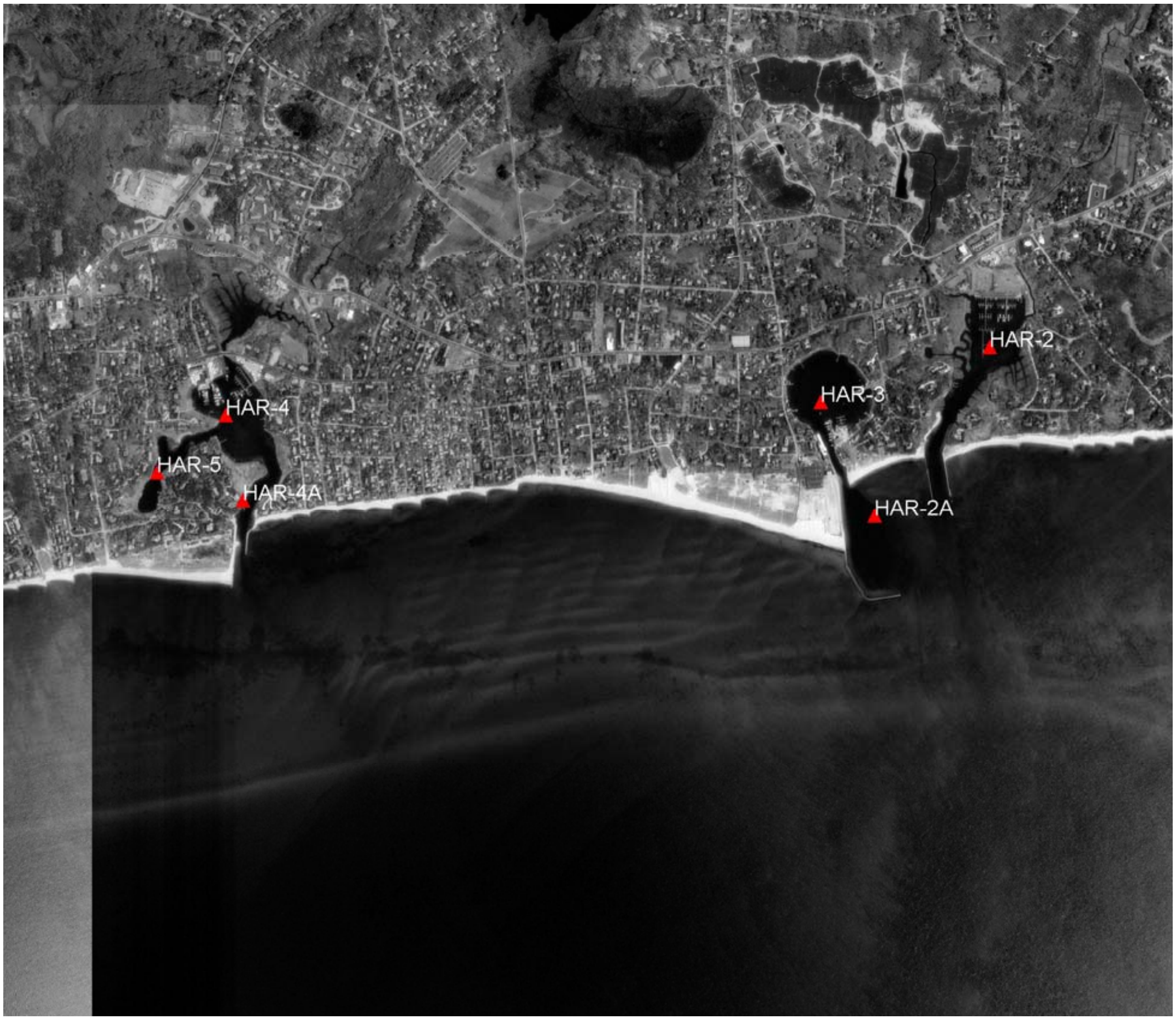


Figure VI-1. Estuarine water quality monitoring station locations in Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. Station labels correspond to those provided in Table VI-1.

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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. 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 Chatham, MA (Howes *et al*., 2003), Falmouth (Ramsey *et al*., 2000); and Mashpee, MA (Howes *et al*., 2004).

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 MEP Technical Team and USGS watershed analysis), as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements were utilized as model boundaries and as calibration data. Hydrodynamic model output (discussed in Section V) provided the remaining information (tides, currents, and bathymetry) needed to parameterize the water quality model of the system.

VI.2.1 Model Formulation

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

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

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

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

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

Harbor estuarine systems was used for the water quality constituent modeling portion of this study.

Based on measured stream flow rates from SMAST and groundwater recharge rates from the watershed analysis, the hydrodynamic model was set-up to include the latest estimate of surface water flows from Allen Pond Stream, Cold Spring Brook, and East Saquatucket Stream along with ground water flowing into the system from watersheds. The Allen Pond Stream has a measured flow rate of 0.37 ft^3/sec (954 m^3/day), Cold Spring Brook has a measured flow rate of 4.22 ft^3/sec (10,328 m^3/day), and East Saquatucket Stream has a measured flow rate of 1.61 ft^3/sec (3,929 m^3/day). The overall groundwater flow rate into the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems are respectively 0.32 ft^3/sec (980 m^3/day), 0.26 ft^3/sec (647 m^3/day), and 0.24 ft^3/sec (597 m^3/day).

For the model, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 5 tidal-day (125 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the watershed land-use analysis, 2) estimates of direct atmospheric deposition, 3) summer benthic regeneration, and 4) localized inputs developed from measured discharges of Allen Pond Stream, Cold Spring Brook, and East Saquatucket Stream. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed direct atmospheric deposition load for Allen Harbor 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 in Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Sections IV.1 and IV.2. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV.3. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment, resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For present conditions, the embayments have over twice the loading rate from benthic regeneration as from watershed loads.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary in Nantucket Sound 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 was set at 0.299 mg/L, based on monitoring data from measurement stations within Nantucket Sound. The open boundary total nitrogen concentration represents long-term average summer concentrations found within Nantucket Sound.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems, 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)
Allen Harbor[1]	4.764	0.227	13.109
Wychmere Harbor[1]	3.866	0.195	13.865
Saquatucket Harbor[1]	2.795	0.151	15.285
Surface Water Sources			
Allen Pond Stream	1.838	-	-
Cold Spring Brook	10.501	-	-
East Saquatucket Stream	3.948	-	-

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge.

VI.2.4 Model Calibration

Calibration of the total nitrogen model proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (*E*) values were varied through the modeled system by setting different values of *E* for each grid material type, as designated in Figure VI-2. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). In contrast, observed values of *E* in the calmer areas of Saquatucket Harbor, Wychmere Harbor and Allen Harbor typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of *E* used in each sub-embayment of the modeled systems are presented in Table VI-3. These values were used to develop the “best-fit” total nitrogen model calibration. For the case of TN modeling, “best fit” can be defined as minimizing the error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

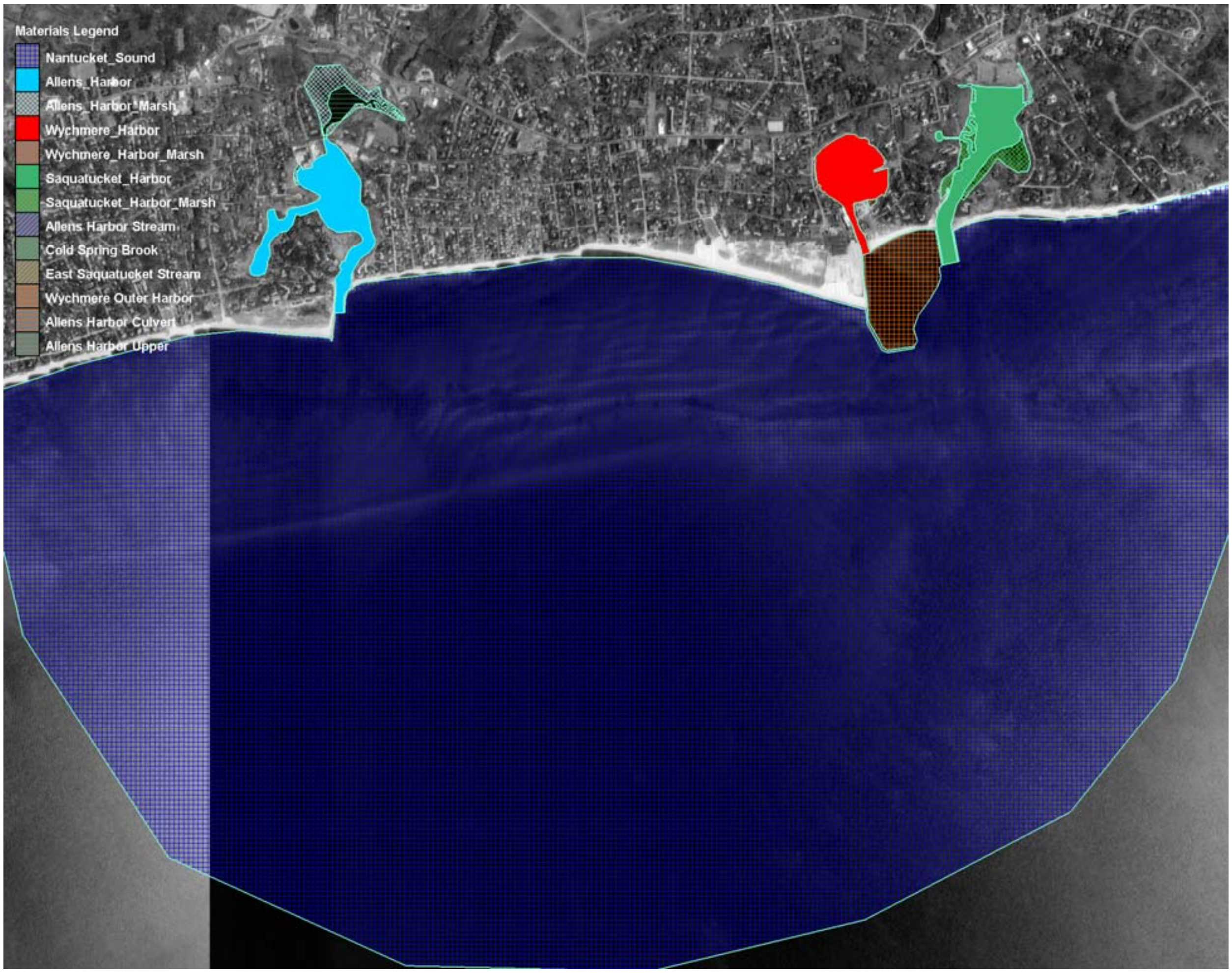


Figure VI-2. Map of Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems water quality model longitudinal dispersion coefficients. Color patterns designate the different areas used to vary model dispersion coefficient values.

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems.

Embayment Division	E m^2/sec
Nantucket Sound	2.90
Allen Harbor	0.45
Allen Harbor Marsh	0.30
Allen Harbor Culvert	1.00
Allen Harbor Upper Marsh	1.00
Allen Harbor Stream	1.20
Saquatucket Harbor	3.00
Saquatucket Harbor Marsh	0.40
Wychmere Harbor	0.20
Wychmere Harbor Marsh	0.20
Wychmere Outer Harbor	0.40
Cold Spring Brook	0.60
East Saquatucket Stream	0.60

Comparisons between model output and measured nitrogen concentrations are shown in plots presented in Figure VI-3. In these plots, means of the water column data and a range of two standard deviations of the annual means at each individual station are plotted against the modeled maximum, mean, and minimum concentrations output from the model at locations which corresponds to the water quality monitoring stations. The emphasis during calibration was to concentrate on representing the conditions measured at the data collection stations within the main basin as opposed to the inlet stations (HAR-2A and HAR-4A). It was felt that those stations more accurately reflected the average conditions within the systems.

For model calibration, the mid-point between maximum modeled TN and average modeled TN was compared to mean measured TN data values, at each water-quality monitoring station. The calibration target would fall between the modeled mean and maximum TN because the monitoring data are collected, as a rule, during mid ebb tide.

Also presented in this figure are unity plot comparisons of measured data versus modeled target values for the system. The model fit is a good representation of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems, with rms error of 0.05 mg/L and an R^2 correlation coefficient of 0.77.

A contour plot of calibrated model output is shown in Figure VI-4 for Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. 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.

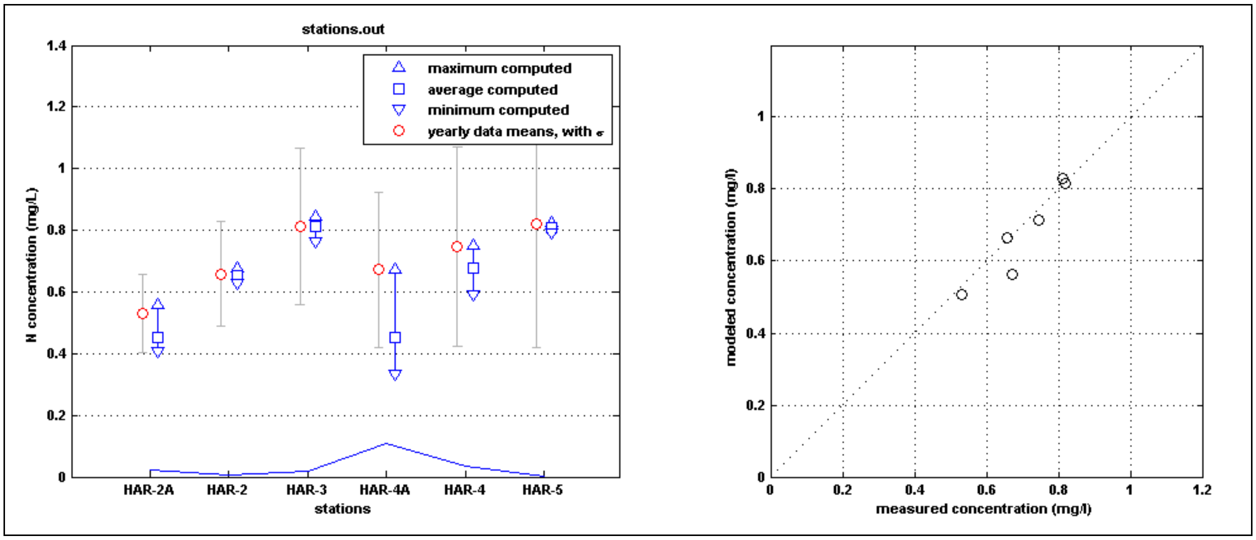


Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of 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.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries 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 31.6 ppt. For groundwater inputs salinities were set at 0 ppt. Groundwater input used for the model was 0.37 ft^3/sec (980 m^3/day) for Allen Harbor, 0.26 ft^3/sec (647 m^3/day) for Wychmere Harbor, and 0.24 ft^3/sec (597 m^3/day) for Saquatucket Harbor. Groundwater flows were distributed evenly in each model through the use of several 1-D element input points positioned along each model's land boundary.

Comparisons of modeled and measured salinities are presented in Figure VI-5, with contour plots of model output shown in Figure VI-6. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems. The rms error of the models was 1.03 ppt. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical systems.

Figure VI-4. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems.

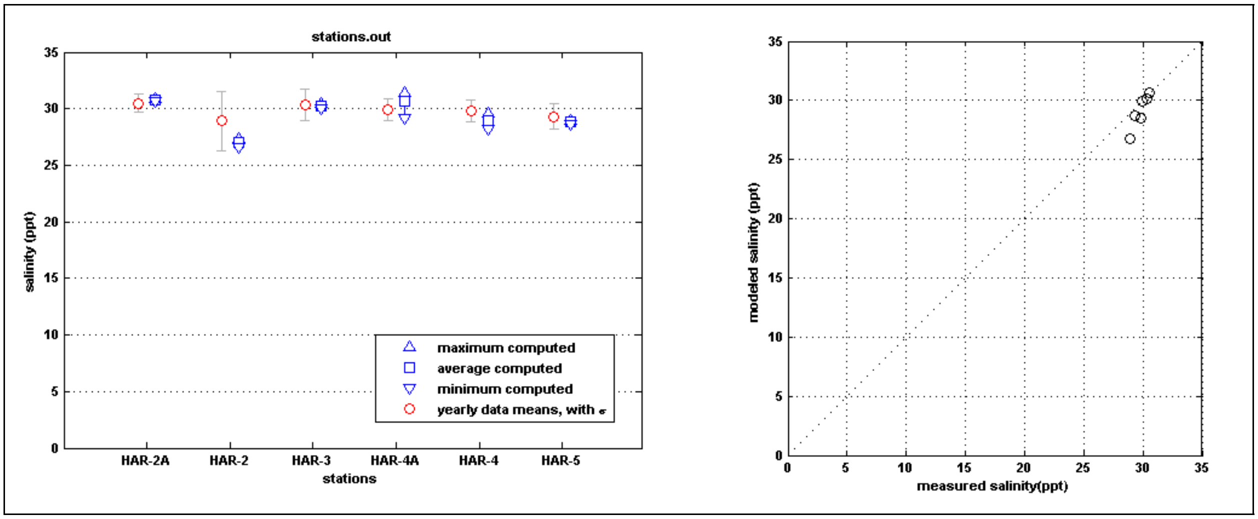


Figure VI-5. Comparison of measured and calibrated model output at stations in the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line.

