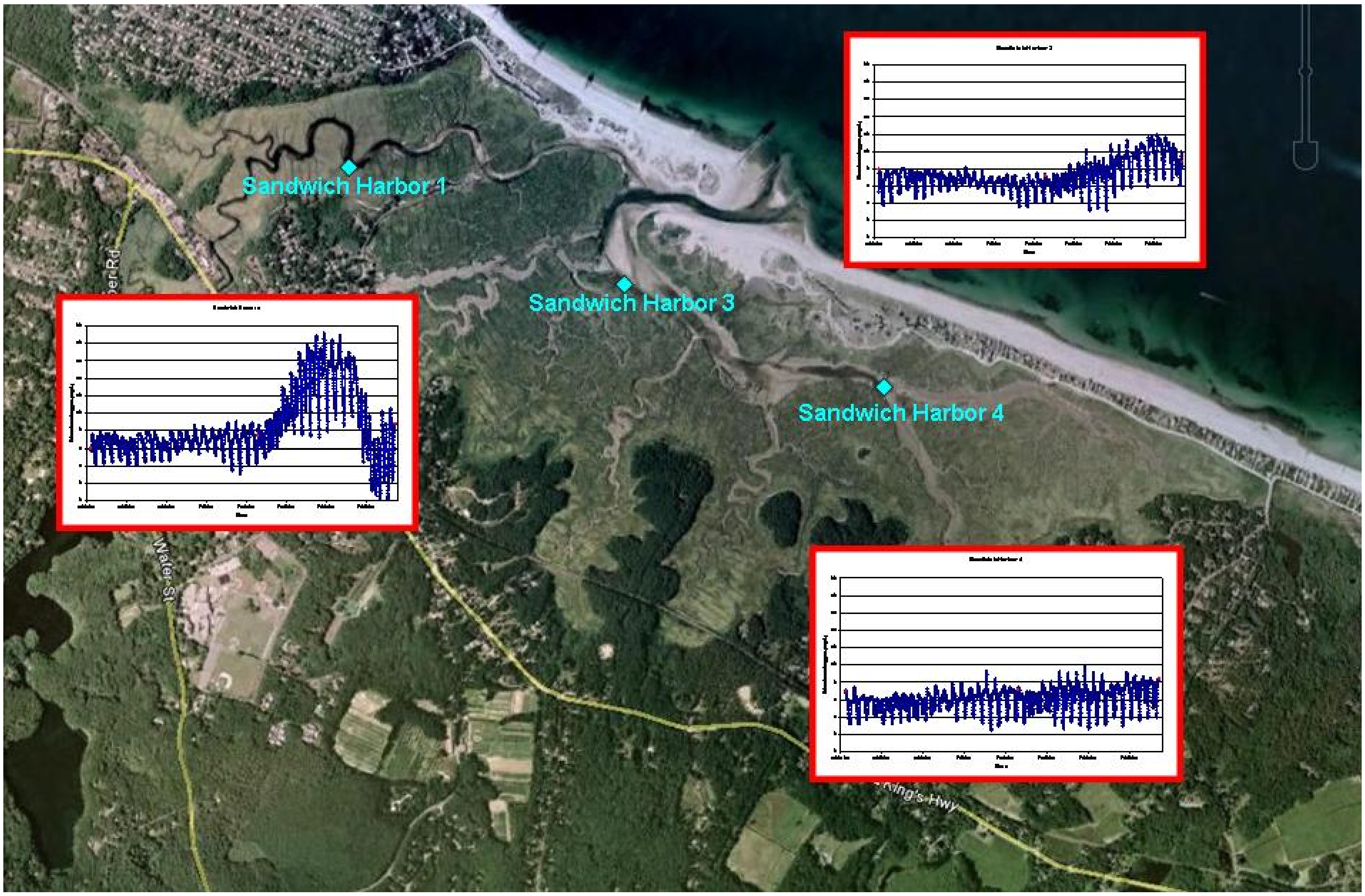
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Sandwich Harbor Estuary Town of Sandwich, Massachusetts



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

REVISED FINAL REPORT – May 2015

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Sandwich Harbor Estuary
Town of Sandwich, Massachusetts

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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 Sandwich Harbor embayment system, a salt marsh dominated coastal embayment within the Town of Sandwich, Massachusetts. Analyses of the Sandwich Harbor embayment system was performed to assist the Town of Sandwich with ongoing nitrogen management decisions associated with the current and future wastewater planning efforts of the Town, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and harbor maintenance programs. As part of the MEP approach, habitat assessment was conducted on the embayment based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Town of Sandwich 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 Sandwich Harbor embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Town) for the protection/restoration of the Sandwich Harbor embayment system.

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

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

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

The Town of Sandwich 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 the Town plans to implement upon its completion. The Town of Sandwich has been working with the MEP Technical Team to also complete a nutrient threshold analysis for the Sandwich Harbor system such that nutrient management can be undertaken in a unified manner across the entire town. The Town of Sandwich with associated working groups has recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making and alternatives analysis. The completion of this multi-step process has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, which is a partnership effort between all MEP collaborators and the Towns across southeastern Massachusetts, Martha's Vineyard and Nantucket Islands. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns' nutrient management groups to predict the impacts on water quality from a variety of proposed management scenarios.

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

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

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

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

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

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

For a comprehensive description of the Linked Model, please refer to the *Full Report: Nitrogen Modeling to Support Watershed Management: Comparison of Approaches and Sensitivity Analysis*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm. A more basic discussion of the Linked Model is also provided in Appendix F of the *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm. The Linked Model suggests which management solutions will adequately protect or restore embayment water quality by enabling towns to test specific management scenarios and weigh the resulting water quality impact against the cost of that approach. In addition to the management scenarios modeled for this report, the Linked Model can be used to evaluate additional management scenarios and may be updated to reflect future changes in land-use within an embayment watershed or changing embayment characteristics. In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries. Unlike many approaches, the Linked Model accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics and accommodates the spatial distribution of these processes. For an overview of several management scenarios that may be employed to restore embayment water quality, see *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm.

Application of MEP Approach: The Linked Model was applied to the Sandwich Harbor embayment system by using site-specific data collected by the MEP and water quality data that was collected as a collaboration between the Coastal Systems Program (UMD-School for Marine Science and Technology) and the Town of Sandwich. The Town of Sandwich was able to implement the appropriate water quality monitoring program in order to develop the necessary baseline to join the MEP program through the support of the Commonwealth of Massachusetts 604(b) grant program. Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Sandwich Planning Department, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Sandwich Harbor embayment system and the systems sub-embayments as appropriate (current and build-out loads are summarized in Table IV-3). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

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

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

The nitrogen thresholds developed in Section VIII-2 were used to determine the amount of total nitrogen mass loading from the watershed in order to maintain the health of the salt marsh dominated Sandwich Harbor system. In more open water dominated systems, a reduction is required for restoration of eelgrass and infaunal habitats, however, such is not always the case in systems dominated by salt marshes (e.g. Namskaket Marsh, Little Namskaket Marsh in the Town of Orleans as well as Cockle Cove Creek in the Town of Chatham). 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 (threshold nitrogen level). 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 adjust nitrogen loads sequentially until the targeted nitrogen concentration is achieved. For the Sandwich Harbor system, the restoration target should reflect both pre-degradation habitat quality and be reasonably achievable. The presentation in this report of nitrogen loading limits aims to establish the general degree and spatial pattern of loading that will be required for protection of this healthy salt marsh dominated embayment system.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen loading guidelines for future nitrogen management in the watershed to the Sandwich Harbor embayment system. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in changes to nitrogen loading (increase or decrease) to the embayment. These scenarios should be developed in coordination with the Town of Sandwich and its consulting engineer such that potential town-wide nitrogen management strategies can be considered in order to effectively examine the effect of load increases/reductions on water column nutrient concentrations in both the Sandwich Harbor system as well as the adjacent Scorton Creek system.

It is important to note that contrary to most other estuarine systems evaluated as part MEP, the threshold concentration for Sandwich Harbor (similar to the adjacent Scorton Creek Marsh) was set higher than present conditions, meaning that the system would be allowed to have a higher load than present while still being able to meet the threshold. Therefore, watershed nitrogen loads were sequentially raised in the model until the nitrogen levels reached the threshold level at the sentinel stations (ensemble average of SH-5,7,9,15) chosen for Sandwich Harbor. It is important to note that load increases could be produced by increasing of any or all sources of nitrogen to the system. The load increases presented in this report represent only one of a suite of potential approaches that need to be evaluated by the community. The current presentation is to establish the general degree and spatial pattern of loading that will be allowable for this system.

<u>2. Problem Assessment (Current Conditions)</u>

A habitat assessment was conducted throughout the Sandwich Harbor system based upon available water quality monitoring data, historical changes in eelgrass distribution (as appropriate), time-series water column oxygen measurements, and benthic community structure. The Sandwich Harbor estuarine system is showing high habitat quality throughout its salt marsh reach. The upper reach appears to be a fully functional tidal salt marsh with deeply incised narrow creeks surrounded by extensive emergent marsh. This reach is typical of New England salt marshes, with smaller tidal creeks and a marsh plain dominated by low marsh and high marsh plant communities with patches of fringing brackish marsh vegetation. The lower reach of the marsh supports a large wetland area to the west along with larger tidal creeks. The lower portion of the system is also heavily influenced by sand transport via nearshore coastal processes associated with adjacent Cape Cod Bay. Plant communities in the lower reach are similar to the upper reach except that there is less fringing brackish water species and the marsh grades to barrier beach/dune vegetation near the tidal inlet. All of the key habitat indicators are consistent within Sandwich Harbor, and particularly its tidal creeks, supporting high quality habitat in line with the system's salt marsh structure and function (Chapter VII).

3. Conclusions of the 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 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 each of the sub-embayment systems in this study were developed to restore or maintain SA waters or high habitat quality. In these systems, high habitat quality was defined as supportive of diverse benthic benthos animal communities. Dissolved oxygen and chlorophyll-*a* were also considered in the assessment.

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Sandwich Harbor embayment system were comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 70%-74% of the controllable watershed nitrogen load to the embayment was from wastewater.

As a salt marsh dominated estuary, Sandwich Harbor, like adjacent Scorton Creek and nearby Namskaket Marsh in the Town of Orleans, does not support eelgrass habitat. As a result, threshold development for protection/restoration of this system focuses on infaunal habitat quality. The primary mechanism for infaunal habitat quality decline in salt marsh creeks of this type is through stimulation of macroalgal production and accumulation.

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Sandwich Harbor estuarine system is based primarily upon: 1) the systems structure and function as a salt marsh, 2) macroalgal distribution, 3) current benthic community indicators and 4) nitrogen levels. Given the database it is possible to develop a site-specific threshold, which is a refinement upon general threshold analysis frequently employed.

The Sandwich Harbor system is presently supportive of high quality salt marsh infaunal habitat throughout its tidal reach. While there is periodic summertime oxygen depletion of creek waters, the levels are consistent with unimpaired New England salt marsh systems. At present, significant macroalgal accumulations do not occur within this macro-tidal estuary at tidally averaged total nitrogen levels of 0.627-0.952 mg N L^{-1} (headwaters) to 0.310 mg N L^{-1} (tidal inlet) and 0.295 mg N L^{-1} (offshore).

The threshold nitrogen levels for the Sandwich Harbor embayment system in the Town of Sandwich were determined as follows:

Sandwich Harbor Threshold Nitrogen Concentrations

- Sandwich Harbor salt marsh is presently below the level of nitrogen loading that would cause impairment to its infaunal habitats (i.e. below its nitrogen threshold level), therefore, a conservative estimate of the threshold was established. The threshold was based upon site-specific data and comparison to other similar systems on Cape Cod where detailed nitrogen threshold studies have been completed (e.g. Scorton Creek, Namskaket Marsh, Little Namskaket Marsh, Cockle Cove Creek). The inter-estuarine comparison focused upon similar salt marshes which are presently experiencing higher nitrogen levels, with and without impairment.

- A principal component of the high tolerance of salt marsh systems to nitrogen inputs from groundwater and surface water inflows is that unlike embayments, creek waters cannot accumulate nutrients over multiple tidal cycles as embayments do. In addition, increasing the nitrogen concentration in the tidal waters that flood the marsh plain will have a negligible or possibly a stimulatory effect on marsh primary and likely secondary production (i.e. an enhancement of habitat). In addition, since the inflowing fresh waters flow down gradient through the marsh creek and out to the adjacent offshore waters, the nitrogen level will never exceed the inflowing freshwater nitrogen level.

- A detailed nitrogen threshold analysis of Cockle Cove Creek (Chatham), a similarly configured salt marsh to Sandwich Harbor, Scorton Creek and Namskaket Creek, was completed by the MEP-SMAST in 2006. In addition to having similar structures, Scorton Creek, Cockle Cove Creek and Namskaket Creek all support similar benthic communities, macroalgal accumulations are sparse to absent in each system and tidal velocities within the central creek are similar. In addition, the infaunal habitats within Namskaket and Cockle Cove Marsh are similar in composition and diversity (dominated by polychaetes and crustaceans, with some mollusks). The dominant species (*Leptocheirus, Paranais*) was also observed in a study of a healthy salt marsh, Great Sippewisset Marsh on Cape Cod.

- Putting all the assessment elements together, it appears that for the Sandwich Harbor Estuary, the critical values are a total nitrogen level of 2 mg N L^{-1} in the headwater stations (SH-5,7,9,15) and a level of 1 mg N L^{-1} in the mid upper reach main channel (check Station SH-11, currently 0.345 mg N L^{-1}). This latter "check" station is not used to set the threshold but serves as a "check" associated with the upper marsh infauna habitat, not significantly diluted by direct freshwater inflows. It should be noted that the tidally averaged total nitrogen level at the middle marsh station in Cockle Cove Creek is currently 1.378 mg N L^{-1} and the tidal inlet station shows concentrations of 0.472 mg N L^{-1}, consistent with the 1 mg N L^{-1} mid marsh station in Namskaket Marsh..

- A more conservative approach was used in setting the threshold for the Sandwich Harbor Estuary. The threshold was based on not exceeding 2 mg L^{-1} overall in the freshwater influenced uppermost tidal reaches of the main creeks. As there are multiple creeks originating at the upland border, the average of the major creek sites was used (SH-5, SH-7, SH-9 and SH-15). The present tidally averaged value for this composite sentinel station is 0.819 mg L^{-1} with a minimum and maximum of 0.627 and 0.952 mg L^{-1}, respectively, well below the threshold. The threshold applies as long as the tidal creek maintains its present hydrodynamic characteristics (flushing and velocity). The nitrogen threshold for Sandwich Harbor Creek is intentionally conservative based upon all available data from comparable systems. While not intuitive, the threshold in Sandwich Harbor Estuary is more restrictive of nitrogen loading than for Namskaket Marsh, since the sentinel stations are farther upgradient in the system and capture higher concentrations than in Namskaket Marsh.

- As presented in Section VIII, the threshold set for this system would allow up to a 137% increase in the total watershed loading to the Sandwich Harbor estuary. In the scenario run developed for the threshold analysis, the watershed increase is achieved solely by increasing the total septic load to the system by 200% (three times the septic load for present conditions).

The overarching conclusion of the MEP analysis of the Sandwich Harbor estuarine system is that protection of this currently healthy salt marsh system will allow for increased nitrogen loading from a variety of watershed sources, however, limits to nitrogen loading have been determined as detailed further in the report. This requires careful long term monitoring of conditions in the marsh system and watershed based management of present and future nitrogen inputs such that nitrogen concentration thresholds specified as supportive of health marsh habitat are not exceeded in the future.

It is recommended that if significant new information is obtained by the Town or the Town's consultant regarding matters pertaining to the content of this threshold report, the MEP Technical Team be contacted to assess the need for re-running the system specific linked models. This is particularly applicable to any major land use changes that occur in the watershed resulting in significant increases in nutrient loading to the estuary from within the watershed or imported from areas external to the watershed. This also applies to any new quantitative information related to beach dynamics (longshore transport) or sea level rise.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Sandwich Harbor estuary system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. (mg/L)
Mill Creek	2.052	6.354	11.205	-	17.559	0.121	2.612	20.292	0.37-0.69	-
Dock Creek	0.636	2.364	3.836	-	6.200	0.359	0.224	6.783	0.32-1.20	-
Old Harbor Creek	1.268	3.981	12.641	-	16.622	0.433	-2.959	14.096	0.30-1.12	-
Combined Total	**3.956**	**12.699**	**27.682**	**-**	**40.381**	**0.913**	**-0.123**	**41.171**	**0.30-1.20**	**1.85**

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 2005– 2007 data, ranges show the upper to lower regions (highest-lowest) of an sub-embayment. Individual yearly means and standard deviations in Table VI-1.
8 Threshold for sentinel sites are located at the Sandwich Harbor water quality stations SH-5, SH-7, SH-9 and SH-15. The threshold is the average of these four stations equal to 1.85 mg/L TN

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Sandwich Harbor estuarine system in Sandwich, 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 change needed to achieve threshold load levels
Mill Creek	17.559	39.970	0.121	3.870	43.960	+127.6%
Dock Creek	6.200	13.871	0.359	0.250	14.480	+123.7%
Old Harbor Creek	16.622	41.904	0.433	-4.051	38.286	+152.1%
Combined Total	**40.381**	**95.745**	**0.913**	**0.069**	**96.726**	**+137.1%**

(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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ADDENDUM

to

Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Sandwich Harbor Embayment System, Sandwich, Massachusetts

At the request of the Town of Sandwich, select responses to comments are provided for the reader to clarify specific aspects of the MEP nutrient threshold analysis for Sandwich Harbor.

MassDEP / Town of Sandwich Comments (MEP Technical Team Response in bold italics):

1) The report should comment on whether the mix of *Spartina* and *Phragmites* would significantly or meaningfully change based on the increased freshwater discharge associated with the projected build-out with no change in wastewater management approach (i.e. septic systems). MEP should also comment on the same question with build-out being addressed by centralized collection, treatment and disposal at a flow rate of 1.3-mgd at 8-mg/l effluent total nitrogen.

   Changes in the freshwater regime of salt marshes can, in some circumstances, affect the distribution and types of marsh plants. However, small changes such as projected by buildout will typically be offset by ongoing local sea level increases. In addition, increased freshwater will only occur if buildout results in net import of potable water. Furthermore, most of any increase in net imported water will tend to increase stream flows which will not influence the Spartina/Phragmites mix. As a result any shift in the Spartina/Phragmites mix will likely be small, but to confirm this requires site specific information not available at this time. Note that the MEP Technical Team focuses on nitrogen effects. Also the reviewer is requesting the Technical Team to make a prediction with no real data, and the MEP does not do this.

2) The report should address the following items:

   a. Impacts of inlet migration, expansion or contraction on the reported results.
   b. Impacts of climate change and sea level rise on the reported results.
   c. Areas of relative certainty and areas of certainty in the modeling effort

The requested items have never been part of the MEP analysis and hence not included within the report. Impacts of inlet migration or contraction can be assessed as scenarios and the impacts of climate change and sea level rise on the reported results would be an entire study in and of itself. However, it should be noted that local sea level rise has not been accelerating significantly over the past 30 years. For an analysis of the modeling effort one might review the report of the Barnstable County Review of the MEP.

3) Discussion of sea level rise (even if to state that it has not been accelerating significantly) is appropriate to address recent questions.

As previously mentioned, the impacts of climate change and sea level rise on the reported results would be an entire study in and of itself as it would require extensive research on how climate change may affect precipitation, recharge, groundwater levels, watershed delineations, N-loads from the watershed, N-loads from atmospheric deposition etc. Moreover, it would be necessary to do extensive research on how sea level rise would affect the geomorphology of the overall marsh system as well as the inlet, its migration over time and the consequence on the efficiency of flushing and residence time etc. We re-iterate that this is well beyond the scope of the MEP as originally conceived but could be researched exhaustively as a separately funded project.

4) p. 25, last para.: Did USGS modeling account for the Long Hill Creek discharge which bypasses the estuary? Furthermore, USGS maintains that it does not have a record of delineating specific Long Hill Creek subwatersheds. The data disks seem to reference these subwatersheds as Quaker Meetinghouse. Was there a name change? Please reconcile or explain.

The regional USGS model generally does not have the benefit of the MEP streamflow information. Based on the measured flow information, the presence of the weir, and the size of the watershed, some portion of the watershed flow was assumed to discharge out of the watershed through the barrier beach. As explained in the text, this seems reasonable given the regular ponding observed in the bog / pond upstream of the gauge. In other subwatersheds, where water could not flow out through the barrier, the gauged flow and modeled flows agreed, adding support to the outflow through the barrier beach argument. Further analysis necessary to further evaluate the flow in this area is beyond the scope of the MEP, although it could be conducted if funds were available. The MEP data disk correctly labels these subwatersheds as Long Hill Creek.

5) Page 58, first full para.: Doesn't the water district mix its pumped volume from all the wells and distribute it throughout the service area? How can the volume from this one well be assigned to a single subwatershed? Please provide an explanation in the text.

Wellhead contributing areas are by their definition the volume of one well within a single watershed, so perhaps the question needs to be clarified. As to how pumped drinking water is distributed, typically public water supply wells on the Cape pump their water directly into the distribution system so water tends to be distributed to accounts close to where it is pumped. <u>Of</u>

course, this can be altered by** **changes in pumping rates of various wells, involvement of water towers, and shifts in areas of concentrated water use, but** ***it is reasonable **to compare the balance between water use within a well contributing area and the pumping rate of the well especially** ***on an average basis*****.***

ACKNOWLEDGMENTS

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 Sandwich and drove for the completion of the Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Sandwich Harbor Estuary. Without these stewards and their efforts, this project would not have been possible and watershed nitrogen planning would lack a quantitative tool to help screen projects for those of maximum effectiveness at minimum cost.

First and foremost we would like to recognize and applaud the commitment shown by the Town of Sandwich in carrying forward with the Massachusetts Estuaries Project and the protection/restoration of all the estuaries of the Town. Of particular note has been the significant time and attention dedicated to this effort by Mr. David Mason. Mr. Mason, Town of Sandwich Health Agent, was critical to establishing the Town of Sandwich Estuarine Water Quality Monitoring Program with guidance from SMAST Coastal Systems Analytical Facility using 604(b) funding from the Commonwealth. Mr. Mason dedicated personal time and effort towards organizing and participating in sample collection to determine the nutrient related water quality throughout both of the Town's estuaries (Sandwich Harbor and Scorton Creek). Without this baseline water quality data the present assessment and threshold analysis would not have been possible. We would also like to acknowledge the field support provided to the MEP by the staff of the Shawme-Crowell Sate Forest who gave us unrestricted use of their facility to complete critical field tasks. Similarly, we would like to acknowledge the assistance and efforts of the Town Planning Department and Nathan Jones, Sandwich Town Planner for assistance in the land-use and build-out analysis and also, Dan Mahoney, Superintendent of the Sandwich Water District for providing and discussing the critical water-use database.

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I. INTRODUCTION

Sandwich Harbor is approximately a 220 hectare (544 acre) salt marsh on the northwestern coast of Cape Cod (Figure I-1), with an adjacent similarly structured estuary, Scorton Creek Marsh, to the east and also within Sandwich. The Sandwich Harbor Estuary is located fully within the Town of Sandwich on Cape Cod Massachusetts. This marsh system is one of the largest on Cape Cod and is a tidal salt marsh receiving tidal flood water through a single tidal inlet to Cape Cod Bay (Figure I-2). Sandwich Harbor Marsh does have a small, deeper water area immediately inside the tidal inlet. However, in both the Sandwich Harbor and Scorton Creek Estuaries, these deeper water regions are "natural", being formed by scour from high tidal velocities, and do not retain significant water volume at low tide. The Sandwich Harbor Estuary is predominantly emergent salt marsh with three main tidal creeks (Mill Creek, Dock Creek, Old Harbor Creek) each with smaller tributary tidal creeks. The watershed contributing nitrogen to the estuarine waters of the Sandwich Harbor Estuary is distributed entirely within the Town of Sandwich making protection or restoration of the system simpler as restoration of any degraded habitats within this Estuary will depend upon the coordinated efforts of only one municipality and its citizens.

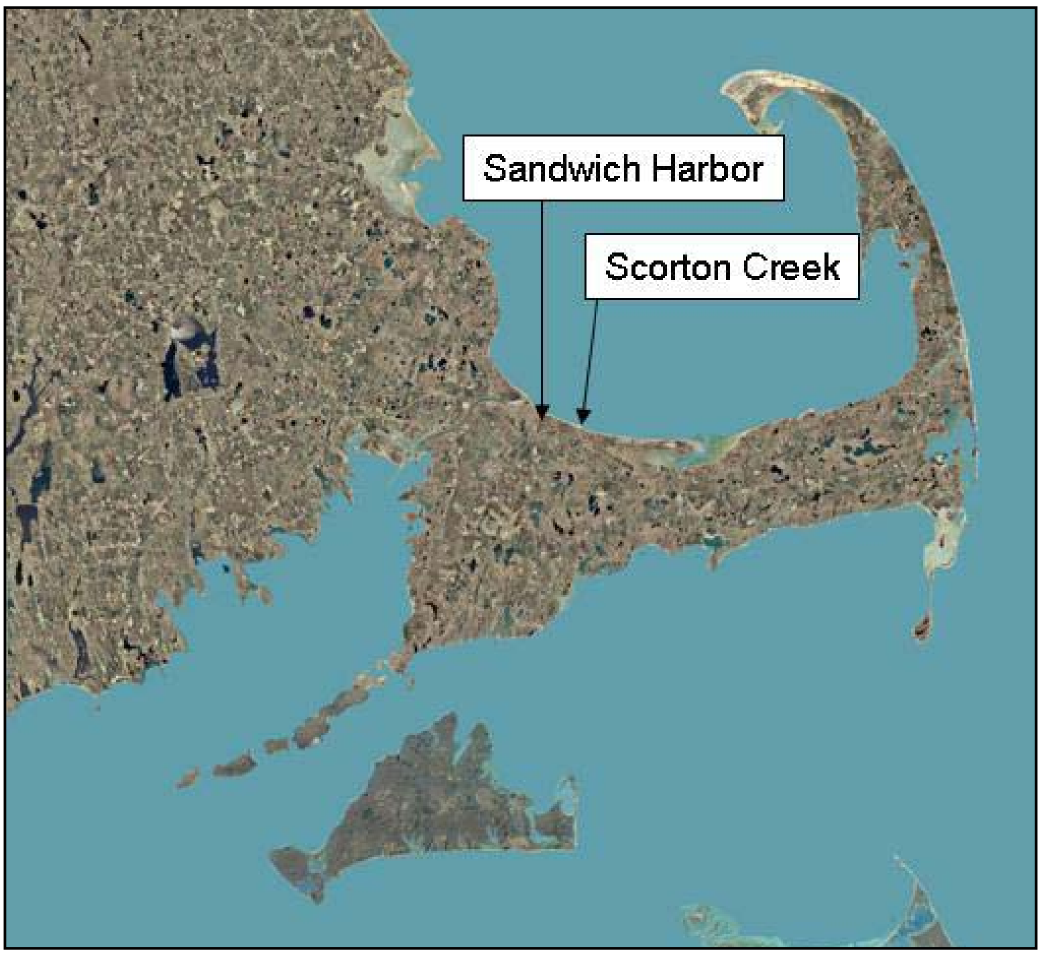


Figure I-1. General location of the Sandwich Harbor and Scorton Creek salt marshes within the Town of Sandwich, MA. on the northwestern shore of Cape Cod.

Figure I-2. Study region for the Massachusetts Estuaries Project assessment and nitrogen thresholds analysis for the Sandwich Harbor Estuary. Tidal waters enter the system from Cape Cod Bay through a single inlet that is not armored. Freshwaters enter the head of the system from the watershed through 2 surface water discharge points (head of Mill Creek and Springhill Creek), with the primary freshwater transport pathway being direct groundwater discharge.

Overall, the Sandwich Harbor Estuary is functioning as a typical New England salt marsh dominated by a few main tidal creeks supporting extensive emergent intertidal salt marsh. These intertidal areas are colonized by low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) with some more brackish marsh plants found in the upper most regions with *Phragmites* areas limited to the upland border. Tidal exchange with the high quality waters of Cape Cod Bay is high, given the ca. 10 foot tide, which has also resulted in tidal creeks which are deeply incised, with near complete drainage at low tide. The result is a coastal basin with a relatively high tolerance for nitrogen inputs from its watershed, due to its flushing and dominance by emergent salt marsh. Observations by the MEP Technical Team indicate a healthy functioning New England Salt Marsh.

Sandwich Harbor Marsh provides both wildlife habitat and serves as a nursery area to offshore fisheries, as well as being a storm buffer and nutrient sink for watershed derived nitrogen. The Town of Sandwich has also provided citizen access through the outer part of the Sandwich Harbor Marshes via an extensive boardwalk that is frequented by many local citizens and visitors each year.

Sandwich Harbor is a large estuary formed behind a barrier beach created by coastal processes associated with sediment transport in the nearshore Cape Cod Bay. This estuarine system is a relatively “young” coastal feature that required significant post glaciation sea-level rise and the formation of the barrier beach, occurring on the order of 2500-4000 years b.p. Similar to other salt marsh dominated systems on the northern coast of Cape Cod (e.g. Namskaket Marsh, Little Namskaket Marsh and nearby Scorton Creek Marsh), Sandwich Harbor Estuary is a shallow basin dominated by emergent salt marsh with some sandy tidal flats, as well as being located within a watershed that includes glacial outwash plain and ice contact deposits (Figure I-3). These subsurface formations consist of material deposited after the retreat of the Laurentide Ice sheet ~15,000 years ago. These deposits, which form the present aquifer soils, are highly permeable and vary in composition from well sorted medium sands to coarse pebble sands and gravels (Oldale, 1992). As such, direct rainwater run-off is typically rather low and most freshwater inflow to these estuarine systems is via groundwater discharge or groundwater fed surface water flows.

Sandwich Harbor Marsh acts as a mixing zone for terrestrial freshwater inflow and saline tidal inflow from Cape Cod Bay. Salinity levels vary with the volume of freshwater inflow as well as the effectiveness of tidal exchange. Given the large tidal flows and nearly complete volumetric exchange, there is presently only minor dilution of salinity throughout most of the estuary at high tide. As a salt marsh, the elevation of the creek bottoms is generally higher than the low tide elevation in the adjacent Bay (e.g. the creeks drain nearly completely at low tide). The result is that at low tide, the salinity of the out flowing water within the tidal creeks is fresh to very brackish, due to the continuing freshwater inflow in the absence of the tidal waters. As a result salinity variations of the creek waters in the upper marsh are very large with the salinity range over the tidal cycle decreasing moderately toward the tidal inlet. Organisms associated with these creeks have developed strategies for dealing with these large salinity variations.

In general, surface water streams are relatively small with the exception of the discharge from Shawme Lake and in concert carry only a small portion of the aquifer recharge to the estuary. As the streams are not well formed, almost all freshwater enters through groundwater seepage at the wetland-upland interface or directly to tidal tributary creeks through creek bottom seepage. This is the pattern observed in other similarly structured salt marshes (e.g. Namskaket Marsh, Barnstable Great Marshes) on Cape Cod which exchange tidal waters with Cape Cod Bay.

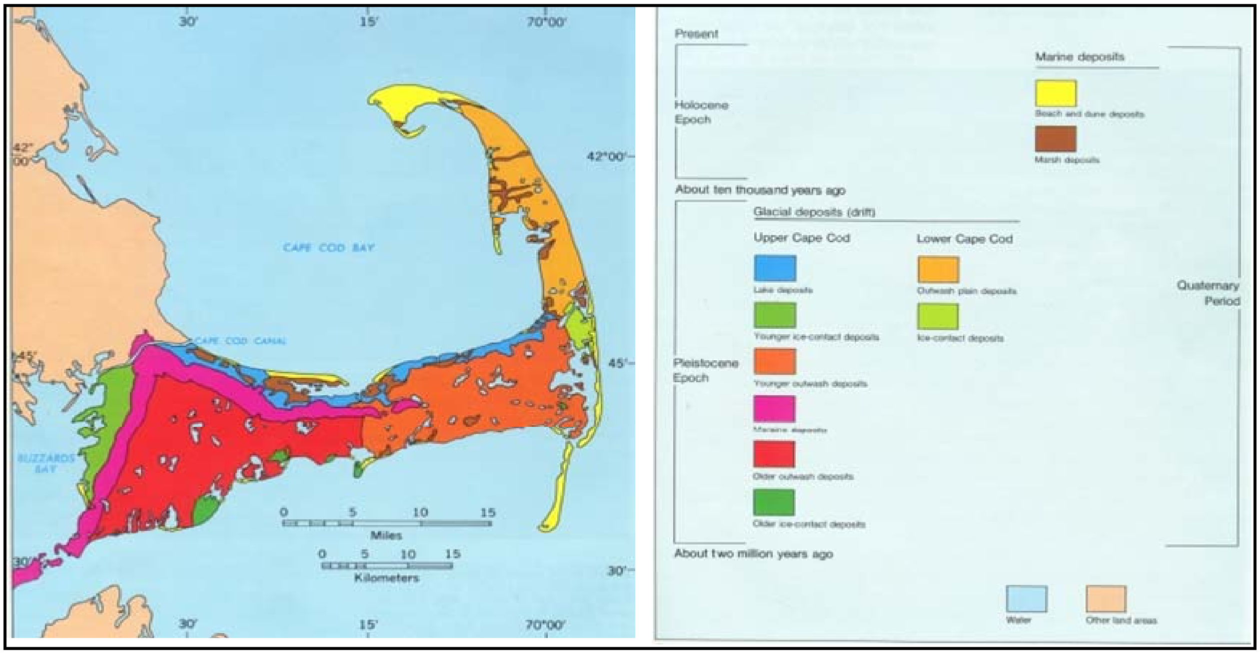


Figure I-3. Geologic map of Cape Cod (generalized from detailed mapping by K. F. Mather, R. P. Goldthwait, L. R. Theismeyer, J. H. Hartshorn, Carl Koteff, and R. N. Oldale).

Tidal exchange with Cape Cod Bay is through a 30 to 75 meter wide inlet (depending on tidal stage) which empties into the nearshore waters off Sandwich Beach. The beach and the inlet are very dynamic geomorphic features, due to the influence of littoral transport processes. These processes may periodically affect the health of this estuary through changes in hydrodynamics wrought by inlet dynamics (see Chapter V). To the extent that the inlet becomes restricted and tidal flushing is reduced, nitrogen loading impacts will be magnified over present conditions. Equally important, to the extent that tide range may become reduced, the health and productivity of the emergent salt marsh would be reduced. Any long term habitat management plan for the Sandwich Harbor Marsh System must recognize the importance of inlet dynamics and include options to maintain tidal exchange.

The primary ecological threat to Sandwich Harbor Marsh resources is potential degradation resulting from nutrient enrichment through either loading from the watershed or reduced tidal flushing. Loading of the critical eutrophying nutrient (nitrogen) has been increasing over the past few decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to this and other outer Cape estuaries (such as Namskaket Marsh, Little Namskaket Marsh and Nauset Harbor in the Town of Orleans), like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater or disposal of treated effluent from municipal treatment facilities. The Town of Sandwich has been among the fastest growing towns in the Commonwealth over the past two decades and does not have centralized wastewater treatment. As levels of nitrogen loading to coastal systems continue to increase, concern has grown in towns across Cape Cod over associated nutrient impacts.

Fortunately for the resource protection of the Sandwich Harbor Estuary, as is the case for other marsh systems like Namskaket Marsh in Orleans, its function as a tidal salt marsh makes it more tolerant of watershed nitrogen inputs than open water embayments, like nearby

Plymouth-Duxbury Harbor, Popponesset Bay or Town Cove or Pleasant Bay on outer Cape Cod. The greater sensitivity of embayments versus wetlands results from their higher residence times compared to salt marshes that virtually empty at each low tide, the fact that there is limited to no exposure of the sediments to the atmosphere at low tide (like the marsh plain), and the fact that these systems have evolved under much lower levels of productivity and organic matter loading than wetlands. For example, the organic carbon content (wt/wt%) of New England Salt Marsh vegetated sediments can frequently reach 20%, while embayment sediments are generally in the 1%-5% range. Yet another difference between system types is that oxygen depletion in the creeks of *pristine* salt marshes can normally occur on summer nights, while embayment bottom waters become hypoxic generally as a result of *eutrophic* conditions, with impairment to benthic communities.

Some additional insight into the nitrogen response by salt marshes can be garnered from long-term chronic nitrogen addition experiments. These have been conducted at multiple sites along the Atlantic coast and specifically in a nearby New England salt marsh, Great Sippewissett Marsh (West Falmouth, MA). This latter project was started by WHOI scientists in 1970 and has been overseen solely by current SMAST Staff since 1985. These studies reveal that nitrogen additions to low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) areas, typically results in increased plant production and biomass and secondary production as well. Nitrogen dynamics have been quantified, which show that as nitrogen is added the initial increased nitrogen available is taken up by the plants, but this plant demand is rapidly satisfied and additional load is denitrified *in situ* by soil bacteria. In the Great Sippewissett Marsh fertilization experiments the denitrification capacity of the sediments has not been exhausted in 30 years of N additions and at levels about 7 times the natural background N input (75.6 g N m^{-2} each growing season).

Salt marsh creek bottoms and creek banks (such as those found in Sandwich Harbor, Scorton Creek, Namskaket Marsh, and Little Namskaket Marsh) have developed under nutrient and organic matter rich conditions, as have the organisms that they support. It is the creek bottoms rather than the emergent marsh which are the primary receptors of increased watershed derived nitrogen in Cape Cod salt marshes. Watershed nitrogen predominantly enters these salt marshes through groundwater or small headwater streams, as is the case in the Sandwich Harbor Estuary. Both surface and groundwater entry focuses on the tidal channels. Even groundwater entry through seepage at the upland interface is channeled to creeks. As the tide ebbs in New England salt marshes (like Sandwich Harbor and Scorton Creek) the freshwater inflow “freshens” the waters and the nitrogen levels in the tidal creeks increase due to the nitrogen entry from the watershed. At low tide the nitrogen levels in the tidal creeks are dominated by watershed inputs.