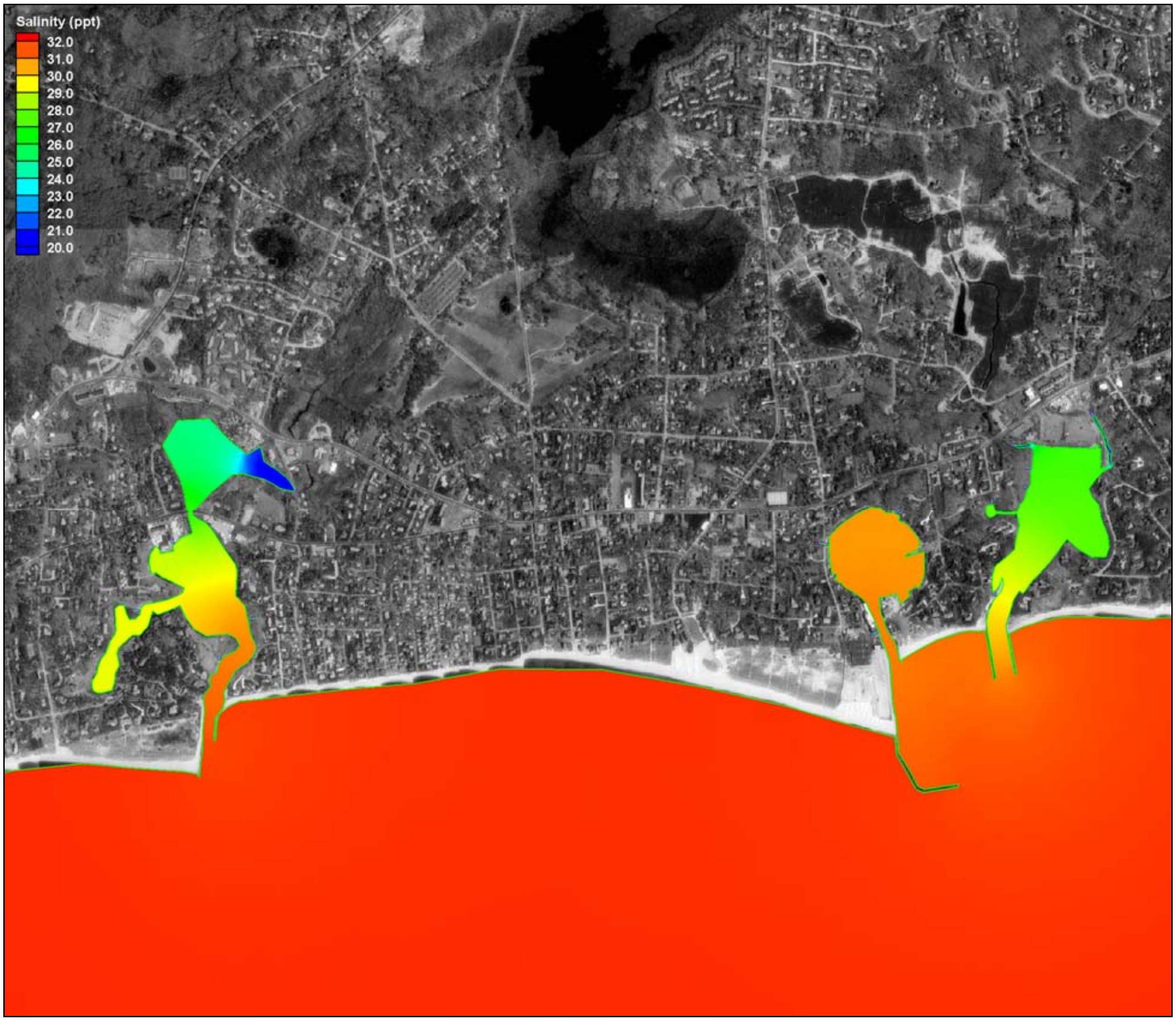


Figure VI-6. Contour plots of modeled salinity (ppt) in the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems.

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 which assumes only atmospheric deposition on the watershed and sub-embayment, as well as a natural forest throughout each watershed. Comparisons of the alternate watershed loading analyses are shown in Table VI-4. Loads are presented in kilograms per day (kg/day) in this Section, since it is inappropriate to show benthic flux loads in kilograms per year due to seasonal variability.

Table VI-4. Comparison of sub-embayment **watershed loads** used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms. For these terms see Table VI-5.

sub-embayment	present load (kg/day)	build out (kg/day)	build out % change	no load (kg/day)	no load % change
Allen Harbor[1]	4.764	5.477	+15.0%	0.063	-98.7%
Wychmere Harbor[1]	3.866	3.975	+2.8%	0.047	-98.8%
Saquatucket Harbor[1]	2.795	3.049	+9.1%	0.038	-98.6%
Surface Water Sources					
Allen Pond Stream	1.838	2.323	+26.4%	0.052	-97.2%
Cold Spring Brook	10.501	11.611	+10.6%	0.337	-96.8%
East Saquatucket Stream	3.948	4.685	+18.7%	0.225	-94.3%

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge, separate from surface water inflows.

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be moderate increases in watershed nitrogen load to the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems as a result of potential future development. For the no load scenarios, a majority of the load entering the watershed is removed; therefore, the load is generally lower than existing conditions by over 90% overall.

For the build-out scenario, a breakdown of the total nitrogen load entering the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems is shown in Table VI-5. The benthic flux for the build-out scenarios is assumed to vary proportional to the watershed load, where an increase in watershed load will result in an increase in benthic flux (i.e., a positive change in the absolute value of the flux), and *vice versa*.

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Table VI-5. Build-out sub-embayment and surface water loads used for total nitrogen modeling of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems, 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)
Allen Harbor[1]	5.477	0.227	14.530
Wychmere Harbor[1]	3.975	0.195	14.127
Saquatucket Harbor[1]	3.049	0.151	16.517
Surface Water Sources			
Allen Pond Stream	2.323	-	-
Cold Spring Brook	11.611	-	-
East Saquatucket Stream	4.685	-	-

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge, separate from surface water inflows.

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Nantucket Sound) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most in the main harbor basin of Allen Harbor, with the largest change occurring along Oyster Creek at Station HAR-5 (10.9%) and the least change occurring in Wychmere Harbor (1.9%). Color contours of model output for the build-out scenario are present in Figure VI-7. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-4, which allows direct comparison of nitrogen concentrations between loading scenarios.

Table VI-6. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems. Sentinel threshold stations are in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Wychmere Harbor	HAR-2A	0.453	0.460	+1.7%
Saquatucket Harbor	**HAR-2**	**0.652**	**0.691**	**+6.0%**
Wychmere Harbor	**HAR-3**	**0.813**	**0.829**	**+1.9%**
Allen Harbor	HAR-4A	0.451	0.478	+5.8%
Allen Harbor	**HAR-4**	**0.679**	**0.749**	**+10.3%**
Allen Harbor	HAR-5	0.808	0.896	+10.9%

Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems, for projected build-out loading conditions. The approximate location of the sentinel threshold stations for Allen Harbor (HAR-4), Wychmere Harbor (HAR-3), and Saquatucket Harbor (HAR-2) are shown.

VI.2.6.2 No Anthropogenic Load

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

Table VI-7. "No anthropogenic loading" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems, 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)
Allen Harbor[1]	0.063	0.227	5.474
Wychmere Harbor[1]	0.047	0.195	4.524
Saquatucket Harbor[1]	0.038	0.151	5.596
Surface Water Sources			
Allen Pond Stream	0.052	-	-
Cold Spring Brook	0.337	-	-
East Saquatucket Stream	0.225	-	-

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge, separate from surface water inflows.

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. The relative change in total nitrogen concentrations resulting from "no load" was significant as shown in Table VI-8, with reductions ranging from 26% occurring in Wychmere Harbor to approximately 54% in Oyster Creek which is part of Allen Harbor. Results for each system are shown pictorially in Figure VI-8.

Table VI-8. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. 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
Wychmere Harbor	HAR-2A	0.453	0.332	-26.7%
Saquatucket Harbor	**HAR-2**	**0.652**	**0.336**	**-48.5%**
Wychmere Harbor	**HAR-3**	**0.813**	**0.421**	**-48.3%**
Allen Harbor	HAR-4A	0.451	0.327	-27.5%
Allen Harbor	**HAR-4**	**0.679**	**0.359**	**-47.2%**
Allen Harbor	HAR-5	0.808	0.371	-54.1%

Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold stations for Allen Harbor (HAR-4), Wychmere Harbor (HAR-3), and Saquatucket Harbor (HAR-2) are shown.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gaged 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor embayment systems in the Town of Harwich, MA, the MEP assessment is based upon data from the water quality monitoring database developed by the Town of Harwich, as well as field survey and historical data collected under the programmatic umbrella of the Massachusetts Estuaries Project. These data on dissolved oxygen, chlorophyll-a, sediment characteristics and benthic infaunal communities were collected by the Coastal Systems Program at SMAST-UMass-Dartmouth in 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, the MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll a (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed centrally located dissolved oxygen sensors within each of the three systems (Allen Harbor, Wychmere Harbor and Saquatucket Harbor) to record the frequency and duration of low oxygen conditions during the critical summer period. It should be noted that the Harwich Water Quality Monitoring Program, in its biweekly samplings, periodically observes bottom water oxygen depletion, with minimum recorded levels $\leq$ 3 mg/L within the main basin of each of the Harbors. This data was used to site the continuously recording oxygen sensors in order to better elucidate the magnitude and duration of bottom water hypoxia in each basin. Since Allen Harbor has a small basin tributary to the main basin, it was necessary to deploy two dissolved oxygen sensors, one in the main basin and one in the tributary basin, to capture the oxygen conditions throughout the open waters of this system.

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 three embayments 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 changing water quality conditions. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. However, for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems, analysis of temporal changes in eelgrass distribution could not be used for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet or additional culverts) in nutrient enrichment as there is no record of eelgrass beds within each of these systems for over a half century. Also of note, Saquatucket Harbor is an "artificial" basin, formed by dredging the Andrews Creek salt marsh, and has been without eelgrass since its creation in 1968 (prior to that it was salt marsh). The presence of eelgrass beds in the nearshore waters immediately adjacent to each of the three systems (seaward of the inlets to each harbor) may provide a basis for linking nutrient enrichment to habitat impairment, but this cannot be linked directly to specific basins within the Harbors. Therefore, the MEP assessment of habitat quality within each of the Three Harbors did not rely on eelgrass habitat, but on other key nitrogen related indicators.

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 the habitat in which they exist. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life-history information on the species and a wide variety of field studies within southeastern Massachusetts waters, including the Wild Harbor oil spill, benthic population studies in Buzzards Bay (Woods Hole Oceanographic Institution) and New Bedford (SMAST), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H’) and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 4 mg L^{-1}. Massachusetts State Water Quality Classification indicates that SA (high quality) waters be able to maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor embayment systems, while being considered small harbors, are still 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. As such, that is the designated water quality that is the target of TMDL's generated under the U.S. Clean Water Act. It is through the MEP and TMDL processes that site specific management targets are developed and under the Town's CWMP that management alternatives are developed 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 (by example, 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 each of the systems (Figure VII-2 and VII-3). 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 precision 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 Saquatucket, Wychmere and Allen Harbor embayment systems were collected during the summer of 2004.

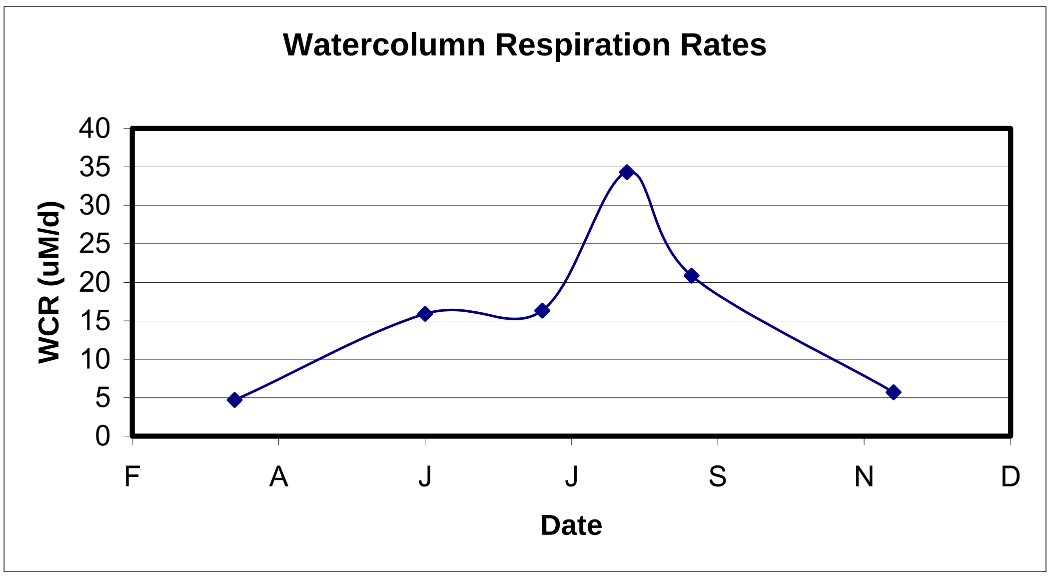


Figure VII-1. Average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability. This figure is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

Similar to other embayments in southeastern Massachusetts, the Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems 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.

Dissolved oxygen and chlorophyll a records were examined both for temporal trends and to determine the percent of the 34-37 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 nutrient enriched waters and some impairment of infaunal habitat quality at each of the mooring sites within each of the basins of the Three Harbors (Figures VII-2 through VII-11). The oxygen data parallels the level of organic matter enrichment from phytoplankton production (chlorophyll a levels) indicative of moderate to high nitrogen enrichment.

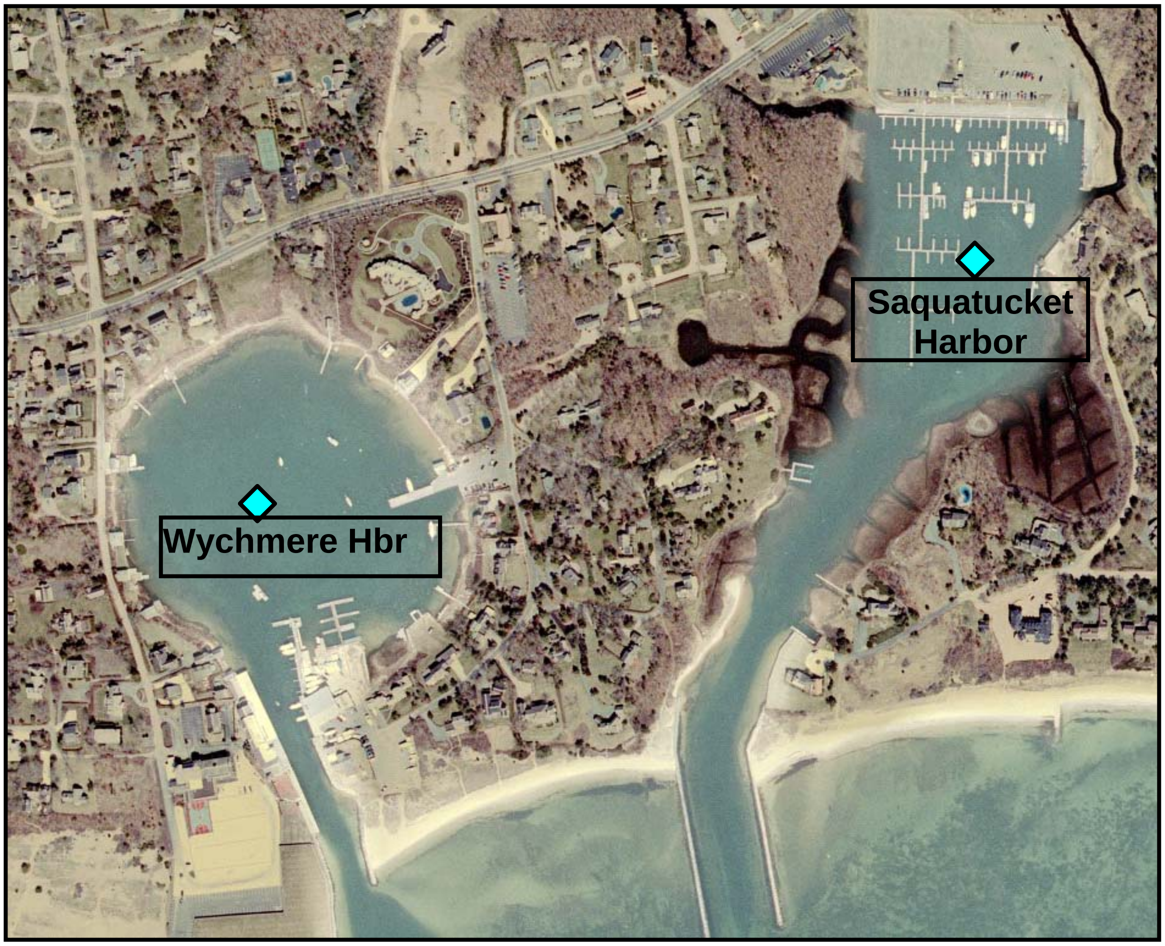


Figure VII-2. Aerial Photograph of the Saquatucket and Wychmere Harbor Systems within the Town of Harwich showing locations of Dissolved Oxygen/Chlorophyll *a* mooring deployments conducted in the summer of 2004.

Assessments based only on the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The critical effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels can also rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The evidence of oxygen levels above atmospheric equilibration in the Allen Harbor, Wychmere Harbor and Saquatucket Harbor systems is a clear indication that these estuaries are nitrogen enriched and that enrichment is causing high levels of plant production. It should also be noted that the uppermost region of Allen Harbor may also be influenced by an upgradient salt marsh that may be enhancing organic matter enrichment in the main basin. However, the distribution of organic matter throughout the Harbor basins strongly supports the contention that nitrogen enrichment and resulting phytoplankton production are the primary cause of increased organic matter and oxygen depletion within the Allen Harbor System.

Figure VII-3. Aerial Photograph of the Allen Harbor System within the Town of Harwich showing locations of Dissolved Oxygen/Chlorophyll *a* mooring deployments conducted in the summer of 2004.

Overall, the dissolved oxygen records clearly indicate oxygen depletion and elevated chlorophyll *a* levels in each of the basins of the Three Harbors (Table VII-1 and VII-2). The extent of oxygen depletion in each basin was similar to those observed by the Harwich Water

Quality Monitoring Program (2001-2008). All sites showed periodic oxygen depletions to levels less than 4 mg L^{-1}, however, the minima varied between basins (between 2 and 3 mg L^{-1}). Equally important, the estuarine response to over-enrichment from nitrogen and the extent of bottom water oxygen depletion is consistent with the levels of phytoplankton biomass (e.g. chlorophyll *a*, Table VII-2), as also observed in other Cape Cod estuaries. Given the basin types and configurations and the levels of oxygen depletion and organic matter enrichment, infaunal habitat impairment within each basin of the Three Harbors is expected. The embayment specific results are as follows:

Saquatucket Harbor **(Figures VII-4 and VII-8):**

The mooring was placed in the middle of the main basin at the outer margin of the marina. The mooring was deployed in the main basin and positioned in the upper one-third of the system in ~2.8 m of water. The sediments throughout the Harbor were very soft unconsolidated muds, generally with a thin oxidized surface layer, but in some places patches of sulfur bacterial mat overlying sulfidic sediments were observed. The oxygen record showed frequent oxygen depletion to < 4 mg L^{-1} and periodic oxygen depletion to <3 mg L^{-1}, with some values in excess of air equilibration in day time. The bottom water rarely reached air equilibration throughout the deployment period. Consistent with the oxygen levels, chlorophyll a was moderate to high, generally 6-20 ug L^{-1}, with frequent excursions over 20 mg L^{-1}. The oxygen and chlorophyll a records provide clear evidence of a system enriched by nitrogen, where phytoplankton production is enhanced with resulting negative effects on the water column oxygen levels. Oxygen uptake results from both respiration within the watercolumn and the sediments, where organic matter accumulates. The sediments of Saquatucket Harbor have very high summertime rates of oxygen uptake, >5000 mg O_2 m^{-2} d^{-1} (D. Schlezinger, personal communication), further evidence that oxygen depletion is being generated by *in situ* processes.