Since the predominant form of nitrogen entering from the watershed is inorganic nitrate, the effect on the creek bottom is to stimulate denitrification, hence nitrogen removal. For example, in a salt marsh in West Falmouth Harbor, Mashapaquit Creek, ~40% of the entering watershed nitrogen is denitrified by the creek bottom sediments on an annual basis. This stimulation of denitrification does not negatively affect the salt marsh, but does result in a reduction of nitrogen loading to the adjacent nitrogen sensitive coastal waters. However, analysis by MEP Staff of salt marsh areas receiving wastewater discharges indicates that at very high nitrogen loads (inputs relative to tidal flushing), macroalgal accumulations can occur. These accumulations are generally found in the creek bottoms and flats and also may drift and settle on the creek banks. Large macroalgal accumulations in tidal creeks can cause impairment of benthic animal communities. Negative effects on creek bank grasses can occur due to accumulation of macroalgae which smothers the grasses and can lead to bank erosion with additional negative effects on benthic organisms. A part of the focus of the present MEP analysis of the Sandwich Harbor Estuary relates to potential macroalgal issues.

The Town of Sandwich is the primary stakeholder to the Sandwich Harbor Estuary, the focus of the current assessment and threshold analysis. The Town of Sandwich was among the first communities to work with the MEP with regard to any existing and potential future degradation of its estuaries. As such, the Town of Sandwich (via the Health Department) undertook a town-wide estuarine monitoring effort, inclusive of both Sandwich Harbor and Scorton Creek Estuaries. Through funding from the Commonwealth of Massachusetts 604(b) Grant Program, a comprehensive water quality monitoring program was developed to acquire the necessary background water quality monitoring data throughout the estuarine waters within the Town of Sandwich such that the MEP Linked Watershed-Embayment Management Modeling Approach could be applied for the development of nutrient thresholds. Moreover, water quality data generated by the Town of Sandwich Water Quality Monitoring Program is consistent with that generated by other Towns engaged in the MEP (including the Town of Orleans which supports salt marsh systems very similar to those in Sandwich) making the data for all the systems in this area cross comparable.

The common focus of the water quality monitoring efforts undertaken by the Town of Sandwich has been to gather site-specific data on the current nitrogen related water quality throughout the Sandwich Harbor and Scorton Creek Estuaries. These data were then utilized to determine the relationship between observed water quality 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 water quality data set developed by the Town of Sandwich Water Quality Monitoring Program in collaboration with the SMAST-Coastal Systems Program at the University of Massachusetts form a baseline from which to gauge long-term changes as watershed nitrogen management moves forward. The Sandwich Water Quality Monitoring Program efforts allowed the MEP to prioritize both of the Sandwich systems for the next step in the restoration/protection and management process.

The MEP effort builds upon the efforts of the water quality monitoring program and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Sandwich Harbor marsh system.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning and nitrogen management alternatives development needed by the Town of Sandwich for protection/restoration of estuarine habitats at the point that they are warranted. While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for the Town of Sandwich to develop and evaluate the most cost effective nitrogen management alternatives to protect/restore the valuable coastal resources that have been affected by nitrogen overloading.

Overall, the Sandwich Harbor Estuary and its emergent salt marshes appear presently to be functioning as a productive healthy New England salt marsh as noted by the MEP Technical Team's field surveys. Nitrogen levels within the tidal creeks do not generally show evidence of impairment of the resources. However, loading of nitrogen from the watershed to the estuary has been increasing over the past few decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to this and other outer Cape estuaries, like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater or disposal of treated effluent from municipal treatment facilities. However, as noted above, salt marshes are relatively insensitive to degradation by nitrogen inputs from the surrounding watershed. This results from the structure of the salt marsh within the upland hydrologic system and the natural nitrogen processing by these systems. In addition, the plants and animals within salt marshes have evolved to accommodate the high organic matter levels within the marsh sediments and associated waters and the associated biogeochemical effects. Critical to the MEP analysis of this salt marsh system is partitioning of the receptors within the emergent salt marsh and large tidal creeks and basins (basins retaining significant tidal volume at low tide).

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The nutrients are primarily related to changes in watershed land-use associated with increasing population within the coastal zone over the past half century. Many of Massachusetts' embayments have nutrient levels that are approaching or are currently over this assimilative capacity, which begins to cause declines in their ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities. At its higher levels, enhanced 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 can be related to changes in land-use as a watershed becomes 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 Sandwich) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the potential decline in health of their estuaries.

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

The Massachusetts Estuaries Project represents the next generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental

Protection (MassDEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the 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 municipalities and MassDEP with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL outlines an implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

The major Project goals are to:

- develop a TMDL working group(s) for coordination and rapid transfer of results,
- determine the nutrient sensitivity of 70 of the embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment model available to evaluate nitrogen management options and to assess impacts of new nitrogen sources at the request of local government and other stewards/stakeholders.

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 ca. 55 Estuaries 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 or proposed future addition of new nitrogen sources (e.g. build-out).

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 suggests "solutions" for the protection or restoration of nutrient related water quality and allows testing of "what if" management scenarios to support evaluation of resulting water quality impact versus cost (i.e., "biggest ecological bang for the buck"). In addition, once a model is fully functional it can be "kept alive" and corrected 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 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:

- 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 NITROGEN 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 Sandwich Harbor embayment system, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer mineral (Weiskel and Howes 1992). Since even Cape Cod "rivers" are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems on Cape Cod (DeSimone and Howes 1998, Weiskel and Howes 1992, Smith *et al.* 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971).

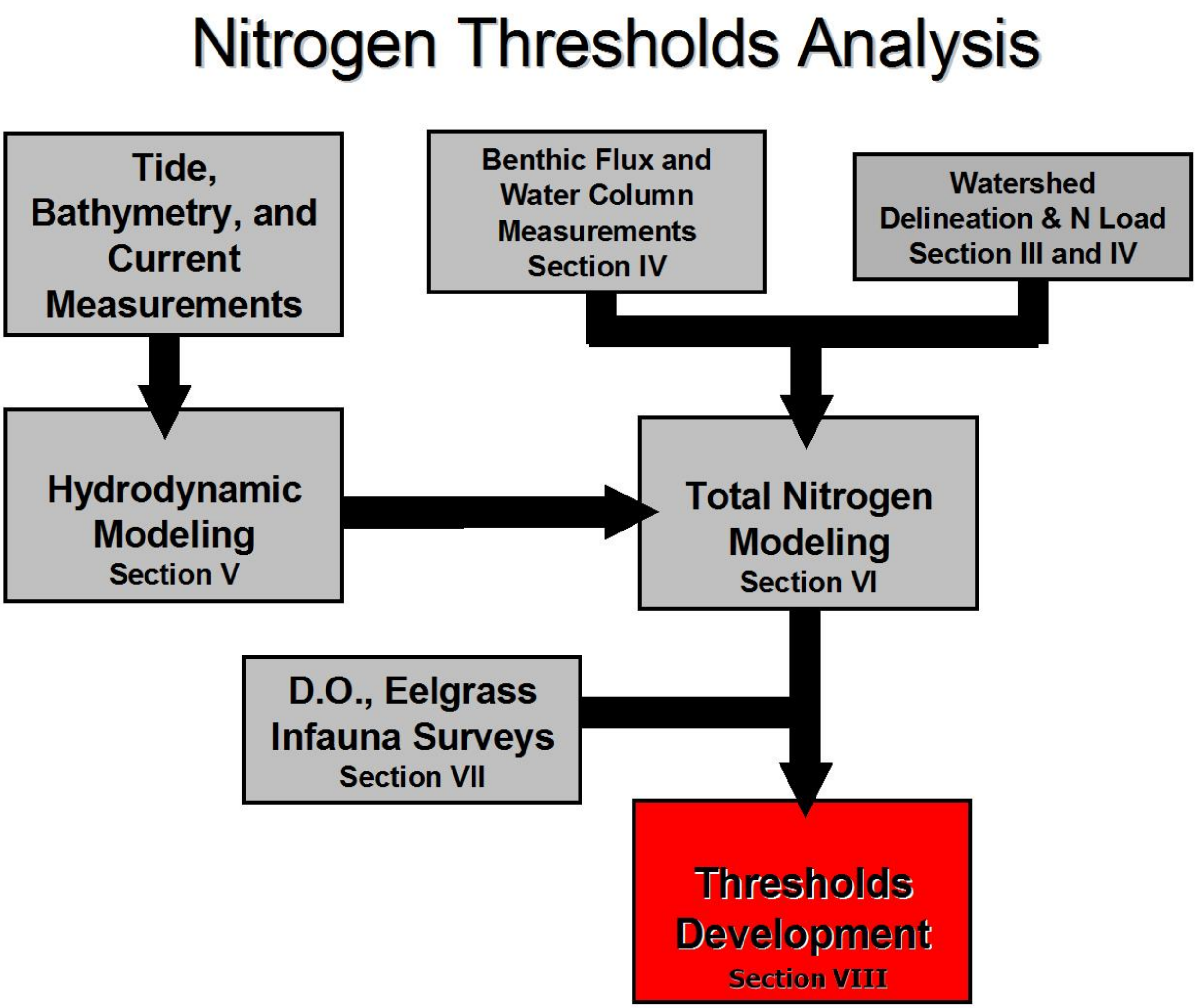


Figure I-4. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach.

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

Each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation. However, as loading increases a point is reached at which the capacity (termed assimilative capacity) is exceeded and nutrient related water quality degradation occurs. As 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, 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 the MEP approach integrates site-specific data on nitrogen levels and the gradient in N concentration throughout the salt marsh dominated estuaries (Sandwich Harbor and Scorton Creek) monitored by the Town of Sandwich Water Quality Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) to “tune” general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

I.3 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” for water quality modeling of the Town of Sandwich estuaries (Sandwich Harbor and Scorton Creek); however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within the systems. Therefore, water quality modeling of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. The spread of pollutants may be analyzed from tidal current information developed by the numerical models.

The MEP water quality evaluation examined the potential impacts of nitrogen loading into the salt marsh dominated estuary of Sandwich Harbor with all its tidal tributaries. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the system. 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 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 Sagamore model for sub-watershed areas designated by MEP. Almost all nitrogen entering the Sandwich Harbor Estuary is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Cape Cod Bay source waters and the marsh system itself was taken from the water quality monitoring program run by the Town of Sandwich (associated with the Coastal Systems Program at SMAST). Measurements of salinity and nitrogen distributions throughout estuarine waters of these estuaries were used to calibrate and validate the water quality model (under existing loading conditions).

I.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Sandwich Harbor Estuary within the Town of Sandwich. A review of existing studies related to habitat health or nutrient related water quality is provided in Chapter II with a more detailed review of prior hydrodynamic investigations presented with the MEP hydrodynamic model development summary in Chapter V. The development of the watershed delineations and associated detailed land use analysis for quantifying the watershed based nitrogen loading to the estuary is described in Chapters III and IV. In addition, nitrogen input parameters to the water quality model are described. Since nitrogen recycling associated with the 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 (Chapter IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission and Town Planning Department data. Offshore water column nitrogen values were derived from an analysis of monitoring station data on the flooding tide (Chapter IV). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Chapter VI. Results of hydrodynamic modeling of embayment circulation are discussed in Chapter 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 Chapter VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of each of the main component creeks was performed that included a review of existing water quality information and the results of benthic and macroalgal surveys (Chapter VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment in Chapter VIII. Additional modeling is conducted if requested by the Town and presented in Chapter IX to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration in a given estuarine system. This latter assessment may also include examining hydrodynamic options for increasing flushing of a system and only represent some of many solutions and is produced to assist the Town in developing a variety of alternative nitrogen management options for the marsh system. In the case of the Sandwich Harbor Estuary, MEP Technical Staff worked with the Town of Sandwich and its consultants to develop a scenario, presented in Chapter IX of this report.

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

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

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

Several studies relating to nitrogen loading, hydrodynamics and habitat health associated with the Sandwich Harbor Estuary have been conducted over the past two decades which were examined in an effort to inform the MEP process. This historical work along with quantitative information on water column parameters over multiple summers (including nitrogen) and coastal processes studies (summarized in Chapter V) has helped advance the MEP effort in regard to Sandwich Harbor. These studies are summarized below.

Circulation and Flushing Modeling of the Sandwich Harbor System, Sandwich, MA. July 1998, Woods Hole Group Inc.: In 1998 the Town of Sandwich retained Woods Hole Group Inc. of Falmouth, MA. to conduct an analysis of circulation and flushing of the Sandwich Harbor System, inclusive of the tidal creeks and marsh plain. The primary purpose of the flushing study was to characterize the tidal flow between the salt marsh system and Cape Cod Bay. Through numerical modeling, average residence time was estimated as an indicator of water quality for the system. The numerical hydrodynamic model was supported with field measurements including water levels and bathymetric information. These input terms were used to calibrate the two-dimensional hydrodynamic model (RMA-2). In total five (5) tide gauges were deployed for a 30-day period to measure tidal elevations and phases. One gauge was deployed offshore from the inlet to Sandwich Harbor and the remaining four were deployed throughout the main tidal creeks of the Sandwich Harbor salt marsh system. The tide gauges were also used to assess the degree of tidal damping and time lags within the system through comparison of tidal stages at the various gauges deployed in the marsh system and the measured tidal stage at the offshore gauge. Of interest was the portrayal of the flooding and drying of the marsh plain and inlet's breached mouth during low tide.

Sandwich Harbor Nutrient Related Water Quality Monitoring: The MEP analysis requires high quality water quality data in order to complete its assessment and modeling approach. The Town of Sandwich Water Quality Monitoring Program (supported by the Massachusetts 604(b) grant program) collected data on nutrient related water quality throughout the estuarine systems of the Town of Sandwich (specifically Sandwich Harbor and Scorton Creek Estuaries). The Town of Sandwich Water Quality Monitoring Program has collected the principal baseline water quality data necessary for ecological management of each of the estuaries of the Town. The Town of Sandwich monitoring program was a citizen-based water quality monitoring program run by the Town of Sandwich Health Department (D. Mason, Town of Sandwich Health Agent and Monitoring Program Coordinator) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD. During the period the monitoring program was actively collecting water samples, the program had a USEPA and MassDEP approved Quality Assurance Project Plan (QAPP), which was operational over the entire period of 2005-2007 (data period for this MEP analysis).

In order to initiate the needed data collection for the Sandwich Harbor and Scorton Creek Estuarine Systems to support a full evaluation of future nutrient management options, the Town of Sandwich initiated the water quality monitoring program in the summer of 2005. While the initial effort was funded solely by the Town, the Town of Sandwich sought and received DEP 604(b) funding support for collection, processing and analyses of water samples throughout each estuary. In total, two grants were obtained allowing water quality data collection at the estuarine stations throughout each summer, 2006 and 2007. Samples and field data were collected from a total of 28 marine sample stations (Sandwich harbor + Scorton Creek), with 15 stations associated with the Sandwich Harbor Estuarine System and 13 stations with the Scorton Creek System. During the course of the three year sampling program, water samples were collected from each station during 6 sample rounds from June through mid-September, 2005-2007, in order to target what is typically the period of poorest nutrient related water quality that is the focus of managing these systems. Marine stations were sampled at approximately two-week intervals during the falling tide (targeting the 2 hours before and after mid-ebb) during the early morning hours (6-9 A.M.).

The common focus of the Town of Sandwich Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout Sandwich Harbor and Scorton Creek Estuaries to support evaluations of observed water quality and habitat health. The Sandwich Water Quality Monitoring Program developed a critical multi-year data set on nitrogen related water quality for this system, necessary to support the MEP assessment and modeling (Figure II-1). The monitoring undertaken was a collaborative effort with the Town of Sandwich Health Department (David Mason) coordinating the field effort and chemical assays being completed by the SMAST Coastal Systems Analytical Facility. The Coastal Systems Analytical Facility is located in the School for Marine Science and Technology UMASS-Dartmouth, 706 S. Rodney French Blvd, New Bedford, MA, and the laboratory Points of Contact are Sara Sampieri 508-910-6325 (ssampieri@umassd.edu) or Mike Bartlett (mbartlett@umassd.edu). Use of the SMAST Analytical Facility ensured sufficient sensitivity and accuracy of the analytical protocols and that proper QA/QC procedures were followed to allow incorporation of the data into the MEP analysis. The baseline water quality data were a prerequisite to entry into the MEP. Implementation of the MEP's Linked Watershed-Embayment Approach necessarily incorporates the quantitative water column nitrogen data (2005-2007) and watershed and embayment data. The watercolumn data is used to establish baseline conditions and in the calibration and verification of the water quality models.

Since the results of the long term Water Quality Monitoring Program (2005-2007) and the above studies indicate that portions of the Sandwich Harbor systems could be threatened by the combination of land-derived nitrogen inputs and intermittent restriction of tidal exchange, the Town of Sandwich undertook participation in the Massachusetts Estuaries Project to complete ecological assessment and water quality modeling for the development of nutrient thresholds for protection of the Sandwich Harbor salt marshes.

Regulatory Assessments of Sandwich Harbor Resources - In addition to locally generated studies, the Sandwich Harbor Estuary is part of the Commonwealth's environmental surveys to support regulatory needs. The Sandwich Harbor Estuary contains a variety of natural resources of value to the citizens of Sandwich as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP also gathers the available information on these resources as part of its assessment, and presents some of them here for reference by those providing stewardship for this estuary and some in Chapter 7 to support the nitrogen thresholds analysis. For the Sandwich Harbor Estuary these include:

- Designated Shellfish Growing Area – MassDMF (Figure II-2)
- Shellfish Suitability Areas – MassDMF (Figure II-3)
- Anadromous Fish Runs - MassDMF (Figure II-4)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-5)
- Mouth of Coastal Rivers – MassDEP Wetlands Program (Figure II-6)

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

Figure II-1. Town of Sandwich Water Quality Monitoring Program for Sandwich Harbor. Estuarine water quality monitoring stations sampled by Town of Sandwich Staff and Volunteers and analyzed at the Coastal Systems Analytical Facility at SMAST during summers 2005, 2006, 2007.

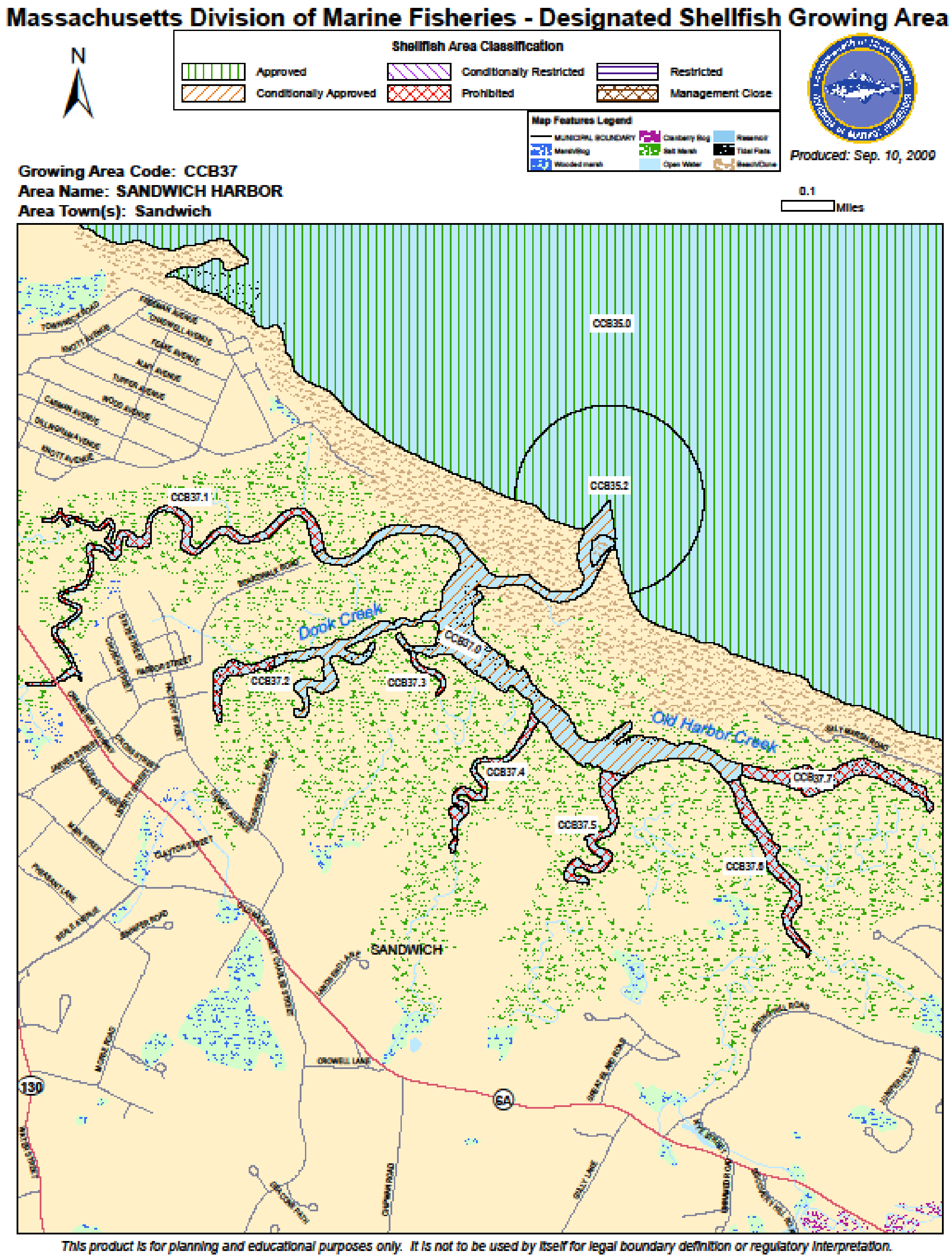


Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination. The prohibited areas are smaller marsh tributary creeks that receive most of the freshwater inflow to the system, while the "conditionally approved areas are in the main tidal creeks that flush with Cape Cod Bay water each tide. Wetland areas with persistent fecal coliform levels >14 cfu per 100 mL may be prohibited to shellfishing until the source of contamination (frequently wildlife & birds) is documented.

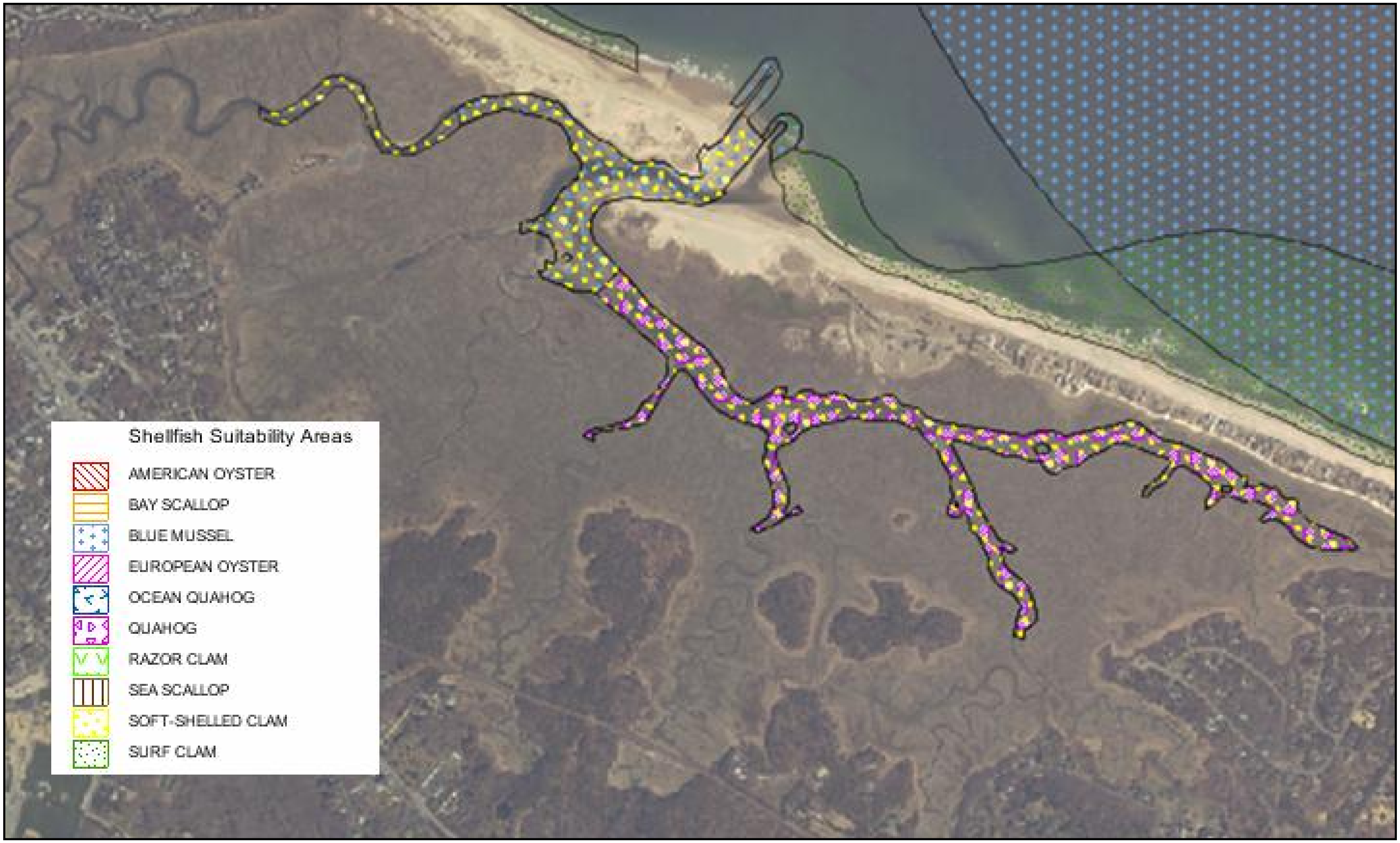


Figure II-3. Location of shellfish suitability areas within the Sandwich Harbor Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean that a shellfish population is "present" or that harvest is allowed (see Figure II-2).

Figure II-4. Anadromous fish runs within the Sandwich Harbor Estuary extending up into Shawme Lake as determined by Mass Division of Marine Fisheries. The red diamonds show areas where fish were observed.

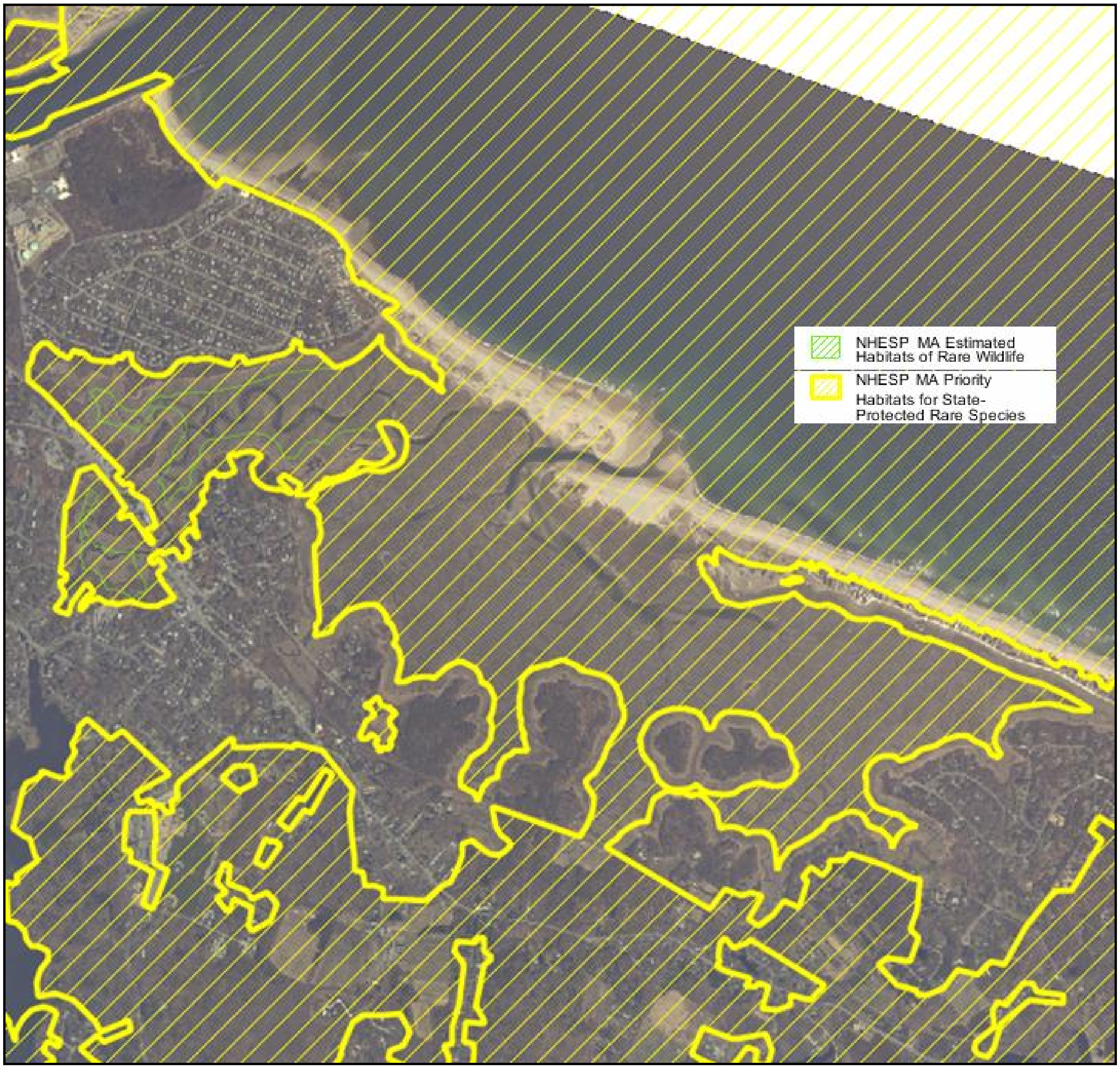


Figure II-5. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Sandwich Harbor Estuary as determined by the Massachusetts Natural Heritage and Endanger Species Program (NHESP).

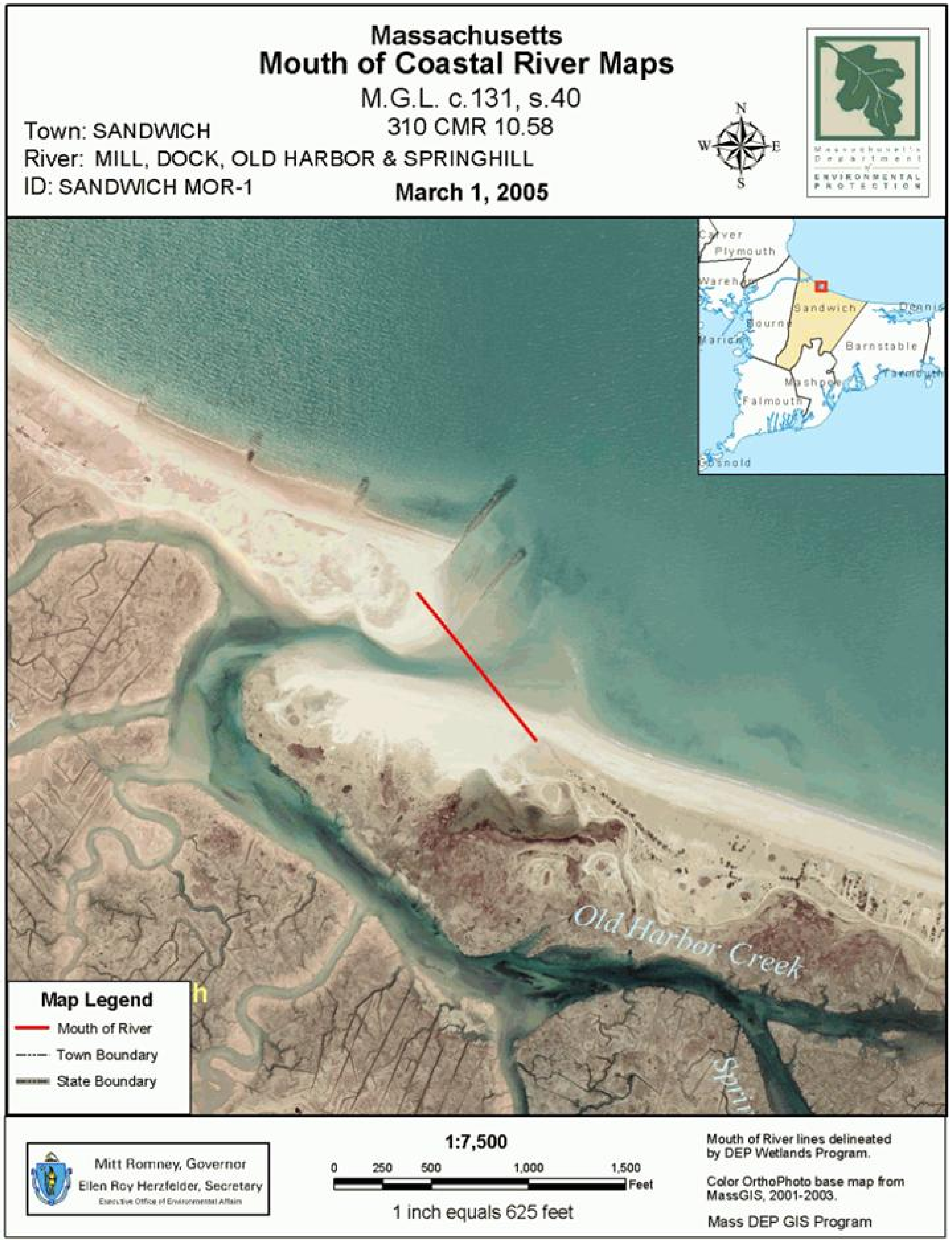


Figure II-6. Mouth of Coastal Rivers designation for Sandwich Harbor as determined by – MassDEP Wetlands Program, under the Massachusetts Rivers Protection Act.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project (MEP) 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 organize and analyze the available data using up-to-date mathematical codes and create better tools to answer the wide variety of questions related to watershed delineation. These questions include surface water/groundwater interactions, groundwater travel times, and drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including Sandwich Harbor. The whole Sandwich Harbor watershed is within the Town of Sandwich boundaries and the watershed is bounded to the east by the Scorton Creek watershed.

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 Sandwich Harbor Estuary system under evaluation by the Project Team. The Sandwich Harbor estuarine system is a shallow, extensively branched, salt marsh-dominated estuary with a single inlet through which it exchanges tidal waters with Cape Cod Bay. Watershed modeling was undertaken to sub-divide the overall watershed to the Sandwich Harbor Estuary into functional sub-units based upon: (a) defining inputs from contributing areas to each major tidal creek/salt marsh region within the Estuary, (b) defining contributing areas to major freshwater aquatic systems which attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands), and (c) defining the land areas with groundwater travel times that are greater and less than 10 years time-of-travel to estuarine waters. These time-of-travel distributions within each sub-watershed are used as a procedural check to gauge the potential mass of nitrogen from “new” development, which has not yet reached the receiving estuarine waters at the time of the MEP analysis. The three-dimensional numerical groundwater model employed to delineate the Sandwich Harbor watersheds was also used to evaluate the contributing areas to public water supply wells in the Sagamore flow cell on Cape Cod; the Sandwich Harbor watershed is located within the regional Sagamore groundwater lens.

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 streams and the portion of the groundwater system discharging directly into an estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Sandwich Harbor Estuary and its various sub-watersheds, such as the Shawme Ponds complex and Spring Hill Creek, were delineated using the most current version of the USGS regional model of the Sagamore Lens flow cell (Walter and Whealan, 2005). The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, *et al.*, 2000) was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4 (Pollock, 2000), which uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies. This approach was used to determine the contributing areas to the Sandwich Harbor Estuary and it was sub-divided (sub-watersheds) to determine portions of recharged water that may flow through fresh water ponds and streams prior to discharging into coastal water bodies and to determine flow and nitrogen loads to each of the major tributary creeks and associated emergent marsh areas comprising the Sandwich Harbor Estuary.

The Sagamore Flow Model grid consists of 246 rows, 365 columns and 20 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top 17 layers of the model extend to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft. The top of layer 8 resides at NGVD 29 with layers 1-7 stacked above and layers 8-20 below. Layer 18 has a thickness of 40 feet and extends to 140 feet below NGVD 29, while layer 19 extends to 240 feet below NGVD 29. The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics (up to 519 feet below NGVD 29 in the Sagamore Lens). In the Sandwich Harbor watershed area, bedrock generally is approximately 150 to 200 feet below NGVD 29 (Walter and Whealan, 2005), although there are deeper portions close to Cape Cod Bay (Fairchild, *et al*., 2012). In the groundwater flow model, this means that the lowest model layer is inactive throughout most of the watershed area. 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 also varies in elevation depending on the location within the lens.

Direct rainwater run-off in these Cape Cod aquifer materials is typically rather low. Lithological 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 in the groundwater models were determined through calibration to observed water levels and stream flows. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Towns and stream flow data collected in 1989-1990 as well as 2003.

The glacial sediments that comprise the aquifer of the Sagamore Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The southern portions of the Sandwich Harbor watershed are located in the Mashpee Outwash Plain Deposits, in which the sediments generally show a fining downward with sand and gravel deposits deposited in glaciofluvial (river) and near-shore glaciolacustrine (lake) environments underlain by fine sand, silt and clay deposited in deeper, lower-energy glaciolacustrine environments. Glacial collapse structures caused by melting of remnant ice blocks form the kettlehole depressions that are now freshwater ponds. As one moves from the most inland portion of the watershed, north toward Cape Cod Bay, the watershed is crossed by the Sandwich Moraine, which was created during a re-advance of the regional lobes of the continental ice sheet that excavated and piled up previously deposited materials. Along the northern edge of the watershed, including most of the salt marsh areas, are Lake Cape Cod Bay Deposits, which tend to be fine sands, silts, and clay. These materials, which underlie most of the salt marsh systems along the northern shore of Cape Cod, were deposited as lake-bottom deposits for a large lake that formed in the southern portion of Cape Cod Bay between the moraines to the south and a relatively stable continental ice sheet position to the north (Walter and Whealan, 2005).

Although these glacial materials vary, modeling and field measurements of contaminant transport at the Massachusetts Military Reservation have shown that groundwater flowpaths are largely unaffected by the transitions between outwash and moraine materials (*e.g*., Masterson, *et al*., 1996). Most of the lake bottom deposit areas along the northern portion are covered by saltwater marshes, but the presence of extensive streams at the margin of the marshes suggests that a large portion of the upgradient aquifer is discharging along this margin. This is largely supported by the good agreement between modeled stream flows associated with Sandwich Harbor and measured MEP streamflows on the gauged streams (see Section IV.2). This agreement is also consistent with similar comparisons in other salt marsh-dominated systems along Cape Cod Bay (*e.g.*, Howes, *et al*., 2007).

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

III.3 SANDWICH HARBOR SYSTEM CONTRIBUTORY AREAS

The refined watershed and sub-watershed boundaries for the Sandwich Harbor Estuary, including Upper and Lower Shawme Ponds and the two MEP-gauged streams, and each of the major estuarine creek/marsh areas (Figure III-1) were determined by the United States Geological Survey (USGS). Model outputs of the watershed boundaries are usually presented as “saw toothed” lines that reflect the movement of modeled particles between the grid cells that make up the groundwater model and how those cells are organized to reflect natural features, such as pond shorelines, river segments, and contributing areas to public water supplies. In order utilize the guidance provided by the model, these modeled lines 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), (d) to more closely match the sub-estuary segmentation of the tidal hydrodynamic model and (e) to address streamflow measurements collected as part of the MEP. The smoothing refinement process was a collaborative effort developed between the USGS and the rest of the MEP Technical Team. The MEP sub-watershed delineation includes 10-yr time-of-travel boundaries. The smoothing simplification of watershed delineations/recharge areas lines and other model outputs usually involved visual curve fitting and checking model outputs against aerial maps of ponds, streams, and wetlands. MEP staff also added “subwatersheds” within the salt marsh/tidal creek system in order to more accurately characterize the spatial distribution of freshwater inputs to the marsh. These delineations were based on natural segmentation within the marsh and used the natural channels as guides. These are not watersheds in the typical sense because water levels during flood tides cover the whole marsh, but these are a reasonable basis for refining the distribution of freshwater inputs to the marsh. Overall, 15 sub-watershed areas were delineated within the Sandwich Harbor study area.

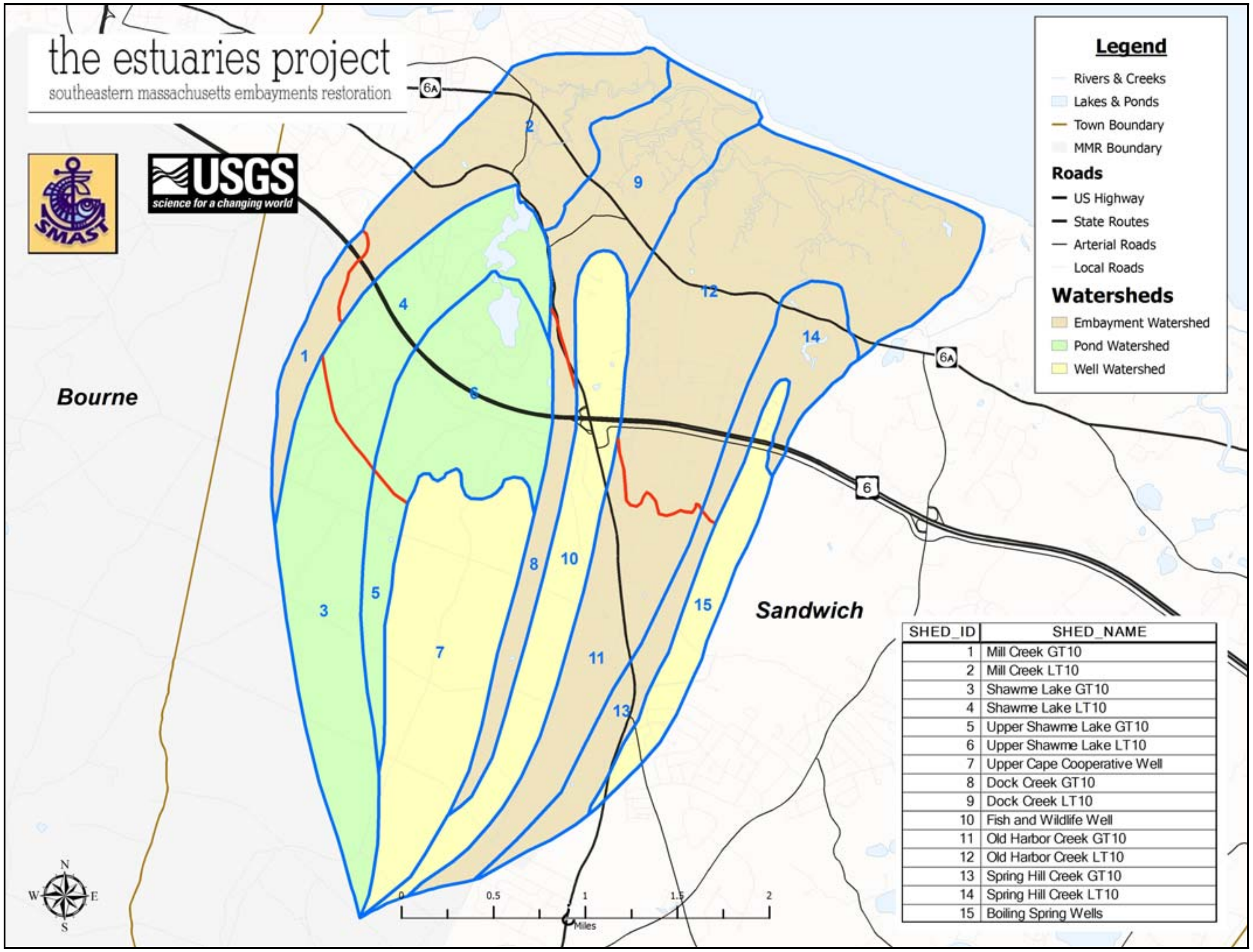


Figure III-1. Watershed delineation for the Sandwich Harbor Estuary (outer line). Subwatershed delineations to each major fresh and estuarine component are based on USGS groundwater model output with modifications to better address pond and estuary shorelines and MEP stream gauge measurements. Subwatersheds to freshwater ponds are colored green, while subwatersheds to public supply wells are colored yellow. Ten-year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names.

Table III-1 provides the daily freshwater discharge volumes for the sub-watersheds as calculated from the areas in the groundwater model; these volumes were used in the salinity calibration of the MEP water quality model and to determine hydrologic turnover in the lakes/ponds, as well as for comparison to the directly measured surface water discharges. The overall estimated freshwater flow into the Sandwich Harbor system from the entire MEP delineated watershed is 51,927 m3/d. Comparison of modeled watershed flow to measured flow at each of the MEP gauges, which collected streamflow measurements between September 2006 and August 2007, were within 10% of each other (see Section IV.2). The measured flows are used for calibration of the estuarine water quality model.

Table III-1. Daily groundwater discharge from each of the sub-watersheds comprising the watershed to the Sandwich Harbor Estuary, as determined from the regional USGS groundwater model.

Watershed	#	Watershed Area (acres)	% contributing to Estuaries	Discharge	
				m^3/day	ft^3/day
Mill Creek GT10	1	120	100%	918	32,430
Mill Creek LT10	2	553	100%	4,241	149,772
Shawme Lake GT10	3	626	100%	4,805	169,699
Shawme Lake LT10	4	449	100%	3,444	121,614
Upper Shawme Pond GT10	5	124	100%	955	33,739
Upper Shawme Pond LT10	6	544	100%	4,175	147,429
Upper Cape Cooperative Wells	7	765	100%	5,873	207,395
Dock Creek GT10	8	199	100%	1,527	53,943
Dock Creek LT10	9	411	100%	3,155	111,427
Fish and Wildlife Well	10	529	100%	4,057	143,257
Old Harbor Creek GT10	11	473	100%	3,632	128,268
Old Harbor Creek LT10	12	1,268	100%	9,734	343,741
Spring Hill Creek GT10	13	208	100%	1,594	56,279
Spring Hill Creek LT10	14	246	100%	1,887	66,625
Boiling Springs Wells	15	252	100%	1,930	68,171
TOTAL SANDWICH HARBOR SYSTEM				51,927	1,833,790

Notes:
1) discharge volumes are based on 27.25 inches of annual recharge on adjusted watershed areas (total watershed areas are shown);
2) listed flows do not include precipitation on the water surface of the estuary
3) totals may not match due to rounding.
4) flows to watersheds 2, 9, and 12 include precipitation on the marsh areas surrounding the channels within the Sandwich Harbor estuary. These watersheds include divisions extending into the marsh that were delineated to provide better spatial assignment of upgradient watershed inputs to the marsh.

The MEP watershed delineation is the second watershed delineation completed in recent years for the contributing area to the Sandwich Harbor Estuary. Figure III-2 compares the delineation completed under the current effort with the delineation completed by the Cape Cod Commission as part of the Coastal Embayment Project (Eichner, *et al*., 1998). The CCC delineation was largely based on local and regional water table measurements collected from available well data over a number of years and normalized to average conditions. The Commission's delineation was incorporated into the Commission's regulations through the four versions of the Regional Policy Plan (CCC, 1996, 2001, 2009, 2012).

The MEP watershed area for the Sandwich Harbor system as a whole is only 3% larger than 1998 CCC delineation (6,841 acres vs. 6,645 acres, respectively). These areas include the estuary surface area. Although the overall area is similar in the two delineations, the areas that are included within the watersheds are slightly different. The MEP watershed is shifted toward the west; portions of the CCC Sandwich Harbor watershed are now part of the Scorton Creek MEP watershed, which was delineated at the same time (Howes, *et al*., 2013). The western boundary of the MEP Sandwich Harbor watershed is shifted approximately 1,300 meters to the west of the CCC western boundary within the southern portion of the watershed, but the boundaries are almost the same near Cape Cod Bay. Most of these differences are due to a shift in both the regional groundwater divide between Cape Cod Bay and Vineyard Sound and the top of the Sagamore Lens to a more northern location in the MEP delineation. The MEP watershed delineation also includes much more refined interior sub-watersheds to various aquatic components of the Sandwich Harbor system, such as selected ponds and streams that were not included in the CCC delineation. The inner subwatershed delineations show the connections between adjacent watersheds and the complexities of flow paths. These refinements are another benefit of the update of the regional USGS groundwater model (Walter and Whealan, 2005).

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

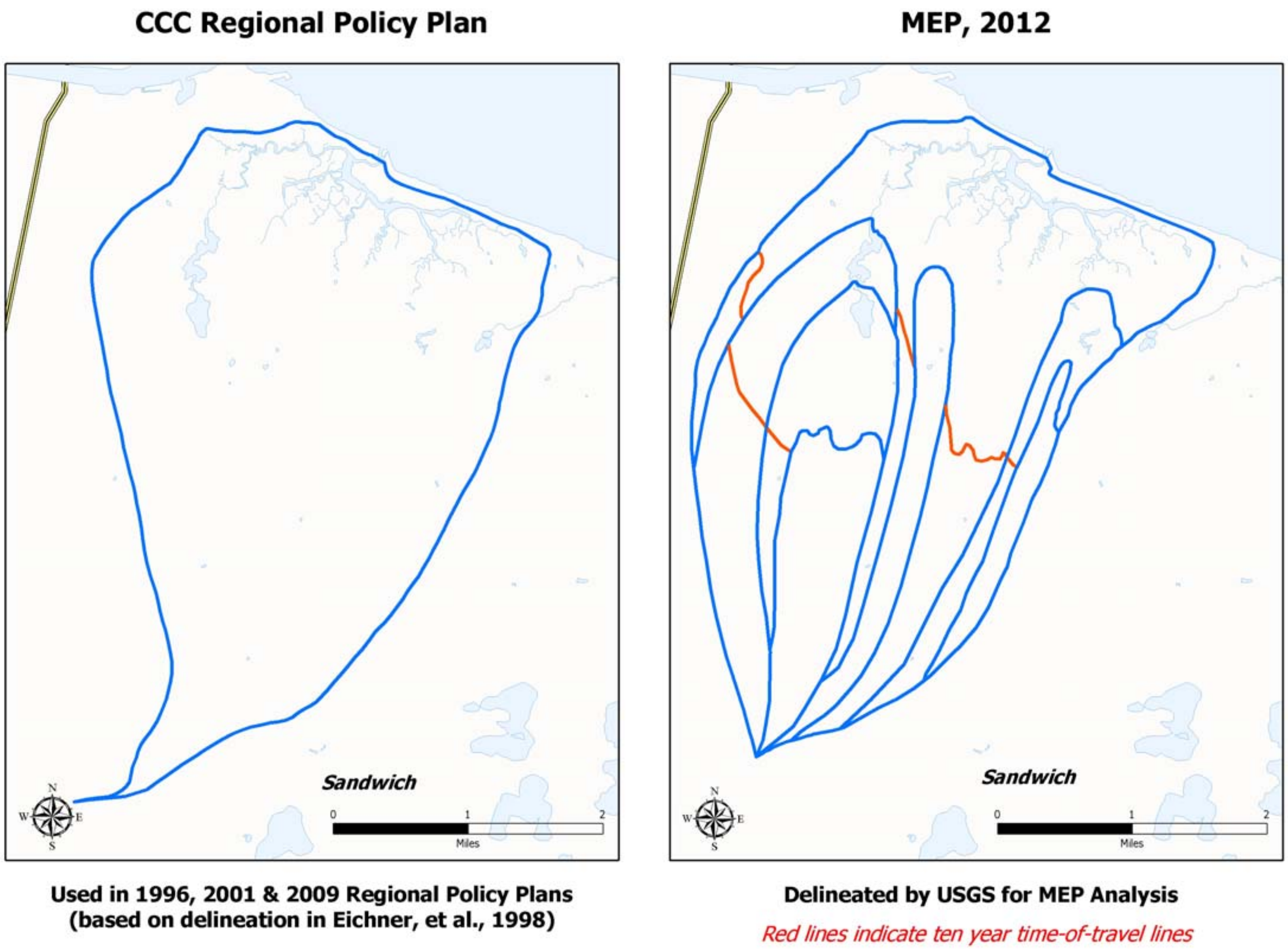


Figure III-2. Comparison of MEP Sandwich Harbor watershed and sub-watershed delineations used in the current assessment (right) and the Cape Cod Commission watershed delineation (left, Eichner, *et al*., 1998), which has been used in four Barnstable County Regional Policy Plans (CCC, 1996, 2001, 2009, 2012). The MEP watershed area for the Sandwich Harbor Estuary as a whole is only 3% larger than the 1998 CCC delineation and is generally shifted toward the west.

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 Sandwich Harbor Estuary as well. Proper 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 wetlands prior to reaching the open waters of the estuary. This latter natural attenuation 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. Permanent burial of nitrogen in the sediments 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 and the watershed attenuation 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 Sandwich Harbor Estuary, the MEP Technical Team developed nitrogen-loading rates (Section IV.1) to each component of estuary and its watersheds (Section III). The Sandwich Harbor watershed was sub-divided to define contributing areas or subwatersheds to each of the major inland freshwater systems and to each major estuarine reach. 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 15 subwatersheds were delineated in the overall Sandwich Harbor watershed, including watersheds to Upper and Lower Shawme Ponds and the two MEP gauged streams (see Chapter III). The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and each tidal reach.

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the estuary. This review involves a temporal review of land use changes, the time of groundwater travel through subwatersheds provided by the USGS watershed model, and review of data at natural collection points, such as streams and ponds. Evaluation and delineation of ten-year time of travel zones are a regular part of the watershed analysis. Ten-year time of travel subwatersheds in the Sandwich Harbor watershed have been delineated for ponds, streams and the estuary itself. Review of less than 10 year and greater than 10 year travel time watersheds indicates that 87% of the unattenuated nitrogen load from the whole watershed is within less than 10 year travel time to the estuary, with 13% of the source loading being more than 10 year groundwater travel time from the estuary (Table IV-1). This review includes refinements for internal transfer of flow within the Boiling Springs wellfield (discussed in Section IV.2). This review indicates that watershed loads and measured water quality data in the estuary should be in balance. MEP staff also reviewed the age of single family residences in the greater than 10 year subwatersheds. This review of year-built information in the town assessor's database indicated that the average age of the 100 single family residences in the greater than 10 year subwatersheds is more than 25 years old. The overall result of the timing of development relative to groundwater travel times (including the GT10 subwatersheds) is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuary (after accounting for natural attenuation, see below) and that the distinction between time of travel in the subwatersheds is not important for modeling existing watershed nitrogen loading conditions. Overall and based on the review of all this information, it was determined that the Sandwich Harbor Estuary's nutrient related habitat quality is currently in balance with its watershed nitrogen load. In addition, new nitrogen sources are also likely to rapidly (~10-15 years) establish a new balance with estuarine waters.

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for most of the load, while information developed from other detailed site-specific studies is applied to other portions. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon subwatershed-specific land uses and pre-determined nitrogen loading rates based on regional analyses. For the Sandwich Harbor Estuary, the model used Town of Sandwich land-use data that is transformed into nitrogen loads using both regional nitrogen loading factors and local watershed-specific data (such as parcel-by-parcel water use). 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 within surface waters during transport is included at a later stage (also from direct measurement).

Natural attenuation of nitrogen during transport from land-to-sea within the Sandwich Harbor watershed was determined based upon a site-specific study of streamflow and assumed attenuation in the upgradient freshwater ponds. Streamflow was characterized at the outlet of Lower Shawme Lake and at Spring Hill Creek where it crosses beneath the regional railroad tracks. Subwatersheds to these stream discharge points allowed comparisons between field collected data from the streams and estimates from the nitrogen-loading sub-model. Nitrogen attenuation in individual ponds is generally estimated based on available information. Attenuation through the ponds is conservatively assumed to equal 50% unless available monitoring and pond physical data is reliable enough to calculate a pond-specific attenuation factor. Since streamflow was measured at the outlet of Lower Shawme Pond, flows at this location represent the cumulative attenuation of both ponds in the system. Streamflow and associated surface water attenuation is included in the MEP's nitrogen attenuation and freshwater flow investigation, presented in Section IV.2.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. In the present assessment, two freshwater ponds have delineated subwatersheds within the Sandwich Harbor watershed: Upper Shawme Lake and Lower Shawme Lake. If smaller aquatic features that have not been included in this MEP analysis were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly (~10%) overestimated given the distribution of nitrogen sources within the watershed.

Table IV-1. Percentage of unattenuated nitrogen loads in less than ten year time-of-travel subwatersheds to Sandwich Harbor.

WATERSHED		LT10	GT10	TOTAL	%LT10
Name		kg/yr	kg/yr	kg/yr	
Mill Creek GT10	1		29	29	0%
Mill Creek LT10	2	3,738		3,738	100%
Shawme Lake GT10	3		126	126	0%
Shawme Lake LT10	4	1,160		1,160	100%
Upper Shawme Pond GT10	5		25	25	0%
Upper Shawme Pond LT10	6	1,711		1,711	100%
Upper Cape Cooperative Wells	7		154	154	0%
Dock Crk GT10	8		67	67	0%
Dock Crk LT10	9	1,459		1,459	100%
Fish and Wildlife Well	10		792	792	0%
Old Harbor Creek GT10	11		405	405	0%
Old Harbor Creek LT10	12	4,228		4,228	100%
Spring Hill Creek GT10	13		306	306	0%
Spring Hill Creek LT10	14	656		656	100%
Boiling Springs Wells	15	673	209	882	76%
Mill Creek LT10 Estuary Surface		44		44	100%
Dock Creek LT10 Estuary Surface		131		131	100%
Old Harbor Creek LT10 Estuary Surface		158		158	100%
Sandwich Harbor Whole System		13,958	2,114	16,072	87%

Notes:

a) Whole system totals may not add due to rounding.

b) Loads have been corrected to 1) include division of portions of nitrogen load from ponds and wellhead protection areas to downgradient subwatersheds and 2) exclude atmospheric loading on the estuary surface waters; if atmospheric loading on the surface of the estuary is included the percentage of load within a less than 10 year time-of-travel remains at 87%.

c) Boiling Springs Wells load (subwatershed #15) is based on review of water use within well contributing area and average total pumped by wellfield. Portion of volume not utilized within contributing area is assumed to be distributed to nearby development, which is located within LT10 subwatersheds.

d) Review of year-built information for single-family residences within the GT10 subwatersheds shows that there are 100 residences in the GT10 subwatersheds. Average year-built for these residences is greater than 25 years. This suggests that average nitrogen loads from the GT10 subwatersheds are also currently reaching the estuary and when combined with the groundwater time-of-travel info confirms that estuarine water quality data is in balance with overall watershed nitrogen loading.

Based upon the evaluation of the watershed systems, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for each subwatershed that directly discharges groundwater to the estuary without flowing through one of the interim pond and stream measuring points. Internal nitrogen recycling was also determined throughout the tidal reaches of the Sandwich Harbor Estuary; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Since the watershed to Sandwich Harbor is entirely within the Town of Sandwich, Estuaries Project staff obtained digital parcel and tax assessor's data from the town to serve as a base for the watershed nitrogen loading model. Digital parcels and land use/assessors data are from 2010. Using GIS techniques, these data were linked to three years (2007-2009) of individual account water use data from the Sandwich Water District. This unified database also contains traditional information regarding land use classifications (MassDOR, 2012) plus additional information developed by the town. It is also the database that the town is using for its current wastewater planning effort. The database efforts were completed with the assistance from GIS staff from the Cape Cod Commission (CCC).

Figure IV-1 shows the land uses within the Sandwich Harbor estuary watershed. Land uses in the study area are grouped into ten land use categories: 1) residential, 2) commercial, 3) industrial, 4) agricultural, 5) mixed use, 6) undeveloped, 7) public service/government, including road rights-of-way, 8) open space, 9) freshwater ponds and 10) properties without assessor's land use codes. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MassDOR, 2012). "Public service" in the MassDOR system is tax-exempt properties, including lands owned by government (*e.g.*, wellfields, schools, open space, roads) and private groups like churches and colleges.

Public service land uses are the dominant land use type in the overall Sandwich Harbor watershed, occupying 66% of the total watershed area (Figure IV-2). Examples of these land uses are lands owned by town and state government (including golf courses, landfills, conservation lands, and wellhead protection lands), housing authorities, and churches. Residential land uses occupy the second largest area with 17% of the overall watershed area. It is notable that land classified by the town assessor as undeveloped is only 7% of the overall watershed area. The majority of the public service lands in the Sandwich Harbor watershed are part of the Massachusetts Military Reservation (MMR), which is located south of Route 6 and covers most of the GT10 subwatersheds. There are, however, also extensive public service lands north of Route 6, including: Heritage Plantation, Massachusetts Division of Fisheries and Wildlife Sandwich Fish Hatchery, Henry T. Wing School and town Conservation Commission lands.

Although the majority of the watershed area is public service land uses, the dominant parcel type in all of the subwatershed groupings are residential land uses. Residential parcels are 76% of the total parcel count in the Shawme Lake subwatershed, 58% of parcels in the Spring Hill Creek subwatershed, and 71% of all parcels in the overall Sandwich Harbor watershed. Single-family residences (MassDOR land use code 101) are the predominant type

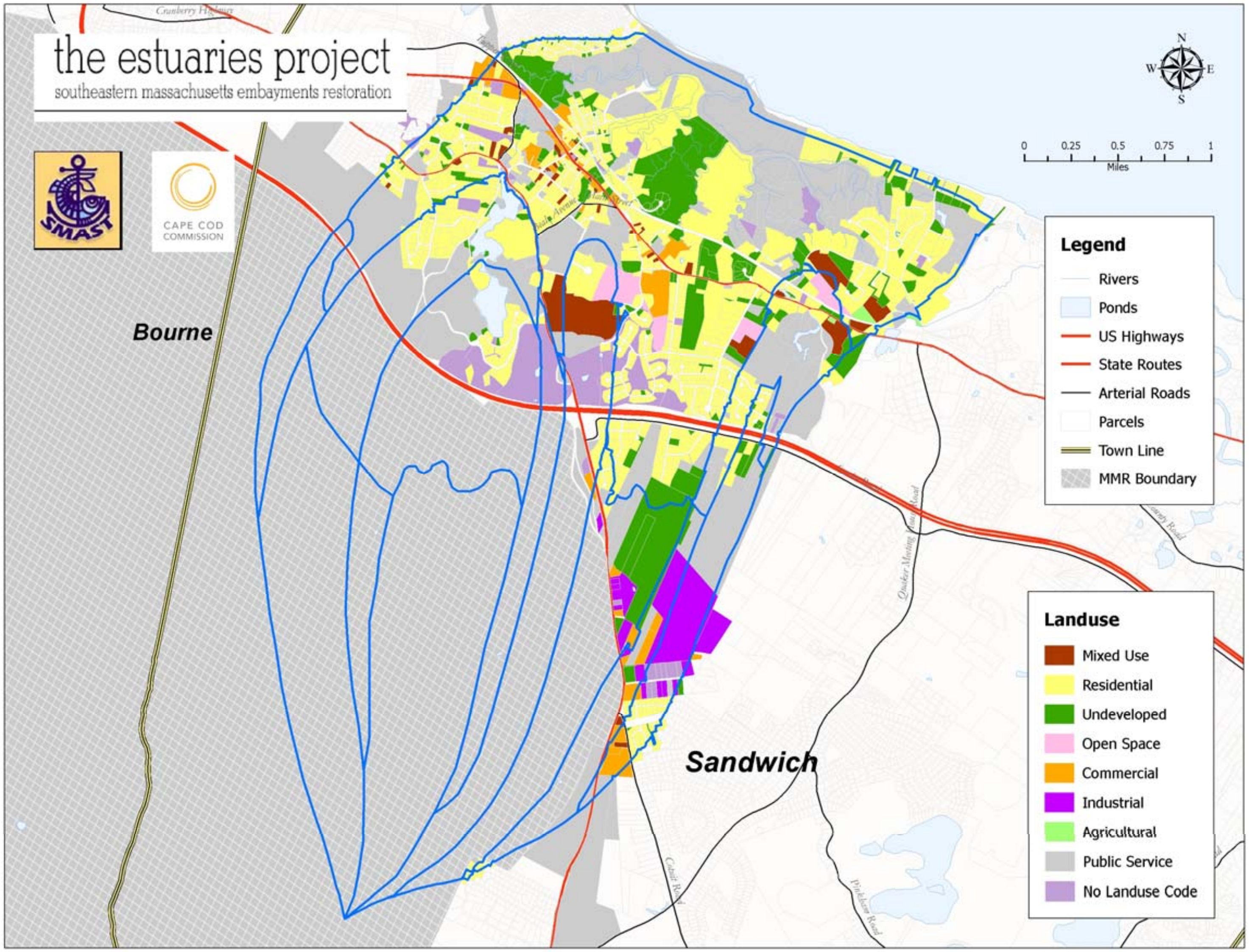


Figure IV-1. Land-use associated with the Sandwich Harbor Estuary watershed and subwatersheds. Watershed is completely within the Town of Sandwich. Land use classifications are based on town assessor classifications and MADOR (2012) categories. Town of Sandwich assessor and parcel data used in this map and the MEP land use evaluation are from the year 2010.

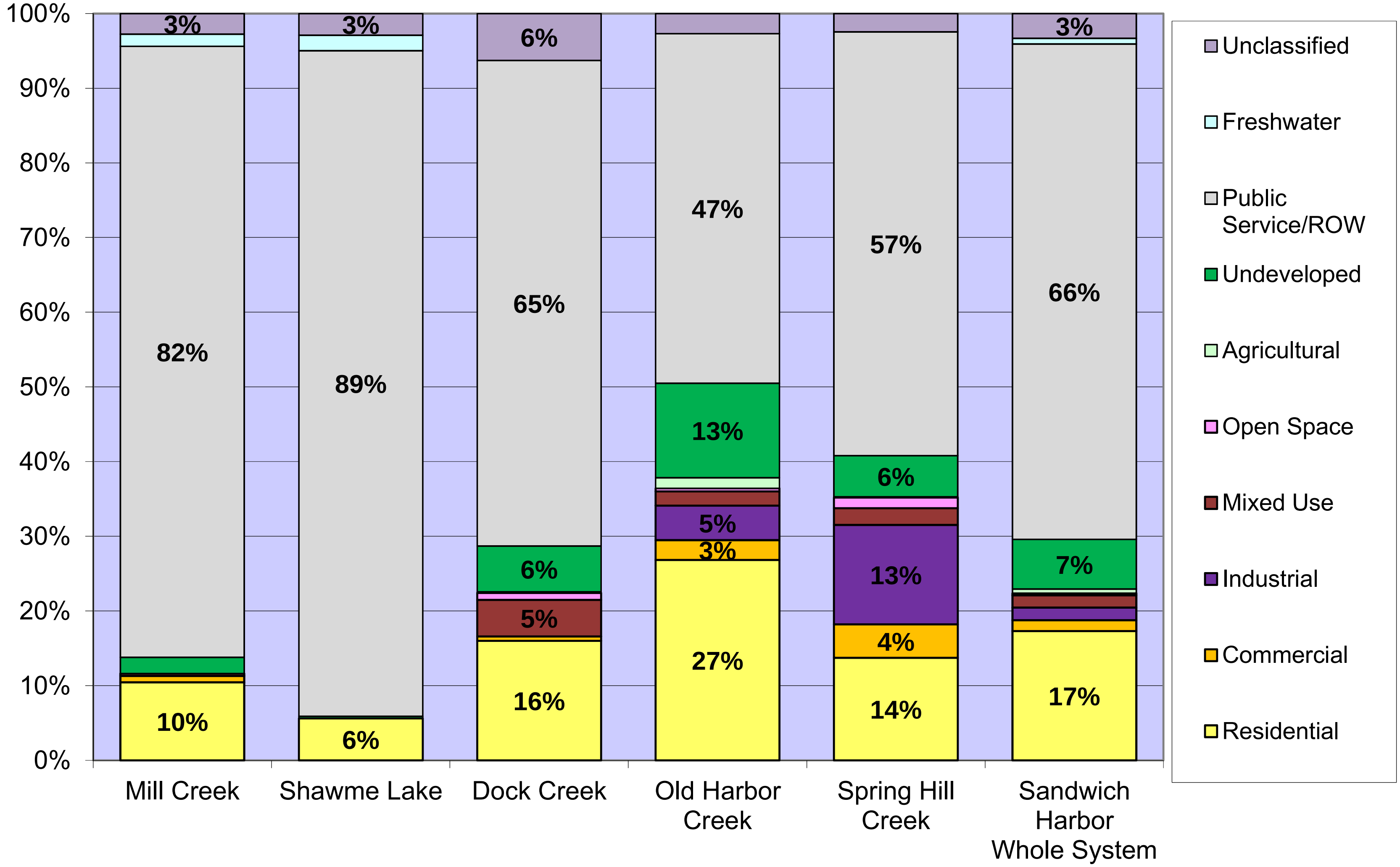


Figure IV-2. Distribution of land-uses within the Sandwich Harbor Estuary whole watershed and component subwatersheds. Land use categories are generally based on town assessor's land use classifications and grouping recommended by MADOR (2012). Unclassified parcels do not have an assigned land use code in the town assessor's databases. Only categories with percentages greater than or equal to 3% are labeled.

of residential parcel, representing 90% to 100% of all residential parcels in the individual subwatersheds, 96% of the residential parcels in the overall watershed to the Sandwich Harbor Estuary watershed, and 95% of the residential parcel area in the overall watershed.

In order to estimate wastewater flows within the Sandwich Harbor study area, MEP staff also obtained parcel-by-parcel water use data from the Sandwich Water District. Three years of water use (years 2007, 2008 and 2009) was obtained (personal communication, Dan Mahoney, Superintendent, 3/11). The water use data was linked to the town parcel database and assessor's data. This data is also the basis for the town's current Watershed Nitrogen Management Plan (Wright-Pierce, 2012).

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

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

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

All nitrogen losses within septic systems are incorporated into the MEP analysis. For example, information developed at the Massachusetts Alternative Septic System Test Center at the Massachusetts Military Reservation on Title 5 septic systems have shown nitrogen removals between 21% and 25%. Multi-year monitoring from the Test Center has revealed that nitrogen removal within the septic tank was small (1% to 3%), with most (20 to 22%) of the removal occurring within five feet of the soil adsorption system (Costa *et al.,* 2001). Downgradient studies of septic system plumes in similar soils 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, MEP staff 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, MEP staff has derived a combined term for an effective N Loading Coefficient (consumptive use times N concentration) of 23.63, to convert water (per volume) to nitrogen load (N mass). This coefficient uses a *per capita* nitrogen load of 2.1 kg N person-yr^{-1} and is based upon direct measurements and corrects for changes in concentration that result from *per capita* shifts in water-use (*e.g.*, due to installing low plumbing fixtures or high versus low irrigation usage).

The nitrogen loads developed using this approach have been validated in a number of long and short term field studies where integrated measurements of nitrogen discharge from watersheds could be directly measured. Weiskel and Howes (1991, 1992) conducted a detailed watershed/stream tube study that monitored septic systems, leaching fields and the transport of the nitrogen in groundwater to adjacent Buttermilk Bay. This monitoring resulted in estimated annual per capita nitrogen loads of 2.17 kg (as published) to 2.04 kg (if new attenuation information is included). Further, modeled and measured nitrogen loads were determined for a small sub-watershed to Mashapaquit Creek in West Falmouth Harbor (Smith and Howes, manuscript in review) where measured nitrogen discharge from the aquifer was within 5% of the modeled N load. Another evaluation was conducted by surveying nitrogen discharge to the Mashpee River in reaches with swept sand channels and in winter when nitrogen attenuation is minimal. The modeled and observed loads showed a difference of less than 8%, easily attributable to the low rate of attenuation expected at that time of year in this type of ecological situation (Samimy and Howes, unpublished data). 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 for more than fifty-five (55) MEP embayments to date. While the MEP septic system nitrogen load is the best estimate possible, to the extent that it may underestimate the nitrogen load from this source reaching receiving waters provides a safety factor relative to other higher loads that are generally used for septic systems in regulatory situations. The lower concentration results in slightly higher amounts of nitrogen mitigation (estimated at 1% to 5%) needed to lower embayment nitrogen levels to a nitrogen target (*e.g.*, nitrogen threshold, cf. Section VIII). The additional nitrogen removal is not proportional to the septic system nitrogen level, but is related to 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 Sandwich Harbor watershed, MEP staff reviewed US Census population values for the Town of Sandwich. 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 Sandwich is 2.75 people per housing unit with 84% of year-round occupancy of available housing units; 2010 Census results are roughly the same: 2.66 and 82%, respectively. Average water use for single-family residences with municipal water accounts in the Sandwich Harbor MEP study area is 173 gpd, while it is 195 gpd in the Scorton Creek MEP study area. If the Sandwich Harbor average flow is multiplied by 0.9 to account for consumptive use, the study area wastewater average flow for a single-family residence is 156 gpd.

In order to provide a check on the measured water use, Sandwich 2000 and 2010 Census average occupancies were used to estimate wastewater flows. Multiplying the Census occupancies by the state Title 5 estimate of 55 gpd of wastewater *per capita* results in an average estimated water use per residence of 151 gpd and 146 gpd, respectively. Correction for minor summer occupancy increase (2X for seasonal residences) increases these estimated flows to 189 gpd and 183 gpd, respectively (vs. 173 gpd measured average). This analysis suggests that population and water use information are in reasonable agreement and that the average water use is reasonably reflective of average wastewater estimates.

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

Water use information exists for 93% of the 1,451 developed parcels in the Sandwich Harbor watershed. Parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (*e.g.*, 101 or 325) and have been confirmed as having buildings on them through a review of aerial photographs, but do not have a listed account in the water use databases. Of the 112 developed parcels without water use accounts, 80 (71%) are classified as single-family residences (land use code 101). These parcels are assumed to utilize private wells and are assigned the MEP Sandwich study area average water use of 184 gpd in the watershed nitrogen loading modules. The MEP Sandwich study area includes the watersheds to both Sandwich Harbor and Scorton Creek. Another 15 developed parcels without water use are parcels classified as other types of residential properties (*e.g.*, multi-family or condominiums). These parcels are assumed to utilize private wells and are assigned the MEP Sandwich study area average water use of 191 gpd and 236 gpd for parcels with the 104 (two family residences) and 109 (multi-family residences) land use codes, respectively.

Wastewater Treatment Facilities

When developing watershed nitrogen loading information, MEP project staff typically seeks additional information on enhanced wastewater treatment in the project study area. This information is reviewed and if judged reliable is included in the watershed nitrogen loading model. MEP staff reviewed MassDEP Groundwater Discharge Permits (GWDPs) database and confirmed with MassDEP staff that no GWDPs were listed within the Sandwich Harbor watershed (personal communication, Brian Dudley, MassDEP, 2/12). A GWDP is required under MassDEP regulations for wastewater treatment systems with design flows greater than 10,000 gallons per day.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of watershed nitrogen loading to estuaries is usually fertilized areas: lawns, golf courses, and cranberry bogs. Residential lawns are usually the predominant source within this category. In order to add this source to the watershed nitrogen loading model for the Sandwich Harbor Estuary, MEP staff reviewed available regional information about residential lawn fertilizing practices and incorporated site-specific information for cranberry bogs and agricultural areas in the watershed. Cranberry bog nitrogen loading was determined based on previous studies conducted in southeastern Massachusetts.

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

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. This assessment, which was initiated prior to the start of the MEP and completed in 2003, 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 nitrogen 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 in the three town survey were found to have the higher rate of fertilizer application and hence higher estimated annual contribution to groundwater of 3 lb/yr.