Wychmere Harbor **(Figures VII-5 and VII-9):**

The mooring was placed in the middle of the main bowl-shaped basin, in ~2.9 m of water. The sediments were soft and very soft unconsolidated organic muds. The sediments were sulfidic, typically with a very thin oxidized layer (~1mm) or sulfur bacterial mat. The oxygen record showed periodic oxygen depletion to < 4 mg L^{-1}, but levels did not go below 3 mg L^{-1}. Oxygen levels in excess of air equilibration in day time were observed, but were not the norm. The bottom water remained below air equilibration for the first half of the deployment period. Consistent with the oxygen levels, chlorophyll a was high, generally 10-25 ug L^{-1}, with frequent excursions over 25 mg L^{-1}. The oxygen and chlorophyll a records provide clear evidence of a system enriched by nitrogen, where phytoplankton production is enhanced with resulting negative effects on the water column oxygen levels. Oxygen uptake results from both respiration within the watercolumn and the sediments, where organic matter accumulates. The sediments of Wychmere Harbor (like Saquatucket Harbor) have very high summertime rates of oxygen uptake, ~5000 mg O_2 m^{-2} d^{-1} (D. Schlezinger, personal communication), further evidence that oxygen depletion is being generated by *in situ* processes.

Allen Harbor (Figures VII-6, 7 and VII-10, 11):

Allen Harbor differs from Saquatucket and Wychmere Harbors in that it has a tributary open water basin off the main basin. As a result, it was necessary to place two moorings in the Allen Harbor System, one at the upper third of the main basin (just seaward of the marina area) and one mid-way up the Allen Creek tributary in ~2.1 and ~1.7 m of water, respectively. The sediments within both basins were soft and very soft unconsolidated organic muds. The sediments were sulfidic, typically with a very thin oxidized layer (~1mm) or sulfur bacterial mat. The oxygen record showed periodic oxygen depletion to < 4 mg L^{-1}, but depletion was significantly greater in Allen Creek compared to the main basin. Main basin bottom water oxygen showed periodic levels of bottom water oxygen in the 3-4 mg L^{-1} range, while the Creek had periodic oxygen declines into the 2-3 mg L^{-1} range. Oxygen levels in excess of air equilibration in day time were observed, but were not the norm. The bottom water generally remained below air equilibration for much of the deployment period at both mooring sites. Consistent with the oxygen levels, chlorophyll a was moderate in the main basin, generally 4-15 ug L^{-1}, with frequent excursions over 15 ug L^{-1}. The greater oxygen depletion in Allen Creek was coupled with the moderate to high chlorophyll a levels, generally ~6-20 ug L^{-1} and frequently was >20 ug L^{-1}.

The oxygen and chlorophyll a records provide clear evidence of a system enriched by nitrogen, where phytoplankton production is enhanced with resulting negative effects on the water column oxygen levels. Oxygen uptake results from both respiration within the watercolumn and the sediments, where organic matter accumulates. The sediments of Allen Harbor main basin, like the adjacent basins of Wychmere and Saquatucket Harbors, have very high summertime rates of oxygen uptake, ~4000 mg O_2 m^{-2} d^{-1} (D. Schlezinger, personal communication). While also high, sediment oxygen uptake within Allen Creek are lower (~2250 mg O_2 m^{-2} d^{-1}), possibly due to a difference in organic matter deposition rates. However, the lower rates in the sediment appear to be more than offset by the higher plankton biomass (i.e. night time water column respiration), as oxygen depletion in the Creek was more severe than observed in the main basin. The difference in oxygen levels within the two basins may also have been enhanced by differences in wind-driven vertical mixing, due to the much greater fetch in the main basin compared to the narrow basin of the Creek.

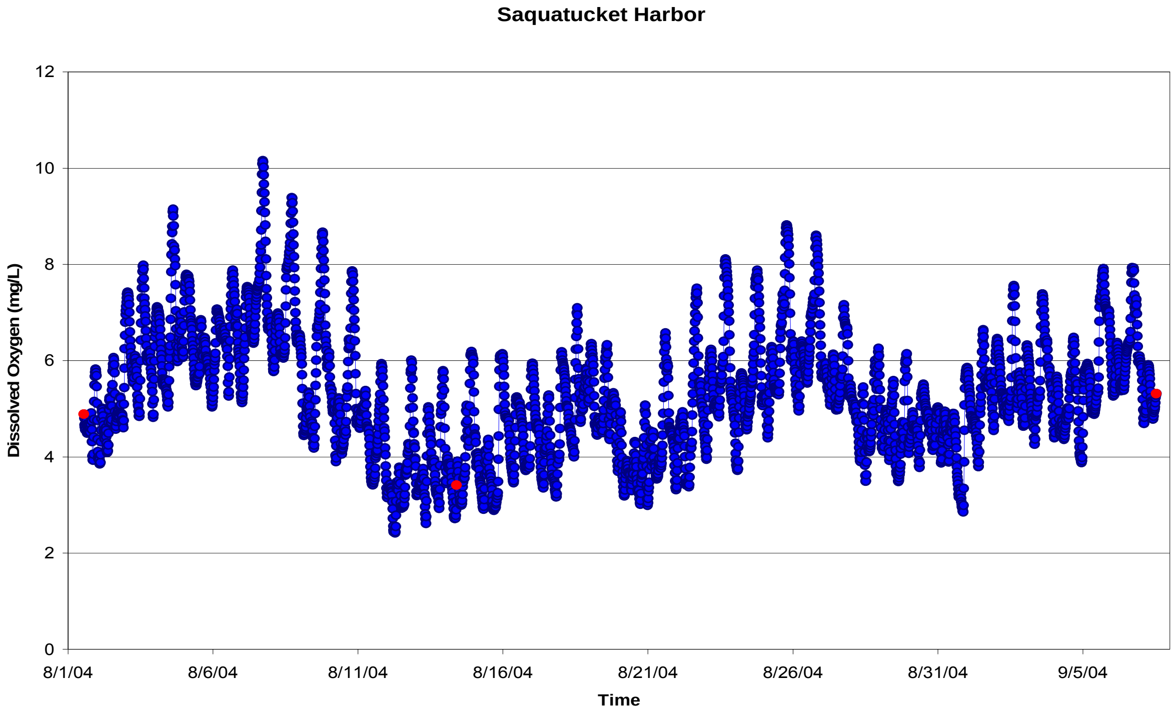


Figure VII-4. Bottom water record of dissolved oxygen in Saquatucket Harbor basin, summer 2004. Calibration samples represented as red dots.

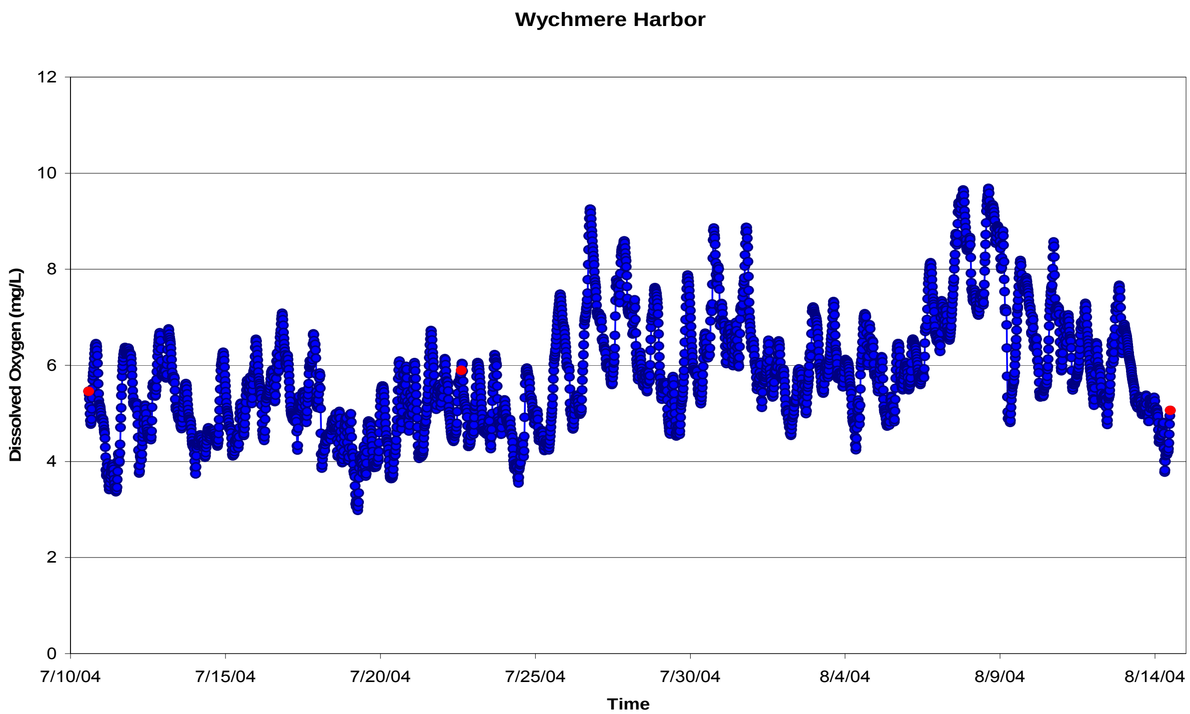


Figure VII-5. Bottom water record of dissolved oxygen in Wychmere Harbor, summer 2004. Calibration samples shown as red dots, data gap due to fouling of sensor.

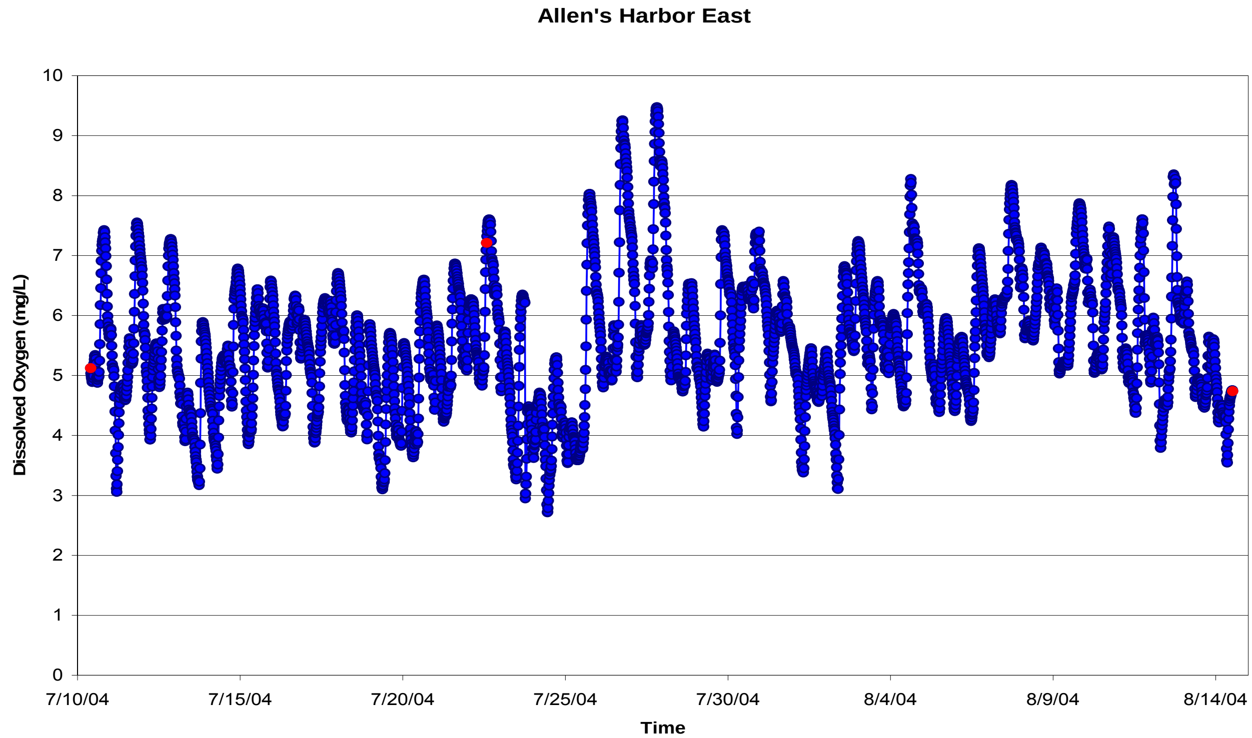


Figure VII-6. Bottom water record of dissolved oxygen at the Allen Harbor (east) mooring location, summer 2004. Calibration samples represented as red dots.

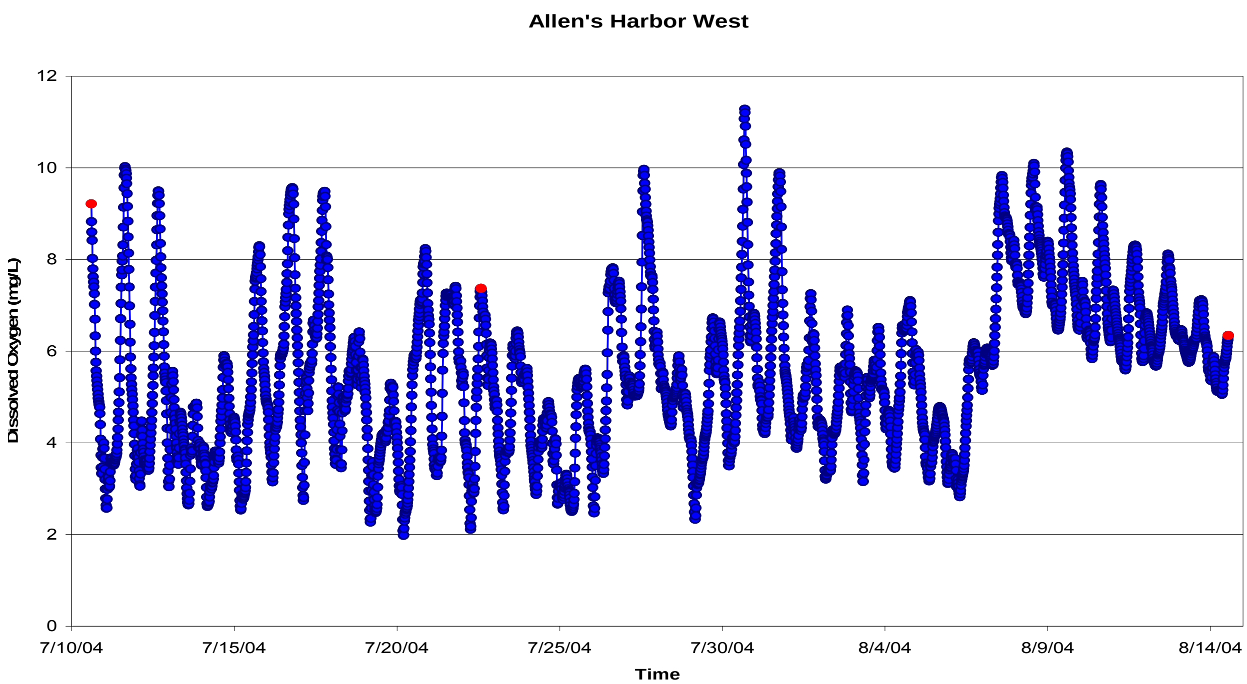


Figure VII-7. Bottom water record of dissolved oxygen at the Allen Harbor (west) mooring location, summer 2004. Calibration samples represented as red dots.

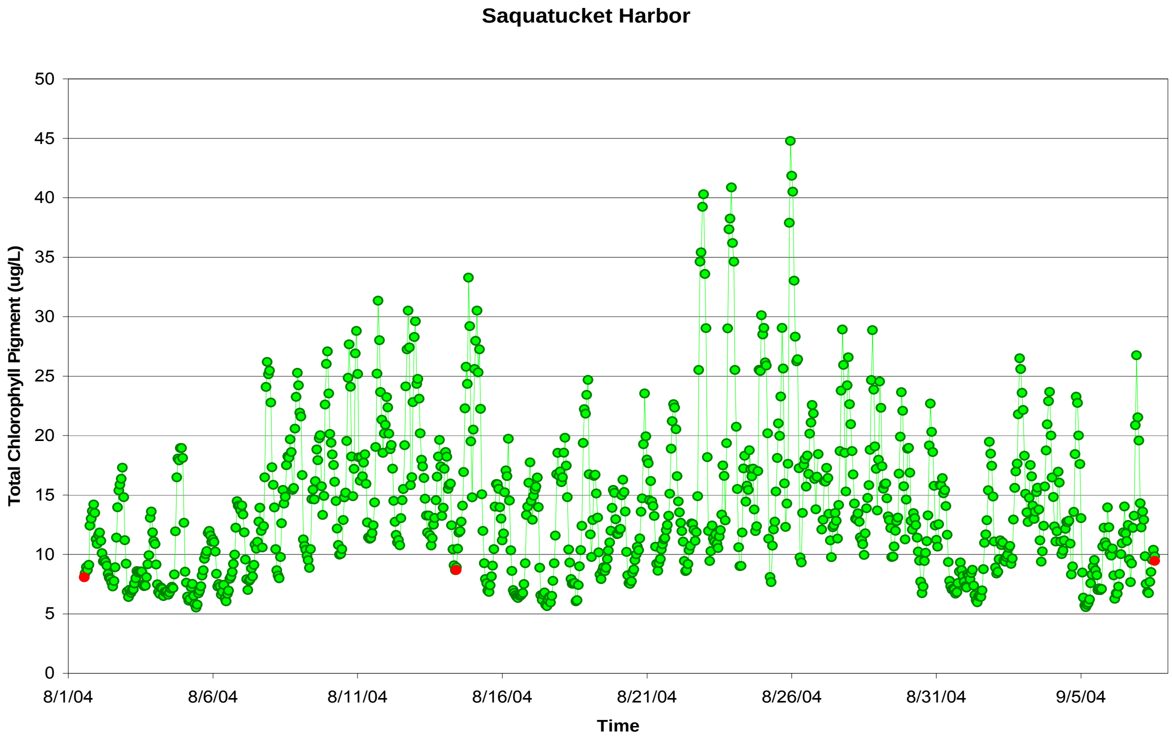


Figure VII-8. Bottom water record of Chlorophyll-*a* in Saquatucket Harbor, summer 2004. Calibration samples represented as red dots.