MEP staff also determined fertilizer loads for site-specific uses. Working with town staff, fertilizer loads were determined for the fields at Wing School, agricultural fields, and Heritage Plantation. Through available local contacts, it was determined that the fields at Wing School are not fertilized (Dave Mason, Sandwich Health Department, 2/13); no fertilizer nitrogen loads were assigned to these fields in the MEP loading. Attempts by both town and MEP staff to contact Heritage Plantation for site-specific fertilizer information were unsuccessful. In order to determine fertilizer nitrogen loads at the plantation, turf and rhododendron areas were estimated from review of aerial photographs. Turf areas were assigned standard MEP turf nitrogen loading factors, while rhododendron factors were based on a review of fertilizer, garden, and university extension service websites. These websites generally reported fertilizer application rates of 2 lbs/100 sq ft with nitrogen percentages of 4 to 10%. MEP staff assumed a 6% nitrogen composition with a fertilizer application rate of 2 lbs/100 sq ft and a 20% leaching rate for the estimated rhododendron areas at the Heritage Plantation.

Nitrogen loads were also added for site-specific agricultural land uses. Cranberry bog fertilizer application rate and percent nitrogen attenuation are based on an enhanced review of nitrogen export from cranberry bogs in southeastern Massachusetts (DeMoranville and Howes, 2009; Howes and Teal, 1995). This review found that nitrogen export from cranberry bogs differs depending on whether water continuously flows through the bog or is pumped or diverted onto the bog (non-flow through bogs) from an outside source of water. Based on this review, MEP analyses use annual nitrogen exports of 6.95 kg/ha for non-flow through bogs and 23.08 kg/ha for flow through bogs. MEP staff reviewed the configuration of the two bogs in the Sandwich Harbor watershed and assigned both bogs the non-flow through bog nitrogen loading rate. The areas of the bogs are based on a MassDEP GIS coverage that is maintained by

MassDEP for Water Management Act permitting (personal communication, Jim McLaughlin, MassDEP SERO, 1/13).

Nitrogen loads were also added based on agricultural animals within the watershed. MEP received parcel-specific farm animal counts from the Town of Sandwich (personal communication, Dave Mason and Tori Hall, Sandwich Health Department, 4/13). These counts indicated the presence of horses and steers within the Sandwich Harbor watershed. Species-specific nitrogen loads were developed based on USDA and other species-specific research on nitrogen manure characteristics, including leaching to groundwater. Loads were assigned to individual farm lots based on the animal counts. Details of these loads are included in the MEP Data Disk that accompanies this report.

Nitrogen Loading Input Factors: Town of Sandwich Landfill

MEP staff reviewed MassDEP's solid waste database and identified one solid waste site within the Sandwich Harbor watershed: the Town of Sandwich Landfill. Project staff contacted town staff, who authorized the release of landfill monitoring data (personal communication, Nate Weeks and Darlene Zelinski, GHD, 3/12). Using the available monitoring information, MEP staff developed a nitrogen load for the landfill site.

The Town landfill is located east of Route 130 and north of Route 6 within the Fish and Wildlife Well subwatershed (subwatershed #9). According to MassDEP records, the landfill is unlined, was closed in 1989 and capped in 2002. Monitoring and water level data are collected twice a year from seven wells located around the landfill. The seven wells are located at four monitoring sites; six of the wells are installed as shallow and deep couplets. Data from May 2003 to December 2010 was provided to MEP staff.

MEP staff reviewed the chemical data, well construction details, depths, and locations, and determined a nitrogen load for the Sandwich Landfill. Groundwater monitoring data includes nitrate-nitrogen, alkalinity, chloride, and other inorganic measures, but does not include total nitrogen measurements or other components of total nitrogen, such as ammonium-nitrogen data. Based on a previous review of monitoring data from the groundwater plume associated with the Town of Brewster landfill (Cambareri and Eichner, 1993), MEP staff determined a relationship between ammonium-nitrogen and alkalinity concentrations (NH_4-N = 0.0352*ALK - 0.3565; $r^2 = 0.82$). This relationship was used to estimate ammonium-nitrogen concentrations from the alkalinity data and these estimates were combined with reported nitrate-nitrogen data to provide an estimate of total nitrogen for each sampling run. Although nitrate-nitrogen and ammonium-nitrogen concentrations are not a complete measure of all nitrogen species, landfills do not tend to release significant portions of dissolved organic nitrogen (Pohland and Harper, 1985).

Review of the 16 available sampling runs showed that wells 102s, 103s, and 103d had the highest average alkalinity concentrations (all >107 mg/L $CaCO_3$) and the lowest dissolved oxygen concentrations (all <1.3 mg/L). The estimated average TN concentration of the three wells is 8.9 mg/L. Using this concentration, the area of solid waste, and the MEP recharge rate for the area, MEP staff developed an estimated annual total nitrogen load of 242 kg from the Sandwich landfill.

It is acknowledged that this approach for estimating a nitrogen load from the Sandwich landfill includes a number of assumptions, but it is appropriate based on the available data. A detailed assessment of all the available data is beyond the scope of the MEP, but staff balanced reasonable estimates of the various factors based on the general MEP guidance from MassDEP to include conservatism in nitrogen loading estimates when uncertainty exists in the data. A more refined evaluation and assessment of the established landfill monitoring well network, including, at a minimum, analysis of total nitrogen concentrations, would help to refine this assessment and future management options.

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas in the Sandwich Harbor assessment are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the CCC's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and MassDEP'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 Sandwich Harbor watershed are summarized in Table IV-2.

Table IV-2. Primary Nitrogen Loading Factors used in the Sandwich Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Sandwich-specific data.

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
Natural Area Recharge	0.072	**Water Use/Wastewater:**	
Direct Precipitation on Embayments and Ponds	1.09	Existing developed single-family residential parcels wo/water accounts and buildout residential parcels:	184 gpd[2]
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (sq ft)[1]	5,000	Existing developed parcels w/water accounts:	Measured annual water use
Residential Watershed Nitrogen Rate (lbs/lawn)[1]	1.08	Commercial and Industrial Buildings without/WU and buildout additions[3]	
Leaching rate	20%	Commercial	
Cranberry Bogs nitrogen release – flow through bogs (kg/ha/yr)	23.08	Wastewater flow (gpd/1,000 ft2 of building):	36
Cranberry Bogs nitrogen release – pump on/pump off bogs (kg/ha/yr)	6.95	Building coverage:	12%
Nitrogen Fertilizer Rate for vegetable crop applications based on loads determined in other MEP assessments		Industrial	
		Wastewater flow (gpd/1,000 ft2 of building):	16
		Building coverage:	10%
		Average Single Family Residence Building Size from watershed data (sq ft)	1,713

Notes:

1) Data from MEP lawn study in Falmouth, Mashpee & Barnstable of over 2,000 lawns (2001).
2) Based on average measured flow in the Sandwich MEP study area
3) Based on characteristics of similarly classified properties with the Town of Sandwich

Road areas are based on GIS information developed by the Massachusetts Executive Office of Transportation, which provides road, sidewalk, and road shoulder widths for various road segments. MEP staff utilized the GIS to sum these segments and their various widths by subwatershed in order to determine nitrogen loads from these impervious surfaces. Project staff also checked this information against parcel-based rights-of-way.

The Town of Sandwich Assessor's database includes building footprint data for individual parcels. This information was used to determine roof areas which were combined with appropriate MEP nitrogen loading factors to determine nitrogen loads from these impervious surfaces.

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information is linked to the parcel coverages, parcels are assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel is located within a respective subwatershed. Following the assigning of boundary parcels, all large parcels are examined individually and are 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. This effort results in "parcelized" watersheds that can be more easily used during the development of management strategies.

The review of individual parcels straddling watershed boundaries includes corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Building footprints, for example, are based on available information contained in the Sandwich assessor's database. Project staff used the average single-family residence building footprint based on available properties in the MEP study area (1,713 sq ft) for any residential units without footprint information. Commercial and industrial footprints for properties without building footprint information are also based on average building coverage of individual lots with similar land uses within the town. Individualized information for parcels with atypical nitrogen loading (condominiums, golf courses, etc.) is 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 Sandwich Harbor Estuary. The assignment effort is undertaken to better define sub-estuary loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

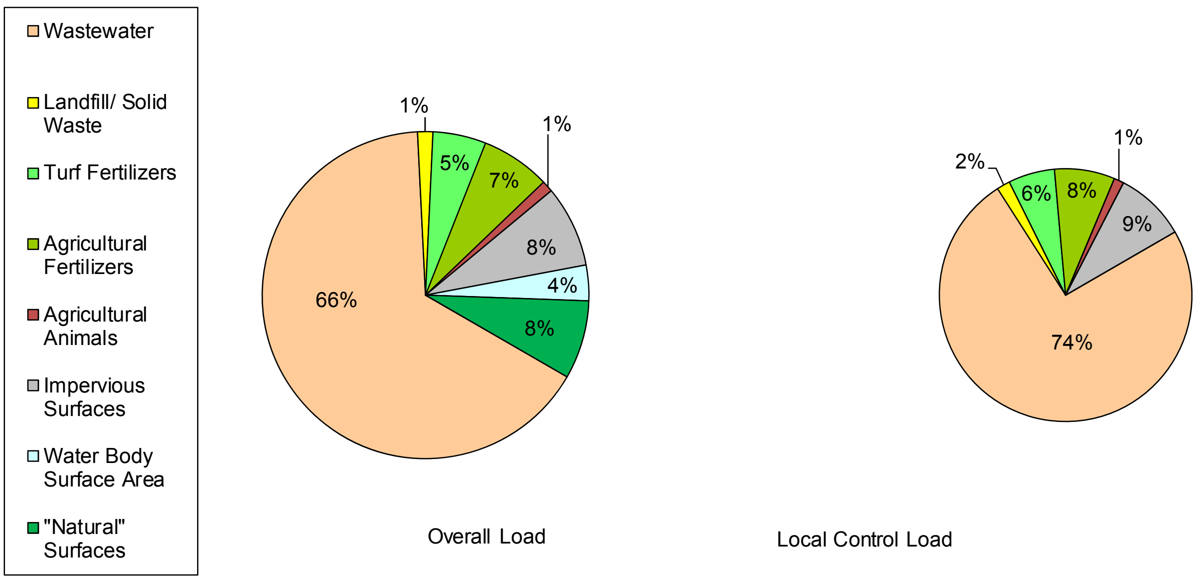
Following the assignment of all parcels, subwatershed modules were generated for each of the 15 subwatersheds in the Sandwich Harbor study area. These subwatershed modules summarize, among other things: water use, parcel area, frequency, private wells, and road area. All relevant nitrogen loading data is assigned to each subwatershed. Individual sub-watershed information is then integrated to create the Sandwich Harbor Watershed Nitrogen Loading module with summaries for each of the individual 15 subwatersheds. The subwatersheds are generally paired with functional embayment/estuary units for the Linked Watershed-Embayment Model's water quality component.

For management purposes, the aggregated estuary watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Sandwich Harbor study area, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), fertilizers (including contributions from agriculture), the town landfill, impervious surfaces, direct atmospheric deposition to water surfaces, and

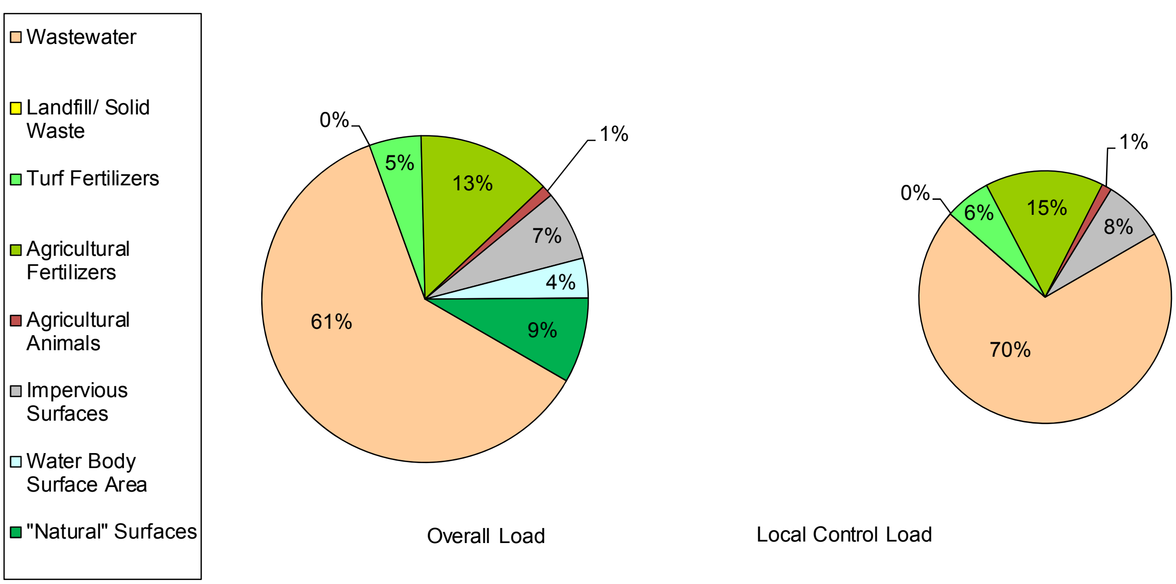
Table IV-3. Sandwich Harbor Watershed Nitrogen Loads. Nitrogen loads are listed by various sources and by subwatershed. Unattenuated nitrogen loads are a sum of all sources without including natural nitrogen attenuation in fresh surface waters. Attenuated nitrogen loads are based on measured and assigned attenuation factors for upgradient streams and freshwater ponds. Stream attenuation factors are based on measured loads (see Section IV.2). All nitrogen loads are kg N yr^{-1}.

		Sandwich Harbor N Loads by Input (kg/y):									% of Pond Outflow	Present N Loads			Buildout N Loads		
Watershed Name	shed ID#	Wastewater	Landfill/ Solid Waste	Turf Fertilizers	Agricultural Fertilizers	Agricultural Animals	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Sandwich Harbor System		**10,552**	**242**	**843**	**1,098**	**180**	**1,290**	**564**	**1,246**	**4,092**		**16,016**		**15,072**	**20,108**		**19,085**
Mill Creek Total		4,273	-	359	930	78	484	276	589	868		6,988		6,454	7,856		7,283
Mill Creek GT10	1	-	-	-	-	-	5	-	24	-		29		29	29		29
Mill Creek LT10	2	3,136	-	214	-	13	285	-	90	572		3,738		3,738	4,311		4,311
Shawme Lake TOTAL		1,137	-	145	930	65	194	231	475	296	100%	3,177	11%	2,643	3,473	11%	2,900
Shawme Lake GT10	3	-	-	-	-	-	-	-	126	-		126		126	126		126
Shawme Lake LT10	4	552	-	84	168	65	94	119	77	235		1,160		1,160	1,395		1,395
Upper Shawme Pond Total		585	-	61	761	-	100	112	272	60	100%	1,891	11%	1,683	1,951	11%	1,737
Upper Shawme Pond GT10	5	-	-	-	-	-	-	-	25	-		25		25	25		25
Upper Shawme Pond LT10	6	585	-	61	761	-	100	112	92	60		1,711		1,711	1,772		1,772
Upper Cape Cooperative Wells	7	-	-	-	-	-	-	-	154	-		154		154	154		154
Mill Creek LT10 Estuary Surface								44				44		44	44		44
Dock Creek Total		1,399	242	161	28	-	221	131	212	1,192		2,394		2,394	3,585		3,585
Dock Crk GT10	8	10	-	0	-	-	17	-	40	-		67		67	67		67
Dock Crk LT10	9	1,064	-	133	-	-	135	-	71	742		1,403		1,403	2,145		2,145
Fish and Wildlife Well	10	326	242	27	28	-	68	-	101	450		792		792	1,242		1,242
Dock Creek LT10 Estuary Surface								131				131		131	131		131
Old Harbor Creek Total		4,880	-	324	141	102	586	158	444	2,032		6,634		6,224	8,666		8,217
Old Harbor Creek GT10	11	250	-	7	-	-	55	-	93	380		405		405	785		785
Old Harbor Creek LT10	12	3,321	-	252	96	-	335	-	223	1,514		4,228		4,228	5,742		5,742
Boiling Springs Wells		548	-	24	-	-	67	-	35	24	76%	673		673	696		696
Spring Hill Creek Gauge TOTAL		761	-	42	45	102	129	-	93	114		1,171	35%	761	1,285	35%	835
Spring Hill Creek GT10	13	211	-	4	-	-	51	-	40	66		306		306	373		373
Spring Hill Creek LT10	14	380	-	30	45	102	57	-	43	40		656		656	696		696
Boiling Springs Wells		170	-	7	-	-	21	-	11	7	24%	209		209	216		216
Old Harbor Creek LT10 Estuary Surface								158				158		158	158		158
Boiling Springs Wells	15	718	-	31	-	-	87	-	45	31		882		882	913		913

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-3). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation in streams and ponds during transport to the estuarine system before use in the embayment water quality sub-model.

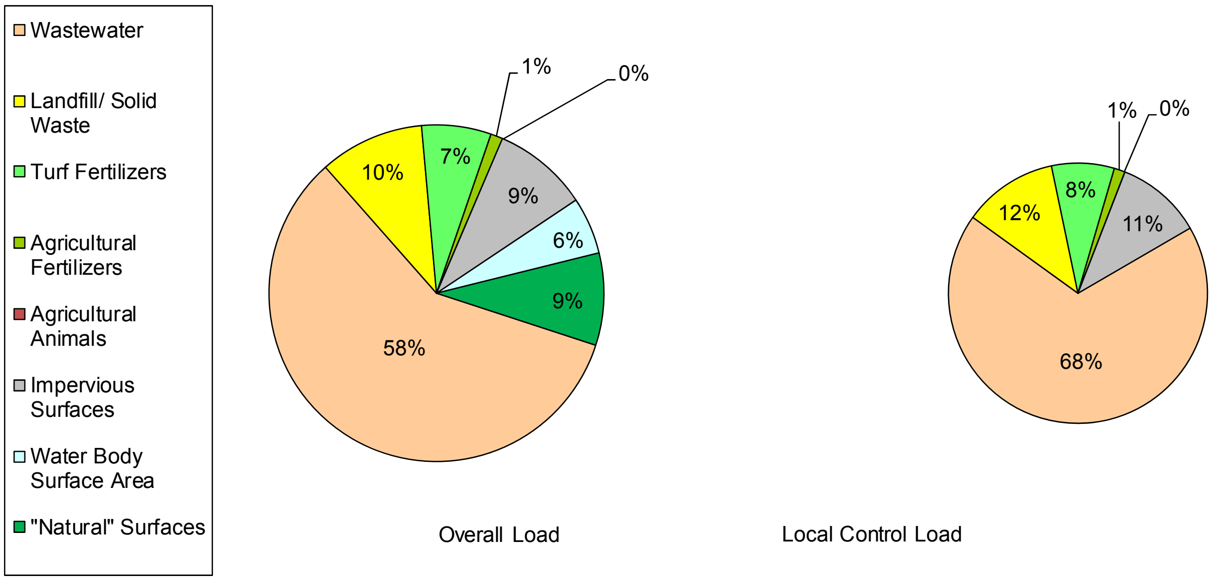


A. Sandwich Harbor Whole System

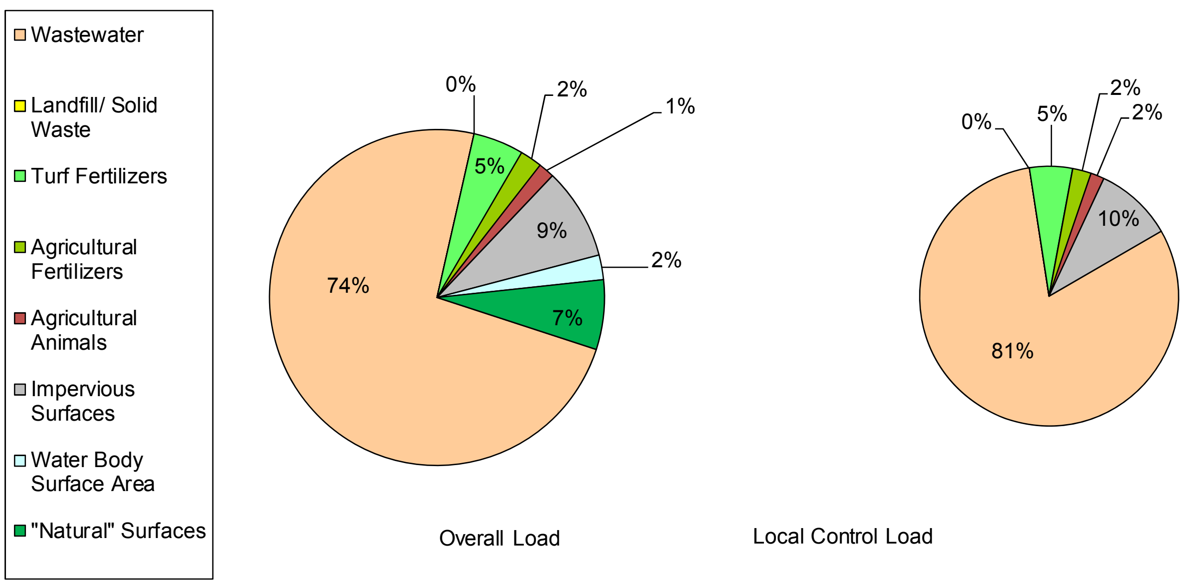


B. Sandwich Harbor: Mill Creek subwatershed

Figure IV-3 (A,B). Source-specific unattenuated watershed nitrogen loads (by percent) to the A) whole Sandwich Harbor watershed and B) Mill Creek subwatershed. "Overall Load" is the total nitrogen input to the watershed from all sources, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.



C. Sandwich Harbor: Dock Creek subwatershed



D. Sandwich Harbor: Old Harbor Creek subwatershed

Figure IV-3 (C,D). Source-specific unattenuated watershed nitrogen loads (by percent) to the C) Dock Creek watershed and D) Old Harbor Creek subwatershed. "Overall Load" is the total nitrogen input to the watershed from all sources, 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 watershed sites of natural nitrogen reduction (or attenuation) prior to the watershed nitrogen reaching an estuary. These ponds are generally kettle hole depressions of the land surface that intercept the surrounding groundwater table revealing what some call “windows on the aquifer.” Groundwater typically flows into the pond along the upgradient shoreline, then lake water flows back into the groundwater system along the downgradient shoreline. Occasionally a Cape Cod pond will also have a stream outlet, which is often a herring run, that also acts as a discharge point or will have their water level artificially manipulated through the use of a dam or weir. These changes to a typical kettle hole pond configuration alter the residence time of water within the pond and can also alter the nitrogen attenuation of the pond ecosystem. Since the nitrogen loads usually flow into a pond with the groundwater, the relatively more productive pond ecosystems incorporate some of the nitrogen into organic matter (plants, phytoplankton), retain some nitrogen in the sediments, and change the nitrogen among its various oxidized and reduced forms. As a result of these interactions, some of the nitrogen in the pond watershed is removed from the watershed prior to reaching estuarine waters, mostly through burial in pond sediments and denitrification within the pond that returns some of the nitrogen to the atmosphere. Following these reductions, the remaining (attenuated) nitrogen loads flow back into the groundwater system along the downgradient side of the pond and eventual discharge into the downgradient estuary or through a stream outlet directly to the estuary. The nitrogen load summary in Table IV-3 includes both the unattenuated and attenuated nitrogen load to each subwatershed.

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

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

In addition to bathymetry, temperature profiles are useful to help understand whether temperature stratification is occurring in a pond. If the pond has an epilimnion (*i.e.*, a well-mixed, relatively warm isothermic, upper portion of the water column) and a hypolimnion (*i.e.*, a deeper, colder layer), the stability and volume of these two layers must be accounted for in the nitrogen attenuation calculations. In these stratified lakes, the upper epilimnion is usually the primary discharge location in the pond for watershed nitrogen loads; the deeper hypolimnion generally has limited interaction with the upper layer during stratification. However, impaired conditions in a deeper hypolimnion can result in significant sediment regeneration of nitrogen.

In these lakes/ponds, regenerated sediment nitrogen can filter into the upper layer and impact measured nitrogen concentrations. For this reason, water quality conditions in the ponds should also be considered when estimating nitrogen attenuation, if appropriate data is available.

Many ponds on Cape Cod have been sampled through the regional Cape Cod Pond and Lake Stewards (PALS) Snapshots and the initiative of local volunteer pond sampling programs. The PALS Snapshots are regional volunteer, late-summer pond sampling supported for the last thirteen years by SMAST and the Cape Cod Commission, with free laboratory services provided by the Coastal Systems Program Laboratory at SMAST. Sampling protocols developed through the PALS program (Eichner *et al*., 2003) have been used for more extensive pond sampling programs in many communities on Cape Cod. Sampling under these protocols has included field collection of temperature and dissolved oxygen profiles and sampling of standardized depths that include some evaluation of the impact of sediment nutrient regeneration. PALS water samples are analyzed at the SMAST laboratory for total nitrogen, total phosphorus, chlorophyll *a*, alkalinity, and pH. In some cases, town programs have generated sufficient sampling data collected throughout a number of summers that modified MEP nitrogen attenuation rates can be reliably assigned to freshwater ponds.

Within the Sandwich Harbor study area, there are two freshwater ponds with delineated watersheds: Upper Shawme Lake and Lower Shawme Lake. The two ponds are connected via a fish ladder that is associated with the dam on the upper pond. The dam was reconstructed in early 2009. These ponds have bathymetric information (Eichner *et al.*, 2003), but have not been sampled during the 13 years of the PALS Snapshots and reviews of available reports did not have recent water quality data. Therefore, neither pond has had sufficient sampling to assign a pond-specific nitrogen attenuation rate. However, stream data was collected by MEP staff from the outlet from Lower Shawme Pond (see Section IV.2) and this can be used to determine the combined system attenuation rate (inclusive of ponds and wetlands). In order to balance this measured MEP data, nitrogen attenuation rates of 11% were assigned to the watershed nitrogen loads from both Upper Shawme Pond and Lower Shawme Pond. It should be noted that loads flowing into Upper Shawme Pond get attenuated by 11% and then flow into Lower Shawme Pond and get attenuated again by 11%. This sequential lowering of loads during transport through the complete pond system results in a total attenuation of ~17% as measured at the MEP stream gauge deployed down gradient of Lower Shawme Pond (Section IV.2). This attenuation rate is low, but similar rates have been assigned to other ponds with stream outlets in previous MEP assessments [*e.g.*, Mill Pond in Three Bays (Howes, *et al*., 2006)]. Typically these ponds with low nitrogen attenuation rates are shallow and have short residence times. They are often mill ponds that have accumulated stream sediments, decreasing their volume over the course of many centuries. Pond-specific water quality data would be required to develop nitrogen attenuation rates for the individual Shawme Ponds.

Buildout

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

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

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

Other provisions of the MEP buildout assessment include town assessor classification of undevelopable lots, standard treatment of commercial and industrial properties, and assumptions for lots less than the minimum areas specified by zoning. Properties classified by the Town of Sandwich assessors as "undevelopable" (*e.g.*, MassDOR codes 132, 392, and 442) are not assigned any development at buildout (unless revised by the town review). Commercial and industrial properties classified as developable are not subdivided; the area of each parcel and the factors in Table IV-2 are used to determine an estimated building size and 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; so, for example, a 10,000 square foot lot classified by the town assessor as a developable residential property (MassDOR 130 land use code) and located in a zoning area with a 40,000 square feet minimum lot size will be assigned an additional residential dwelling in the MEP buildout scenario. Most town zoning bylaws have a lower minimum lot size for pre-existing lots (usually 5,000 square feet) that will minimize instances of regulatory takings. Existing developed residential properties that are larger than zoning's minimum lot sizes are also assigned additional development potential only if enough area is available to accommodate at least one additional lot as specified by the zoning minimum.

Following the completion of the initial buildout assessment for the Sandwich Harbor watersheds, MEP staff reviewed the results with town officials. MEP staff reviewed the preliminary watershed buildout results with Nathan Jones, Sandwich Town Planner in June 2012. Provisions were included in the final buildout for the proposed development associated with Community Green and South Sandwich Village. The configuration of these developments and their associated nitrogen loads was based on the most current proposal at the time, which were contained in the Draft Environmental Impact Report (DEIR) (HWG, 2012). The proposal includes 62 units for Community Green and a community wastewater treatment facility (WWTF) with a total Title 5 flow of 140,000 gpd. The proposed WWTF would discharge wastewater nitrogen loads within the Scorton Creek watershed (subwatershed to Long Hill Creek) with a 10 mg/L TN discharge, but also remove 251 kg/yr of wastewater nitrogen from the Sandwich

Harbor watershed (subwatershed #15 to Boiling Spring Well) through the connection of existing properties to the WWTF. The DEIR also mentions connection of additional development to the WWTF, which would increase the flow to 320,000 gpd, but it was not clear at the time of the DEIR submittal where the additional connections would occur. MEP staff discussed the use of the DEIR Title 5 flows, rather than estimates of actual water use, with Town staff and it was agreed that Title 5 flows were appropriately conservative given the large mix of potential uses and uncertainties regarding additional connections. Impacts of alternative buildout scenarios involving South Sandwich Village could be evaluated in subsequent scenarios using the MEP linked model for Sandwich Harbor estuary. All other suggested changes from Sandwich staff based on the initial review were incorporated into the final MEP buildout for Sandwich Harbor.

All the parcels with additional buildout potential within the Sandwich Harbor watershed are shown in Figure IV-4. 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 nitrogen additions. All wastewater loads are assumed to come from standard on-site septic systems. Cumulative unattenuated buildout loads are indicated in a separate column in Table IV-3. It should be noted that this is one example of a buildout scenario; alternative assumptions about future development could be developed to assess the water quality impacts of other buildout scenarios. Based on the MEP assessment, buildout additions within the Sandwich Harbor watersheds will increase the unattenuated watershed nitrogen loading rate by 26%.

Parcels colored green, red, and orange are developed parcels (residential, commercial and industrial, respectively) with additional development potential based on current zoning, while parcels colored blue, purple, and yellow are corresponding undeveloped parcels classified as developable by the town assessor. Parcels along watershed boundaries are assigned to subwatersheds to 1) minimize the splitting of properties for future management purposes and 2) achieve a match of area with the modeled watersheds of 2% or less. Developable parcels are based on town assessor classifications and minimum lot sizes specified in current town zoning; these parcels are assigned estimated nitrogen loads in MEP buildout calculations. Buildout also includes proposed development of South Sandwich Village as detailed in the DEIR (HWG, 2012), which was the most current proposal at the time. All initial buildout results were reviewed with town officials and any corrections were incorporated into the final buildout nitrogen loads.

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 Sandwich Harbor Embayment System being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1).

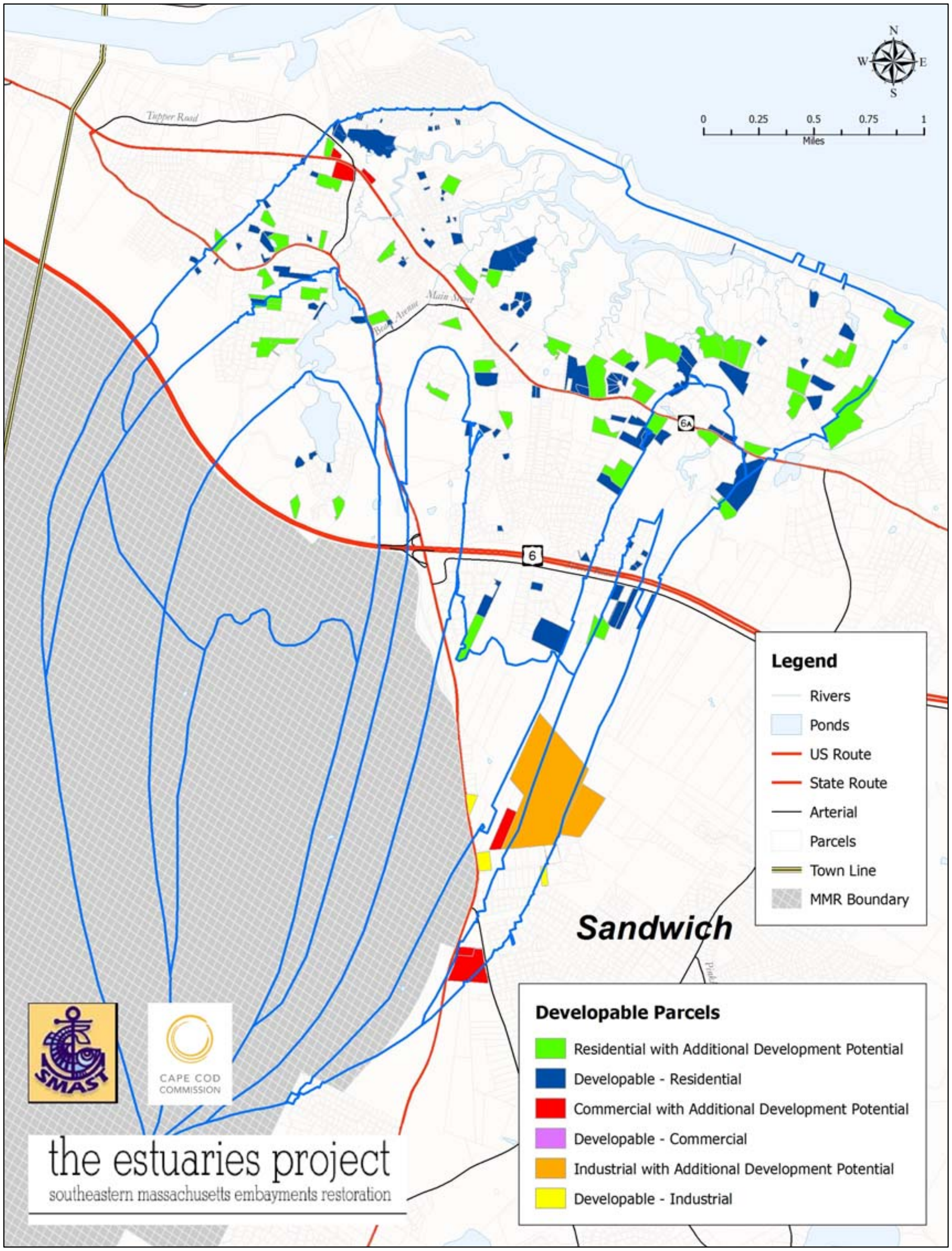


Figure IV-4. Developable Parcels in the Sandwich Harbor watershed.

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 Sandwich Harbor watershed). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. However, in most watersheds in southeastern Massachusetts, nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the watershed for the Sandwich Harbor embayment system, a portion of the freshwater flow and transported nitrogen passes through two main surface water systems (e.g. Lower Shawme Lake discharging into the head of Mill Creek which is a tidal creek that flows into the Sandwich Harbor system and flow from a small freshwater impoundment that becomes Springhill Creek flowing into Sandwich Harbor) prior to entering the estuary, producing the opportunity for reductions in nutrient loading, primarily through 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 the Sandwich Harbor embayment system. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the perimeter of the embayment system in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). These additional site-specific studies were conducted in the 2 major surface water flow systems in the Sandwich Harbor watershed, 1) flow from Lower Shawme Lake into Mill Creek and Sandwich Harbor and 2) freshwater from Springhill Creek into the Sandwich Harbor Estuary.

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 each freshwater stream discharging to the estuary provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up gradient from the various gauging sites. Flow and nitrogen load were determined at two gauge locations for 16 months of record (Figures IV-6 and IV-7). During the study period, a velocity profile was completed at each gauge location in each of the creeks every month to two months. The summation of the products of creek subsection areas of the channel cross-section and the respective measured velocities represent the computation of instantaneous flow (Q) through a given creek.

Determination of flow at the gauges on the two main surfacewater inflows to the Sandwich Harbor Estuary were calculated from the measured values obtained for cross sectional area of each creek as well as creek specific velocity. Freshwater discharge was represented by the summation of individual discharge calculations for each channel subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire channel cross section were not averaged and then applied to the total creek 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” gauge deployment period allowed for the development of a stage-discharge relationship (rating curve) that could be used to obtain flow volumes from the continuous record of stage measured by the recording stream gauges. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given creek. These hourly stages values where then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. A complete annual record of flow in the creeks (365 days) was generated for the surface water discharge flowing into the head of the tidal creeks downgradient from (a) Shawme Lake and (b) the small impoundment at the head of Springhill Creek.

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

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream flowing into Mill Creek (Sandwich Harbor) from Shawme Lake

Located up gradient of the gauge site on the stream discharging into the head of Mill Creek is a freshwater pond system (Upper Shawme Lake and Shawme Lake) and unlike many of the freshwater ponds on Cape Cod, this pond system has a surface water outlet rather than draining solely to the aquifer along its down-gradient shore. This outflow may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation taking place in the pond. In addition, nitrogen attenuation also occurs within associated wetland areas, riparian zones and streambed associated with the Creek. The combined rate of nitrogen attenuation within these areas was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the Creek above the gauge site and the measured annual discharge of nitrogen to the tidally influenced head of Mill Creek / Sandwich Harbor Estuary, Figure IV-5.

At the gauge site (situated immediately down-gradient of the intersection of Water Street and Main Street), a continuously recording vented calibrated water level gauge was installed to yield the level of water in the freshwater creek discharging from Shawme Lake and which carries the flows and associated nitrogen load to the head of the tidally influenced Mill Creek which drains into Sandwich Harbor. The gauge was located as far down gradient along the Creek reach as possible such that freshwater flow could be measured at low tide while also capturing as much contribution of flow and load from the up-gradient watershed. Based on the stage record, however, the location of this specific gauge did not appear to be tidally influenced. To confirm the lack of tidal influence as observed in the stage record, salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average salinity for all the water samples collected over the entire gauge deployment period was determined to be 0.1 ppt (freshwater). Therefore, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked approximately monthly each time the site was visited and a flow measurement obtained. The gauge on the Creek was installed on June 5, 2006 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Actual stage data collection continued until November 15, 2007 for a total deployment of 17 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 gauge site based upon these flow measurements and measured water levels at the gauge site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the head of Mill Creek and subsequently, a main tidal channel with the Sandwich Harbor Estuary. This measured attenuated mass discharge is reflective of the combined effect of biological processes occurring in Upper Shawme Lake and Shawme Lake, as well as the

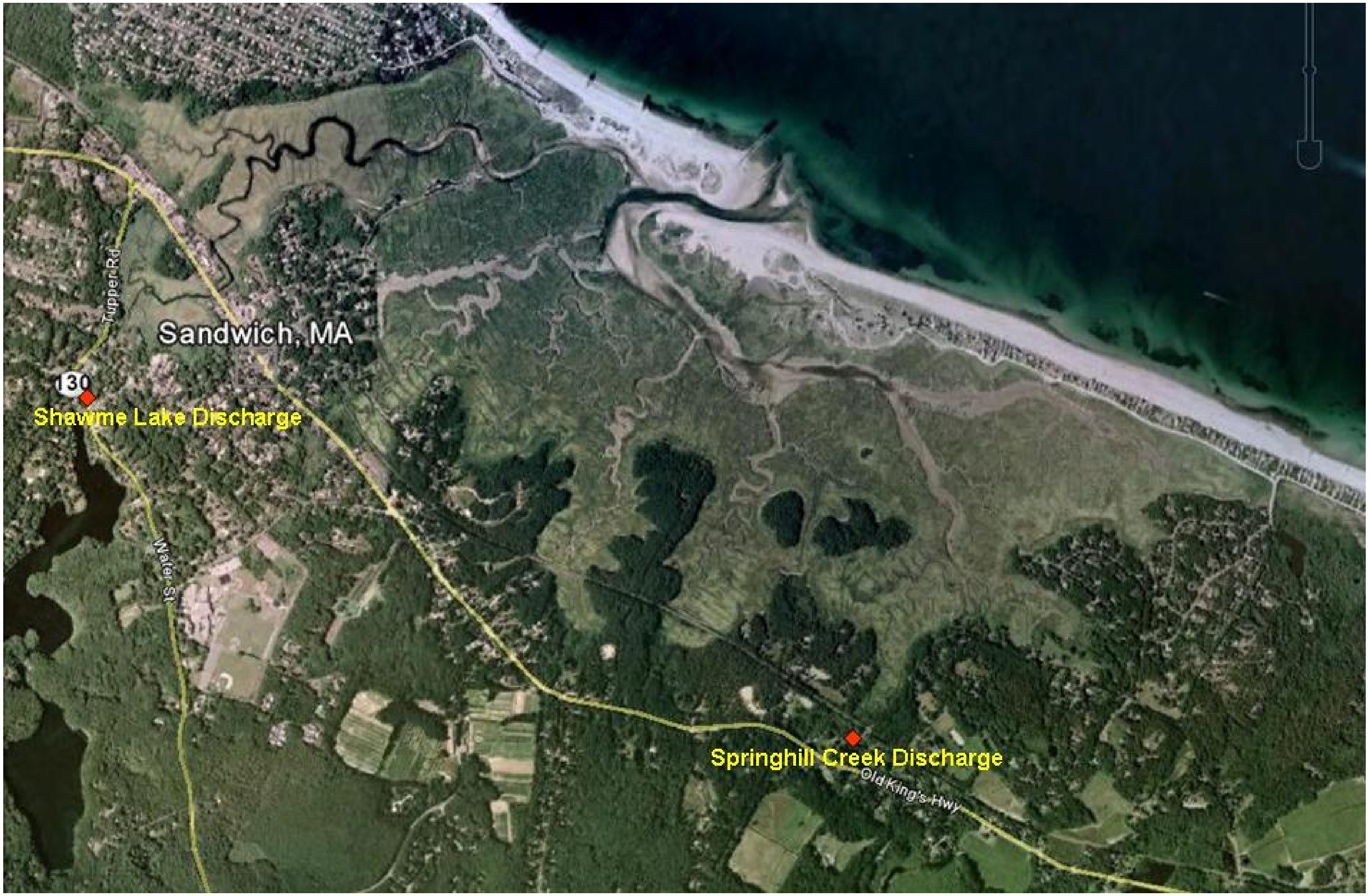


Figure IV-5. Location of Stream gauges (red symbol) in the Sandwich Harbor Watershed.

stream channel and riparian zone contributing to nitrogen attenuation **(**Figure IV-6 and Table IV-4). 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 gauge site.

The annual freshwater flow record for the discharge from Shawme Lake as 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 lake was 10% above the long-term average flows based on recharge. 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 21,478 m^3/day compared to the long term average flows determined by the USGS modeling effort (19,252 m^3/day). This slight difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the Creek discharging from Shawme Lake indicates that the Creek is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Creek outflow from Shawme Lake were low, 0.336 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 7.22 kg/day and a measured total annual TN load of 2,635 kg/yr. In the Creek (freshwater), nitrate was an extremely small portion of the total nitrogen pool (7%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was largely taken up by plants within the small up-gradient pond (Shawme Lake) or stream ecosystems prior to discharge to Mill Creek. This is further supported when considering that organic forms (dissolved and particulate organic nitrogen) constitute 87 percent of the total nitrogen load discharging to the head of Mill Creek and the Sandwich Harbor Estuary. The low concentration of inorganic nitrogen (0.036 mg N L^{-1}) in the out flowing creek waters also suggests active biological cycling in the lakes. In addition, the low nitrate level (0.025 mg N L^{-1}) suggests the possibility for additional uptake by freshwater systems upgradient from the gauge location is unlikely in this system, as inorganic nitrogen appears significantly attenuated already. Opportunities for enhancing nitrogen attenuation elsewhere in the overall sub-watershed to the Sandwich Harbor system could be considered, keeping in mind there is not likely to be much more natural attenuation to be gained from the Shawme Lake sub-watersheds.

From the measured nitrogen load discharged by the Creek to the east branch of the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that moderate nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary is occurring. Based upon lower total nitrogen load (2,635 kg yr^{-1}) discharged from the freshwater Creek compared to that added by the various land-uses to the associated watershed (3,177 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 17% (i.e. 17% 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 hydrologic and biogeochemical characteristics of the up-gradient pond(s) capable of attenuating nitrogen. The directly measured nitrogen loads from the Creek was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

Table IV-4. Comparison of water flow and nitrogen discharges from the 2 major surfacewater systems (freshwater) discharging to the Sandwich Harbor Estuary. The "Stream" data is from the MEP stream gaging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	**Shawme Lake Discharge**[a] Sandwich Harbor	**Springhill Creek Discharge**[a] Sandwich Harbor	**Data Source**
Total Days of Record	365[b]	365[c]	(1)
Flow Characteristics			
Stream Average Discharge (m3/day) **	21,478	4,356	(1)
Contributing Area Average Discharge (m3/day)	19,252	3,938	(2)
Discharge Stream 2005-06 vs. Long-term Discharge	10.36%	9.60%	
Nitrogen Characteristics			
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.025	0.108	(1)
Stream Average Total N Concentration (mg N/L)	0.336	0.461	(1)
Nitrate + Nitrite as Percent of Total N (%)	7%	23%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	7.22	2.01	(1)
TN Average Contributing UN-attenuated Load (kg/day)	8.704	3.208	(3)
Attenuation of Nitrogen in Pond/Stream (%)	17%	37%	(4)

(a) Flow and N load to stream/creek discharging to the Mill Creek and Old Harbor Portions of the Sandwich Harbor system and includes apportionments of Pond contributing areas.
(b) September 1, 2006 to August 31, 2007.
(c) September 1, 2006 to August 31, 2007.
** Flow is an average of annual flow for 2006-2007 in both surfacewater systems

(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 creeks to Sandwich 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.

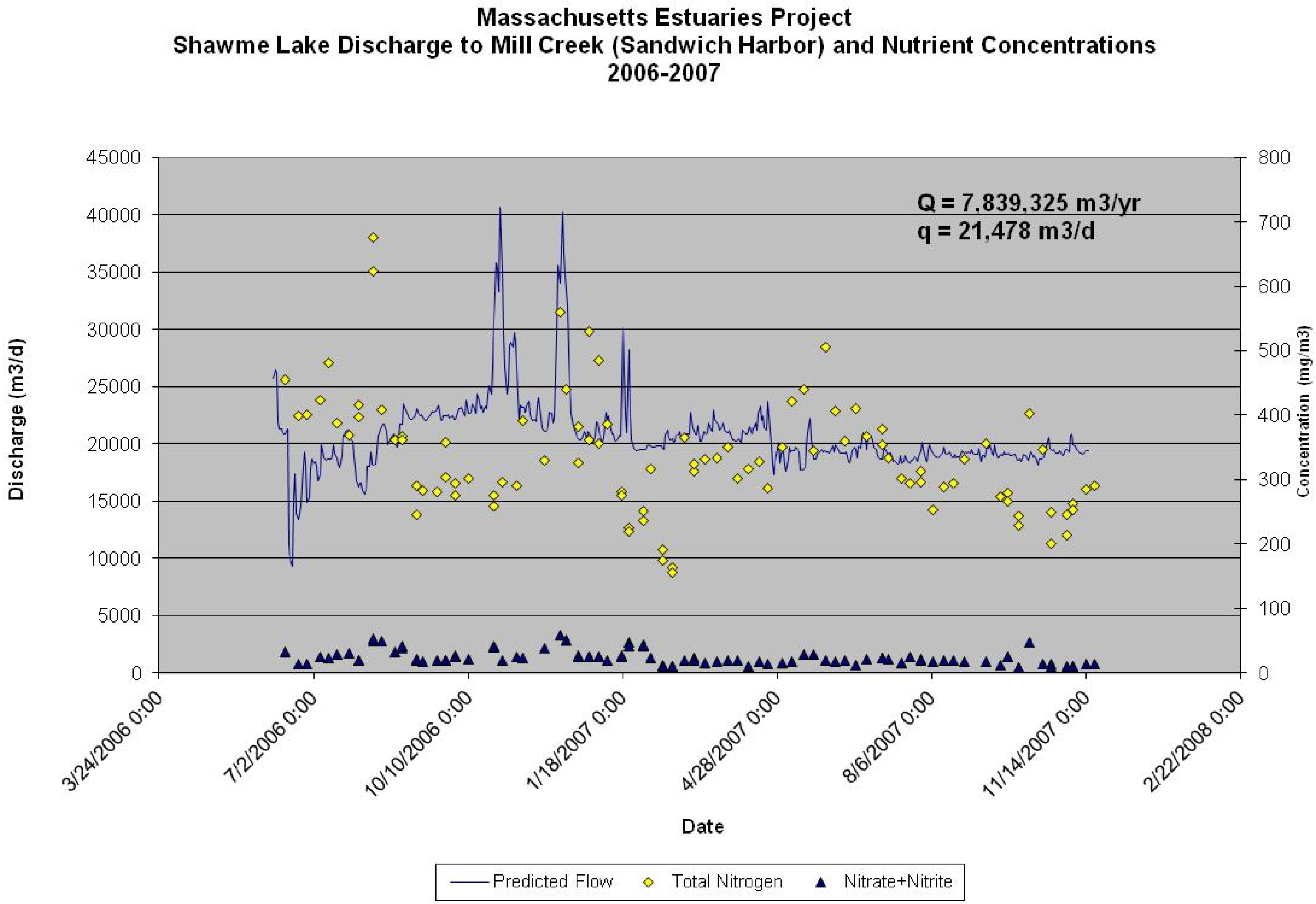


Figure IV-6. Stream flowing from Shawme Lake directly into the head of Mill Creek to Sandwich Harbor Estuary (solid blue line), nitrate+nitrite (blue triangle) and total nitrogen (yellow diamond) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Sandwich Harbor Estuary (Table IV-4).

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Springhill Creek flowing into Sandwich Harbor

Located up gradient of the gauge site on Springhill Creek discharging into a main channel of the Sandwich Harbor Estuary is a small un-named freshwater pond and unlike many of the freshwater ponds on Cape Cod, this small pond has a surface water discharge rather than draining solely back into the aquifer along its down-gradient shore. This outflow through Springhill Creek, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within associated wetland areas, riparian zones and streambed associated with the Creek. The combined rate of nitrogen attenuation in these areas was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the Creek above the gauge site and the measured annual discharge of nitrogen to the tidally influenced portion of Springhill Creek, Figure IV-5.

At the Creek gauge site (situated immediately down-gradient of Springhill Road but up-gradient of the railroad bed), a continuously recording vented calibrated water level gauge was installed to yield the level of water in the freshwater creek discharging from the up-gradient pond and which carries the flows and associated nitrogen load to the Sandwich Harbor Estuary. As Springhill Creek is tidally influenced, the gauge was located as far downgradient along the Creek reach such that freshwater flow could be measured at low tide. To confirm that freshwater was being measured the stage record was analyzed for any semi-diurnal variations indicative of tidal influence and salinity measurements were conducted on the weekly water quality samples collected at the gauge site. Average low tide salinity was determined to be 0.1 ppt (freshwater). Therefore, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked approximately monthly each time the site was visited and a flow measurement obtained. The gauge on the Creek was installed on June 5, 2006 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Actual stage data collection continued until November 15, 2007 for a total deployment of 17 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 Springhill Creek site based upon these flow measurements and measured water levels at the gauge site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge from Spring Hill Creek and subsequently, to the Sandwich Harbor Estuary. This measured attenuated mass discharge is reflective of the biological processes occurring in the small up-gradient pond as well as the stream channel and riparian zone contributing to nitrogen attenuation (Figure IV-7 and Table IV-4). 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 gauge site.

The annual freshwater flow record for Springhill Creek discharging from the pond as measured by the MEP was compared to the long-term average flows determined by the USGS watershed modeling effort (Table III-1). As noted in Figure III-1, the USGS watershed to the Springhill Creek gauge includes the Boiling Springs wellfield contributing area (subwatershed #15). Water use within the gauge watershed is a small portion (~10%) of the average volume

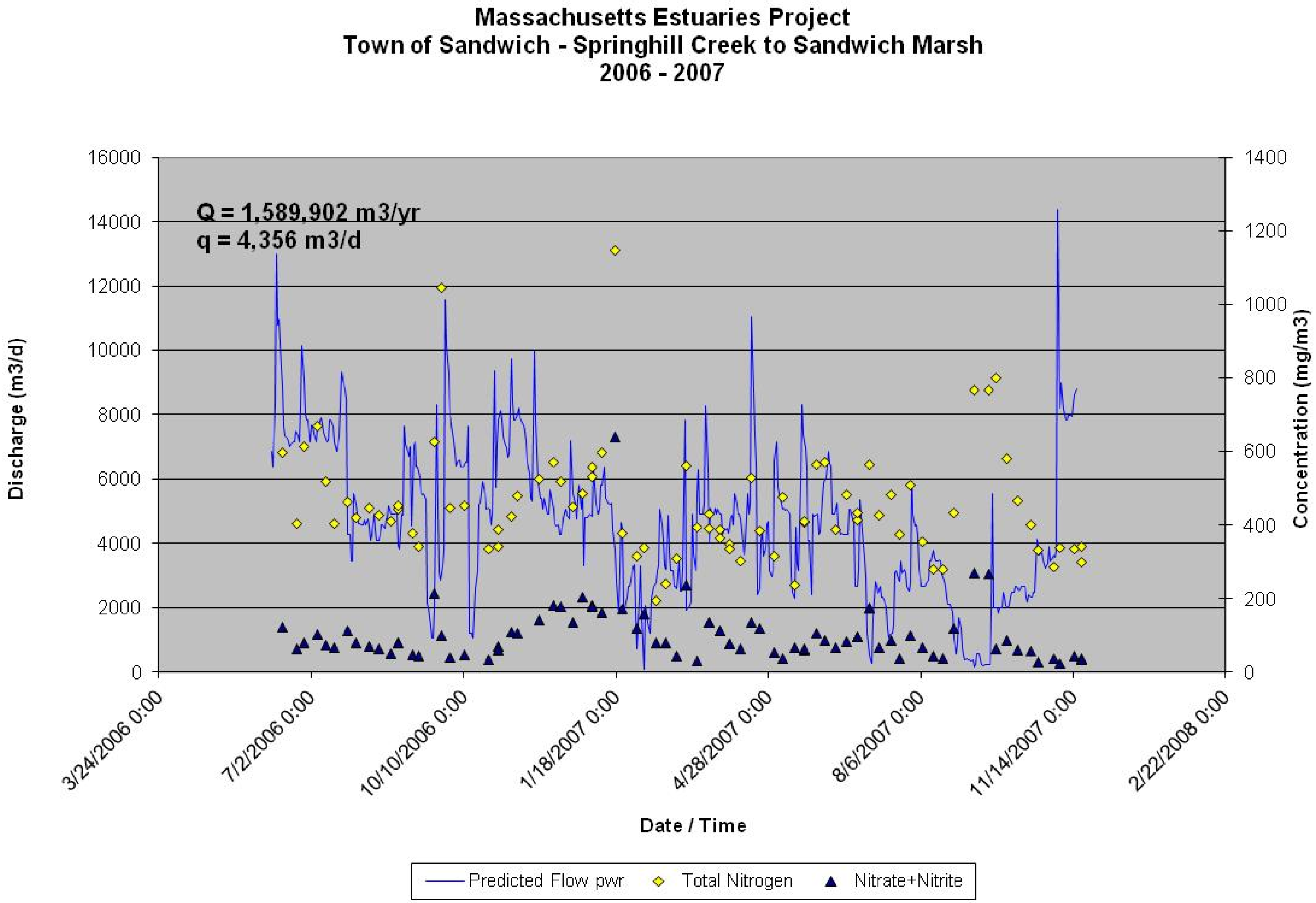


Figure IV-7. Springhill Creek flowing directly into the Old Harbor Creek portion of the Sandwich Harbor Estuary (solid blue line), nitrate+nitrite (blue triangle) and total nitrogen (yellow diamond) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to the estuary Harbor (Table IV-4).

Table IV-5. Summary of annual volumetric discharge and nitrogen load from the freshwater discharge from Shawme Lake to Mill Creek (Sandwich Harbor Estuary). Flows and loads based upon the data presented in Figures IV-6 and IV-7 and Table IV-4.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Shawme Lake Discharge from Lake to Mill Creek (MEP)	**September 1, 2005 to August 31, 2006**	**7,839,325**	**195**	**2635**
Shawme Lake Discharge from Lake to Mill Creek (CCC)	Based on Watershed Area and Recharge	**7,026,980**	--	--
Springhill Creek Discharge to Sandwich Harbor (MEP)	**September 1, 2005 to August 31, 2006**	**1,589,902**	**171**	**733**
Springhill Creek Discharge to Sandwich Harbor (MEP)	Based on Watershed Area and Recharge	**1,437,370**	--	--

pumped by the wellfield. MEP staff reviewed average wellfield pumping on a number of timeframes (2005-2007 and 2000-2011) and compared these to measured flow in the creek. In order to achieve a reasonable balance with measured MEP flows, the portion of the pumped volume not utilized in the gauge watershed was assigned to the Old Harbor LT10 subwatershed (subwatershed #12). This subwatershed includes substantially more developed parcels than the gauge subwatershed and this assumption is reasonable based on this land use distribution and proximity to the wellfield. With this correction, the measured freshwater discharge from the Creek is within 10% of the long-term average modeled flows based on the groundwater model. 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 4,392 m^3/day compared to the long term average flows determined by the USGS modeling effort (3,938 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 Creek was considered to be negligible given the relatively small flow and associated load. It also is within reasonable balance with the readings at the Shawme Lake gauge and the Long Hill gauge in the nearby Scorton Creek watershed (Howes, *et al.*, 2013). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Springhill Creek discharging to Sandwich Harbor would indicate that the Creek is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Spring Hill Creek outflow were relatively low, 0.461 mg N L^{-1}, yielding a modest daily total nitrogen discharge to the estuary of 2.01 kg/day and a measured total annual TN load of 733 kg/yr. In the freshwater creek discharge nitrate was significantly less than half, only 23%, of the total pool of nitrogen, indicating that groundwater nitrogen (typically dominated by nitrate) transported through the freshwater ponds and creek was largely converted to organic forms by plants within the small up-gradient pond or stream ecosystems. This is further supported when considering that dissolved and particulate organic nitrogen constitutes 69 percent of the total nitrogen load discharging to the Sandwich Harbor system from Springhill Creek. The relatively low concentration of dissolved inorganic nitrogen (0.147 mg N L^{-1}) in the out flowing creek waters also suggests that additional nitrogen may be similarly transformed. In addition, the low nitrate level (0.108 mg N L^{-1}) suggests the possibility for enhancing uptake by freshwater systems up-gradient from the gauge location is limited. Inorganic nitrogen appears well attenuated by the small upgradient pond. This would not be the case if nitrate levels were high.

From the measured nitrogen load discharged by Springhill Creek to the Sandwich Harbor Estuary and the nitrogen load determined from the watershed based land use analysis, it appears that in addition to nitrogen transformation, nitrogen removal is occurring. Based upon the measured lower total nitrogen load (753 kg yr^{-1}) discharged from the freshwater Creek compared to that added by the various land-uses to the associated watershed (1,171 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 37% (*i.e.,* 37% 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 hydrologic and biogeochemical characteristics of the up gradient pond(s) capable of attenuating nitrogen. The directly measured nitrogen loads from Springhill Creek was used in the Linked Watershed-Embayment Modeling of water quality (see Section 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 Sandwich Harbor Estuary. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Water column Exchange of Nitrogen

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

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

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

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading to the Sandwich Harbor system. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for Determining Sediment-Water column Nitrogen Exchange

For the Sandwich Harbor Embayment System, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. In the Sandwich Harbor Marsh system, sediment samples (15 cores) were collected from 14 sites (Figure IV-6) in July-August 2006, focusing on obtaining an areal distribution that would be representative of nutrient fluxes throughout the system but also considering tributary "basins" such as the narrow tidal creeks that extend landward off the main embayment channel/basin. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The number of core samples from each site (Figure IV-8) during the Sandwich Harbor incubation are as follows:

Sandwich Harbor System Benthic Nutrient Regeneration Cores

- SH-1 1 core (Mill Creek Channel)
- SH-2 1 core (Mill Creek Channel)
- SH-3 2 core (Mill Creek Channel)
- SH-4 1 core (Lower Old Harbor Creek)
- SH-5 1 core (Dock Creek Channel)
- SH-6 1 core (Dock Creek Channel)
- SH-7 1 core (Lower Old Harbor Creek)
- SH-8 1 core (Lower Old Harbor Creek)
- SH-9 1 core (Lower Old Harbor Creek)
- SH-10 1 core (Lower Old Harbor Creek)
- SH-11 1 core (Upper Old Harbor Creek)
- SH-12 1 core (Upper Old Harbor Creek)
- SH-13 1 core (Upper Old Harbor Creek)
- SH-14 1 core (Upper Old Harbor Creek)

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

Sediment-water column exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1998) for nutrients and metabolism. Upon return to the field laboratory, the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and orthophosphate (Murphy and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-20^{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 [*508-910-6325*]. 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.

Figure IV-8. Sandwich Harbor Estuary, a marsh dominated system with deeply incised tidal creeks. Locations (green symbols) of sediment sample collection for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-6.

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

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

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-9).

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

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

Sediment Nitrogen Release by Standard Core Approach: Sediment sampling was conducted throughout the main tidal channel of the Sandwich Harbor Estuary as well as the significant tidal creeks that feed into the main channel (Old Harbor Creek) of the system. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content, as well as sediment type and an analysis of each site's tidal flow velocities. As expected flow velocities are generally low in the uppermost reaches of the tidal creeks and high in the lower portions of the system situated closer to the inlet to the system. 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.

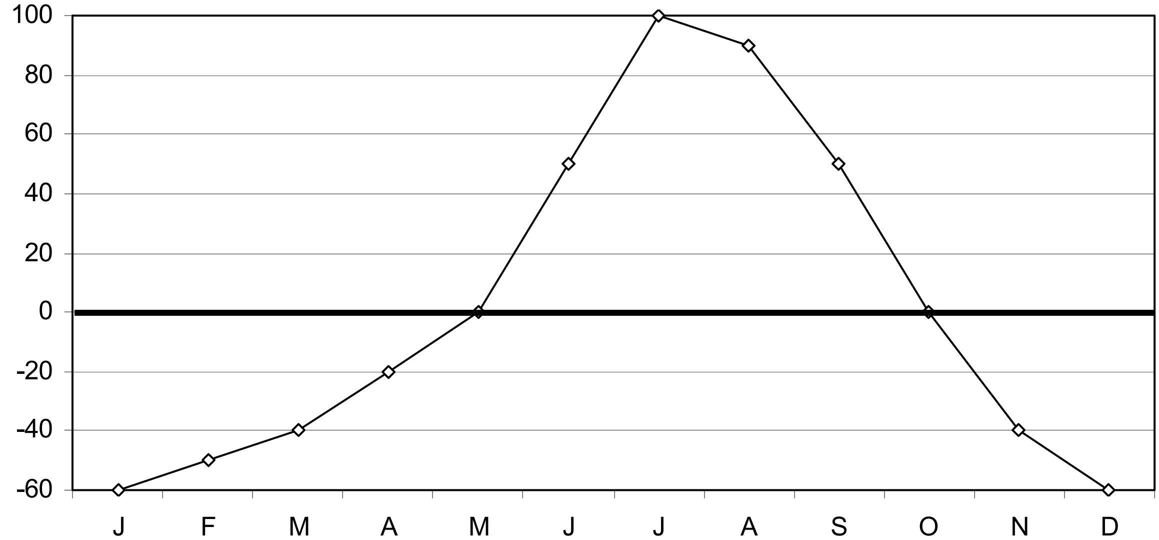


Figure IV-9. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (Chapter V). Two levels of settling 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 Sandwich Harbor Estuary were comparable to other salt marsh dominated systems on Cape Cod with similar configurations and flushing rates. The spatial distribution of nitrogen release/uptake by the sediments of the Sandwich Harbor Estuary ranged from 6.0-41.4 mg N m^{-2} d^{-1} in the smaller tidal creek areas tributary to Old Harbor Creek and showed net uptake in the main creek -6.4 to -17.9 mg N m^{-2} d^{-1} (Old Harbor Creek). This compares favorably to rates of nitrogen release measured in similar salt marshes located in the Town of Orleans. The spatial distribution of nitrogen release/uptake by the sediments of Namskaket Marsh and adjacent Little Namskaket Marsh were 45.4 vs. 64.5 mg N m^{-2} d^{-1}, respectively, for the smaller tidal creek areas of the upper marsh and -21.2 vs. -7.8 mg N m^{-2} d^{-1}, respectively, for the lower larger creek areas of those two salt marsh dominated systems. In general, Namskaket Marsh showed slightly lower release rates (both less positive and more negative) than Little Namskaket Marsh, possibly related to their differences in tidal creek length or marsh "size", as they both presently have similar rates of watershed N loading. Overall, the pattern and rates of uptake and release in the salt marsh dominated areas of these Orleans Estuaries are similar and compare well to rates measured by the MEP throughout the Sandwich Harbor Estuary.

Net nitrogen release or uptake from the sediments within the Sandwich Harbor Estuary were also comparable to those in the adjacent Scorton Creek Estuary. The spatial distribution of nitrogen release/uptake by the sediments of Scorton Creek ranged from net release in the organic rich main tributary creeks to Old Harbor Creek, 25.5 mg N m^{-2} d^{-1} to net uptake throughout the lower sandy tributary creeks to Long Hill and Scorton Shore, -19.9 and -12.7 mg N m^{-2} d^{-1}, respectively

Net nitrogen release or uptake from the sediments within the Scorton Creek Estuary were also similar to other salt marsh systems on Cape Cod. For example, net nitrogen uptake in the lower salt marsh main creek (-6.4 to -17.9 mg N m^{-1} d^{-1}) was similar to that observed for the salt marsh areas in the Centerville River System (-4.5 to -13.2 mg N m^{-1} d^{-1}) and Cockle Cove Salt Marsh, Chatham (MEP Centerville River Final Nutrient Technical Report 2006, MEP Cockle Cove Technical Memorandum-Howes et al. 2006) and the lower basin of the Little River marsh system (-3.1 mg N m^{-1} d^{-1}). The net release rates from the smaller organic rich tributary creeks are similarly comparable to other systems. For example, the upper reaches of the Herring River wetland system in the Town of Harwich (9.7-10.5 mg N m^{-1} d^{-1}), Wild Harbor River in the Town of Falmouth (1.4 mg N m^{-1} d^{-1}) and salt marsh dominated portions of the Back River (Bourne) and the Slocums and Little River Estuaries (Dartmouth) support similarly small net release rates of 6.5 mg N m^{-2} d^{-1} and 4.6-9.0 mg N m^{-2} d^{-1}, respectively.

The sediments within the Sandwich Harbor Estuary showed nitrogen fluxes typical of similarly structured systems with low to moderate watershed nitrogen loading in the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the low moderate nitrogen loading to this system and it relatively high flushing rate.

Net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the Sandwich Harbor Estuary/Salt Marsh (Chapter VI) are presented in Table IV-6. There was a clear spatial pattern of sediment nitrogen flux, with net release from the sediments of the upper reach of the tidal creek and net uptake by the sediments of the lower tidal creek region. The sediments within the Sandwich Harbor Estuary showed nitrogen fluxes typical of similarly structured systems with low to moderate watershed nitrogen loading and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the low nitrogen loading to this system and its relatively high flushing rate.

Table IV-6. Rates of net nitrogen return from sediments to the overlying waters throughout the Sandwich Harbor Estuary. 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})			SH- i.d. *
	Mean	S.E.	N	
Sandwich Harbor Estuary				
Mill Creek	41.4	18.4	4	1, 2, 3
Dock Creek	6.0	5.7	2	5, 6
Lower Old Harbor Creek	-17.9	2.9	5	4, 7, 8, 9, 10
Upper Old Harbor Creek	-6.4	8.5	4	11, 12, 13, 14

* Station numbers refer to Figures IV-8.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This hydrodynamic study was performed for Sandwich Harbor, located completely within the Town of Sandwich, Massachusetts, at the southwest corner of Cape Cod Bay. It is the receiving basin of groundwater flow from the historic central village of the Town. A topographic map detail in Figure V-1 shows the general study area. Sandwich Harbor is a salt marsh with an unstructured inlet that is generally bound by Town Neck to the west and Spring Hill to the east. The average elevation of the marsh plain is +3.5 feet NAVD. The lowest elevations of the system exist in the inlet channel, where maximum depths of approximately -10 feet NAVD occur. The total surface coverage of the Sandwich Harbor system is approximately 615 total acres, which includes about 520 acres of the marsh plain.

Tidal exchange with Cape Cod Bay dominates circulation in the Harbor. From measurements made in the course of this study, the average offshore tide range is 9.3 feet. As indicated by the lack of attenuation of high tide elevations across the inland extents of the marsh creeks of Sandwich Harbor, tidal flushing appears very efficient throughout the tidal reaches of the system. Tidal flow is mainly distributed within the harbor by a primary creek channel (Old Harbor Creek) and the secondary channels (Mill Creek, Dock Creek and Spring Hill Creek). Several tertiary channels branch forth from these main creeks.

The hydrodynamic study of the Sandwich Harbor system proceeded as two component efforts. In the first portion of the study, bathymetry and tide data were collected in order to accurately characterize the physical system, and to provide data necessary for the modeling portion of the study. The bathymetry survey of Sandwich Harbor was performed to determine the variation of depths throughout the main tidal creeks. This survey addressed the previous lack of adequate bathymetry data for these channels. In addition to the bathymetry survey, tides were recorded at five stations for 43 days. These tide data were necessary to run and calibrate the hydrodynamic model of the system.

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

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

V.2 DATA COLLECTION AND ANALYSIS

The field data collection portion of this study was performed to characterize the physical properties of Sandwich Harbor. Bathymetry data were collected throughout the system so that it could be accurately represented as a computer hydrodynamic model and flushing rates could be determined for the system. In addition to the bathymetry, tide data were also collected throughout the Harbor in order to run the circulation model with real tides, and also to calibrate and verify its performance.

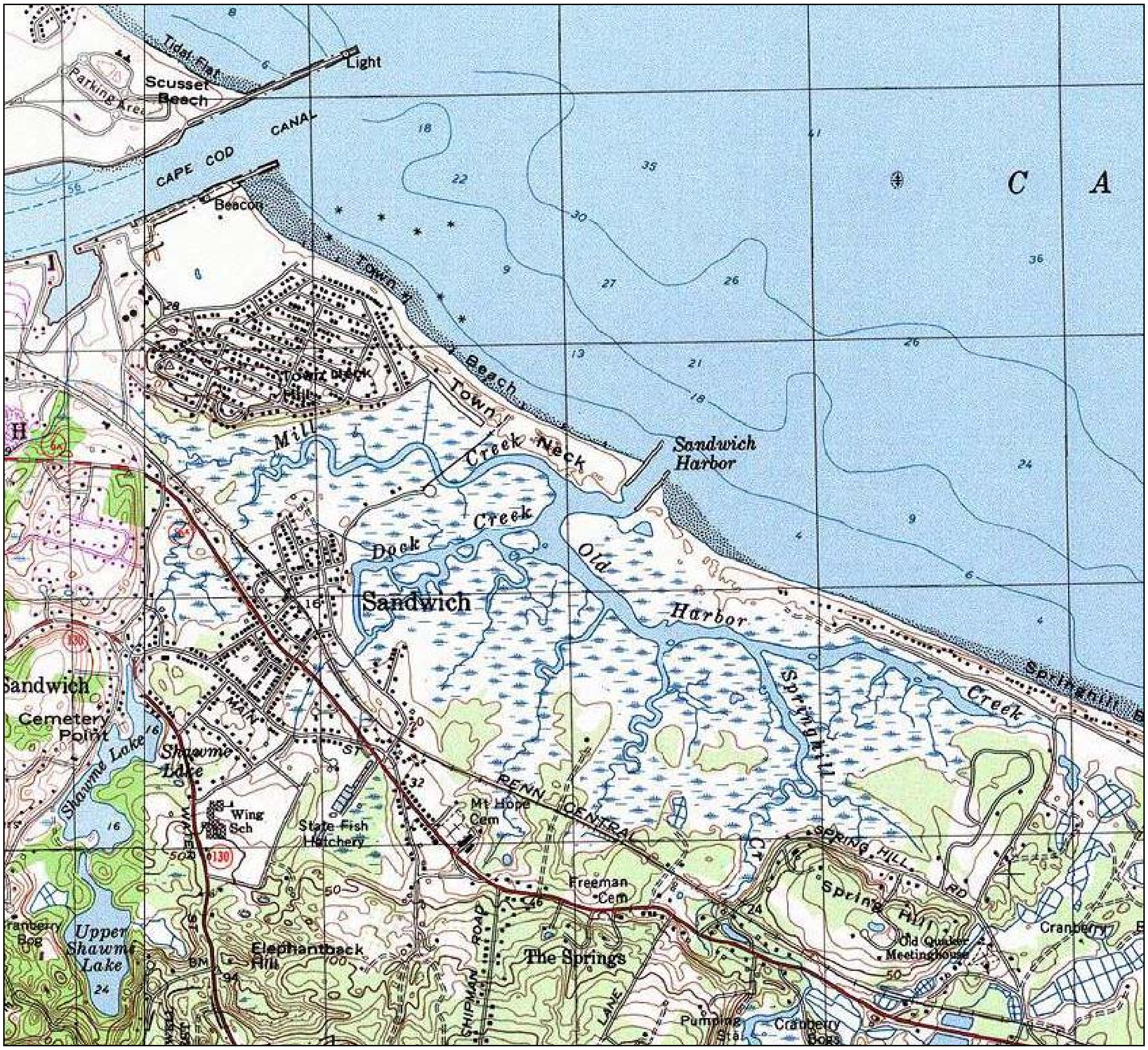


Figure V-1. Topographic map detail of Sandwich Harbor.

V.2.1 Bathymetry Data

Bathymetric data was collected in the Sandwich salt water embayments (Scorton Creek and Sandwich Harbor), as part of a larger town-wide effort, over the course of two separate surveys occurring in the Summer of 2008. The surveys employed an Odem HydroTrac fathometer mounted on a 16-foot motor skiff. Positioning data were collected using a differential GPS. The position data from the GPS and the depth data from the fathometer were recorded digitally in real time using the Hypack hydrographic survey software package. Where practical, predetermined survey transects were followed at regular intervals. Marsh channels in the upper portion of the marsh areas were also surveyed, where depths allowed the passage of the survey boat. Collected bathymetry data was tide-corrected to account for the change in water depths as the tide level changed over the survey period. The tide-correction is performed using tide data collected while the survey was run.

Additional topographic and bathymetric data was gathered from NOAA's Coastal Services Center which provide the 2007 US Army Corps of Engineers (USACE) Topographic and Bathymetric Lidar Dataset for the region, which covers most of the marsh plain, and the 2011 LiDAR flight by the USGS, which covers areas further inland that were not included in the 2007 flight . The complied elevation dataset, including elevations from the bathymetry survey, is shown in Figure V-2.

Figure V-2. Bathymetric/Topographic data used to develop the RMA-2 hydrodynamic model. Points are colored to represent the bottom elevation relative to NAVD. The data sources used to develop the grid mesh are the 2008 bathymetry survey, and the NOAA LiDAR data.

V.2.2 Tide Data Collection and Analysis

Tide data records were collected concurrently at five gauging stations shown in Figure V-2, located offshore in Cape Cod Bay (S-1), at the upper and lower reaches of Old Harbor Creek (S-4 and S-2, respectively), in Dock Creek (S-5) and Mill Creek (S-6). The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 43-day period between July 22 and September 4, 2008. The elevation of each gauge was surveyed relative to the NAVD vertical datum. The Cape Cod Bay tide record was used as the open boundary condition of the hydrodynamic model. Data from inside the system were used to calibrate the model.

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

Plots of the tide data from the three gauges are shown in Figure V-3 for the entire 43-day deployment. The spring-to-neap variation in tide range is easily discernible in these plots. The data record begins during a period of neap tides. A week later there is a period of spring tides, which occurs around the time of the new moon of August 1. Following this spring tide is a continuing cycle of neap and spring tides. The minimum neap tide range in the offshore record is only 5.4 feet (August 11), while the maximum spring tide rage is 13.0 feet (August 2).

A visual comparison between tide elevations offshore and at the different stations in the system shows that the tide amplitude in the marsh is controlled by the elevation of the different marsh creeks. There is only a minor reduction of the water elevation at times of high tide (about 3 inches). Low tide elevations increase with excursion into the marsh. Just inside the inlet low tide is 2 feet higher than offshore. At the farthest inland reaches of the main marsh creeks the elevation of low tide is more than 5 feet higher than offshore.