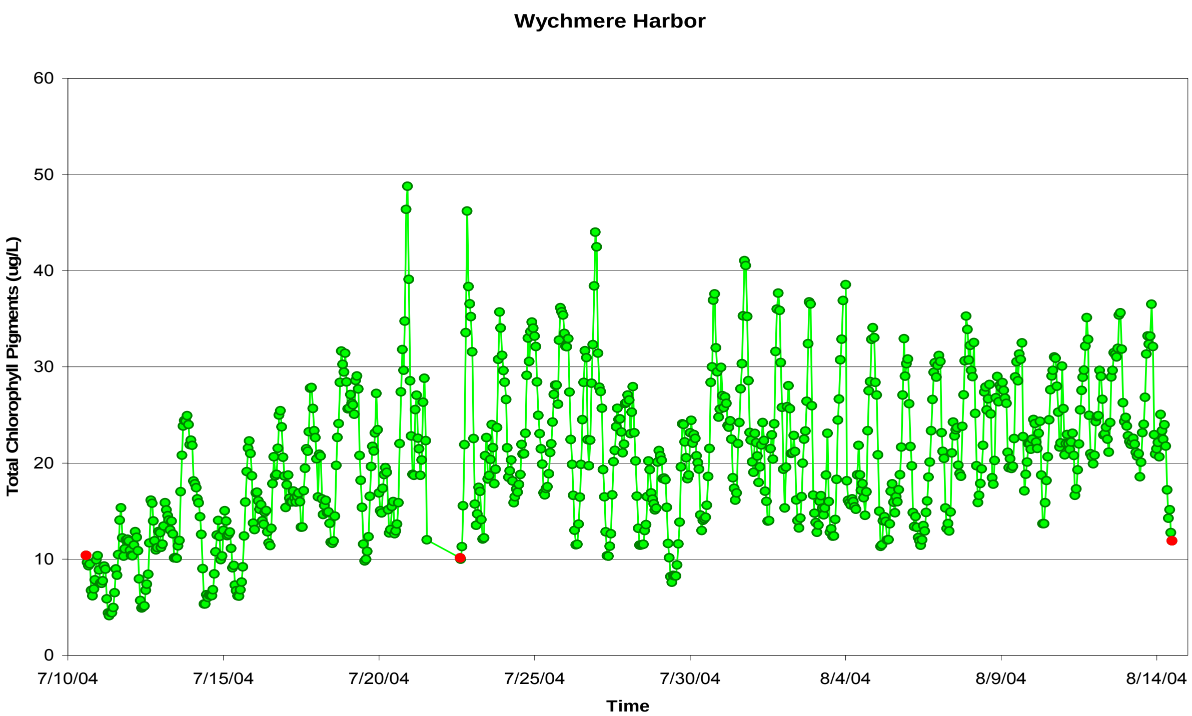


Figure VII-9. Bottom water record of Chlorophyll-*a* in Wychmere Harbor, summer 2004. Calibration samples represented as red dots.

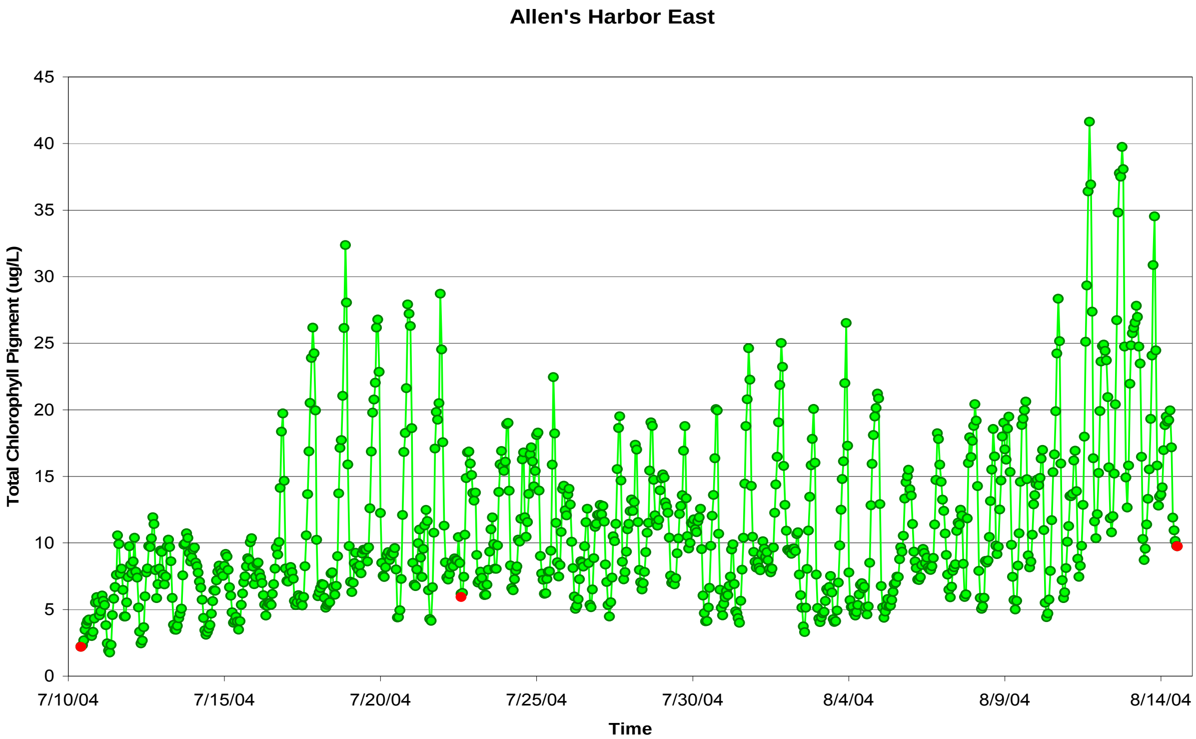


Figure VII-10. Bottom water record of Chlorophyll-*a* at the Allen Harbor (east) mooring location, summer 2004. Calibration samples represented as red dots.

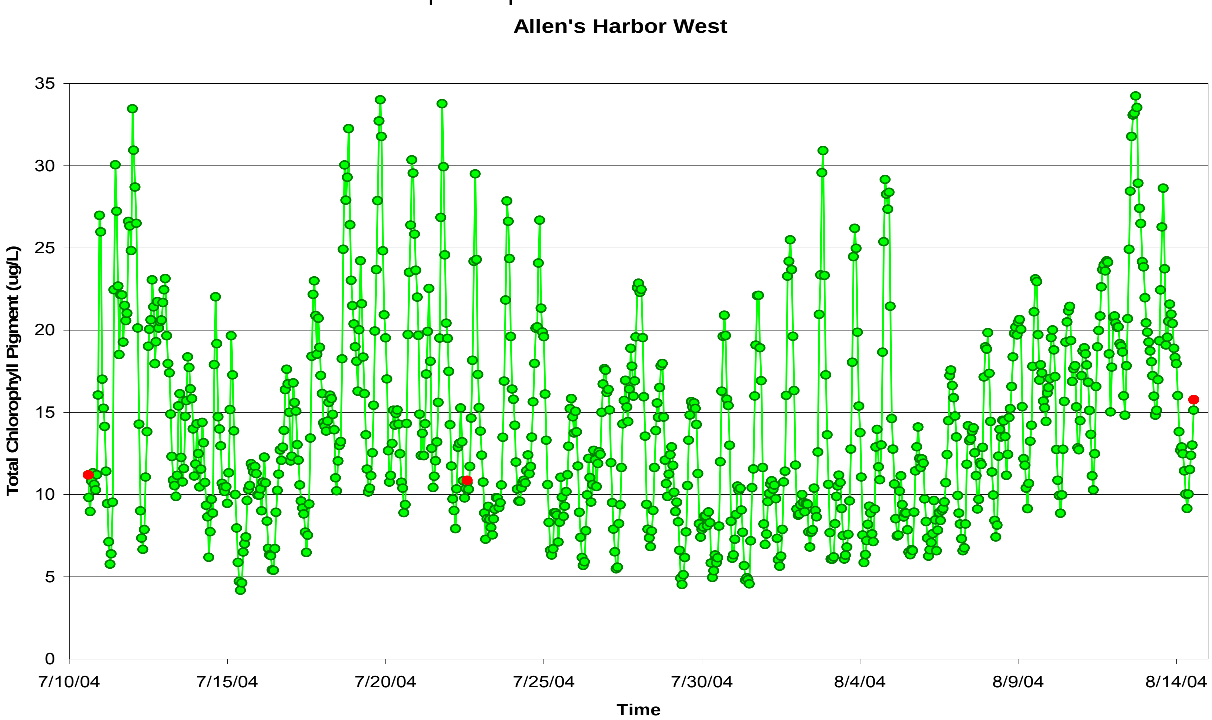


Figure VII-11. Bottom water record of Chlorophyll-*a* at the Allen Harbor (west) mooring location, summer 2004. Calibration samples represented as red dots.

Table VII-1. Percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels. Allen Harbor, Wychmere Harbor and Saquatucket Harbors within the Town of Harwich, MA.

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Allens Harbor West	7/10/2004	8/14/2004	**34.95**	**64%**	**41%**	**22%**	**5%**
			Mean	0.66	0.43	0.24	0.08
			Min	0.04	0.01	0.01	0.01
			Max	2.73	1.50	0.68	0.20
			S.D.	0.69	0.41	0.18	0.05
Allens Harbor East	7/10/2004	8/14/2004	**35.1**	**68%**	**32%**	**7%**	**0%**
			Mean	0.55	0.22	0.10	0.03
			Min	0.02	0.02	0.01	0.01
			Max	1.95	0.90	0.32	0.05
			S.D.	0.52	0.20	0.08	0.03
Saquatucket Harbor	8/1/2004	9/7/2004	**37.0**	**73%**	**44%**	**17%**	**2%**
			Mean	0.55	0.25	0.16	0.06
			Min	0.01	0.01	0.01	0.01
			Max	2.59	1.01	0.76	0.13
			S.D.	0.60	0.25	0.17	0.04
Wychmere Harbor	7/10/2004	8/14/2004	**34.91**	**62%**	**28%**	**4%**	**0%**
			Mean	0.44	0.23	0.09	0.01
			Min	0.01	0.01	0.01	0.01
			Max	2.68	1.30	0.39	0.01
			S.D.	0.52	0.27	0.11	N/A

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.

Mooring Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Allens Harbor West	7/10/2004	8/14/2004	34.9	**99%**	**72%**	**40%**	**18%**	**6%**
Mean Chl Value = 14.4 ug/L			Mean	5.76	0.57	0.30	0.18	0.12
			Min	0.04	0.04	0.04	0.04	0.04
			Max	14.08	3.92	0.92	0.63	0.38
			S.D.	6.55	0.71	0.23	0.13	0.09
Allens Harbor East	7/10/2004	8/14/2004	35.1	**91%**	**44%**	**22%**	**9%**	**4%**
Mean Chl Value = 11.1 ug/L			Mean	1.45	0.32	0.20	0.15	0.11
			Min	0.13	0.04	0.04	0.04	0.04
			Max	5.67	1.96	0.46	0.38	0.25
			S.D.	1.75	0.31	0.11	0.10	0.08
Saquatucket Harbor	8/1/2004	9/7/2004	37.0	**100%**	**70%**	**36%**	**15%**	**7%**
Mean Chl Value = 14.3 ug/L			Mean	18.48	0.67	0.25	0.17	0.13
			Min	0.04	0.04	0.04	0.04	0.04
			Max	36.92	3.92	0.75	0.33	0.33
			S.D.	26.07	0.62	0.16	0.09	0.10
Wychmere Harbor	7/10/2004	8/14/2004	34.9	**96%**	**90%**	**71%**	**49%**	**25%**
Mean Chl Value = 20.4 ug/L			Mean	8.41	3.14	0.69	0.35	0.24
			Min	0.04	0.04	0.04	0.04	0.04
			Max	32.08	15.88	3.96	1.46	0.63
			S.D.	15.79	4.95	0.89	0.28	0.14

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass distribution and analysis of historical data was conducted for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor Embayment Systems by the MassDEP Eelgrass Mapping Program as part of the MEP technical effort. Field surveys of the Three Harbors were conducted in 1995 and 2001 by MassDEP, as part of this program, with additional observations during summer and fall 2004 by the SMAST/MEP Technical Team. Analysis of available aerial photography from 1951 was conducted to reconstruct the eelgrass distribution prior to the present level of development of the watershed. The primary use of the eelgrass data within the MEP approach is to indicate (a) if eelgrass once or currently colonizes a basin and (b) any large-scale system-wide shifts in distribution. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 (Figures VII-12 and 13). This temporal information can be used to determine the stability of the eelgrass community in many systems.

All of the available information on eelgrass relative to these three heavily altered harbor systems indicates that these embayments have not supported eelgrass over the past half century and likely have not supported eelgrass for over a century. Saquatucket Harbor was originally a tidal river salt marsh system (historically known as Andrews River) until it was dredged to create the present harbor in 1968-69. Similarly, Wychmere Harbor was never a natural harbor but rather was a salt pond with a small tidal brook that was made navigable in the late 1880's. Clearly these systems have never supported eelgrass. While Allen Harbor historically consisted of a main basin, it appears that there has been alteration to enhance it as a harbor for the Town. The MassDEP analysis indicates that eelgrass habitat was not present within the three systems in 1951 nor in 1995 or 2001, consistent with the history of alteration of these systems and their present level of nitrogen related water quality.

It should be noted that while no eelgrass habitat could be documented within any of the three estuaries, the adjacent nearshore waters of Nantucket Sound do support eelgrass habitat (Figure VII-12). The acreage of eelgrass in these near shore Nantucket Sound waters appears to be relatively stable, although there does seem to be alteration of the bed configuration as a result of maintenance of the tidal inlets in the 1995 & 2001 distribution maps. This MassDEP analysis is based upon available aerial photos from 1951 and field surveys in 1995 and 2001.

As eelgrass habitat could not be documented to exist, either historically or presently, within Saquatucket, Wychmere or Allen Harbors, the thresholds analysis for these systems is necessarily focused on restoration of their impaired infaunal animal habitats. However, it is likely that nitrogen management within these three systems will improve eelgrass and infaunal habitat within the down-gradient near shore waters of the Sound. This down-gradient effect, to the extent that it occurs, will be a by-product of the restoration of each harbor and was not part of the thresholds analyses for each of these systems.

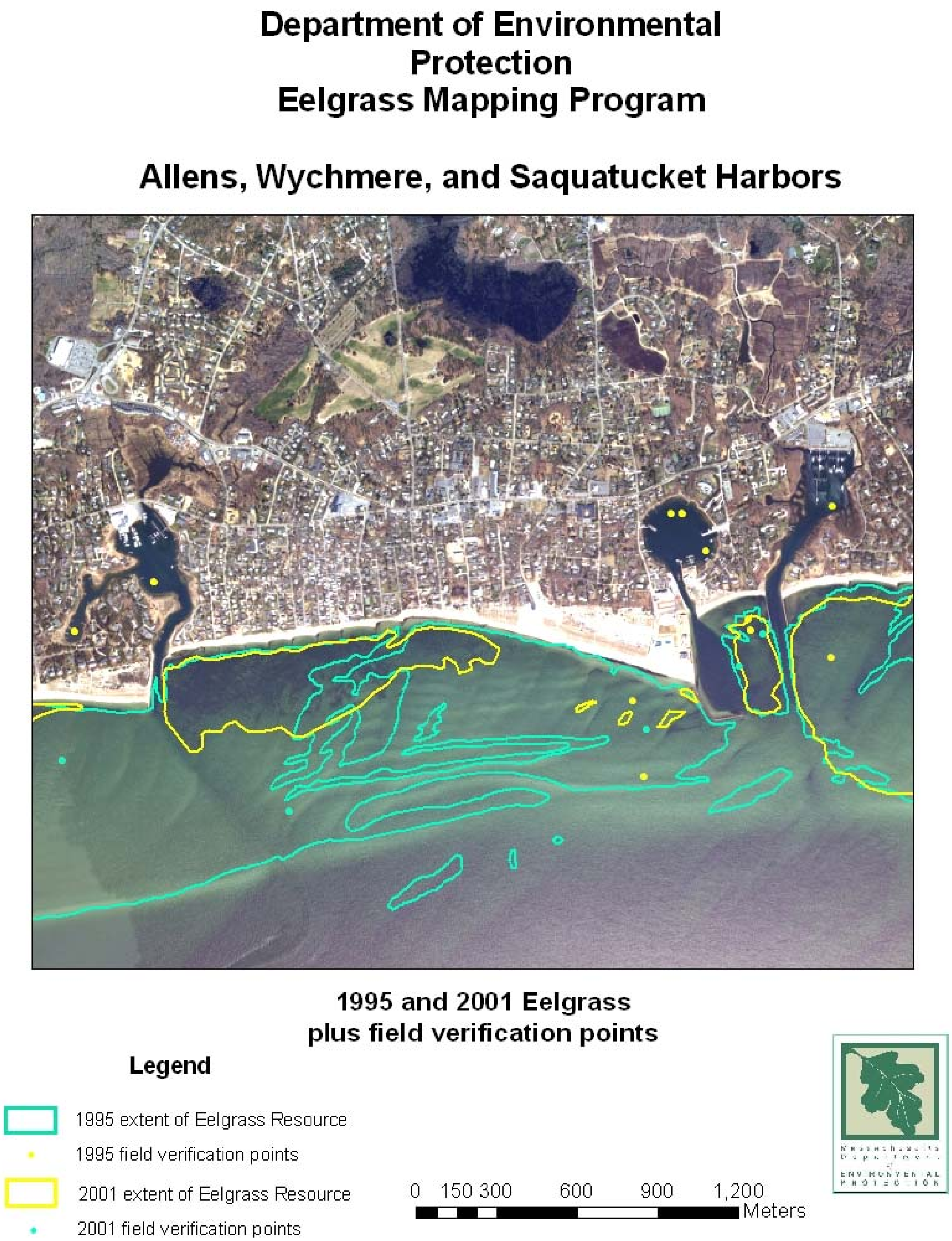


Figure VII-12. Eelgrass bed distribution within the nearshore waters of Nantucket Sound immediately adjacent the inlets to Saquatucket Harbor, Wychmere Harbor and Allen Harbor. No *Zostera marina* was found to exist within either of the three systems during recent surveys (1995 and 2001) or in the historical analysis (1951). Field surveys by the MEP Technical Team in 2004 indicate the lack of eelgrass in all three Harbors. All data was provided by the MassDEP Eelgrass Mapping Program.

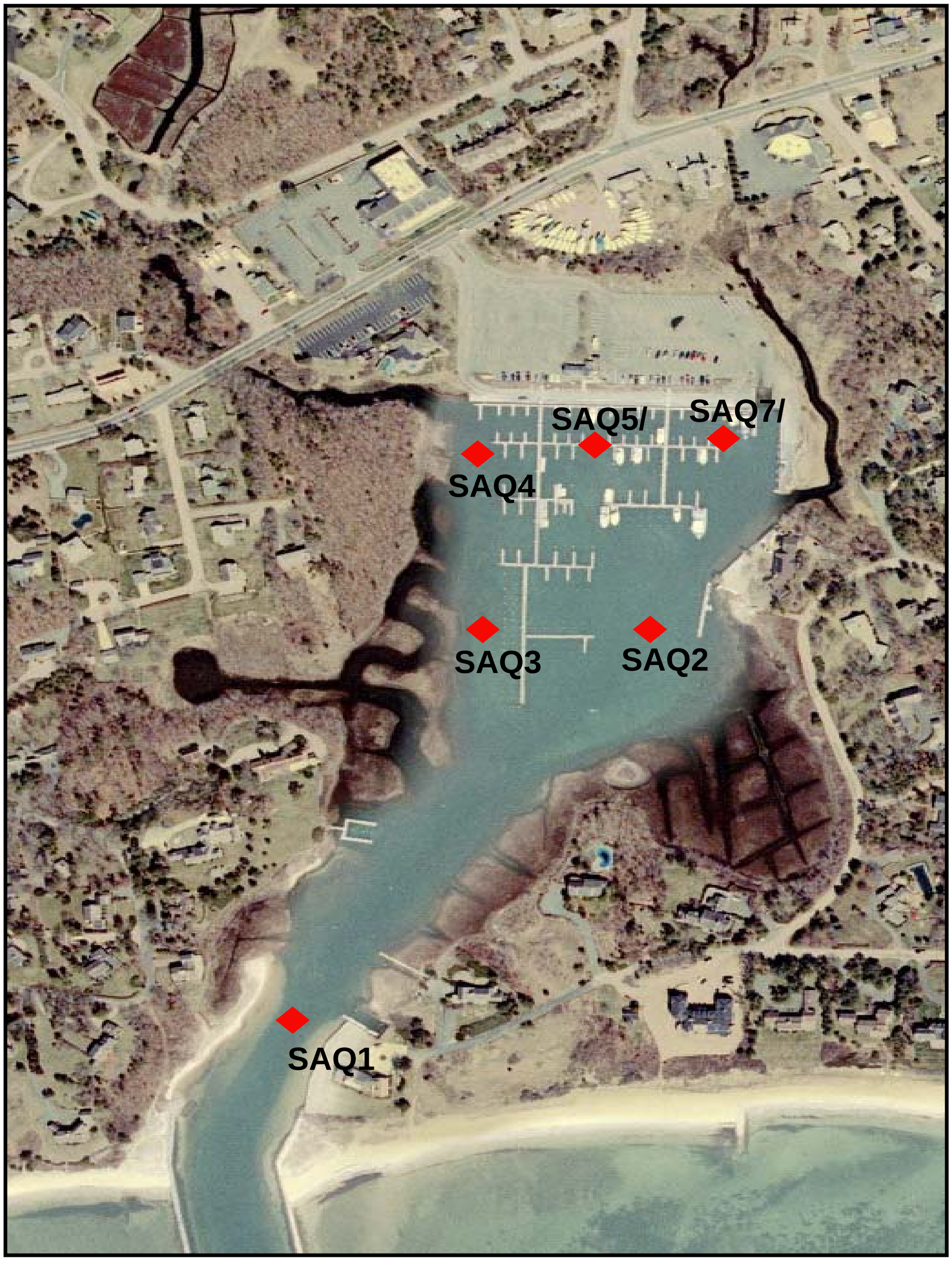


Figure VII-13. Aerial photograph of the Saquatucket Harbor System showing location of benthic infaunal sampling stations (red symbol) for 2004.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 6 locations throughout Saquatucket Harbor, 3 locations in Wychmere Harbor and 7 locations in Allen Harbor (Figures VII-14, 15 and 16). In some cases multiple assays were conducted. In estuaries 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 (Table VII-3). It should be noted that given the documented absence of eelgrass habitat within this estuary, infaunal animal habitat quality is the primary focus of thresholds analysis and restoration goals. As each of these three systems supports infaunal communities throughout, the benthic infauna analysis was used for determining the level of impairment (not impaired→moderately impaired→significantly impaired→severely degraded) within each of the basins of each harbor system. 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, 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. The assessment of infaunal habitat quality (below) is based upon both the infaunal community characteristics, and the type of ecosystem (basin, salt marsh, eelgrass bed) and stresses represented by salinity variation, macroalgal accumulations and organic matter enrichment (e.g. nitrogen loading).

The MEP infauna study indicated that the Allen Harbor, Wychmere Harbor and Saquatucket Harbors are presently supporting impaired benthic animal habitat throughout each systems open water basins. This assessment is consistent with the absence of eelgrass and the levels of oxygen depletion and chlorophyll a in their waters and observations of the sediments specifically. Each of the basins is dominated by a gammarid amphipod community comprised mostly of *Ampelisca abdita* and *Microdeutopus anomalus*. In some areas the amphipods have constructed dense "mats", which typically breakup in the fall/winter period. Dominance of this type of benthic community is indicative of nitrogen and organic enrichment, but is "transitional", i.e. usually associated with a shift from low enrichment to high enrichment or high enrichment to low enrichment and is therefore not indicative of severe degradation, but rather an intermediate level of stress. The MEP Technical Team has observed similar amphipod communities in other harbors. For example, as Boston Harbor "recovered" as nutrients and organic matter discharges were lowered, areas of severely degraded benthic habitat (virtually devoid of animals) were colonized initially by amphipod communities. These communities will over time be replaced by deep burrowing large forms under even lower levels of nutrient loading. While much of the benthic habitat within these three harbors was dominated by amphipods, the small tributary in Allen Harbor (Allen Creek), also showed areas dominated by *Capitella capitata*, a stress indicator species, which is opportunistic and found in disturbed areas such as associated with hypoxia, macroalgal accumulation or physical disturbance. Capitella has also been observed in high organic matter deposition areas, such as around the Hurricane Barrier and Palmers Island in New Bedford Harbor, a localized area of significant impairment, where *Capitella capitata* was found to predominate.

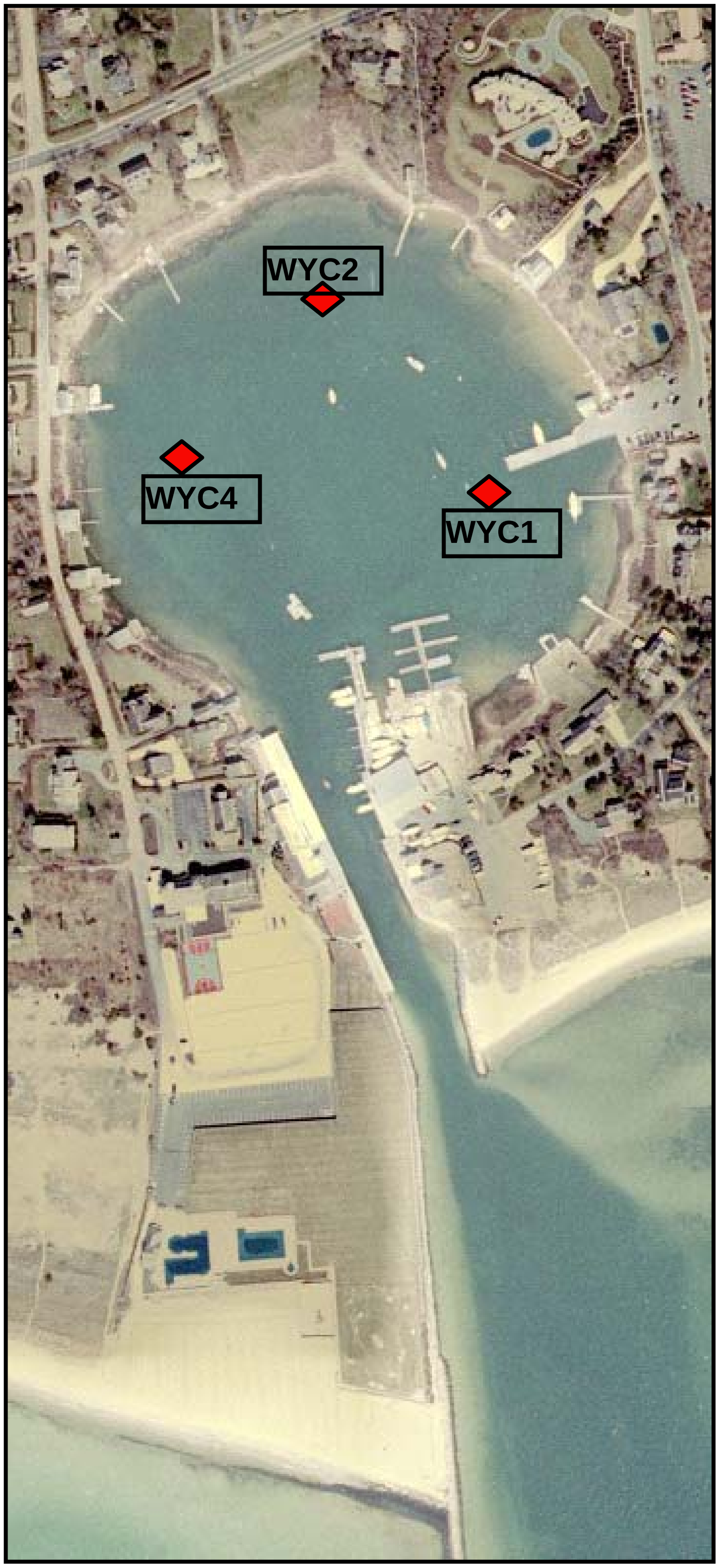


Figure VII-14. Aerial photograph of the Wychmere Harbor System showing location of benthic infaunal sampling stations (red symbol) for 2004.

Figure VII-15. Aerial photograph of the Allen Harbor System showing location of benthic infaunal sampling stations (red symbol) for 2004.

Table VII-3. Benthic infaunal community data for Allen Harbor, Saquatucket Harbor and Wychmere Harbor estuaries within the Town of Harwich. 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 (surface area = 0.0625 m^2). The communities in each of the main basins was dominated by gammarid amphipods.

	Station	Total Species	Total Individuals	#Species Calc @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Allen's Harbor						
Main Basin	**Sta. 3,4,5,7,8**	**15**	**1518**	**6**	**1.56**	**0.42**
Creek	**Sta. 1,2**	**12**	**928**	**6**	**0.97**	**0.27**
Saquatucket Harbor						
Inner Basin	**Sta. 4,5,7**	**14**	**944**	**8**	**1.80**	**0.48**
Outer Basin	**Sta. 1,2,3**	**9**	**1920**	**5**	**1.35**	**0.36**
Wychmere Harbor						
Main Basin	**Sta. 1,2,4**	**12**	**1057**	**7**	**1.76**	**0.50**
Station numbers refer to ID's on maps presented above.						

The Allen Harbor basins showed benthic habitat quality consistent with the observed differences in bottom water hypoxia and chlorophyll a levels (Section VII.1). The main basin had moderate numbers of species with very high numbers of individuals and moderate diversity and low-moderate evenness indicative of a moderate to significant level of habitat impairment. In contrast, the Creek basin supported less species at lower densities and some areas dominated by stress indicators, indicating a higher level of impairment or significantly impaired condition. Saquatucket and Wychmere Harbors were found to be generally similar to the main basin of Allen Harbor, with moderate numbers of species with high densities and moderate diversity and low-moderate evenness. Although generally benthic production throughout each of the main basins of the three harbors is high, the domination by species tolerant of high organic matter indicates that the habitat is moderately to significantly impaired by nitrogen enrichment. These impairments are associated with organic enrichment by phytoplankton blooms and periodic oxygen depletion. The addition of macroalgal accumulations within Allen Creek may be partially causing the lower (significantly impaired) benthic habitat quality in this basin.

The observed benthic habitat quality is completely consistent with the observed levels of oxygen depletion, chlorophyll a and macroalgal accumulations (only found in Allen Creek). These indicators are supported by the total nitrogen concentrations found by the Harwich Water Quality Monitoring Program, where TN levels in all basins exceeded 0.65 mg N L^{-1}, with the highest levels observed in Allen Creek. The MEP generally has found benthic habitat quality to be highest in open water basins with TN levels generally between 0.50-0.55 mg N L^{-1}.

The community indicators are consistent with the water quality parameters, indicating habitat impairment due to nitrogen enrichment. The interacting influences of nutrient enrichment, oxygen depletion, phytoplankton blooms and macroalgal accumulation, underscores the need for the use of multiple indicators in determining habitat health.

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish area closures as well as the suitability of a system for the propagation of shellfish in a given system. As is the case with many harbor systems on Cape Cod, large portions of the lower and middle reaches of the Saquatucket Harbor and Allen Harbor and all of the Wychmere Harbor are conditionally approved for shellfishing during specific times during the year, typically the cold winter months, while due to the active marinas in the inner reaches of Saquatucket Harbor and Allen Harbor, shellfishing is prohibited year round, as a precaution to protect public health (Figures VII-16, 17, 18).

MassDMF has also mapped those areas that appear to be suitable for shellfish propagation, should the water quality conditions support shellfish. Most of the shellfish growing area within the Three Harbors relates to quahogs (Mercenaria), portions of Saquatucket Harbor have also been identified for oysters and bay scallop, Wychmere Harbor for soft shell clams (Mya) and Allen Harbor for soft shell clams and oysters. Improving benthic habitat within each of these systems will also likely enhance conditions for the growth (and set) of these shellfish species (Figures VII-19, 20, 21). It is clear that the Three Harbors present a diversity of resources for use by the citizens of the Town of Harwich, all of which will be enhanced by recovery from their present levels of habitat impairment resulting from nitrogen enrichment.

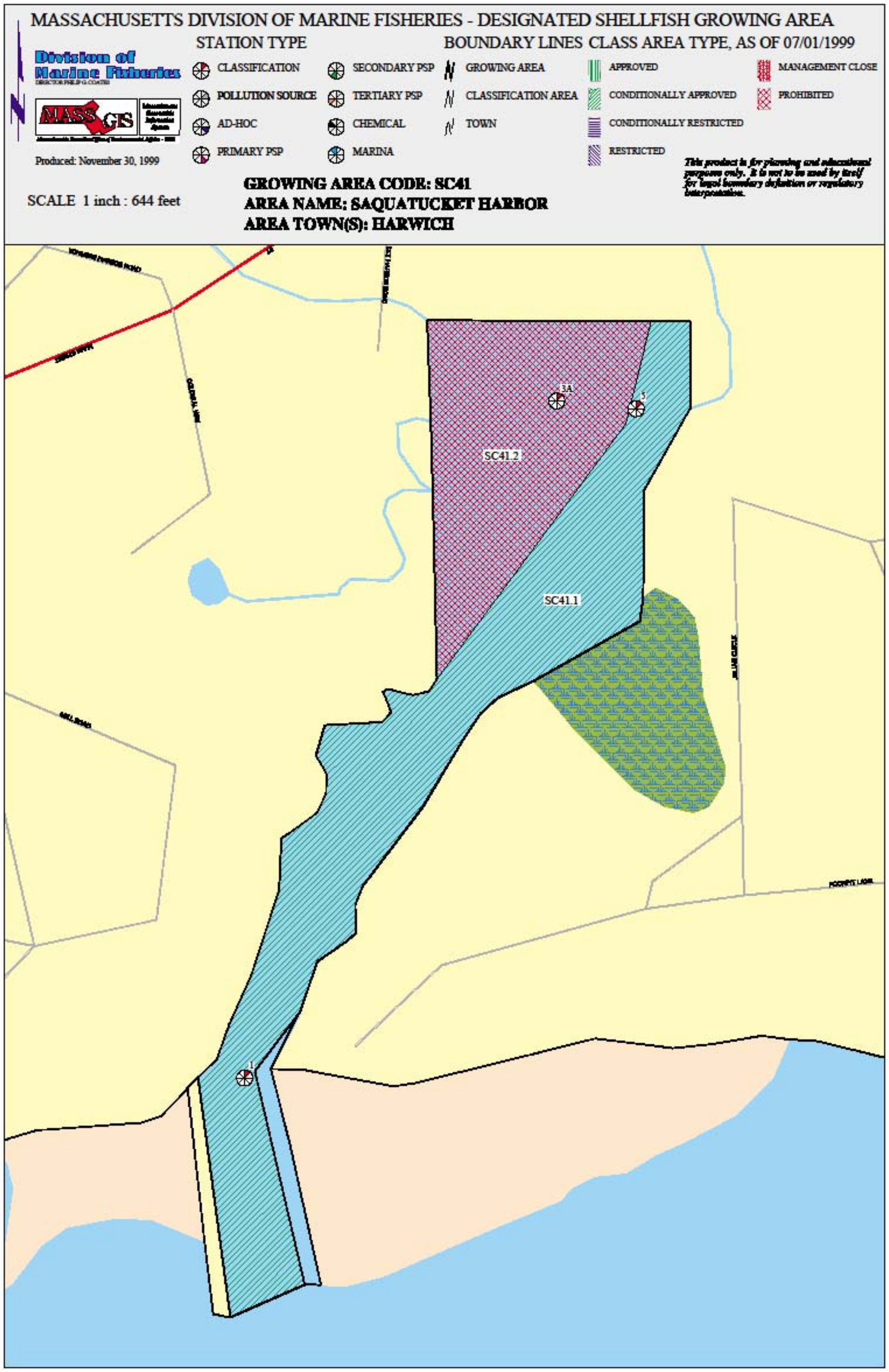


Figure VII-16. Division of Marine Fisheries shellfish growing areas and closure status for the Saquatucket Harbor system, Harwich, MA.