V.2.2.a Tide Datums

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from a 30-day subset of the tide records. These datums are presented in Table V-1. For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data was available; however, these datums still provide a useful comparison of tidal dynamics within the system. The Mean Higher High (MHH) and Mean Lower Low (MLL) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (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 results presented in Table V-1 emphasize that tidal damping throughout the marsh is manifest by the higher elevation of the low water datums at the upper portions of the main tidal creeks. Damping is also evident by the apparent delay in the timing of slack high and low tide at the different stations (Figure V-4). All gauges inside the Harbor have a high tide delay of approximately 40 minutes compared to offshore. The delay of high tide is greatest at the Mill Creek station, where low tide occurs two and three-quarters after low tide offshore.

V.2.2.b Tide Harmonic Analysis

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

A harmonic analysis was performed on the time series from each gauge location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The observed astronomical tide is the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-5. The amplitudes and phase of 21 known tidal constituents result from this procedure. Table V-2 presents the amplitudes of seven tidal constituents computed for the Sandwich Harbor station records. The M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an offshore amplitude of 1.7 feet. The total range of the M_2 tide is twice the amplitude, or 3.4 feet.

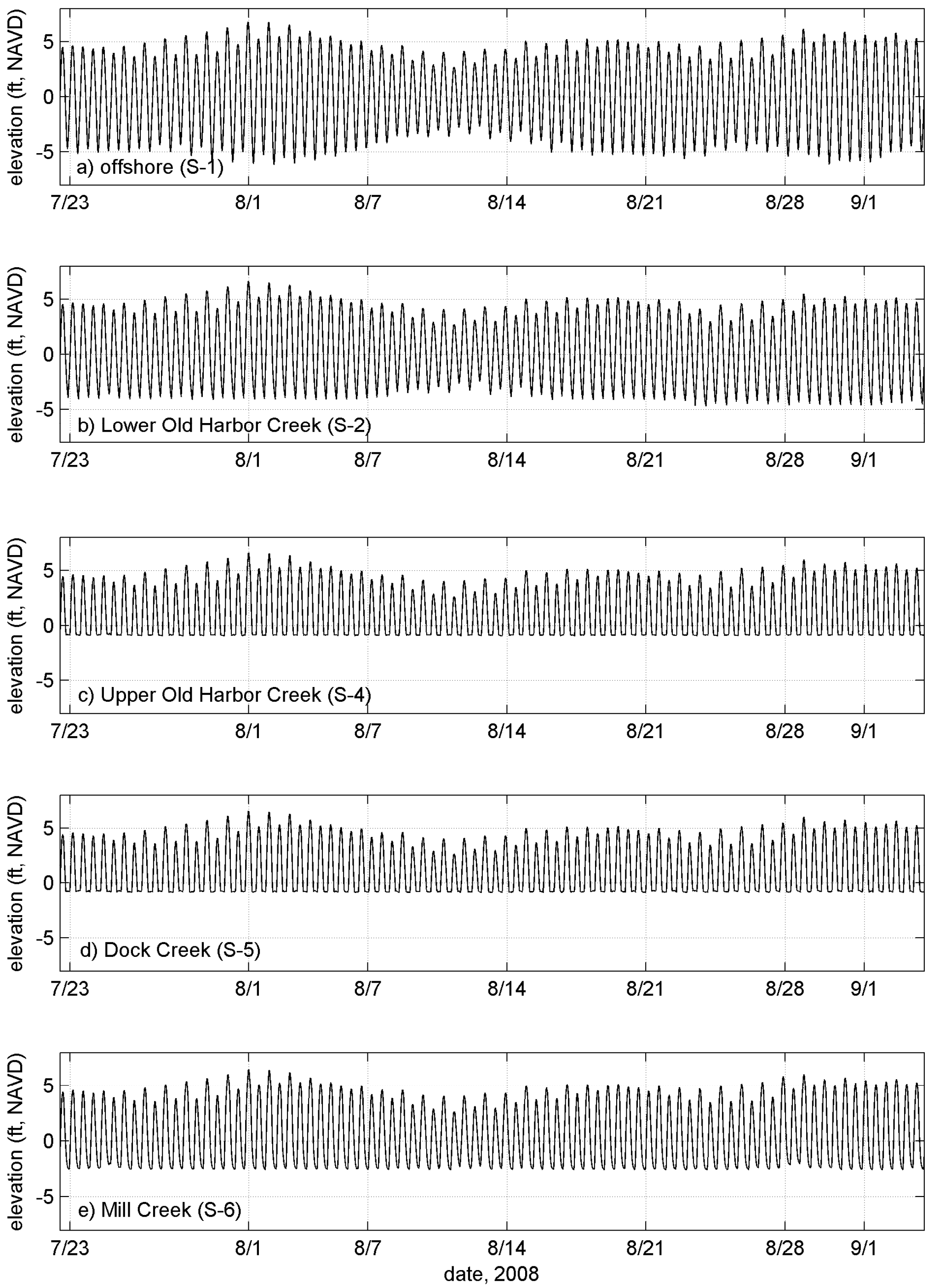


Figure V-3. Plots of observed tides for stations in Sandwich Harbor, for the 43-day period between July 22 and September 4, 2008. All water levels are referenced to the NAVD vertical datum.

Table V-1. Tide datums computed from 30-day records collected offshore and in the Sandwich Harbor system in July and August 2008. Datum elevations are given relative to NAVD vertical datum.

Tide Datum	Cape Cod Bay	Lower Old Harbor Creek	Upper Old Harbor Creek	Dock Creek	Mill Creek
Maximum Tide	6.8	6.6	6.6	6.5	6.5
MHHW	5.2	5.1	5.1	5.1	5.0
MHW	4.6	4.6	4.6	4.6	4.6
MTL	0.0	0.4	1.9	1.9	1.0
MLW	-4.7	-3.8	-0.9	-0.8	-2.5
MLLW	-4.9	-3.9	-0.9	-0.9	-2.5
Minimum Tide	-6.2	-4.1	-0.9	-0.9	-2.6
Mean Range	9.3	8.5	5.5	5.4	7.1

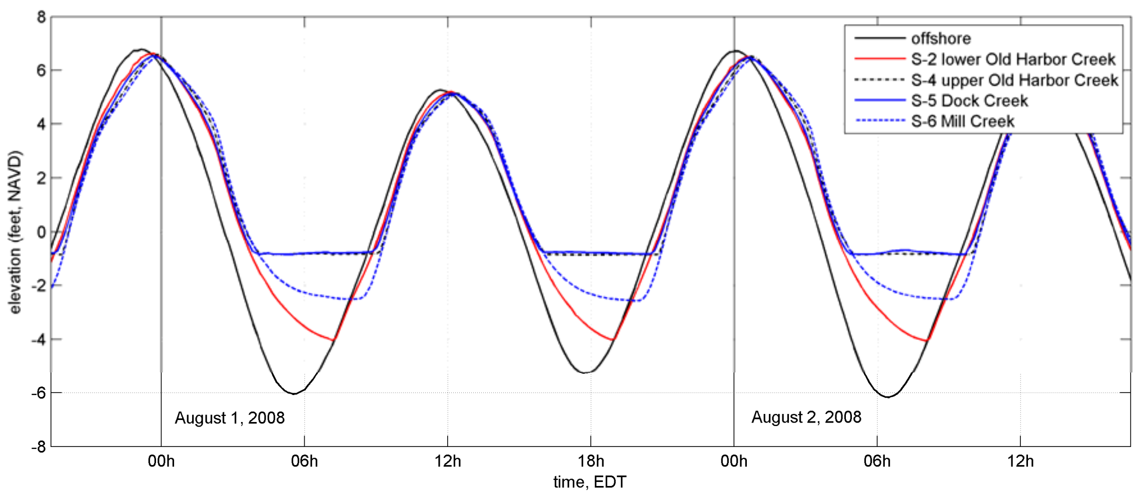


Figure V-4. Four-day tide plot showing tides measured in Cape Cod Bay and at stations in the Sandwich Harbor system. Demonstrated in this plot is the frictional damping effect that slightly decreases the elevation of high tide and greatly increases the elevation of low tide at the harbor entrance and in Mill Creek.

The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.3 feet and 0.2 respectively. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, also contribute to the total tide signal, with amplitudes of 0.3 feet and 0.4 feet, respectively. The M_4 and M_6 tides are higher frequency harmonics of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water.

Generally, it can be seen that as the total tide range is attenuated through the system there is a corresponding reduction in the amplitude of the individual tide constituents. The M_4 is one constituent that is observed to increase in amplitude between the offshore station and the stations inside the harbor. The M_6 also increases in amplitude by a smaller amount between the inlet and the upstream gauges. Again, this is due to energy transferring from the M_2 to these overtides due to frictional losses across the system.

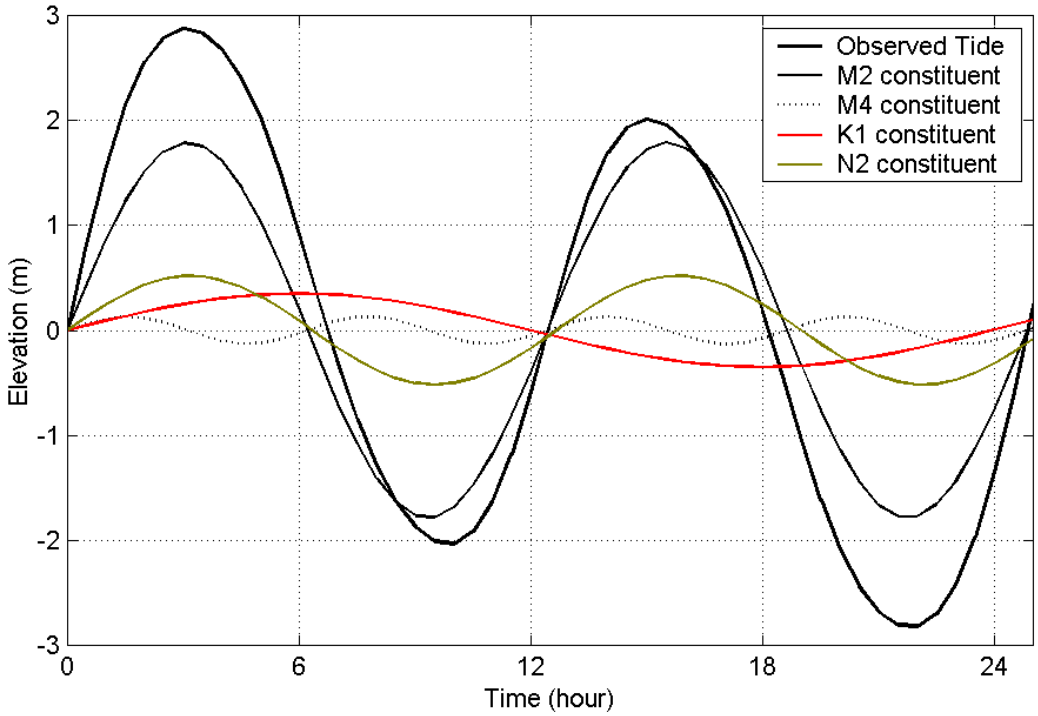


Figure V-5. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-2. Tidal Constituents computed for tide stations in the Sandwich Harbor system and offshore in Cape Cod Bay, July to September 2008.

	Amplitude (feet)						
Constituent	M_2	M_4	M_6	S_2	N_2	K_1	O_1
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82
Cape Cod Bay	4.36	0.08	0.14	0.73	0.88	0.47	0.45
Lower Old Harbor Creek	3.96	0.15	0.03	0.60	0.69	0.43	0.46
Mill Creek	3.50	0.49	0.16	0.52	0.57	0.42	0.45
Upper Old Harbor Creek	2.70	0.72	0.15	0.43	0.47	0.36	0.38
Dock Creek	2.69	0.72	0.14	0.42	0.47	0.35	0.39

Together with the change in constituent amplitude across Harbor, the phase change of the tide is easily seen from the results of the harmonic analysis. Table V-3 shows the delay of the M_2 at different points in the Sandwich Harbor system, relative to the timing of the M_2 constituent in Cape Cod Bay, offshore the harbor entrance. Between the offshore and the inlet basin there is a 19 minute delay in the M_2. This is not a large delay, considering that the period of this constituent is more than 12 hours. A larger delay is seen in the analysis of the data at the upper ends of the marsh creeks. The delay is greatest at the Mill Creek gauging station, where the M_2 phase is more than 30 minutes later than offshore.

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

The results of an analysis to determine the energy distribution (or variance) of the measured water elevation records for the gauge records in Sandwich Harbor compared to the energy content the astronomical tidal signal (re-created by summing the contributions from the 21 constituents determined by the harmonic analysis) is presented in Table V-3. Subtracting the tidal signal from the original elevation time series resulted in the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary. Figure V-6 shows the comparison of the measured tide from Cape Cod Bay, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual. It is possible that some of the observed residual tide signal (higher frequency changes) is due to the influence of the Cape Cod Canal, which communicates with Buzzards Bay. Tides in Cape Cod and Buzzards Bay are not synchronized, and the canal has a demonstrable effect on tides in the north end of Buzzards Bay (Howes, et al., 2013).

Table V-4 shows that the variance of tidal energy was largest in the offshore signal, as should be expected. The analysis also shows that tides are responsible for nearly 100% of the water level changes in Cape Cod Bay and all of Sandwich Harbor for the gauge deployment period. This indicates that the hydrodynamics of the system is influenced predominantly by astronomical tides. The non-tidal residual is largest by percentage in the upper reach of the main Old Harbor Creek channel.

Table V-3. M_2 tidal constituent phase delay (relative to Cape Cod Bay station) for gauge locations in the Sandwich Harbor system, determined from measured tide data.

Station	Delay (minutes)
Inlet Basin	18.7
Mill Creek	31.4
Dock Creek	20.4
Old Harbor Creek	24.5

Table V-4. Percentages of Tidal versus Non-Tidal Energy for stations in the Sandwich Harbor system and Cape Cod Bay, July to September, 2008.

TDR Location	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Cape Cod Bay	11.09	99.5	0.5
Inlet Basin	9.01	98.8	1.2
Mill Creek	4.72	97.6	2.4
Dock Creek	4.67	97.8	2.2
Old Harbor Creek	4.72	97.6	2.4

V.2.2.a Tide Flood and Ebb Dominance

An investigation of the flood or ebb dominance of different areas in the Sandwich Harbor system was performed using the measured tide data. Marsh systems are typically flood dominant, meaning that maximum flood tide velocities are greater than during the ebb portion of the tide. Flood dominance indicates a tendency to collect and trap sediment, which is required to maintain healthy marsh resources.

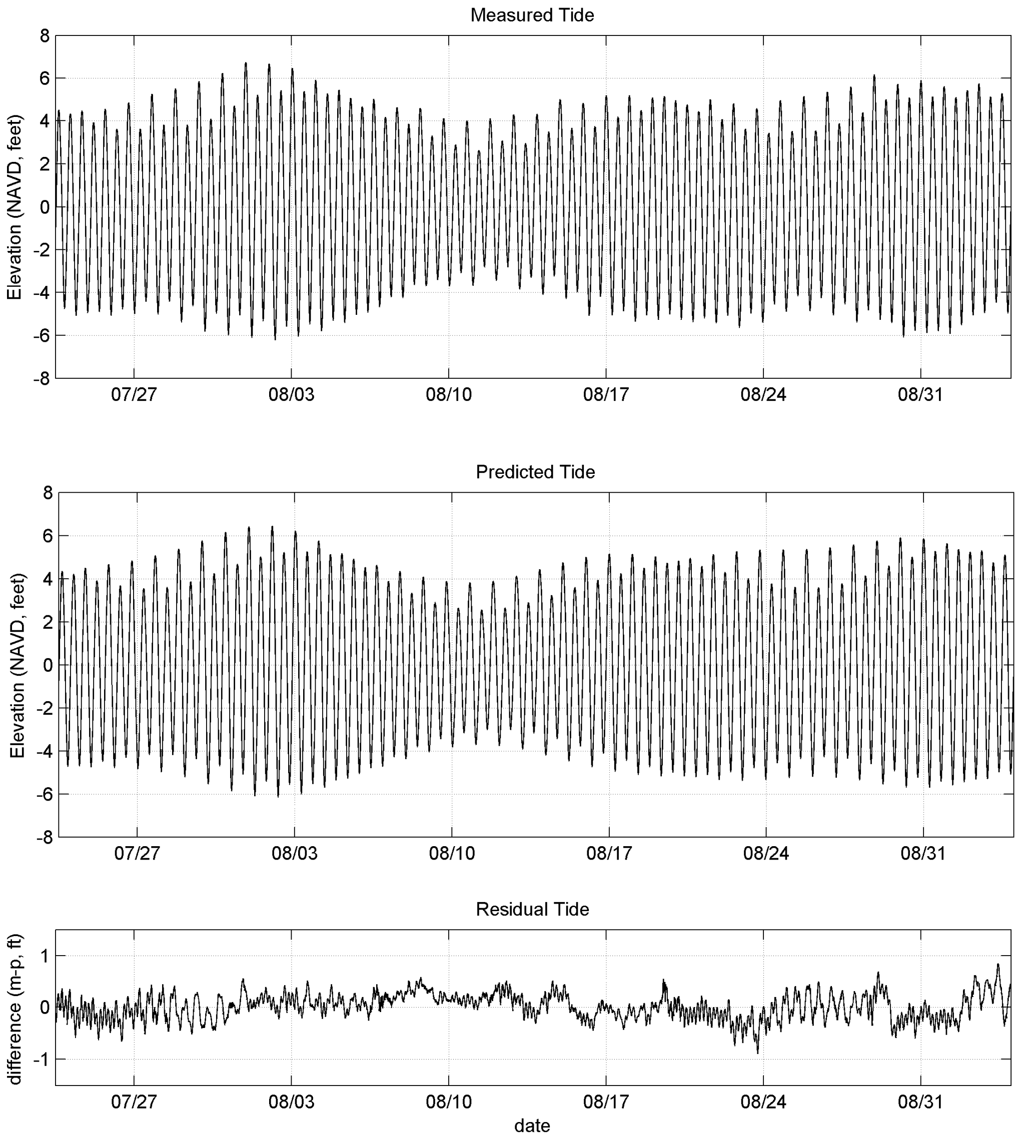


Figure V-6. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 21 individual tide constituents determine in the harmonic analysis of the Cape Cod Bay gauge data, collected offshore Sandwich Harbor. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (r=m-p).

Flood or ebb dominance in channels of a tidal system can be determined by performing a harmonic analysis of either tidal currents or elevations. A discussion of the method of relative phase determination is presented in Friedrichs and Aubrey (1988). For this method, the same M_2 and M_4 tidal constituents presented in Table V-2 were used as the basis of this analysis.

The relative phase difference is computed as the difference between two times the M_2 phase and the phase of the M_4, expressed as $\Phi=2M_2-M_4$. If Φ is between 0 and 180 degrees

(0<Φ<180), then the channel is characterized as being flood dominant, and peak flood velocities will be greater than for peak ebb. Alternately, if Φ were between 180 and 360 degrees (180<Φ<360), then the channel would be ebb dominant. If Φ is exactly 0 or 180 degrees, neither flood nor ebb dominance occurs. For Φ equal to exactly 90 or 270 degrees, maximum tidal distortion occurs and the velocity residuals of a channel are greatest. This relative phase relationship is presented graphically in Figure V-7.

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

The five gauge stations in the harbor were used for this analysis. These data make it possible to characterize the flood or ebb dominance of different areas of the system from offshore (S-1 in Cape Cod Bay) through to the upper reaches of the main tidal creeks (e.g., SH-4 in Old Harbor Creek).

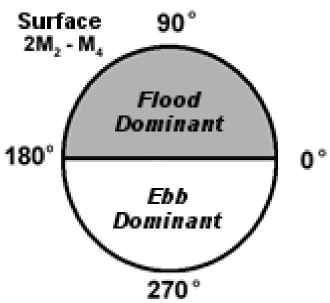


Figure V-7. Relative velocity phase relationship of M2 and M4 tidal elevation constituents and characteristic dominance, indicated on the unit circle. Relative phase is computed as the difference of two times the M2 phase and the M4 phase (2M2-M4). A relative phase of exactly 90 or 270 degrees indicates a symmetric tide, which is neither flood nor ebb dominant.

The results of this velocity analysis of the Sandwich Harbor measured tide data show that although the offshore gauge is ebb dominant, all interior gauge station are indeed flood dominant, as is expected for a marsh. The computed values of $2M_2$-M_4 are presented in Table V-5. It is also seen that the upper portions of the marsh creeks tend to be weekly flood dominant, which indicates that the upper areas of the Harbor are closer to being in equilibrium. An estuary may be initially strongly flood dominant. Over time as sediment collects within the estuary basin and builds up the marsh plain, it becomes less flood dominant and closer to being in equilibrium.

Table V-5. Sandwich Harbor relative tidal phase differences of M_2 and M_4 tide constituents, determined using tide elevation record records.

location	$2M_2$-M_4 relative phase (deg)	Characteristic dominance
Cape Cod Bay, S-1	217.7	Moderate Ebb
Inlet Basin, S-2	52.3	Moderate Flood
Old Harbor Creek, S-4	8.0	Weak Flood
Dock Creek, S-5	7.3	Weak Flood
Mill Creek, S-6	32.6	Moderate Flood

V.3 HYDRODYNAMIC MODELING

For the modeling of the Sandwich Harbor system, MEP Technical Team members from Applied Coastal Research and Engineering (ACRE) utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in the Harbor. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2 for numerous flushing studies on Cape Cod, including Nauset Harbor, Popponesset Bay, Nantucket Harbor, Falmouth "finger" Ponds (Howes *et al*, 2005), Three Bays (Kelley *et al*, 2003) and Barnstable Harbor (Wood, *et al*, 1999).

V.3.1 Model Theory

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

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 prototypical system. Element boundaries may either be curved or straight.

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

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

V.3.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. 2009 digital aerial orthophotos, the 2008 bathymetry survey data, and available LiDAR topography were imported to SMS, and a finite element grid was generated to represent the estuary. The aerial photograph was used to determine the land boundary of the system, as well as determine the surface coverage of salt marsh. The bathymetry and topography data were interpolated to the developed finite element mesh of the system. The completed grid consists of 13,943 nodes, which describe 5,424 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth is -16ft (NGVD) along the open boundary of the grid in Cape Cod Bay, and the typical modeled marsh plain elevation is 3.5 ft, based on the LiDAR measurements. The completed grid mesh of the Sandwich Harbor system is shown in Figure V-8.

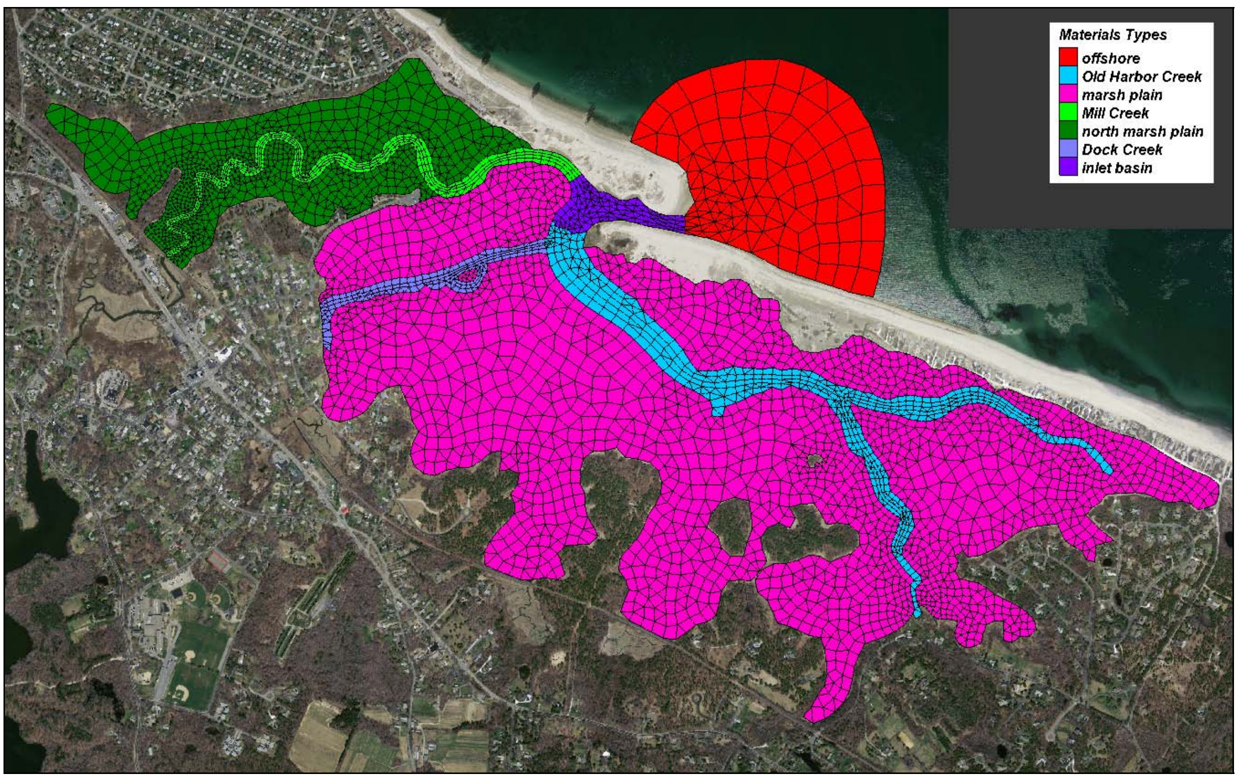


Figure V-8. Plot of hydrodynamic model grid mesh for Sandwich Harbor. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Sandwich Harbor. Areas of marsh were included in the model because they represent a significant portion of the total surface area of this system. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Grid resolution is generally governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution is employed where complex flow patterns are expected, generally near the inlet. Appropriate implementation of wider node spacing and larger elements reduces computer run time with no sacrifice of accuracy.

V.3.2.2 Boundary condition specification

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

V.3.2.3 Calibration

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

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

Once visual agreement was achieved, a 7-day period (14 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section V.2. The 7-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibration was performed for a 7-day period beginning July 27, 2008 at 0600 EDT.

After the model was calibrated, an additional verification run was made in order test the model performance in a time period outside of the calibration period. The model verification was performed for the seven-day period beginning August 16, 2000 at 0000 EDT.

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

V.3.2.3.a Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient, and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.020 and 0.070 were specified for all element material types. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels and marsh plains with higher friction (Henderson, 1966).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning's coefficients were matched to bottom type. For example, lower friction coefficients were specified for the main marsh creeks, versus the extensive marsh plain areas of the Harbor, which provide greater flow resistance by the presence of marsh vegetation. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based on ranges provided by the available engineering references (Chow, 1959). Values were incrementally changed as appropriate to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-6.

Table V-6. Manning's Roughness and eddy viscosity coefficients used in simulations of the Sandwich Harbor system. These embayment delineations correspond to the material type areas shown in Figure V-11.

System Embayment	bottom friction	eddy viscosity lb-sec/ft^2
Cape Cod Bay	0.025	100
Old Harbor Creek channel	0.020	50
Sandwich Harbor marsh Plain	0.050	100
Mill Creek channel	0.020	50
Mill Creek marsh plain	0.050	100
Dock Creek Channel	0.020	50
Inlet Basin	0.020	50

V.3.2.3.b Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 50 and 100 lb-sec/ft^2 (Table V-6). The higher values were used offshore and on the marsh plain.

V.3.2.3.c Marsh porosity processes

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

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

A best-fit of model output for the measured data was achieved using the aforementioned values for friction and turbulent exchange. Figures V-9 through V-13 illustrate sections of the 7-day simulation periods for the calibration model. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the system embayments. Four tidal constituents were selected for constituent comparison: the K_1, M_2, M_4 and M_6. After calibrating the model its performance was further corroborated by running the model for an additional verification time period (August 17 through August 24, 2008).

Measured tidal constituent amplitudes are shown in Table V-7 for the calibration and Table V-8 for the verification simulation. The constituent amplitudes shown in this table differ from those in Table V-2 because constituents were computed for only the separate 7-day sub-sections of the month-long period represented in Table V-2. In Tables V-7 and V-8, error statistics are shown for the calibration and verification.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The errors associated with tidal constituent amplitude for both the calibration and verification simulations were on the order of 0.1 ft, which is of the same order magnitude of the accuracy of the tide gauges (0.25 ft). Time lag errors for the main estuary reach were generally less than the time increment resolved by the model and tide data (10 minutes), indicating good agreement between the model and data. The skill of the model calibration is also demonstrated by the high degree of correlation (R^2) and low RMS error shown in Table V-9 for all stations.

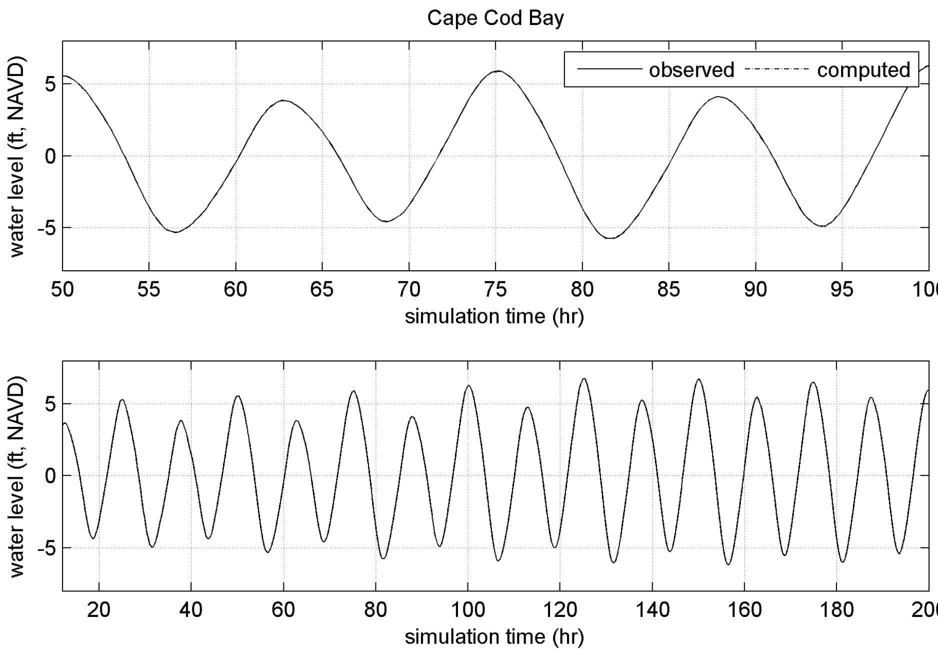


Figure V-9. Comparison of model output and measured tides for the TDR station offshore for the final calibration model run (July 27, 2008 at 0600 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

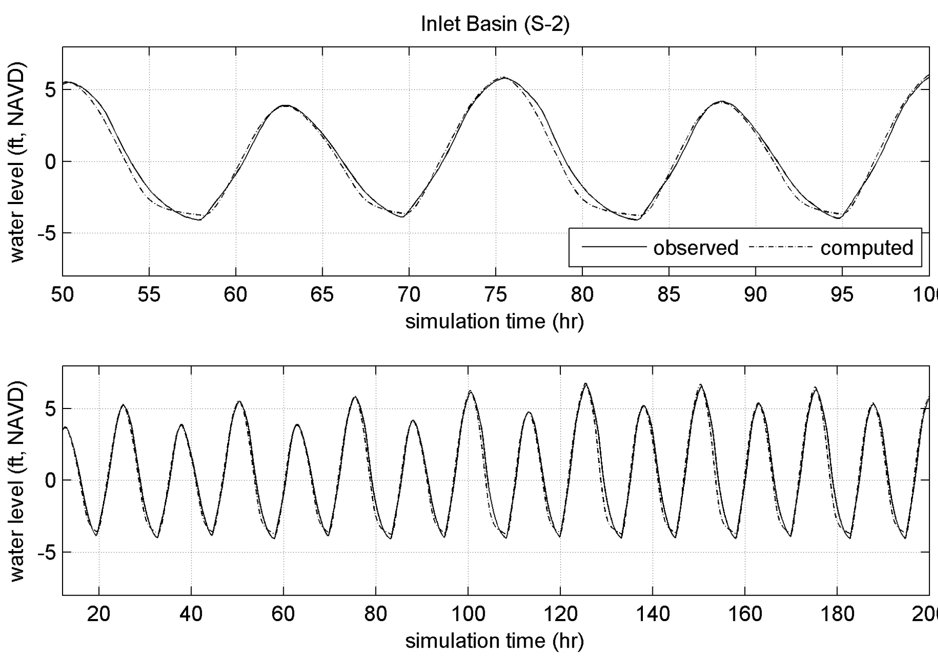


Figure V-10. Comparison of model output and measured tides for the TDR location at the inlet basin (S-2) for the final calibration model run (July 27, 2008 at 0600 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

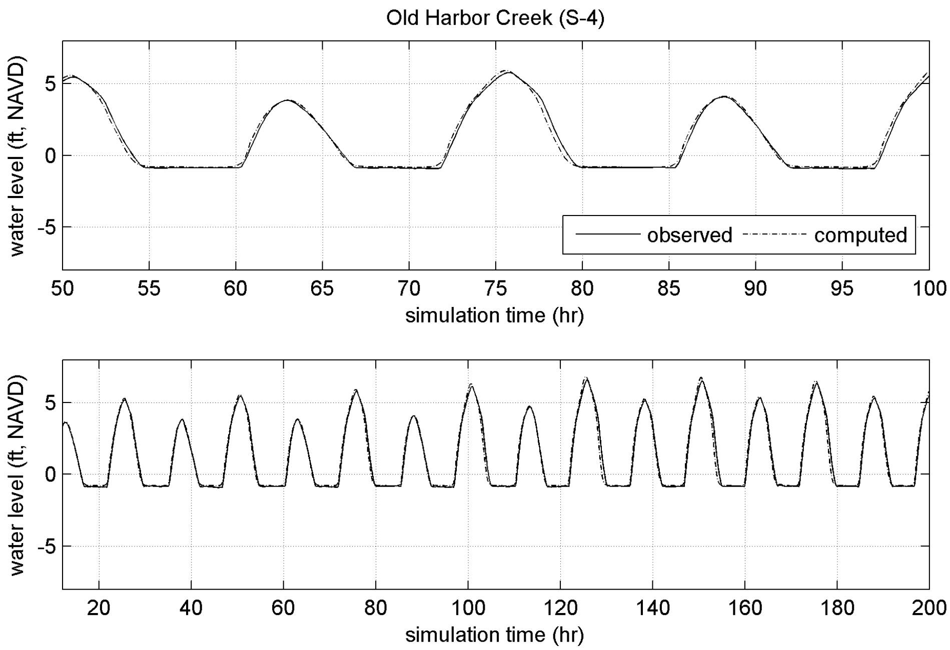


Figure V-11. Comparison of model output and measured tides for the TDR location in Old Harbor Creek (S-4) for the final calibration model run (July 27, 2008 at 0600 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

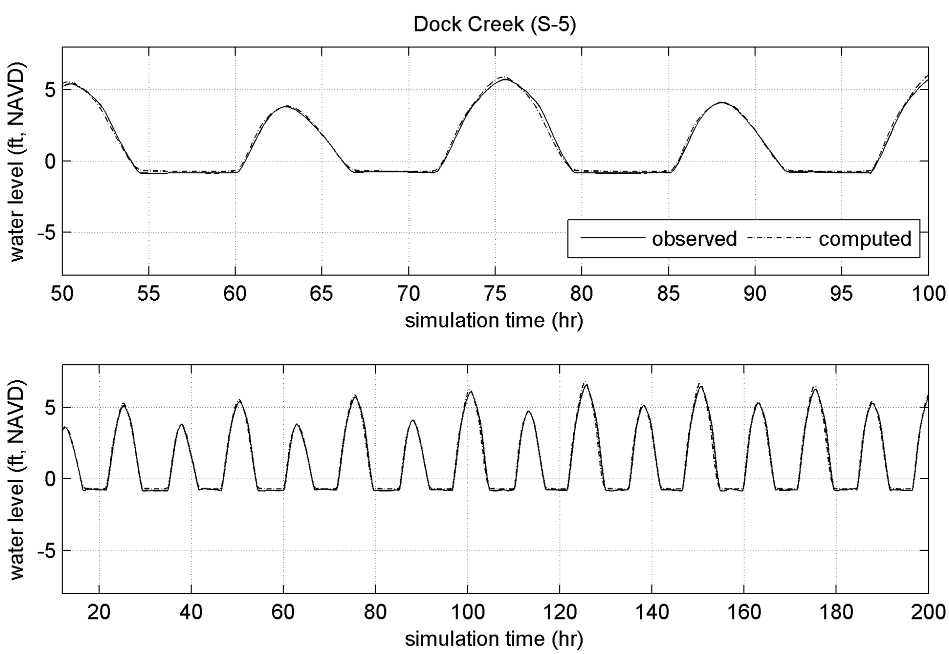


Figure V-12. Comparison of model output and measured tides for the TDR location in Dock Creek (S-5) for the final calibration model run (July 27, 2008 at 0600 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

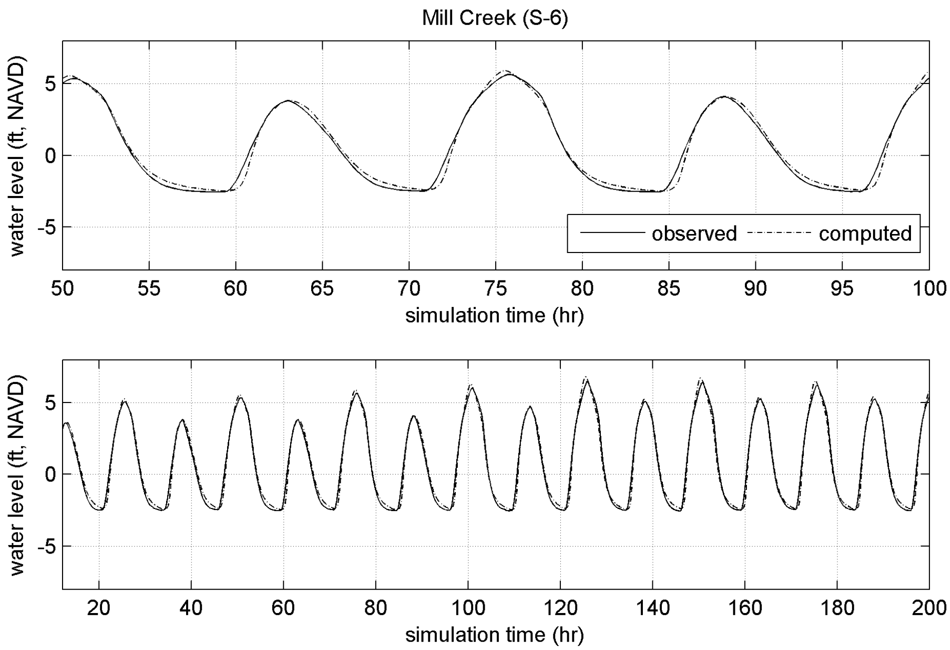


Figure V-13. Comparison of model output and measured tides for the TDR location in Mill Creek (S-6) for the final calibration model run (July 27, 2008 at 0600 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

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

Model calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay	5.10	0.10	0.18	0.86	38.6	-12.9
Inlet Basin	4.48	0.35	0.16	0.76	42.6	56.1
Old Harbor Creek	3.10	0.91	0.16	0.65	47.2	88.1
Dock Creek	3.03	0.88	0.15	0.64	46.6	84.9
Mill Creek	3.84	0.77	0.27	0.75	58.3	78.2
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay	5.10	0.09	0.18	0.86	39.2	-11.0
Inlet Basin	4.40	0.23	0.05	0.77	49.7	43.5
Old Harbor Creek	3.07	0.81	0.21	0.68	52.6	94.8
Dock Creek	3.05	0.81	0.20	0.66	50.2	91.1
Mill Creek	3.86	0.53	0.24	0.75	56.3	77.0
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay	0.00	0.01	0.00	0.00	1.2	2.0
Inlet Basin	-0.08	-0.12	-0.11	0.01	14.7	-13.0
Old Harbor Creek	-0.03	-0.10	0.05	0.03	11.1	6.9
Dock Creek	0.02	-0.07	0.05	0.02	7.5	6.4
Mill Creek	0.02	-0.24	-0.03	0.00	-4.1	-1.2

Table V-8. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for Sandwich Harbor, during modeled verification time period.

Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Model calibration run						
Cape Cod Bay	4.66	0.10	0.17	0.24	-22.9	63.3
Inlet Basin	4.15	0.34	0.13	0.21	-18.8	-56.4
Old Harbor Creek	2.72	0.91	0.10	0.17	-14.4	-32.0
Dock Creek	2.66	0.87	0.11	0.16	-14.9	-33.4
Mill Creek	3.50	0.82	0.26	0.20	-2.6	-37.1
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay	4.66	0.10	0.17	0.24	-22.3	63.2
Inlet Basin	4.15	0.23	0.06	0.21	-12.8	-55.2
Old Harbor Creek	2.74	0.90	0.14	0.17	-10.7	-26.0
Dock Creek	2.73	0.89	0.13	0.16	-12.8	-28.8
Mill Creek	3.62	0.67	0.19	0.20	-7.12	-38.9
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Cape Cod Bay	0.00	0.00	0.00	0.00	1.1	-0.1
Inlet Basin	0.00	-0.11	-0.07	0.00	12.2	1.3
Old Harbor Creek	0.02	-0.01	0.04	0.00	-9.4	-1.8
Dock Creek	0.07	0.02	0.02	0.00	4.4	4.7
Mill Creek	0.12	-0.15	-0.07	0.00	7.6	6.2

Table V-9. Error statistics for the Sandwich Harbor hydrodynamic model, for model calibration and verification.

	Calibration		Verification	
	R^2	RMS error	R^2	RMS error
Cape Cod Bay	1.00	0.00	1.00	0.00
Inlet Basin	0.98	0.49	0.98	0.38
Old Harbor Creek	0.98	0.30	0.99	0.16
Dock Creek	0.99	0.22	1.00	0.11
Mill Creek	0.99	0.33	0.98	0.33

V.3.3 Model Circulation Characteristics

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

Figure V-14. Example of Sandwich Harbor hydrodynamic model output for a single time step during a flooding tide. Color contours indicate velocity magnitude, and vectors indicate the direction of flow. Areas of marsh are also shown as the solid black lines within the model domain.

As another example, from the calibration model run of the Sandwich Harbor system, the total flow rate of water flowing through the inlet culvert can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-15. During spring tides, the maximum flood flow rates reach 12,000 ft^3/sec at the Sandwich Harbor inlet. Maximum ebb flow rates during spring tides are slightly smaller (10,200 ft^3/sec), which is another indication that the system is flood dominant.

V.3.4 Flushing Characteristics

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

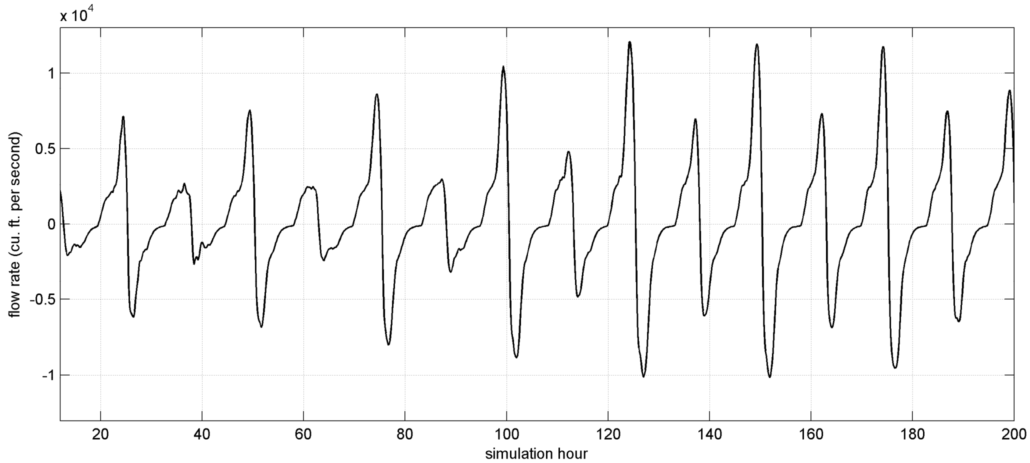


Figure V-15. Time variation of computed flow rates at the Sandwich Harbor inlet. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flow indicated flooding tide flows,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

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

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

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

In addition to system residence times, a second residence, the local residence time, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using Mill Creek as an example, the system residence time is the average time required for water to migrate from Mill Creek, through the inlet basin of Old Harbor Creek, out through the inlet and into Cape Cod Bay. Alternatively, the local residence time is the average time required for water to migrate from Mill Creek and to Old Harbor Creek (not all the way to the Bay). Local residence times for each sub-embayment are computed as:

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

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

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

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

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

Residence times were calculated as the volume of water (based on the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged over a flood tidal cycle (tidal prism). Units were converted to days. The volume of the entire estuary was computed as cubic feet. Only volume for the whole system were considered in this analysis, since the nature of the Sandwich Harbor system does not allow for convenient or meaningful subdivisions with regard to residence time calculation. System mean volume and tide prism are presented in Table V-10.

Table V-10. Sandwich Harbor mean volume and average tidal prism during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Sandwich Harbor System	35,973,900	61,633,700

Residence times were averaged for the tidal cycles comprising a representative 7 day period (14 tide cycles), and are listed in Table V-11. The modeled time period used to compute the flushing rates started July 26, 2008 similar to the model calibration period, and included the transition from neap to spring tide conditions. The RMA-2 model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume. Since the 7 day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

Table V-11. Computed System and Local residence times for the Sandwich Harbor system.

Embayment	System Residence Time (days)	Local Residence Time (days)
Sandwich Harbor System	0.3	0.3

The computed flushing rates for the entire system show that as a whole, the system flushes very well. A flushing time of 0.3 days for the entire estuary shows that on average, water is resident in the system for less than one day. The low local residence times for the whole of the Sandwich Harbor system show that water quality in the system is not impacted negatively by tidal flushing. This is a typical result for marsh dominated estuaries, where the tide prism volume is larger than the mean volume of the system.

For the smaller sub-embayments of the Harbor system, computed system residence times are typically one to four orders of magnitude longer than their corresponding local residence time. System residence times provide a qualitative measure that helps to identify the relative sensitivity of different sub-embayments to nutrient loading.

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

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

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

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

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the embayment was an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated hydrodynamic model representing the transport of water within the Sandwich Harbor system. Files of node locations and node connectivity for the RMA-2V model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic model output used for the water quality model calibration was the 7 day (14 tide cycle) period beginning July 27, 2008 0600 EDT. This period overlaps with that used in the flushing analysis presented in Chapter V. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic “steady state”, and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayments

Three primary nitrogen loads to the Sandwich Harbor embayment were utilized 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 Sandwich Harbor system, consisting of the background concentrations of total nitrogen in the water entering from Cape Cod Bay. 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 the area map presented in Figure VI-1. The multi-year averages present the “best” comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data are the minimum required to provide a baseline for MEP analysis. Three years of data (collected between 2005 and 2007) were available for stations in the harbor.

Table VI-1. Measured data and modeled nitrogen concentrations for the Sandwich Harbor estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of all measurements. Data represented in this table were collected in the summers of 2005, 2006 and 2007.

Location	Monitoring station	Data Mean	s.d. all data	N	model min	model max	model average
Offshore	SH-1	0.295	0.051	27	0.295	0.295	0.295
Inlet basin	SH-2	0.315	0.055	17	0.295	0.355	0.310
Lower Dock Creek	SH-3	0.320	0.104	15	0.287	0.425	0.327
Lower Mill Creek	SH-4	0.370	0.090	15	0.253	0.454	0.332
Upper Mill Creek	SH-5	0.694	0.235	17	0.460	0.716	0.627
Lower Old Harbor Creek	SH-6	0.302	0.047	16	0.295	0.354	0.310
Upper Dock Creek	SH-7	1.196	0.444	19	0.512	1.294	0.891
Sandwich Harbor	SH-8	0.302	0.036	18	0.295	0.416	0.343
Sandwich Harbor	SH-9	1.120	0.373	19	0.633	1.190	0.952
Sandwich Harbor	SH-10	0.325	0.067	18	0.295	0.348	0.313
Mid Old Harbor Creek	SH-11	0.310	0.051	17	0.295	0.345	0.312
Lower Spring Hill Creek	SH-12	0.316	0.058	18	0.295	0.342	0.315
Upper Spring Hill Creek	SH-13	0.590	0.116	16	0.381	0.387	0.385
Upper Old Harbor Creek	SH-14	0.492	0.098	18	0.315	0.420	0.361
Upper Old Harbor Creek	SH-15	0.746	0.219	15	0.763	0.841	0.806

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 Sandwich Harbor estuarine system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of Sandwich Harbor. Like the RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. The MEP Technical Team has utilized this model in water quality studies of other embayment systems in southeastern Massachusetts, including Pleasant Bay (Howes *et al*., 2006); New Bedford Harbor (Howes *et al*., 2008); Edgartown Great Pond, MA (Howes *et al*., 2008) and Scorton Creek (Howes et al., 2014) to name a few.

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

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

VI.2.1 Model Formulation

The formulation of the model is for two-dimensional depth-averaged systems in which concentration in the vertical direction is assumed uniform. The depth-averaged assumption is justified since vertical mixing by wind and tidal processes prevent significant stratification in the modeled embayment. 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 is the water quality constituent concentration; t is time; u and v are the velocities in the x and y directions, respectively; D_x and D_y are the model dispersion coefficients in the x and y directions; and σ is the constituent source/sink term. Since the model utilizes input from the RMA-2 model, a similar implicit solution technique is employed for the RMA-4 model.

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

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

VI.2.2 Water Quality Model Setup

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

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

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included: 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-watershed to the embayment were distributed by watershed. For example, the watershed load for Mill Creek was input at the head of the creek. Benthic loads were distributed at a specific number of grid elements within the separate tidal creeks in the Harbor system.

The loadings used to model present conditions in the Sandwich Harbor system are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each portion of the overall 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. In the main marsh channel, Old Harbor Creek, the net benthic flux is negative which indicates a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in Cape Cod Bay, offshore the harbor inlet, was set at 0.295 mg/L, based on SMAST data collected offshore of the Harbor inlet.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Mill Creek	17.559	0.121	2.612
Dock Creek	6.200	0.359	0.224
Old Harbor Creek	16.622	0.433	-2.959
System Total	40.381	0.912	-0.123

VI.2.4 Model Calibration

The development of the Sandwich Harbor water quality model began with the parameterization and calibration of the salinity model. Salinity is a conservative water quality constituent and therefore ideally suited for model calibration. Model dispersion coefficients were adjusted so that model output salinity matched measured data from the harbor. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (E) values were varied through the modeled system by setting different values of E for each grid material type, as designated in Section V. Observed values of E in coastal estuary areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of E used in each sub-embayment of the modeled system are presented in Table VI-3. These values were used to develop the “best-fit” salinity model calibration. For the case of salinity 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 the model domain.

The only required inputs into the RMA-4 salinity model of the system, in addition to the RMA-2 hydrodynamic model output, were salinities at the model open boundary, rain, surface water and groundwater inputs. The open boundary salinity in Cape Cod Bay was set at 31.1 ppt. Surface water and groundwater input salinities were set at 0 ppt. The total fresh water inputs to the model are 10.0 ft^3/sec (0.28 m^3/sec) for the Mill Creek watershed, 3.6 ft^3/sec (0.10 m^3/sec) for the Dock Creek watershed, 2.2 ft^3/sec (0.06 m^3/sec) for the Spring Hill Creek watershed, and 5.5 ft^3/sec (0.15 m^3/sec). Groundwater flows were distributed evenly in the model along elements positioned along the model’s land boundary.

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

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

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

Embayment Division	E m^2/sec
Cape Cod Bay	10
Old Harbor Creek	10
Old Harbor Creek marsh plain	10
Mill Creek	10
Mill Creek marsh plain	10
Dock Creek	10
Inlet basin	10

Also presented in Figure VI-3 are unity plot comparisons of measured data verses modeled target values for each system. The computed R^2 correlation is 0.92 and the root mean squared (rms) error is 3.2 ppt, both of which demonstrate an excellent fit between modeled and measured data for this system.

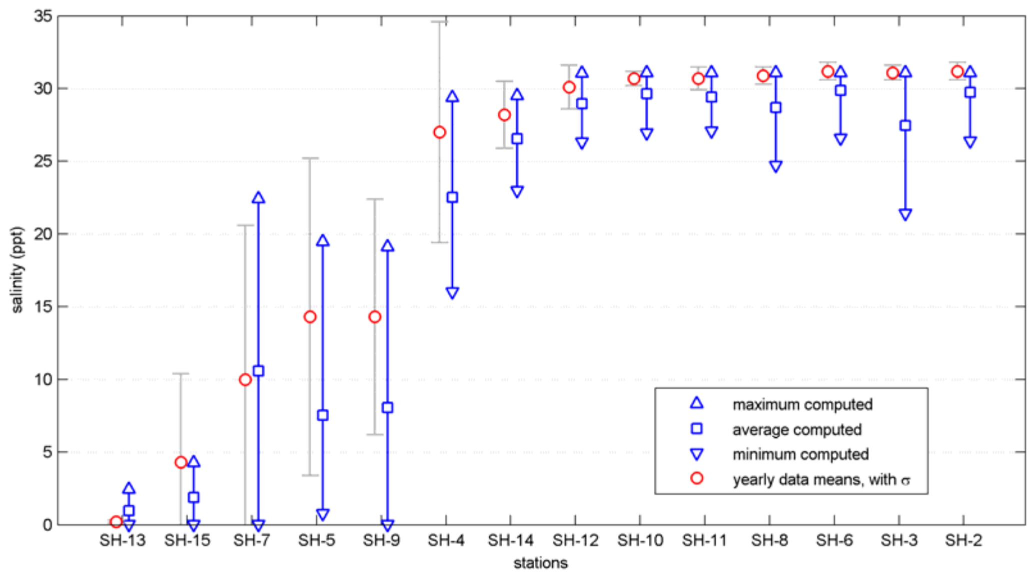


Figure VI-2. Comparison of measured total salinity and calibrated model output at stations in the Sandwich Harbor system. Station labels correspond with the MEP IDs provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period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

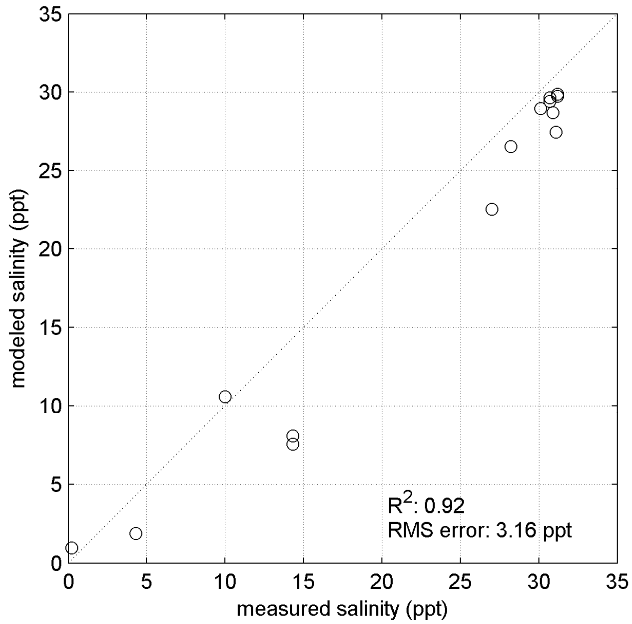


Figure VI-3. Model salinity calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are 0.92and 3.16 ppt respectively.

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

VI.2.5 Model Verification

In addition to the model calibration based on salinity, the numerical water quality model performance was verified by modeling total nitrogen (TN). This step was performed for the Sandwich Harbor system using TN measurements collected at the same stations as the salinity data and N loads from Table VI-2. For the TN verification, none of the model dispersion coefficients were changed from the values used in the salinity calibration. Comparisons of modeled and measured TN concentrations are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. The R^2 correlation of the model and measurements is 0.84 and the rms error of the model is 0.12 mg/L.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

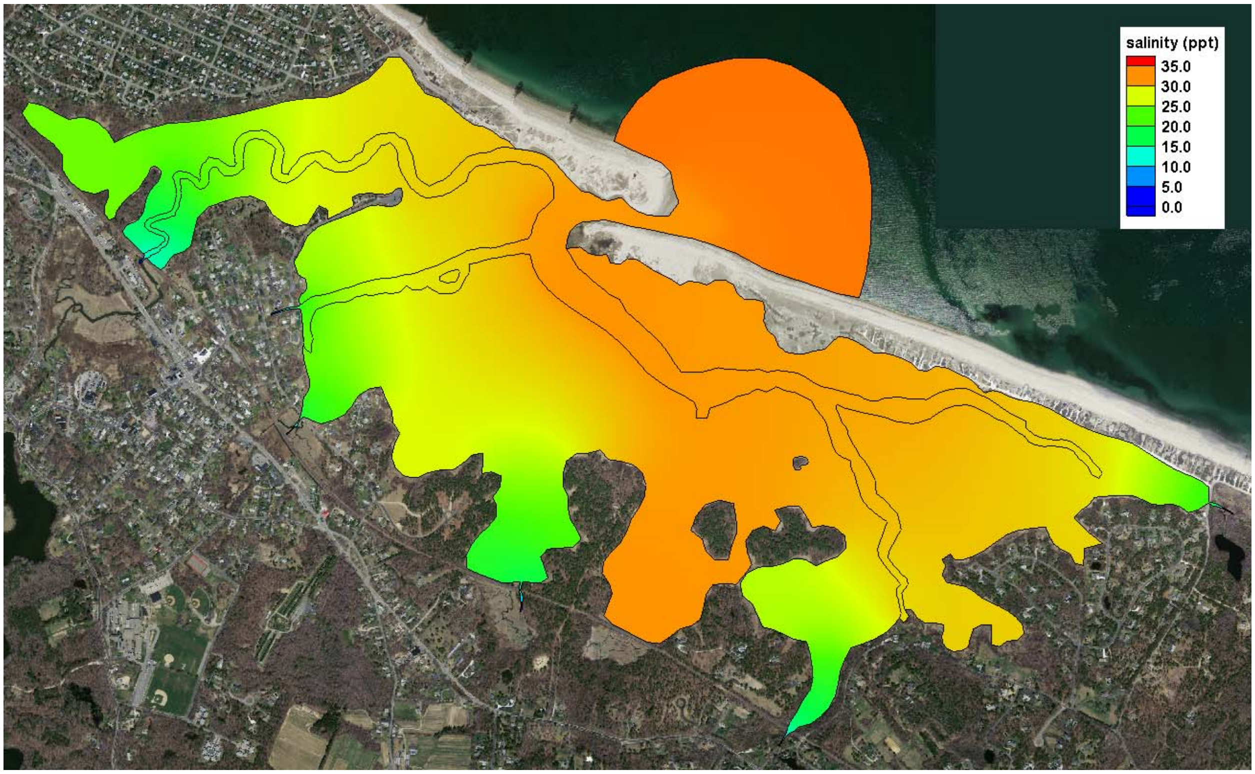


Figure VI-4. Contour Plot of average modeled salinity (ppt) in the Sandwich Harbor system.

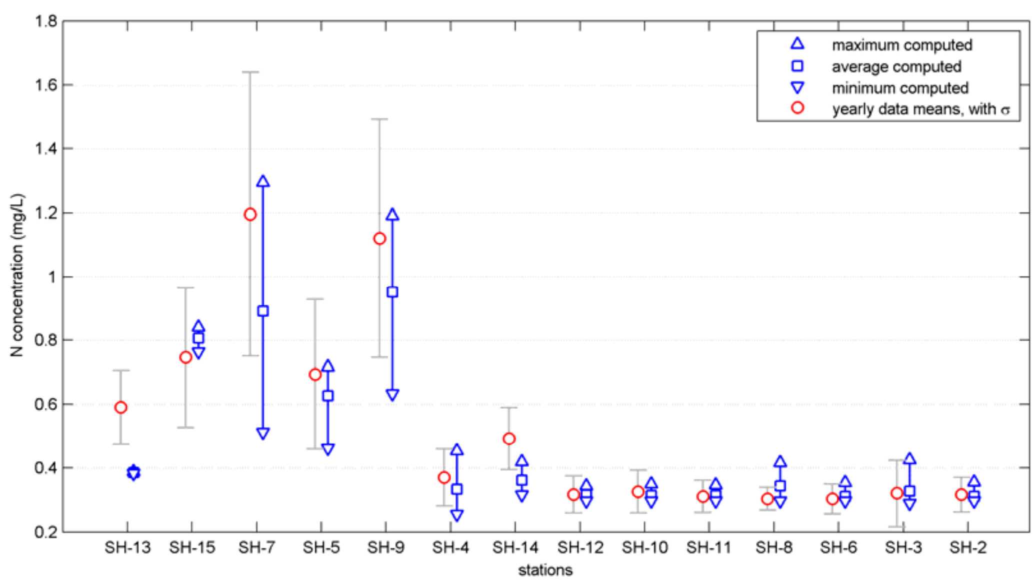


Figure VI-5. Comparison of measured and calibrated TN model output at stations in Sandwich Harbor. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along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

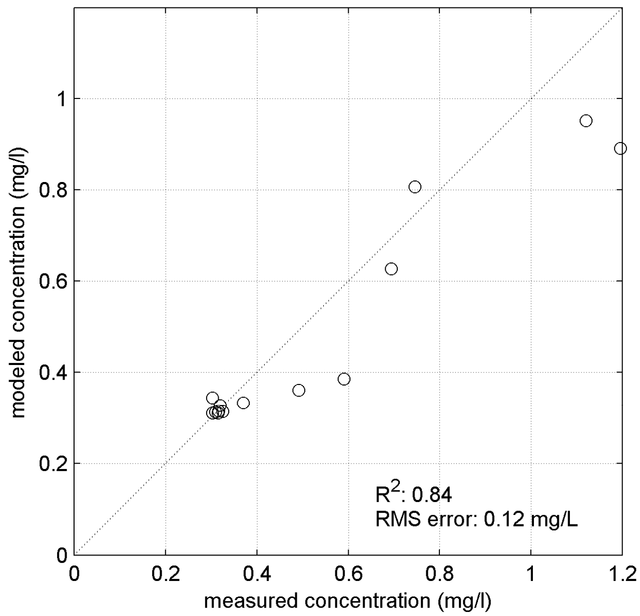


Figure VI-6. Model TN target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) is 0.84 and RMS error for this model verification run is 0.12 mg/L.

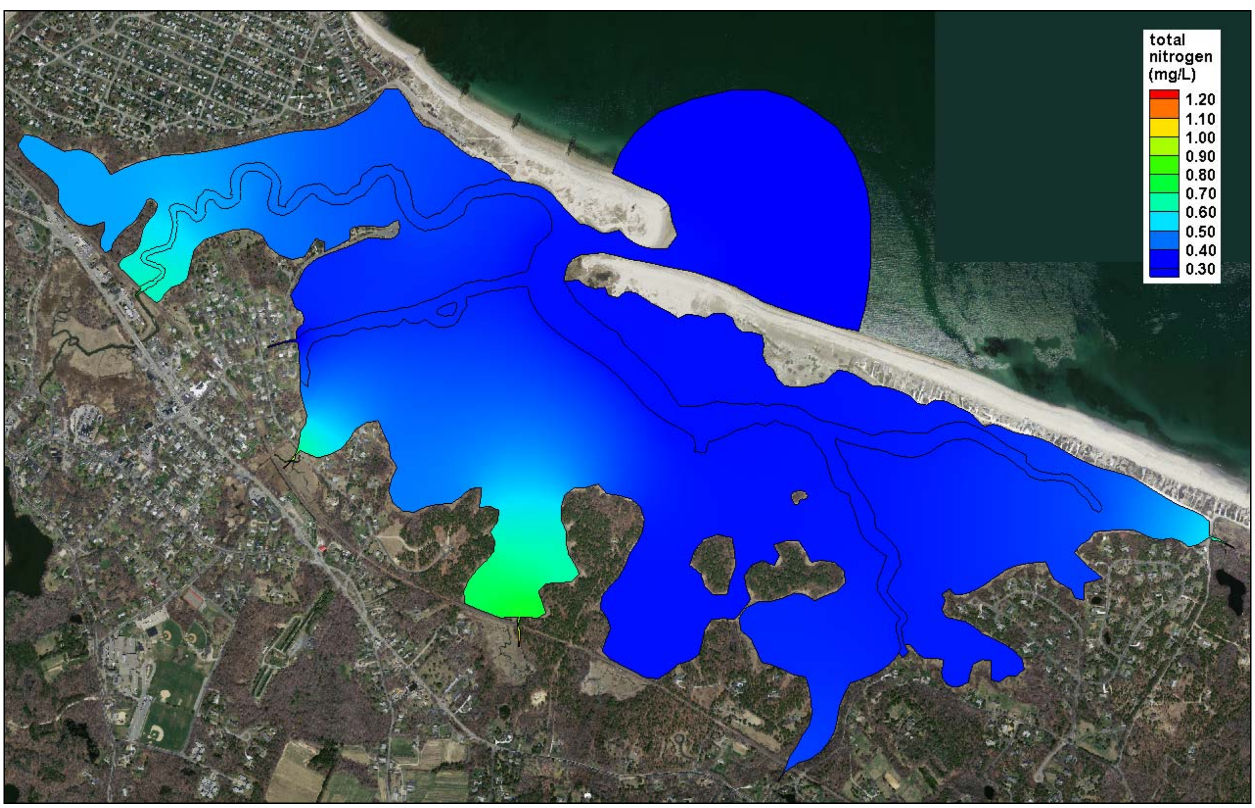


Figure VI-7. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Sandwich Harbor system

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

sub-embayment	present load (kg/day)	Build-out (kg/day)	build-out % change	no load (kg/day)	no load % change
Mill Creek	17.559	19.833	+13.0%	2.052	-88.3%
Dock Creek	6.200	9.463	+52.6%	0.636	-89.7%
Old Harbor Creek	16.622	22.079	+32.8%	1.268	-92.4%
System Total	40.381	51.375	+27.2%	3.956	-90.2%

VI.2.6.1 Build-Out

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

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Mill Creek	19.833	0.121	2.827
Dock Creek	9.463	0.359	0.231
Old Harbor Creek	22.079	0.433	-3.164
System Total	51.375	0.912	-0.106

Following development of the nitrogen loading estimates for the build-out scenario, the water quality models of the system was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). In this table, the percent change *P* over background presented in this table is calculated as:

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

where N is the nitrogen concentration at the indicated monitoring station for present conditions and the loading scenario (i.e., build-out in this case), and also in Cape Cod Bay (background). Total nitrogen concentrations in the receiving waters (i.e., Cape Cod Bay) remained identical to the existing conditions modeling scenarios. For build-out, the percent increase in modeled TN concentrations is greatest at the lower Mill Creek monitoring station (SH-4), where concentrations increase more than 120% above background. The largest TN magnitude change occurs at station SH-7 at upper Dock Creek, where average TN increases 0.39 mg/L. A contour plot showing average TN concentrations throughout the harbor system is presented in Figure VI-8 for the model of build-out loading.

Table VI-6. Comparison of model average total N concentrations from present loading and the **build-out scenario**, with percent change over background in Cape Cod Bay (0.295 mg/L), for the Sandwich Harbor system.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out (mg/L)	% change
Inlet basin	SH-2	0.310	0.318	+49.7%
Lower Dock Creek	SH-3	0.327	0.348	+68.6%
Lower Mill Creek	SH-4	0.332	0.380	+128.4%
Upper Mill Creek	SH-5	0.627	0.698	+21.6%
Lower Old Harbor Creek	SH-6	0.310	0.319	+55.3%
Upper Dock Creek	SH-7	0.891	1.281	+65.3%
Sandwich Harbor	SH-8	0.343	0.368	+50.6%
Sandwich Harbor	SH-9	0.952	1.259	+46.8%
Sandwich Harbor	SH-10	0.313	0.323	+53.8%
Mid Old Harbor Creek	SH-11	0.312	0.322	+56.9%
Lower Spring Hill Creek	SH-12	0.315	0.326	+56.6%
Upper Spring Hill Creek	SH-13	0.385	0.422	+41.0%
Upper Old Harbor Creek	SH-14	0.361	0.397	+55.3%
Upper Old Harbor Creek	SH-15	0.806	1.083	+54.1%

VI.2.6.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering each sub-embayment for the no anthropogenic load ("no load") scenarios is shown in Table VI-7. The benthic flux input to each embayment was reduced (toward zero) based on the reduction in the watershed load (as discussed in 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.

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations at each monitoring station. Again, total nitrogen concentrations in the receiving waters (i.e., Cape Cod Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was large, with all areas of the system experiencing reductions greater than 100%, compared to the background concentration of 0.295 mg/L in Cape Cod Bay (Table VI-8). Average TN concentrations drop below background in Cape Cod Bay because the relatively large freshwater inflow to the Harbor dilutes the small N load to the system. A contour plot showing TN concentrations throughout the system is presented in Figure VI-9.

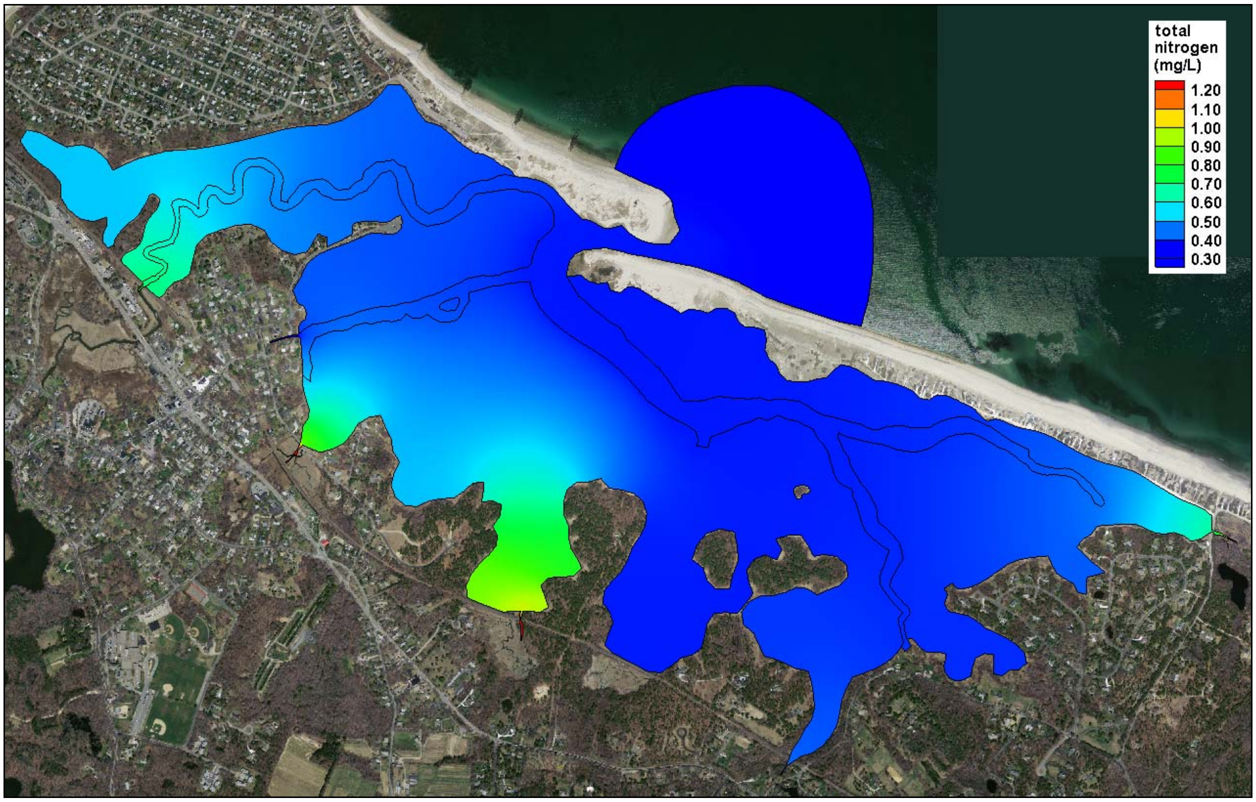


Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Sandwich Harbor system, for projected build-out scenario loading conditions.

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

Station Location	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Mill Creek	2.052	0.121	1.905
Dock Creek	0.636	0.359	0.194
Old Harbor Creek	1.268	0.433	-2.232
System Total	3.956	0.912	-0.132

Table VI-8. Comparison of model average total N concentrations from present loading and the "**No anthropogenic loading**" ("no load"), with percent change over background in Cape Cod Bay (0.295 mg/L), for the Sandwich Harbor system.

Station Location	monitoring station (MEP ID)	present (mg/L)	"no load" (mg/L)	% change
Inlet basin	SH-2	0.310	0.285	-164.9%
Lower Dock Creek	SH-3	0.327	0.270	-178.7%
Lower Mill Creek	SH-4	0.332	0.232	-268.4%
Upper Mill Creek	SH-5	0.627	0.144	-145.6%
Lower Old Harbor Creek	SH-6	0.310	0.285	-164.5%
Upper Dock Creek	SH-7	0.891	0.220	-112.5%
Sandwich Harbor	SH-8	0.343	0.279	-133.5%
Sandwich Harbor	SH-9	0.952	0.165	-119.8%
Sandwich Harbor	SH-10	0.313	0.283	-163.6%
Mid Old Harbor Creek	SH-11	0.312	0.281	-183.3%
Lower Spring Hill Creek	SH-12	0.315	0.277	-192.4%
Upper Spring Hill Creek	SH-13	0.385	0.043	-379.5%
Upper Old Harbor Creek	SH-14	0.361	0.260	-153.1%
Upper Old Harbor Creek	SH-15	0.806	0.097	-138.7%

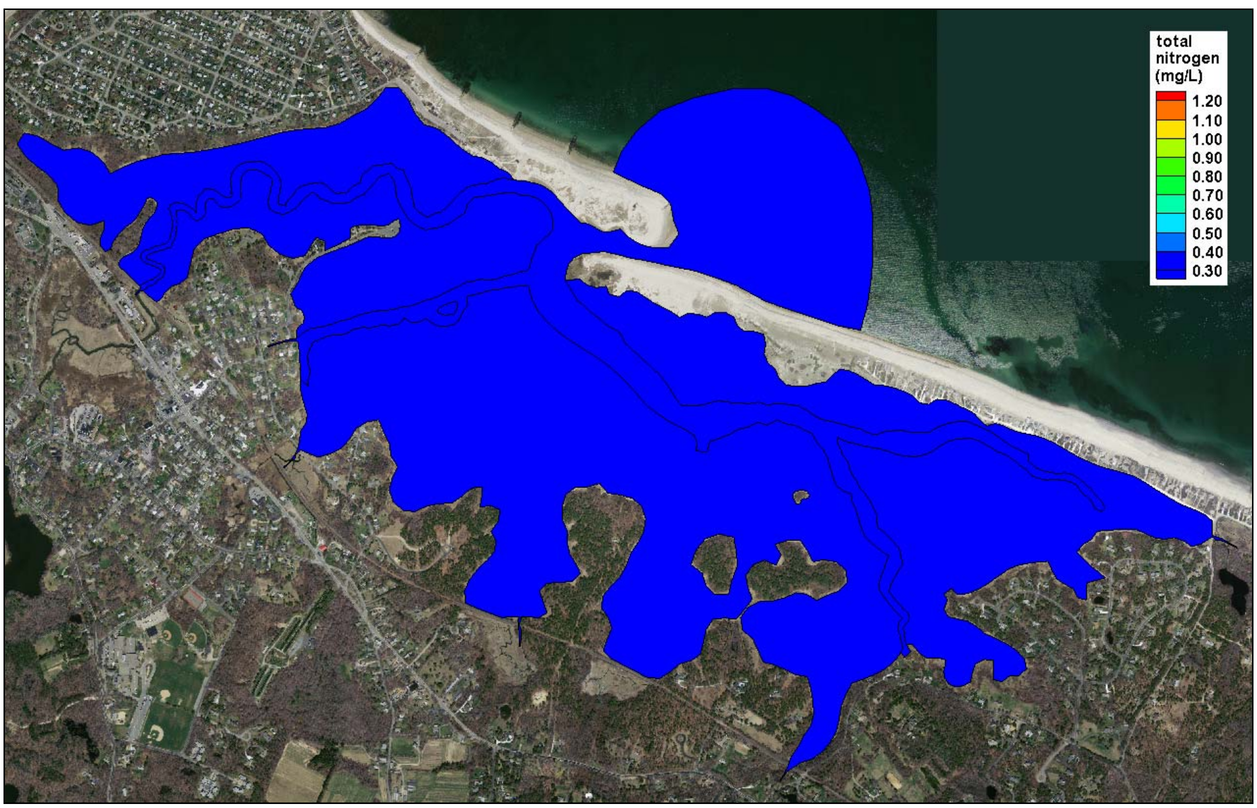


Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in Sandwich Harbor, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Sandwich Harbor Estuary in the Town of Sandwich, MA, our assessment is based upon data from the water quality monitoring database (2005, 2006, 2007) developed by the Town of Sandwich with technical support from the Coastal Systems Program (UMASS-SMAST), surveys of eelgrass distribution (1951, 1995, 2001, 2006), benthic animal communities (fall 2006), sediment characteristics (summer 2006), and dissolved oxygen and chlorophyll-*a* records (summer 2006). These data form the basis of an assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for this system (Chapter VIII). It should be noted that nitrogen enrichment occurs through 2 primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with the low nitrogen waters of Cape Cod Bay. The Sandwich Harbor Estuary has increasing nitrogen loading from the associated watersheds from shifting land-uses and has periodically (in the past) had restricted tidal exchange. Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs, however, this is more so the case in a classic embayment setting as opposed to estuaries that are more salt marsh dominated and have higher assimilative capacities for nitrogen.