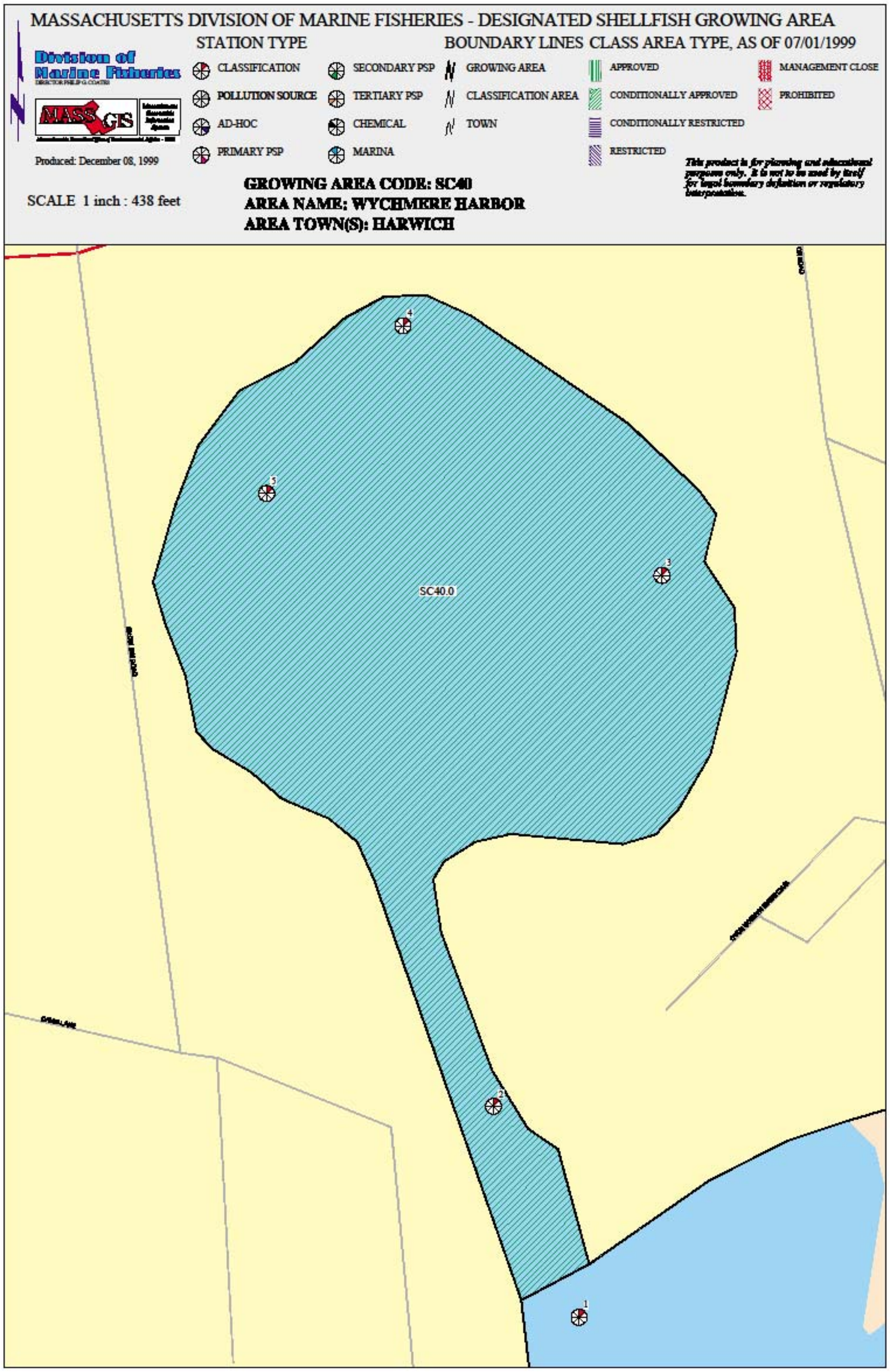


Figure VII-17. Division of Marine Fisheries shellfish growing areas and closure status for the Wychmere Harbor system, Harwich, MA.

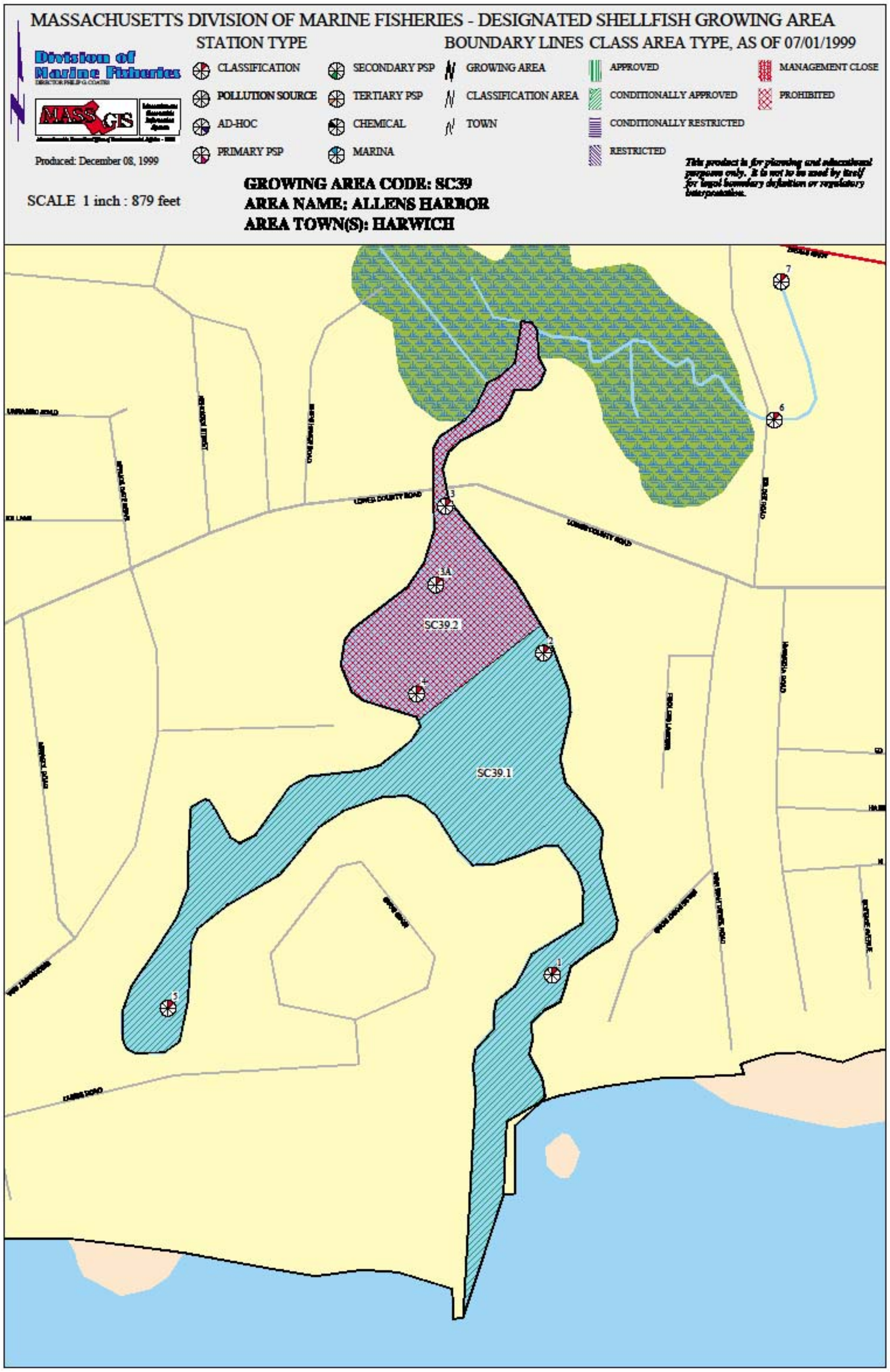


Figure VII-18. Division of Marine Fisheries shellfish growing areas and closure status for the Allen Harbor system, Harwich, MA.

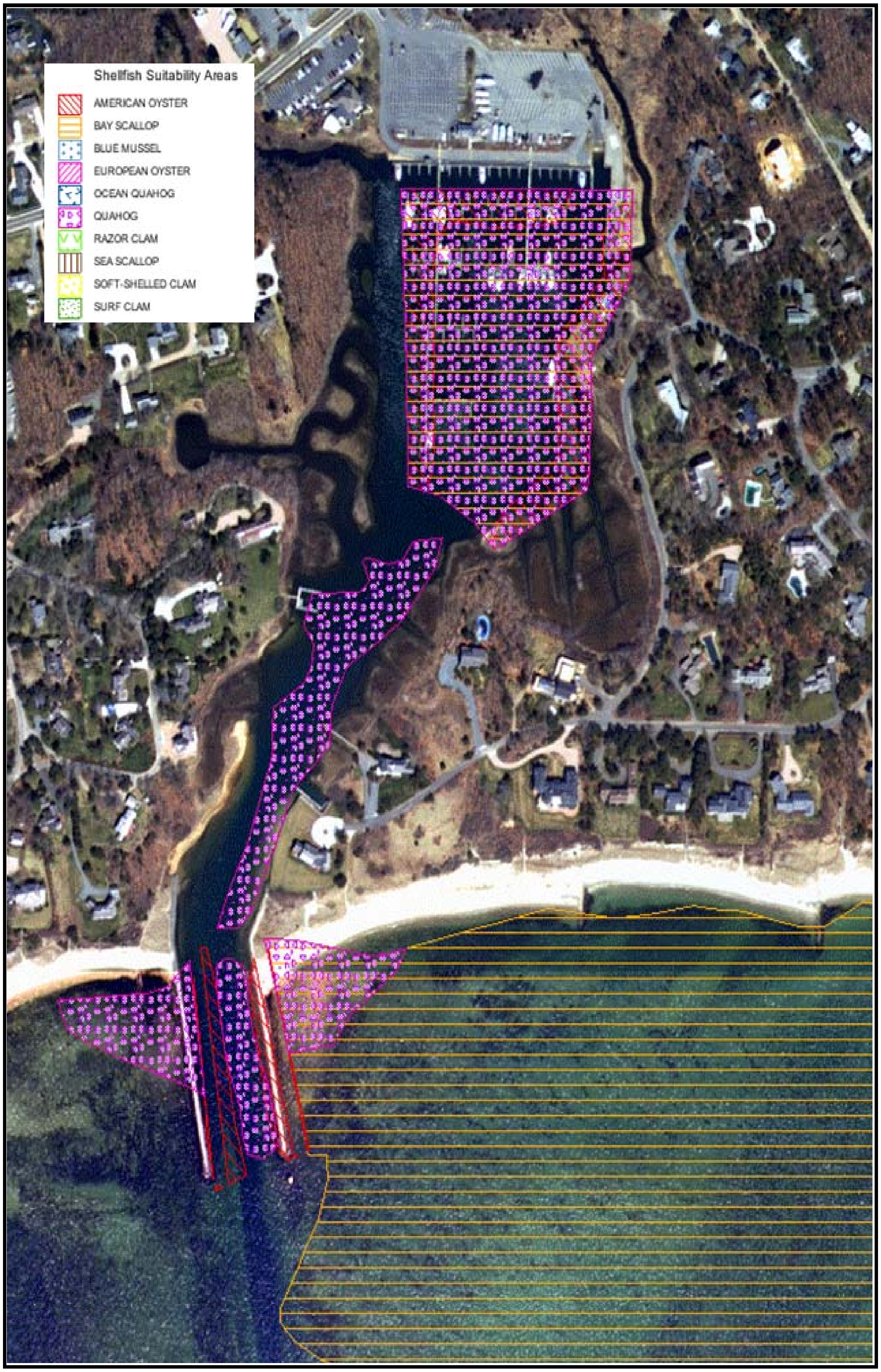


Figure VII-19. Areas within the Saquatucket Harbor system, Harwich, MA. that are suitable habitat for specific shellfish species. Source: Mass GIS. Note that the map indicates habitat and does not indicate the presence of significant shellfish density.

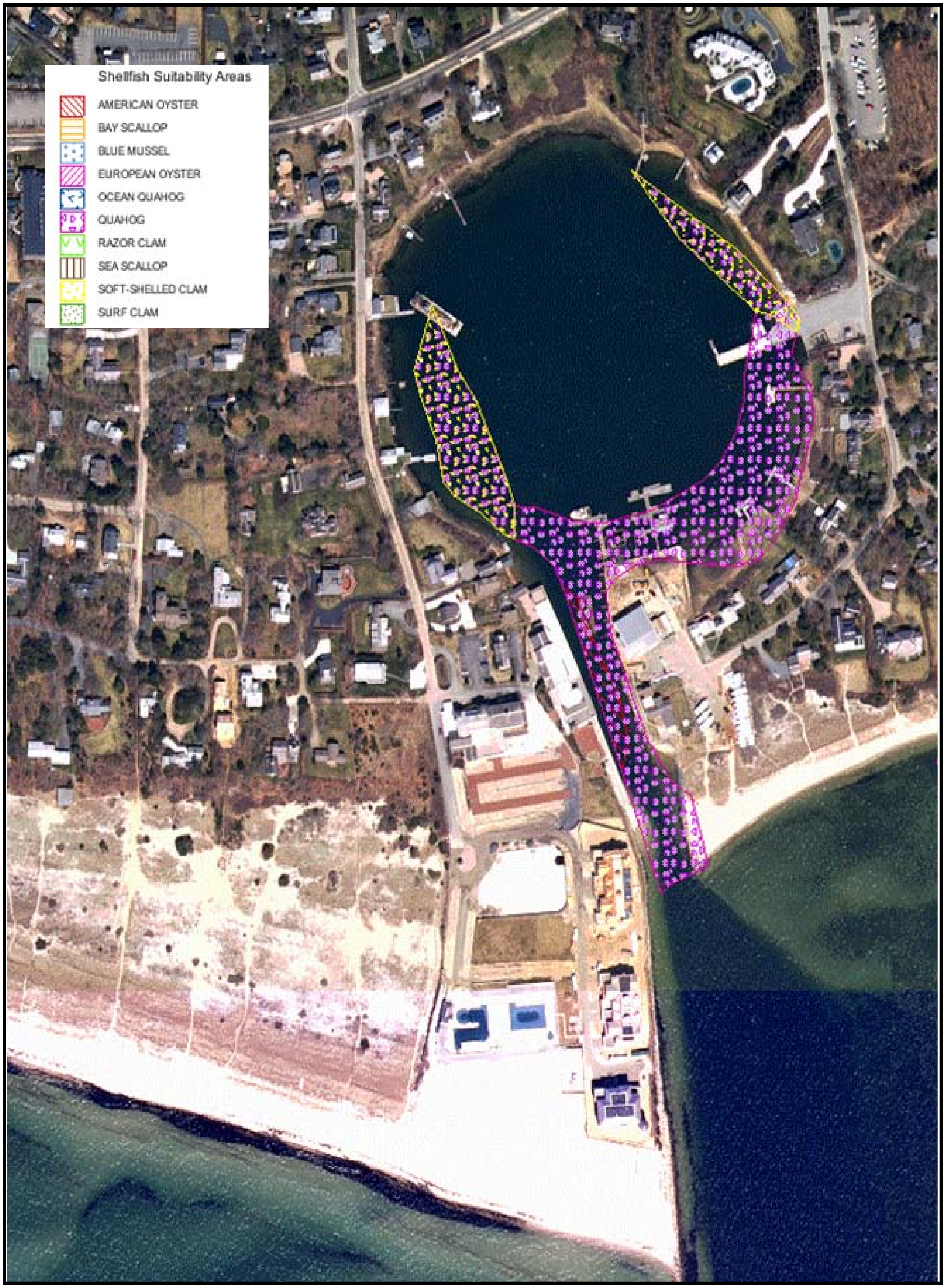


Figure VII-20. Areas within the Wychmere Harbor system, Harwich, MA. that are suitable habitat for specific shellfish species. Source: Mass GIS. Note that the map indicates habitat and does not indicate the presence of significant shellfish density.

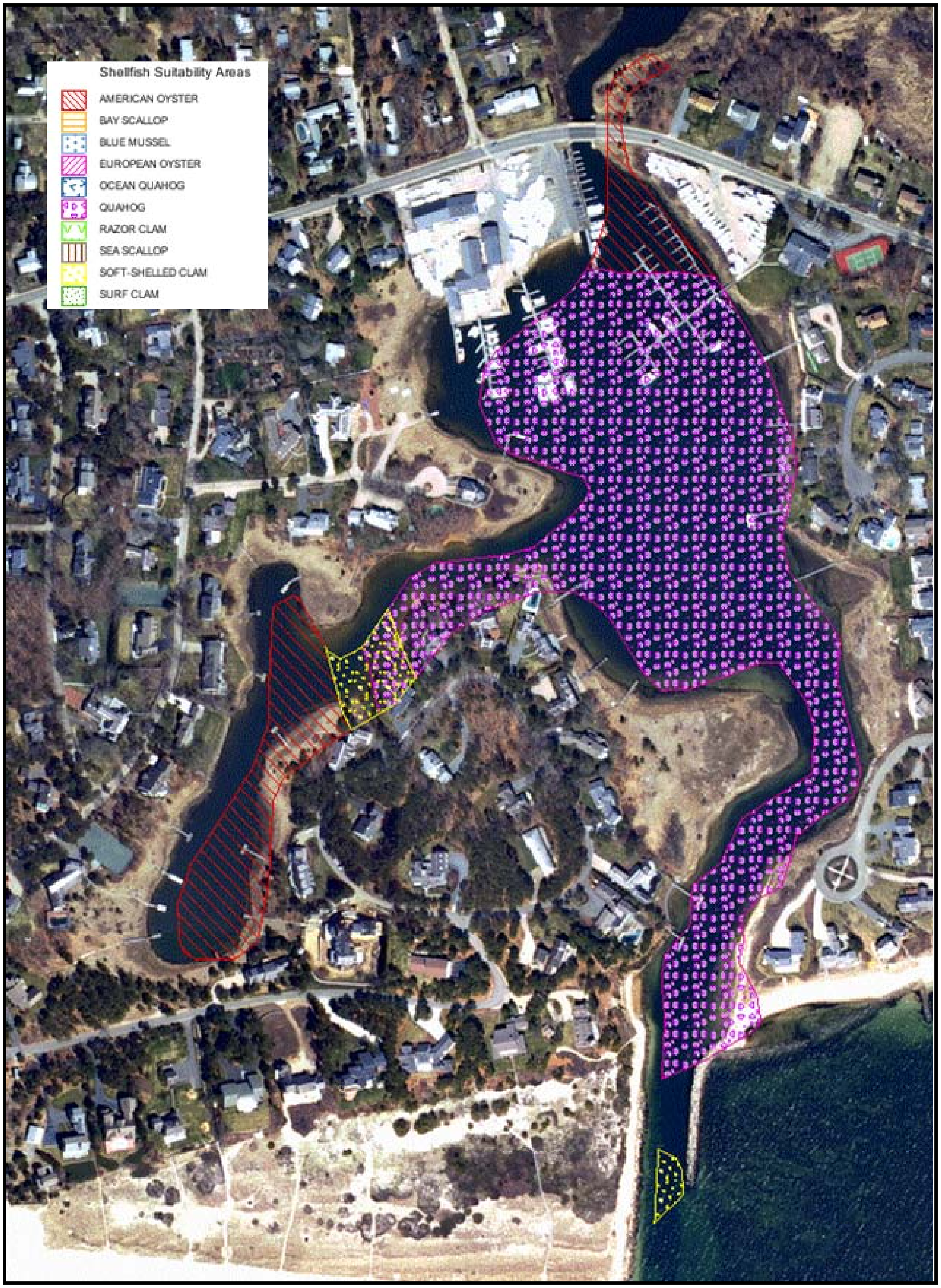


Figure VII-21. Areas within the Allen Harbor system, Harwich, MA. that are suitable habitat for specific shellfish species. Source: Mass GIS. Note that the map indicates habitat and does not indicate the presence of significant shellfish density.

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 estuarine basin and its associated watershed nitrogen load further strengthen the analysis. These data were collected to support threshold development by the MEP for each of the three harbor systems in Harwich: Allen Harbor, Wychmere Harbor and Saquatucket Harbor and were discussed in Chapter VII. Nitrogen threshold development builds on these data and links habitat quality to summer water column nitrogen levels from the baseline developed by the Harwich Water Quality Monitoring Program, coordinated by the Town of Harwich and conducted with technical and analytical support from the Coastal Systems Program at SMAST-UMass Dartmouth.

The three harbors in Harwich are each simple estuaries comprised of a main open water basin and single tidal inlet, although Allen Harbor also includes a small tributary basin. As such, each system contains only a single major functional basin, surrounded by its watershed. Given the configuration of each of the harbors and the relatively similar depths of each (generally 2m-3m), these systems almost certainly have similar sensitivities to nitrogen enrichment and organic matter loading. The MEP evaluation of habitat quality supported by each harbor considers the natural structure of each system and its ability to support eelgrass beds and the types of infaunal communities that they support. At present, Saquatucket Harbor, Wychmere Harbor and Allen Harbor are presently supporting moderately to significantly impaired habitat quality throughout the open water basins (Table VIII-1). Impairment is indicated by the absence of eelgrass, the structure of the benthic communities, periodic oxygen depletion and high levels of chlorophyll a and typical concentrations of total nitrogen of 0.65-0.82 mg N L^{-1} in the basin waters. For each harbor, all of the health indicators support a consistent assessment as presented below:

Eelgrass: The absence of eelgrass throughout Allen Harbor, Saquatucket Harbor and Wychmere Harbor is consistent with the observed nitrogen and the chlorophyll levels and the structure of the basins comprising these estuaries. Equally important, all of the available information on eelgrass relative to these three systems indicates that they have not supported eelgrass over the past half century (MassDEP maps) and likely longer. Saquatucket Harbor was originally a tidal river salt marsh system, Andrews River, until it was dredged to create the present harbor in 1968-69 (Chapter I). As such, it has never supported eelgrass beds.

It should be noted that the absence of eelgrass within these basins is consistent with their present total nitrogen levels (>0.65 mg N L^{-1}; Chapter VI) which are much higher than found to be supportive of eelgrass habitat in similarly configured basins on Cape Cod. For example, the eelgrass bed within the outermost basin of the Lewis Bay System, Hyannis Harbor, was found to have TN levels of 0.30-0.35 mg N L^{-1}, while the eelgrass beds within outer harbor basin of West Falmouth Harbor are at 0.31-0.33 mg N L^{-1}. Chlorophyll levels within the basins found to be supporting eelgrass are similarly much lower than that observed in the basins of the three harbors. Similarly, eelgrass was lost within the Lower Centerville River at a tidally averaged TN of 0.395 mg N L^{-1}, as was also the case within Waquoit Bay at 0.39 mg N L^{-1}, concentrations much lower than found within the basins of the three harbors.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Allen Harbor, Saquatucket Harbor, Wychmere Harbor estuaries (Three Harbors) on Nantucket Sound within the Town of Harwich, MA., based upon assessment data presented in Chapter VII. Each estuary is presently functioning primarily as an open water embayment typical of coastal embayment basins on Cape Cod. Allen Harbor has a small tributary basin and a creek.

Health Indicator	Harwich Three Harbors Estuaries			
	Allen Harbor		Saquatucket Harbor	Wychmere Harbor
	Main Basin	Creek		
Dissolved Oxygen	MI[1,4]	SI[2,4]	MI-SI[3]	MI[1,4]
Chlorophyll	MI-SI[5]	SI[6]	SI[6]	SI-SD[7]
Macroalgae	--[11]	MI-SI[9]	--[11]	MI[10]
Eelgrass	--[12]	--[12]	--[12]	--[12]
Infaunal Animals	MI-SI[13]	SI[14]	MI-SI[13]	MI-SI[13]
Overall:	**MI[15]**	**SI[16]**	**MI-SI[17]**	**MI-SI[17]**

1 – oxygen levels generally >4 mg/L, with periodic depletions 4-3 mg/L.
2 – frequent oxygen depletions to <4 mg/L, periodically to 3-2 mg/L.
3 – oxygen levels generally >4 mg/L, with frequent depletions to 4-3 mg/L
4 – soft/fluid organic muds, thin oxidized surface zone (RPD 1-3mm) with regions showing recent anoxia (sulfidic) or patches of sulfur bacterial mat.
5 – moderate chlorophyll a levels generally ~4-15 ug/L, frequently >15 ug/L
6 – moderate-high chlorophyll a levels generally ~6-20 ug/L, frequently >20 ug/L
7 – high chlorophyll a levels generally ~10-25 ug/L, frequently >25 ug/L
9 – high density of drift algae, Ulva and a red branched form.
10 -- drift algae (Ulva, Gracillaria, Codium) present, sparse microphyte mat
11 -- drift algae sparse or absent, little surface microphyte mat.
12 – no evidence this basin has been historically supportive of eelgrass, and no eelgrass in MassDEP (C. Costello) assessments of 1951, 1995,2001.
13 – moderate numbers of species and very high number individuals. Low diversity & eveness; dominated by moderate organic enrichment indicator species (gammarid amphipods)
14 – moderate species numbers & high number individuals. Low diversity & eveness; patches dominated by moderate (gammarid amphipods) or high (*Capitella*) organic enrichment indicator sp.
15 – Moderate Impairment based upon moderate oxygen depletion, elevated chlorophyll; infaunal communities dominated with high numbers of individuals with moderate species, with moderate to low diversity and low evenness, dominated by moderate organic enrichment indicators (gammarid amphipods). No history of eelgrass habitat in this basin.
16 – Significant Impairment based upon oxygen depletion, high chlorophyll, sulfidic sediments; moderate numbers of species and high number individuals. Low diversity and eveness; patches dominated by moderate-high organic enrichment indicator species (gammarid amphipods or *Capitella*). No history of eelgrass habitat in this basin.
17 – Moderate-Significant Impairment based upon oxygen depletion, high chlorophyll; infaunal communities dominated with high numbers of individuals with moderate species, with moderate to low diversity and low evenness, dominated by moderate organic enrichment indicators (gammarid amphipods). No history of eelgrass habitat in this basin.

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

As eelgrass habitat could not be documented to exist, either historically or presently, within Saquatucket, Wychmere or Allen Harbors (Section VII.3), the thresholds analysis for these systems necessarily focuses on restoration of each systems impaired infaunal animal habitats. However, it is likely that nitrogen management within these three systems will improve eelgrass and infaunal habitat within the down-gradient nearshore waters of Nantucket Sound. This down-gradient effect, to the extent that it occurs, will be a by-product of the restoration of each harbor, but was not part of the thresholds analyses for each of these systems.

Water Quality: Overall, the dissolved oxygen records clearly show oxygen depletion and elevated chlorophyll *a* levels in each of the basins of the three harbors at levels that stress benthic animal communities and therefore cause impaired habitat quality (Table VII-1 and VII-2). The MEP measurements are fully consistent with the observed extent of oxygen depletion in each estuary as measured through traditional surveys by the Harwich Water Quality Monitoring Program. The basins of Allen Harbor, Saquatucket Harbor and Wychmere Harbor each showed periodic oxygen depletions to levels less than 4 mg L^{-1}, however, the minima varied between basins, between 2 and 3 mg L^{-1} (Section VII.2). Also, the extent of bottom water oxygen depletion was consistent with the levels of phytoplankton biomass (e.g. chlorophyll *a*, Table VII-2), as also found for other Cape Cod estuaries.

The main basin of Saquatucket Harbor exhibited frequent oxygen depletions to < 4 mg L^{-1} and periodic oxygen depletion to <3 mg L^{-1}, indicative of a moderate to significantly impaired system. Some values were in excess of air equilibration in day time, but the bottom water rarely reached air equilibration throughout the MEP deployment period. The chlorophyll a levels were moderate to high, generally 6-20 ug L^{-1}, with frequent excursions over 20 mg L^{-1}, indicative of a significantly impaired system. The sediments throughout the Harbor were very soft unconsolidated muds, generally with a thin oxidized surface layer, but in some places patches of sulfur bacterial mat overlying sulfidic sediments were observed, indicative of low oxygen concentrations in overlying waters. These data all provide clear evidence of a system enriched by nitrogen, where phytoplankton production is significantly enhanced with resulting negative effects on the water column oxygen levels and impaired benthic animal habitat.

The main basin of Wychmere Harbor had periodic depletion of bottom water oxygen to < 4 mg L^{-1}, but levels did not go below 3 mg L^{-1}, indicative of a moderately impaired system. Oxygen levels in excess of air equilibration in day time were observed, but were not the norm. The bottom water remained below air equilibration for the first half of the deployment period. Consistent with the oxygen levels, chlorophyll a was high, generally 10-25 ug L^{-1}, with frequent excursions over 25 mg L^{-1}, indicative of a significantly impaired to severely degraded system. The sediments were soft and very soft unconsolidated organic muds. The sediments were sulfidic, typically with a very thin oxidized layer (~1mm) or sulfur bacterial mat, indicative of low oxygen concentrations in overlying waters. These data clearly indicate a system enriched by nitrogen, where phytoplankton production is enhanced with resulting negative effects on the water column oxygen levels and impaired benthic animal habitat.

Allen Harbor differs from Saquatucket and Wychmere Harbors in that it has a tributary open water basin off the main basin. Both basins have periodic depletion of bottom water oxygen levels to < 4 mg L^{-1}, but depletion was significantly greater in Allen Creek when compared to the main basin. Main basin bottom water oxygen showed periodic levels of bottom water oxygen in the 3-4 mg L^{-1} range, indicative of a moderately impaired system. The Creek had greater oxygen declines into the 2-3 mg L^{-1} range, indicative of a significantly impaired system. Oxygen levels in excess of air equilibration in day time were observed, but were not the norm. The bottom water generally remained below air equilibration at both sites. Consistent with the extent of oxygen depletion, chlorophyll a was moderate in the main basin, generally 4-15 ug L^{-1}, with frequent excursions over 15 ug L^{-1}, indicative of a moderate to significantly impaired system. In contrast, the greater oxygen depletion in Allen Creek was coupled with higher chlorophyll a levels, generally ~6-20 ug L^{-1} and frequently >20 ug L^{-1}, indicative of a significantly impaired system. The sediments within both basins were soft and very soft unconsolidated organic muds. The sediments were sulfidic, typically with a very thin oxidized layer (~1mm) or sulfur bacterial mat. These data are clear evidence of a system enriched by nitrogen, where phytoplankton production is enhanced with resulting negative effects on the water column oxygen levels and impaired benthic animal habitat, particularly in Allen Creek.

Infaunal Communities: The infaunal study indicated that the basins comprising Allen Harbor, Wychmere Harbor and Saquatucket Harbors are presently supporting impaired benthic habitat and that there is little variation within each estuary and even between the estuaries. This latter observation likely stems from their similar configuration, single tidal inlet and developed watersheds. The benthic animal habitat assessment is consistent with the present absence of eelgrass and the levels of oxygen depletion and chlorophyll a in the waters of each harbor and observations of the sediments themselves (Section VII.4).

Each of the basins of the three harbors is dominated by a gammarid amphipod community, dominated by *Ampelisca abdita* and *Microdeutopus anomalus*. Dominance of the benthic community by amphipods is indicative of nitrogen and organic enrichment, but is "transitional", i.e. usually associated with a shift from low enrichment to high enrichment or high enrichment to low enrichment and is therefore not indicative of severe degradation, rather intermediate stress. In addition, the main basins had moderate numbers of species with very high numbers of individuals and moderate diversity and low-moderate evenness indicative of habitat impairment. The predominance of these communities and structure throughout the main basins of Allen Harbor, Wychmere Harbor and Saquatucket Harbors is indicative of moderate to significant levels of impairment of benthic habitat. However, these communities will be replaced by deep burrowing large forms as nitrogen enrichment is reduced. While much of the benthic habitat within the three harbors was dominated by amphipods, the small tributary in Allen Harbor, Allen Creek, also supported benthic communities with less species at lower densities than the main basins and in some areas were dominated by stress indicators, e.g. C*apitella capitata*. The dominance of this species in some areas indicates a lower level of habitat quality (i.e. significant impairment), than indicated for the main basins.

The observed benthic habitat quality is completely consistent with the observed levels of oxygen depletion, chlorophyll a and macroalgal accumulations (only found in Allen Creek). These indicators are supported by the total nitrogen concentrations found by the Harwich Water Quality Monitoring Program, where TN levels in all basins exceeded 0.65 mg N L^{-1}, with the highest levels observed in Allen Creek. The MEP generally has found benthic habitat quality to be highest in open water basins with TN levels generally between 0.50-0.55 mg N L^{-1}.

The community indicators are consistent with the water quality parameters, indicating habitat impairment due to nitrogen enrichment. Integrating this information, it appears that benthic animal habitat is the most appropriate target for nitrogen management of these three estuarine systems (Section VIII.2). This goal is the focus of the MEP management alternatives analysis presented in Chapter IX.

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 threshold for maintaining high quality habitat within the Saquatucket Harbor, Wychmere Harbor and Allen Harbor Embayment Systems is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. Given the database it is possible to develop a site-specific threshold, which is a refinement upon general threshold analysis frequently employed.

The overall results indicate that the Saquatucket Harbor, Wychmere Harbor and Allen Harbor open water estuarine basins are presently supporting moderately-significantly impaired benthic animal habitat and that Allen Creek is significantly impaired. Further, as eelgrass habitat is not a present or historical component of these estuaries, restoration of benthic animal habitat is the target for restoration of each of these three systems.

As the infaunal habitat quality within each of the basins is fully consistent with the oxygen and chlorophyll measurements and typical total nitrogen concentrations for each basin, this consistency supports the contention that management of nitrogen is the mechanism to restoring the quality of this critical habitat. At present the monitoring data indicates total nitrogen levels of 0.65-0.82 mg N L^{-1}, levels higher than found by the MEP to be supportive of "healthy" benthic communities. For example, high quality benthic habitats within the Bumps River and Lower Centerville River were found at TN levels <0.46 mg N L^{-1}. Similarly, the moderate impairment of infaunal habitat in the inner basins of Hyannis Inner Harbor were found at only slightly higher tidally averaged total nitrogen levels of 0.518-0.574 mg N L^{-1}. These data are consistent with a variety of studies 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 terminal basins (e.g. Eel Pond in Bourne) where healthy infaunal habitat had a slightly lower threshold level, 0.45 mg N L^{-1}. Further analysis of the Centerville River Estuary indicates moderate impairment at tidally averaged TN levels >0.5 mg N L^{-1} (0.526 mg N L^{-1}) in Scudder Bay and at 0.543 mg TN L^{-1} in the mid reach of the Centerville River. Moderate impairment was also observed at the same TN levels (0.535-0.600 mg N L^{-1}) extant 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 each of the basins of the three harbors.

The sentinel stations for each of the three estuaries are located within the main basin at the long-term water quality monitoring stations: Saquatucket Harbor (HAR-2), Wychmere (HAR-3) and Allen Harbor (HAR-4). However, given the potential for tidal restriction to Allen Creek, it is necessary to include a secondary "check" station specific to that basin (HAR-5). The sentinel stations are situated (as originally were the monitoring stations) such that achieving the nitrogen threshold target at each sentinel station should restore benthic animal habitat throughout the associated estuary. The secondary check station in Allen Creek is to merely provide a check on the acceptability of conditions within the tributary basin at the point that the threshold level is attained at the sentinel station and to control for potential tidal restriction between this tributary basin and the main basin. 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 benthic animal habitat throughout each of the three harbors. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary check station 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-1.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen load reductions within the Allen Harbor watersheds necessary to achieve the threshold nitrogen concentrations required a 55% reduction in the total septic watershed nitrogen load for all the sub-watersheds flowing into Allen Pond Stream, as well as removing 80% of total septic watershed nitrogen load associated with Watershed #3 which directly contributes groundwater to Allen Harbor. Wychmere Harbor required nitrogen load reductions within all the sub-watershed to achieve the threshold nitrogen concentrations. To achieve the threshold, a 100% reduction in the total septic watershed nitrogen load was required for all the sub-watersheds flowing into Wychmere Harbor. The nitrogen load reductions within the Saquatucket Harbor watersheds necessary to achieve the threshold nitrogen concentrations required a 55% reduction in the total septic watershed nitrogen load for the sub-watersheds flowing into Cold Spring Brook and East Saquatucket Stream, as well as removing 80% of total septic watershed nitrogen load within Watershed #16 which directly contributes groundwater to Saquatucket Harbor. The equal distribution for Cold Spring Brook and East Saquatucket Stream was done to demonstrate that the removals could be distributed in a variety of combinations as long as the combined total mass load reduction for Saquatucket Harbor is met. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

The reduction in septic loading is shown in Table VIII-2. The nitrogen septic load reductions within the Allen Harbor and Saquatucket Harbor estuaries systems were reduced by approximately 80% for the threshold model run along with a 100% reduction in nitrogen septic load for Wychmere Harbor. The reduction in nitrogen septic loads was also required for the tributaries flowing into Allen Harbor and Saquatucket Harbor which were reduced by approximately 55% for the threshold model run to meet the threshold nitrogen concentrations.

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 load reductions to meet the threshold and the removal of septic loads depicted in Table VIII-2. The total nitrogen loads for Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuarine systems are 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.

Figure VIII-1. Contour plot of modeled average total nitrogen concentrations (mg/L) in the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems, for threshold conditions (<0.50 mg N L^{-1} at the sentinel stations HAR-4, HAR-3, and HAR-2).

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. 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[2]
Allen Harbor[1]	4.214	0.841	-80.0%
Wychmere Harbor[1]	3.208	0.000	-100.0%
Saquatucket Harbor[1]	2.545	0.507	-80.1%
Surface Water Sources			
Allen Pond Stream	1.426	0.642	-54.9%
Cold Spring Brook	7.775	3.499	-55.0%
East Saquatucket Stream	2.926	1.274	-56.5%

[1] Total estuarine reach which receives septic N inputs through direct groundwater discharge, separate from surface water inflows.

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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. 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
Allen Harbor[1]	4.764	1.392	-70.8%
Wychmere Harbor[1]	3.866	0.660	-82.9%
Saquatucket Harbor[1]	2.795	0.756	-72.9%
Surface Water Sources			
Allen Pond Stream	1.838	1.055	-42.6%
Cold Spring Brook	10.501	6.225	-40.7%
East Saquatucket Stream	3.948	2.296	-41.8%

[1] Total estuarine reach which receives N inputs from the watershed through direct groundwater, separate from surface water inflows.

Table VIII-4. Threshold sub-embayment loads and attenuated surface water loads used for total nitrogen modeling of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems, 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)
Allen Harbor[1]	1.392	0.227	8.216
Wychmere Harbor[1]	0.660	0.195	6.030
Saquatucket Harbor[1]	0.756	0.151	10.670
Surface Water Sources			
Allen Pond Stream	1.055	-	-
Cold Spring Brook	6.225	-	-
East Saquatucket Stream	2.296	-	-

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge separate from surface water inflows.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel stations is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel stations, a reduction in TN concentration of approximately 24% is required at Saquatucket Harbor station HAR-2, approximately 39% is required at Wychmere Harbor station HAR-3, and approximately 27% is required at Allen Harbor station HAR-4.

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 to enhance nitrogen attenuation associated with restored wetlands or ecologically engineered ponds/wetlands. 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 the quality of associated aquatic resources 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 Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. Sentinel threshold station are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Wychmere Harbor	HAR-2A	0.453	0.367	-19.0%
Saquatucket Harbor	**HAR-2**	**0.652**	**0.494**	**-24.2%**
Wychmere Harbor	**HAR-3**	**0.813**	**0.500**	**-38.5%**
Allen Harbor	HAR-4A	0.451	0.380	-15.9%
Allen Harbor	**HAR-4**	**0.679**	**0.498**	**-26.6%**
Allen Harbor	HAR-5	0.808	0.545	-32.5%

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

IX. ALTERNATIVES TO IMPROVE WATER QUALITY

IX.1 PRESENT LOADING WITH DREDGING OF ALLEN HARBOR AND OYSTER CREEK WITHIN ALLEN HARBOR

Portions of Allen Harbor are proposed to be dredged and Oyster Creek within Allen Harbor is currently being dredged. Dredging does have potential positive effects for lowering benthic flux, however, benthic flux is generally based upon more recently deposited organic matter and deposition made up to months prior. While there is some contribution of decaying organic matter that is years old, the contribution of each age of deposit decreases over time. As such, removing the sediment does ultimately lower the benthic flux for a while, however, in the absence of watershed management of nitrogen loads, organic matter in the estuary will build-up quickly and within a few years, equilibrium between benthic flux and the water column is re-established. While this may seem to make dredging a short term solution, this also indicates that the sediments re-establish equilibrium quickly with a water column that has its nitrogen level decreased by management alternatives.

To examine the influence the increased depths has upon overall nitrogen load, a scenario was run using the present loading conditions with dredging templates in place. There were no changes to the septic and watershed loads from present conditions (discussed in Section VI) for this alternative. Table IX-1 presents the various components of nitrogen loading for Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems under present loading conditions.

The dredging template for Allen Harbor was provided by Coastal Engineering Company, Inc. The dredging encompasses most of the main harbor basin to a depth of -7.0 feet MLW (-8.4 feet NGVD29). The Oyster Creek dredging template was provided by A. M. Wilson Associates, Inc. The Oyster Creek dredging is confined along 16-foot wide channel with 3:1 slopes to a depth of -4.0 feet MLW (-5.4 feet NGVD29). Figure IX-1 shows the interpolated grid bathymetry for Allen Harbor after dredging which was used for hydrodynamics and nitrogen modeling.

Table IX -1. Sub-embayment loads used for total nitrogen modeling of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems, 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)
Allen Harbor[1]	4.764	0.227	13.109
Wychmere Harbor[1]	3.866	0.195	13.865
Saquatucket Harbor[1]	2.795	0.151	15.285
Surface Water Sources			
Allen Pond Stream	1.838	-	-
Cold Spring Brook	10.501	-	-
East Saquatucket Stream	3.948	-	-

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge, separate from surface water inflows.

Total nitrogen modeling results for existing conditions with dredging in Allen Harbor and Oyster Creek indicates that the dredging has a detrimental effect towards meeting the nitrogen threshold target at Station HAR-4 in Allen Harbor (Table IX-2 and Figure IX-2). The result of dredging is an increase in nitrogen concentration in the embayment. Nitrogen concentration increases are minimal ranging from approximately 0.3% in outer Oyster Creek to under 1.5% in Allen Harbor at the threshold station. Overall, this scenario indicates that to reduce the overall nitrogen load effectively, removing septic loads from the watersheds is the most practical and effective approach.

Table IX-2. Comparison of model average total N concentrations from present loading scenarios (with and without the dredging of Allen Harbor and Oyster Creek), with percent change, for the Allen Harbor system. The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Wychmere Harbor	HAR-2A	0.453	0.453	0.0%
Saquatucket Harbor	**HAR-2**	**0.652**	**0.652**	**0.0%**
Wychmere Harbor	**HAR-3**	**0.813**	**0.813**	**0.0%**
Allen Harbor	HAR-4A	0.451	0.451	-0.1%
Allen Harbor	**HAR-4**	**0.679**	**0.689**	**+1.5%**
Allen Harbor	HAR-5	0.808	0.810	+0.3%

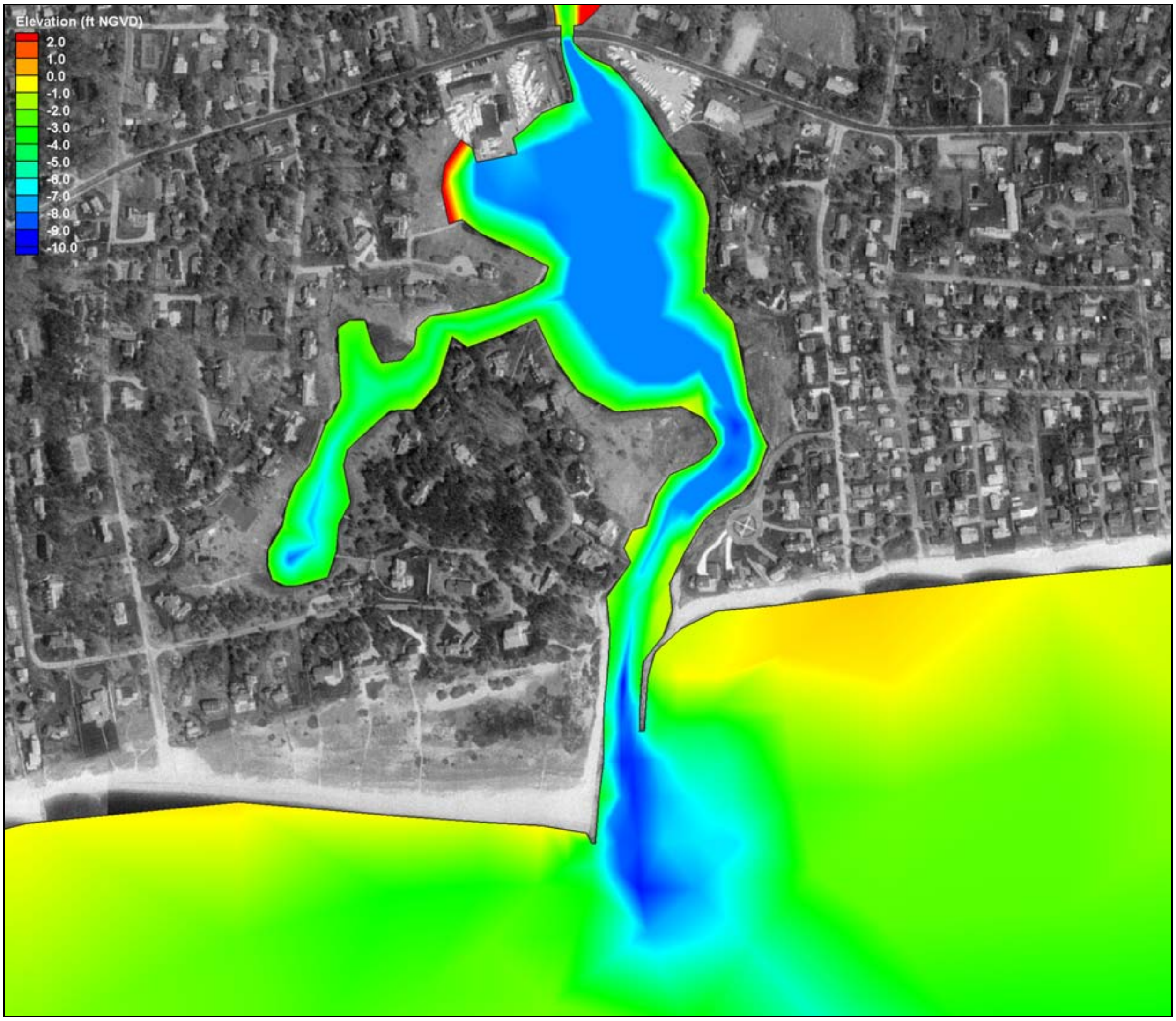


Figure IX-1. Depth contours of the Allen Harbor with the proposed dredging of Allen Harbor and Oyster Creek.

Figure IX-2. Contour plots of modeled total nitrogen concentrations (mg/L) in Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems, for present loading conditions, with the dredging of Allen Harbor and Oyster Creek. The approximate location of the sentinel threshold stations for Allen Harbor (HAR-4), Wychmere Harbor (HAR-3), and Saquatucket Harbor (HAR-2) are shown (<0.50 mg N L^{-1} at the sentinel stations HAR-4, HAR-3, and HAR-2).

IX.2 BUILDOUT LOADING WITH ENHANCED NITROGEN ATTENUATION IN BANK STREET BOG/COLD SPRING BROOK LEADING TO SAQUATUCKET HARBOR

In order to address potential reductions in buildout nitrogen loads reaching Saquatucket Harbor, town officials requested a scenario with enhanced nitrogen attenuation in Cold Spring Brook. As described in Chapter 4, the watershed nitrogen loading model includes a 35% attenuation in Cold Spring Brook under existing conditions (Figure IX-3). Detailed MEP streamflow measurements have been collected near Hoyt Road in order to adequately characterize nitrogen loads from the Brook into the Harbor. However, water quality and streamflow readings at upstream locations have been very limited, so town officials requested MEP staff to select an appropriate enhanced attenuation rate for the Bank Street Bogs.

Based on water quality monitoring from freshwater ponds with bathymetric data in the Harwich MEP study area, nitrogen attenuation rates have ranged between 72 and 92%. Estimates of nitrogen attenuation in the Muddy Creek wetland system on the boundary of Harwich and Chatham based on refined sampling of sediments and water quality range as high as 86% (White, *et al*., 2008). When water quality data is not available, MEP standard procedures generally assign an attenuation rate of 50% to freshwater ponds and 30% to freshwater streams. Based on the limited water quality data available and the lack of internal characterization of the Bank Street Bogs system, MEP staff assigned a conservative 50% attenuation (a 15% increase) to the bog system for this scenario.

While nitrogen generally travels unimpeded through sandy outwash aquifers, once it is discharged to surface water systems (lakes, ponds, streams, wetlands, salt marshes) it is taken up and transformed by biological systems. While the pathways vary, the basic steps are that the nitrogen is taken up by plants/phytoplankton/algae which eventually enter the sediments as detritus, feces, senescent cells. Decay in the sediments releases the bound ammonium which is then oxidized to nitrate and either escapes the sediment system or is denitrified to nitrogen gas. The result is that only a fraction of the nitrogen entering this process remains to be further cycled or transported to the down-gradient estuarine waters. In addition, in some systems if the entering nitrate levels are high, then microorganisms in the surficial sediments may be able to access it and denitrify it directly. In either case, some fraction of the watershed nitrogen is denitrified to nitrogen gas, before it can stimulate eutrophication in the receiving estuarine waters.

In the Bank Street Bogs, the level of enhancement of the attenuation that is presently naturally occurring will depend upon the ability of the system to take up dissolved nitrogen which presently passes through it and trap particulate nitrogen. In addition, to the extent that nitrate is being exported from the bogs, enhancing the ability of the sediment microorganisms to access this nitrate and denitrify it would increase the systems removal as well. Generally evaluating mechanisms for increasing the residence time of the freshwater flowing through the system or creating depositional basins is the first phase of analysis, after determining the specific sites within the bog system that are and aren't presently removing nitrogen.

Alternative 2 examines the influence attenuation rates have upon the watershed loading to Saquatucket Harbor. The watershed loading for Saquatucket Harbor was altered by changing the attenuation rate in the Bank Street Bogs from 35-percent to 50-percent for the Build-Out nitrogen loading conditions. The nitrogen loading conditions were developed and presented in Section VI.2.6, with the only modification being the revised attenuation rate for the Bank Street Bogs. Table IX-3 illustrates the overall change to watershed loads resulting from this alternative. Based on the assumptions developed for this alternative, Table IX-4 presents the various components of nitrogen loading for Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems.

Table IX-3. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of build-out and alternative build-out loading scenarios of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	Build-out (kg/day)	Alternative build-out load (kg/day)	alternative % change
Allen Harbor[1]	5.477	5.477	0.0%
Wychmere Harbor[1]	3.975	3.975	0.0%
Saquatucket Harbor[1]	3.049	3.049	0.0%
Surface Water Sources			
Allen Pond Stream	2.323	2.323	0.0%
Cold Spring Brook	11.611	8.932	-23.1%
East Saquatucket Stream	4.685	4.685	0.0%

[1] Total estuarine reach which receives N inputs from the watershed through direct groundwater discharge, separate from surface water inflows.

Table IX-4. Alternative build-out sub-embayment and surface water loads used for total nitrogen modeling of the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems, 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)
Allen Harbor[1]	5.477	0.227	14.530
Wychmere Harbor[1]	3.975	0.195	14.127
Saquatucket Harbor[1]	3.049	0.151	14.951
Surface Water Sources			
Allen Pond Stream	2.323	-	-
Cold Spring Brook	8.932	-	-
East Saquatucket Stream	4.685	-	-

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge, separate from surface water inflows.

Table IX-5. Comparison of model average total N concentrations from build-out loading and the alternative build-out scenario, with percent change, for the Allen Harbor, Wychmere Harbor and Saquatucket Harbor estuaries systems. Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	Build-out (mg/L)	Alternative build-out (mg/L)	% change
Wychmere Harbor	HAR-2A	0.460	0.454	-1.5%
Saquatucket Harbor	**HAR-2**	**0.691**	**0.644**	**-10.3%**
Wychmere Harbor	**HAR-3**	**0.829**	**0.822**	**-1.5%**
Allen Harbor	HAR-4A	0.478	0.477	0.0%
Allen Harbor	**HAR-4**	**0.749**	**0.748**	**0.0%**
Allen Harbor	HAR-5	0.896	0.896	0.0%

Comparison of model results between build-out loading conditions and alternative build-out loading scenario with higher attenuation rate shows that there is a minor reduction to the total nitrogen concentrations at stations HAR-2, HAR-2A, and HAR-3 (Table IX-5). The reduction in TN concentration are -10.3%, -1.5%, and -1.5% at each respective station. The increased attenuation rate in Bank Street Bogs does not meet the selected threshold level for the sentinel site within the Saquatucket Harbor (HAR-2 <0.50 mg N L^{-1}); however it does reduce the total nitrogen load to the estuarine system.

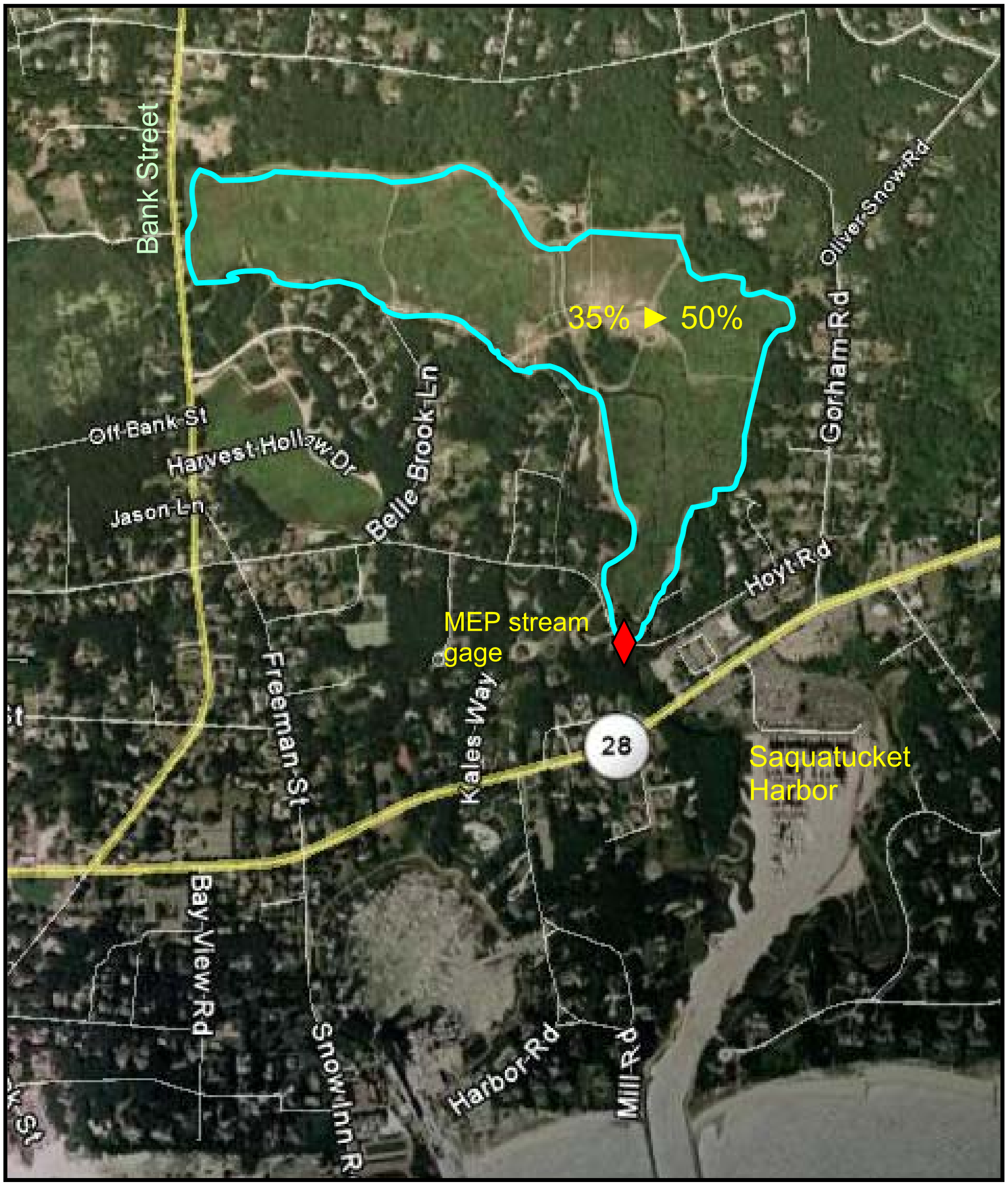


Figure IX-3. Bank Street Bogs and Cold Spring Brook Enhanced Natural Nitrogen Attenuation Scenario. The existing conditions watershed model includes a 35% nitrogen attenuation in the Bank Street Bogs/Cold Spring Brook (see Chapter IV and outlined above). The brook takes a rather tortuous route through the ditches (and irrigation pond) of former cranberry bogs before converging to discharge near the MEP stream gage. For the requested enhanced nitrogen attenuation scenarios, MEP staff increased the Bank Street Bogs attenuation from 35% to 50%. This attenuation rate is thought to be appropriately conservative without any additional, more refined, characterization of the nitrogen loads and water flows within the bogs.

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