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen threshold determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll-*a* (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed autonomous dissolved oxygen sensors in Sandwich Harbor at locations that would be representative of the dissolved oxygen conditions at critical locations in the system, namely a location in Mill Creek, a location in the main tidal channel not too far up gradient from the inlet and a third site also on the main tidal channel but just down gradient of the confluence of two large tidal creeks draining the upper marsh (Figure VII-2). The dissolved oxygen moorings were deployed to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds in the near shore waters of Sandwich Harbor was conducted for comparison to historic records (MassDEP Eelgrass Mapping Program, C. Costello). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the Sandwich Harbor Estuary, temporal changes in eelgrass distribution could not provide a basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet) in nutrient enrichment, as MassDEP surveys were limited to near shore waters of Cape Cod Bay between the Cape Cod Canal and the inlet to Sandwich Harbor. Surveying completed by the SMAST-MEP Technical Team in the summer of 2006 did not reveal, as would be expected in a tidal salt marsh system, the presence of any eelgrass within the estuary itself. As a result, nutrient threshold determination was based strongly on results from the dissolved oxygen and chlorophyll mooring data as well as the benthic infaunal community characterization.

In areas that do not support eelgrass beds, benthic animal indicators were used to assess the level of habitat health from “healthy” (low organic matter loading, high D.O.) to “highly stressed” (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of their habitat. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life-history information of 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 tidal creeks within the Sandwich Harbor Estuary are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality and that it is the designated water quality that is the target of TMDL's generated under the U.S. Clean Water Act. It is through the MEP and TMDL processes that site specific management targets are developed and under the Town's CWMP that management alternatives are designed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern

Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the bottom of the tidal creeks within key regions of the Sandwich Harbor Estuary (Figure VII-2). The dissolved oxygen sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployments. In addition periodic calibration samples were collected at the depth of each sensor and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the Sandwich Harbor system were collected during the summer of 2006.

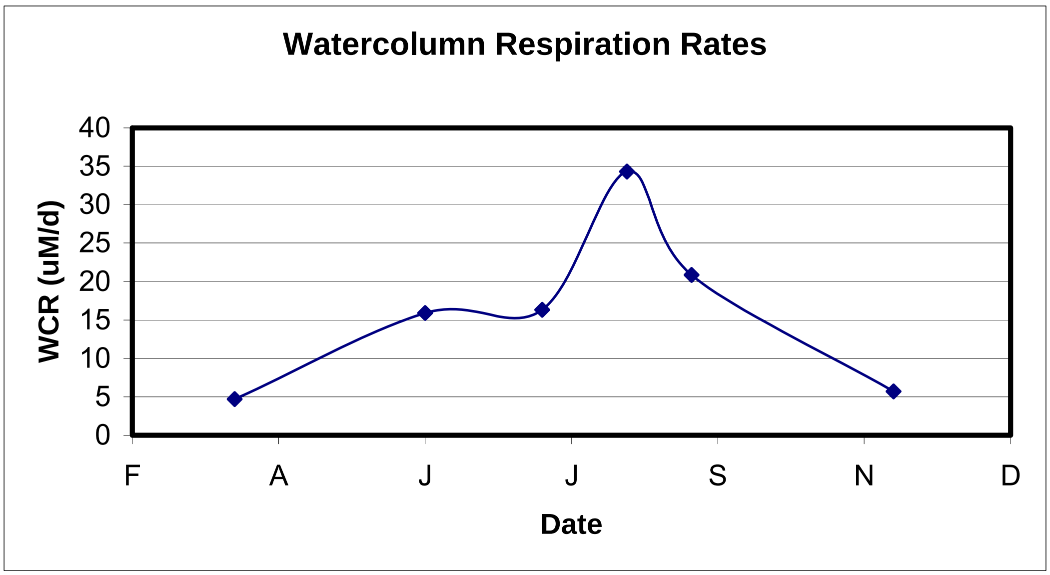


Figure VII-1. Example of typical average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System, Cape Cod (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter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

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

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

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 38 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 the degree of organic matter and nutrient enrichment of the tidal creek system associated with the mooring sites within the tidal creeks of the Sandwich Harbor Estuary (Figures VII-3 through VII-8). The oxygen data is consistent with the high organic matter loads from the adjacent vegetated marsh plain, as phytoplankton biomass (chlorophyll-*a* levels) are low in this estuary. Both the levels of oxygen depletion and chlorophyll levels that averaged only 2.9 to 5.6 ug L^{-1} over the deployment period are indicative of a low level of nitrogen and organic matter enrichment from phytoplankton. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in a particular location. However, nitrogen enrichment also results in increased phytoplankton (or epibenthic algae) production, as evidenced by oxygen levels that rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The absence of elevated oxygen levels is consistent with the oxygen variations being the response to the naturally organic rich nature of tidal salt marsh creeks. In these systems the oxygen dynamic is driven by consumption within the tidal creeks, with re-oxygenation through phytoplankton production being limited. As the creeks drain nearly completely at low tide and the rise in oxygen levels is primarily through the entry of oxygen rich coastal waters on the flooding tide.

The dissolved oxygen records indicate that the upper regions of the central tidal salt marsh creek of the extensive Sandwich Harbor salt marsh system as well as the tidal Mill Creek tributary to the main central tidal creek have periodic oxygen depletion to 4 mg L^{-1} or lower in some cases (Table VII-1). Such oxygen depletion is typical of organic and nutrient rich New England salt marsh systems, supporting high habitat quality as the animal and plant communities resident have evolved under these conditions. Salt marshes are nutrient and organic matter enriched as part of their ecological design, which makes them such important nursery areas for adjacent offshore waters. However, a natural consequence of their organic rich sediments is periodic oxygen depletion within the tidal creeks, particularly during the summer. The observed level of oxygen depletion in the Sandwich Harbor salt marsh system is expected, as was the nearly identical pattern recorded by the MEP Technical Team in adjacent Namskaket and Little Namskaket Creeks, both located on Cape Cod Bay in the Town of Orleans. Assessment of habitat quality must necessarily consider the natural function and tolerances of the specific estuarine ecosystems being evaluated. The specific results are as follows:

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Table VII-1. Days and percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels within the Sandwich Harbor embayment system. Data collected by the Coastal Systems Program, SMAST.

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)
Sandwich Harbor 1	**6/20/2006**	**7/28/2006**	**38.1**	**21%**	**12%**	**4%**	**14%**
			Mean	0.22	0.20	0.20	0.14
			Min	0.02	0.02	0.08	0.01
			Max	0.43	0.34	0.31	0.26
			S.D.	0.11	0.08	0.08	0.10
Sandwich Harbor 3	**6/20/2006**	**7/28/2006**	**38.02**	**18%**	**6%**	**2%**	**0%**
			Mean	0.18	0.13	0.10	NA
			Min	0.03	0.03	0.07	0.00
			Max	0.51	0.24	0.15	0.00
			S.D.	0.11	0.06	0.03	NA
Sandwich Harbor 4	**6/20/2006**	**7/28/2006**	**37.99**	**39%**	**22%**	**9%**	**2%**
			Mean	0.26	0.16	0.11	0.08
			Min	0.01	0.01	0.01	0.02
			Max	0.77	0.33	0.23	0.18
			S.D.	0.14	0.09	0.06	0.07

Table VII-2. Duration (days and % of deployment time) that chlorophyll-*a* levels exceed various benchmark levels within the Sandwich Harbor Estuary. "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)
Sandwich Harbor 1	**6/20/2006**	**7/28/2006**	**30.5**	**43%**	**8%**	**3%**	**1%**	**0%**
Mean Chl Value = 5.6 ug/L			**Mean**	0.28	0.27	0.16	0.14	0.06
			Min	0.04	0.08	0.04	0.04	0.04
			Max	1.54	1.00	0.46	0.29	0.08
			S.D.	0.32	0.29	0.18	0.13	0.03
Sandwich Harbor 3	**6/20/2006**	**7/28/2006**	**13.50**	**20%**	**2%**	**0%**	**0%**	**0%**
Mean Chl Value = 4.1 ug/L			**Mean**	0.21	0.29	N/A	N/A	N/A
			Min	0.04	0.29	0.00	0.00	0.00
			Max	1.17	0.29	0.00	0.00	0.00
			S.D.	0.31	N/A	N/A	N/A	N/A
Sandwich Harbor 4	**6/20/2006**	**7/28/2006**	**19.45**	**6%**	**0%**	**0%**	**0%**	**0%**
Mean Chl Value = 2.9 ug/L			**Mean**	0.10	N/A	N/A	N/A	N/A
			Min	0.04	0.00	0.00	0.00	0.00
			Max	0.21	0.00	0.00	0.00	0.00
			S.D.	0.06	N/A	N/A	N/A	N/A

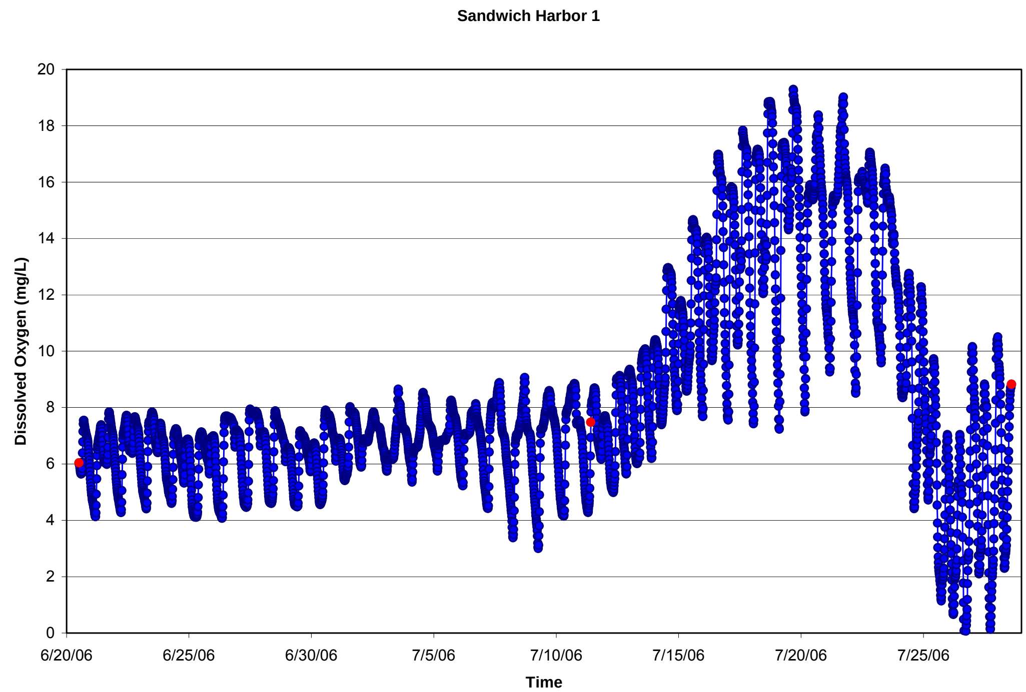

Figure VII-3. Bottom water record of dissolved oxygen at the Sandwich Harbor 1 station, Summer 2006. Calibration samples represented as red dots.

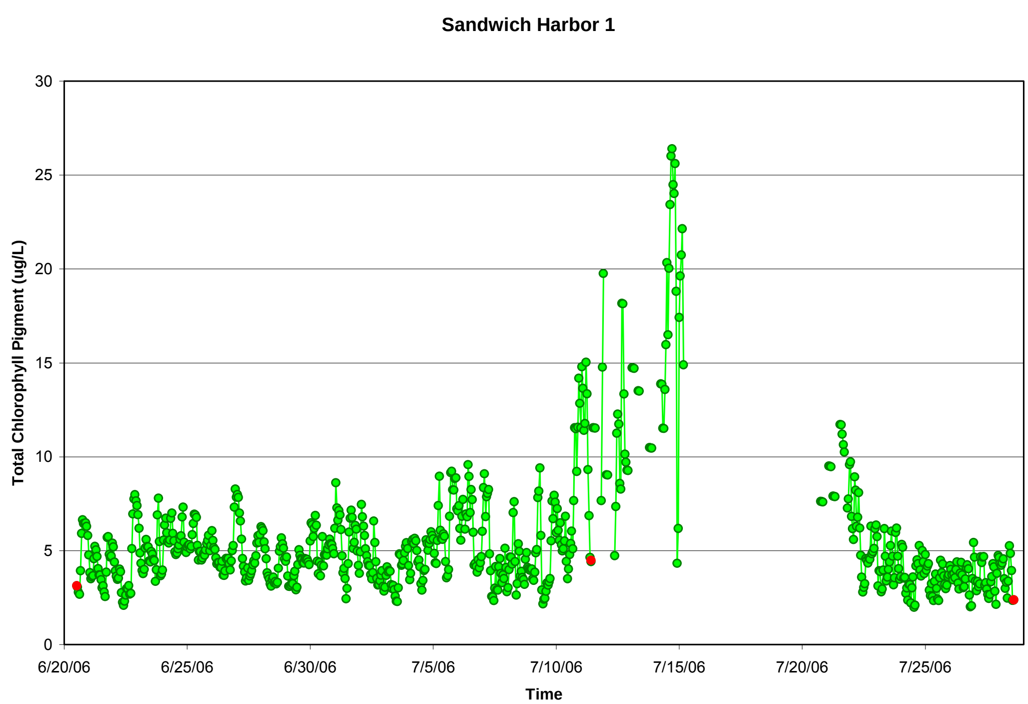

Figure VII-4. Bottom water record of Chlorophyll-*a* in the Sandwich Harbor 1 station, Summer 2006. Calibration samples represented as red dots. Data gaps due to sensor error.

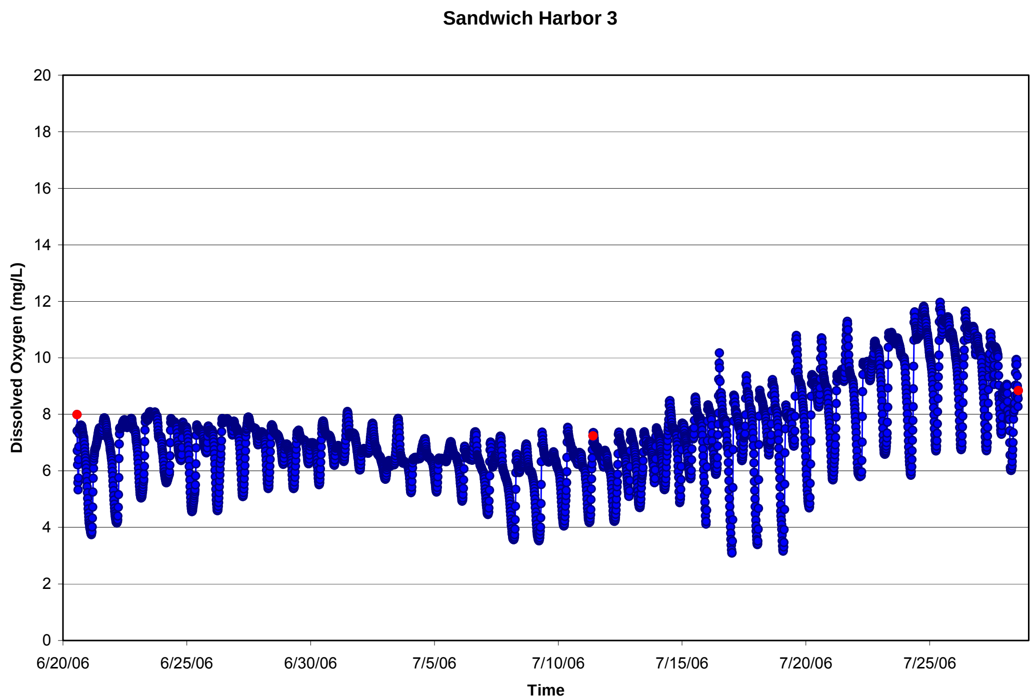

Figure VII-5. Bottom water record of dissolved oxygen at the Sandwich Harbor 3 station, Summer 2006. Calibration samples represented as red dots.

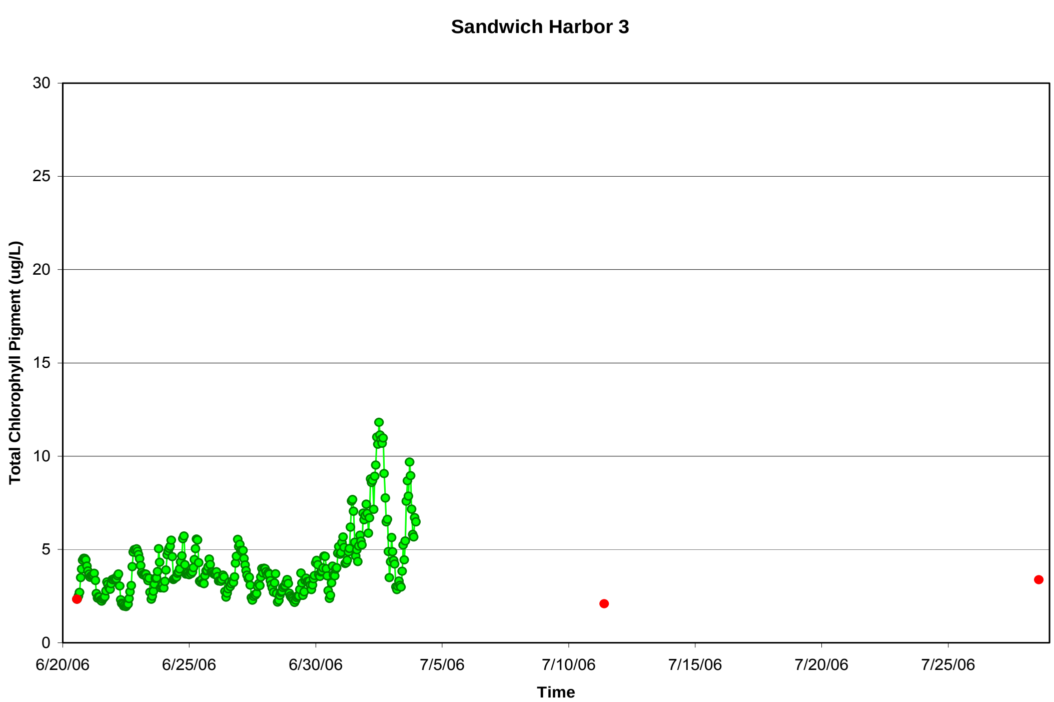

Figure VII-6. Bottom water record of Chlorophyll-*a* in the Sandwich Harbor 3 station, Summer 2006. Calibration samples represented as red dots. Data gaps due to sensor error.

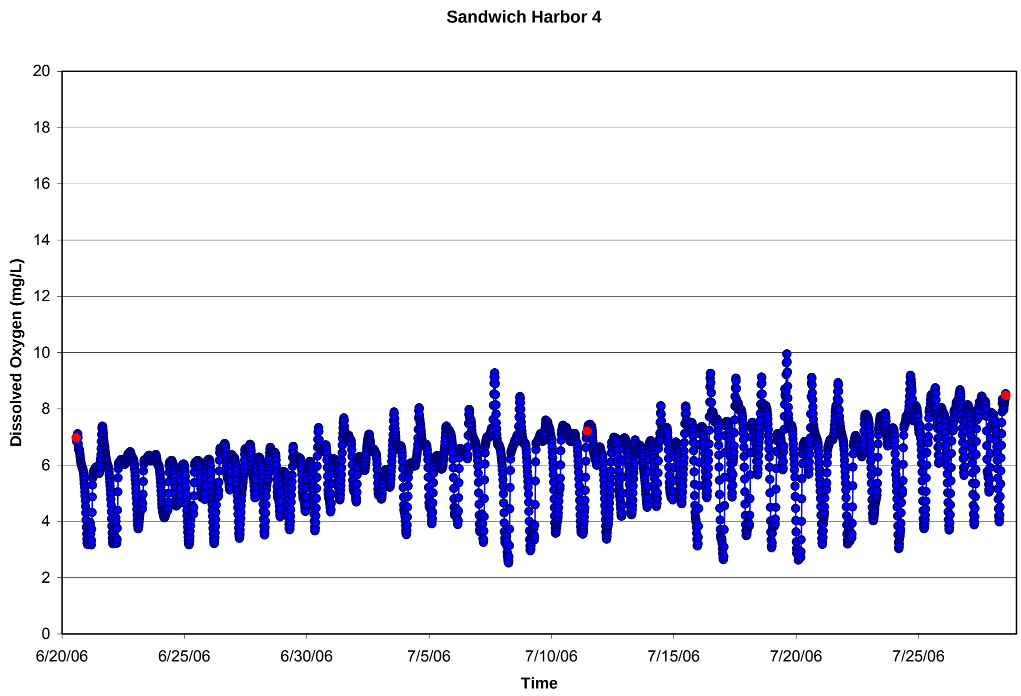

Figure VII-7. Bottom water record of dissolved oxygen at the Sandwich Harbor 4 station, Summer 2006. Calibration samples represented as red dots.

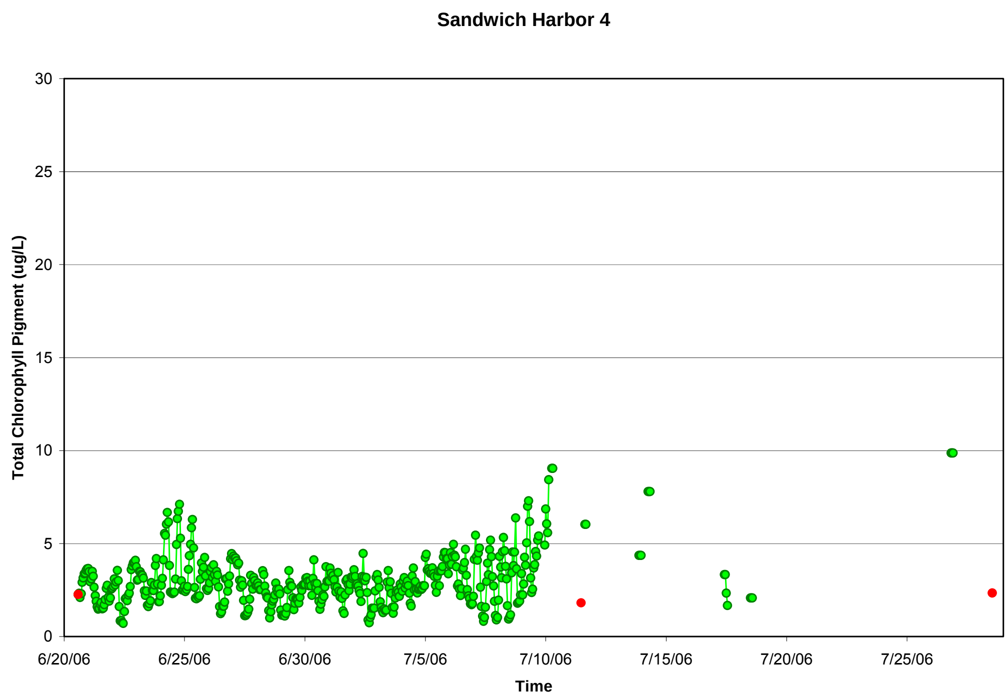

Figure VII-8. Bottom water record of Chlorophyll-*a* in the Sandwich Harbor 4 station, Summer 2006. Calibration samples represented as red dots. Data gaps due to sensor error.

Sandwich Harbor DO/CHLA Mooring 1,3,4 (Figures VII-3 through VII-8):

Sandwich Harbor functions primarily as a tidal salt marsh throughout its estuarine reach. The upper reach has deeply incised narrow creeks surrounded by extensive emergent marsh vegetated with typical New England high and low marsh plants. The lower reach has broader creeks with sediments formed from marsh deposits and sand transported in by coastal processes. The lower reach is transitional from the highly organic sediments of the upper marsh to the sandy near shore sediments of adjacent Cape Cod Bay. The tide range in adjacent Cape Cod Bay is large, ~10 ft (Chapter V), and the salt marsh areas are regularly flooded at high tide and the salt marsh creeks drain nearly completely with each ebb tide.

It is interesting to note that the pattern of oxygen depletion was generally similar at each mooring site. Dissolved oxygen from the water quality monitoring program tended to only decline below 5 mg L^{-1} periodically in the lower tidal reaches of the marsh and generally remained high in the upper tidal reaches (Stations SDH-8 to SDH-14). The large diurnal shifts in dissolved oxygen reflected within Mill Creek where the Sandwich Harbor 1 mooring was located are consistent with the high productivity within the marsh, high levels of oxygen uptake by the organic matter rich marsh sediments and tidal changes in salinity and temperature which influence oxygen solubility (e.g. incoming tides transport oxygen rich waters). This is similarly the case with the records obtained from the Sandwich Harbor 3 mooring located on the main tidal creek as well as the Sandwich Harbor 4 mooring located further up the main tidal creek but at the confluence of two channels that drain portions of the upper marsh to the east. The relatively low chlorophyll-*a* concentrations at all the mooring locations during the period the CHLA sensors were operational, 3 - 6 ug L^{-1} (with the exception of one bloom period), reflect the offshore waters, as the near complete exchange of tidal waters on each tide in the creeks does not allow for chlorophyll levels to build. The absence of a strong diurnal oxygen cycle for most of the record, indicative of nitrogen enriched embayments (due to stimulation of phytoplankton), supports the concept that the marsh processes are the primary control on oxygen dynamics at this site. In fact, the daily average dissolved oxygen concentration varied inversely with the tidal amplitude suggesting that longer residence time and greater areal submergence of the marsh was responsible for the lowest oxygen observed oxygen levels. Further evidence for the dominance of marsh processes is the lack of linkage between the observed variations in chlorophyll and the extent of oxygen depletion. In embayments, oxygen minima are typically observed as a bloom declines (senesces), a pattern not seen at this site. Consistent with this latter observation is that the tidally averaged TN level at the mooring sites was only 0.36 mg N L^{-1} and <0.38 mg L^{-1} throughout the tidally dominated creeks accounting for most of the marsh. Note that areas of freshwater discharge generally had higher TN levels at low tide. By comparison, the tidally averaged TN level at the DO mooring site in Namskaket Marsh, a salt marsh system similar to the Sandwich Harbor system, was 0.488 mg N L^{-1}. Like Sandwich Harbor, dissolved oxygen and chlorophyll levels exhibited characteristics consistent with healthy salt marsh environments. In traditional embayment systems on Cape Cod, these TN levels typically do not result in the level of oxygen depletion found in the salt marsh creeks such as Sandwich Harbor, Scorton Creek or Namskaket and adjacent Little Namskaket Estuaries in the Town of Orleans. It is clear that internal processes associated with the organic rich sediments of the salt marsh are a predominant control of oxygen levels. It should be noted that the level of TN in Sandwich Harbor Estuary is quite low, as is the chlorophyll-*a*, due to the robust tidal flushing with low nitrogen Cape Cod Bay waters; the observed oxygen declines are typical of salt marsh creeks, and does not indicate impairment in that type of environment. These data support the contention that the Sandwich Harbor salt marshes are not nitrogen impairedVII.3 Eelgrass Distribution - Temporal Analysis

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data is key part of the MEP Approach. Surveys were conducted in the vicinity of the Sandwich Harbor System by the DEP Eelgrass Mapping Program as part of the MEP effort in 1995 and 2001. These surveys were essentially in the near shore waters of Cape Cod Bay, between the mouth of the Cape Cod Canal and the inlet to Sandwich Harbor. The primary use of the data is to indicate (a) estuarine regions that have historically or presently support eelgrass habitat, and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1995 to 2001 (Figure VII-9). This temporal information can be used to determine the stability of the eelgrass community.

Eelgrass surveys were not undertaken for the tidal creek that constitutes the Sandwich Harbor Estuary by the MassDEP Eelgrass Mapping Program (C. Costello), as this "basin" is the central tidal creek with large tributary creeks supporting an extensive salt marsh, similar to adjacent Scorton Creek or Ellisville Harbor. Tidal creeks do not generally support eelgrass habitat, particularly when the creek nearly completely drains during each ebb tide, as is the case for the Sandwich Harbor Estuary (Mill Creek and Old Harbor Creek). In addition, the baseline 1951 analysis could not be performed by MassDEP due to the lack of adequate aerial photos. However, there is no evidence of eelgrass previously colonizing this system or similar marsh systems on Cape Cod. The MEP Technical Team did confirm the lack of eelgrass in the tidal creeks to the Sandwich Harbor System while undertaking field surveys as part of the benthic regeneration and infauna studies and during the deployment and recovery of the instrument moorings. The absence of eelgrass in the Sandwich Harbor Estuary was expected from the structure and function of the estuary, and does not indicate nor is it related to nutrient enrichment.

In contrast, eelgrass is present offshore to the west of the inlet to Sandwich Harbor. Based on the 2001 eelgrass survey conducted by the DEP Eelgrass Mapping Program offshore, there was evidence of a potential decline in the coverage of the offshore beds between 1995 and 2001. However, it is not possible at this time to determine if this represents an anthropogenically driven decline or natural variation at this site, potentially due to coastal processes. Additional temporal sampling may be undertaken by the MassDEP Eelgrass Mapping Program to address this issue.

Based upon all available information, it appears that the Sandwich Harbor Estuary is not structured to support eelgrass habitat. Therefore, threshold development for protection/restoration of this system will focus on infaunal habitat quality. This is typical for New England salt marshes, which are naturally organic and nutrient rich and generally contain little water in the creeks at low tide. This conclusion has been confirmed in a wide range of salt marsh dominated basins throughout southeastern Massachusetts by the MEP Technical Team.

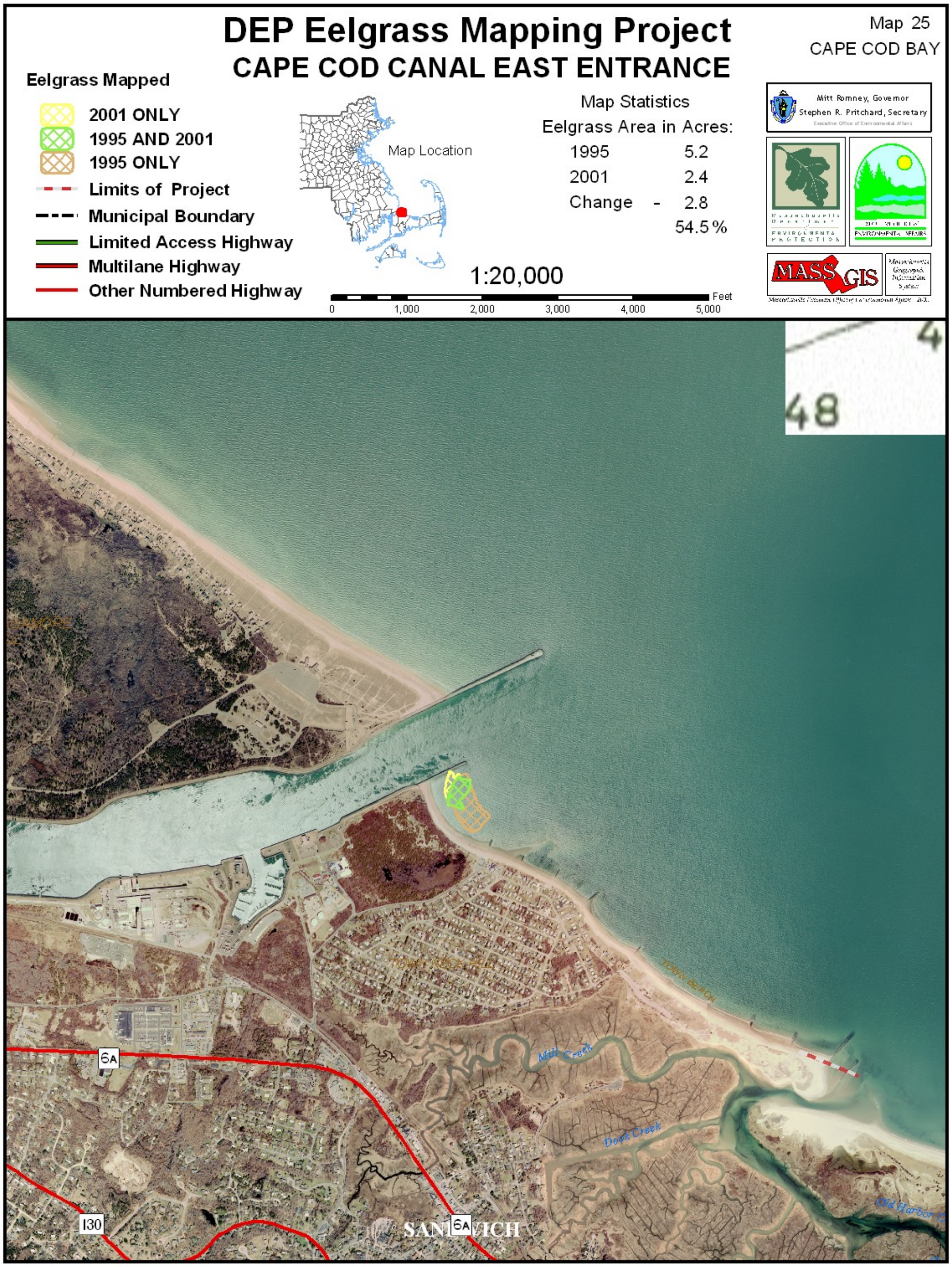

Figure VII-9. Eelgrass bed distribution offshore of Sandwich Harbor Estuary and the Cape Cod Canal. Beds delineated in 1995 are circumscribed by the brown outline with a composite of 1995 and 2001 outlined in green (map from the MassDEP Eelgrass Mapping Program). Surveying did not extend into the salt marsh tidal creeks, however, no eelgrass was observed in the Sandwich Harbor system during SMAST-MEP surveying conducted in 2006.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 9 locations within the Sandwich Harbor Embayment System (Figure VII-10), with replicate assays at each site. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, although there are no eelgrass beds in the Sandwich Harbor Marsh system, this is likely to have more to do with the structure of the system. As such, to the extent that the Sandwich Harbor Marsh can support healthy infaunal communities given specific nutrient conditions in the water column, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

Sandwich Harbor Infaunal Characteristics:

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

The infauna study of the Sandwich Harbor Estuary indicated that the tidal creeks of the estuary are presently supporting a typical salt marsh infaunal habitat with high productivity. Infauna communities within the tidal creek were indicative of the organic rich environment typical of salt marshes and consistent with the observed levels of oxygen depletion and water column TN. The communities within the smaller tributary creeks to Old Harbor Creek generally had moderate to high numbers of individuals (200 - 3000 individuals per sample) with moderate numbers of species (9-15) and diversity (2.2 - 2.6). The main tidal creek (Old Harbor Creek) showed similar but slightly lower habitat metrics (1000 individuals/sample; 11 species; diversity 2.2) likely due to the high water velocities and swept sands. The observed communities were typical of New England salt marsh creek bottom environments in summer. The communities generally contained some organic enrichment tolerant species. However, species like *Capitella* and *Streblospio,* typically observed in impaired embayment habitats, like nearby Rock Harbor lower basin in the Town of Orleans, generally did not dominate and there were significant numbers of crustaceans and polychaetes. However, tubificids were important (not dominant) at some stations. Evenness was also moderate to high in the tributary creeks and lower estuary, which also had some deep burrowing organisms. In contrast, the mid and lower reach of the main channel was found to have high water velocities which have winnowed the fines from the sediments and created a medium to coarse sand with shifting sediments. The result is similar to tidal inlets or Chatham Harbor's shifting sands which do not support extensive benthic habitat, being naturally disturbed. The observed communities were typical of New England salt marsh creek bottom environments in summer.

Overall, the Infauna Survey indicated that most areas within Sandwich Harbor Estuary are supporting infauna habitat typical of organic rich New England salt marshes, hence high quality relative to this estuarine ecosystem type. This is supported by the sparse presence of macroalgae (mainly drift) and the absence of algal mats within the creek bottoms, which can result if there is "excessive" external nitrogen loading. The near absence of macroalgal accumulations is consistent with the relatively low total nitrogen levels within this system, generally <0.39 throughout (tidally averaged), with higher TN levels at the uppermost regions of creeks strongly influenced by freshwater entry at low tide. By comparison, in Namskaket Marsh which is a similar salt marsh system also fed by low nutrient waters from Cape Cod Bay, macroalgal accumulations were also absent with the relatively low total nitrogen levels of 0.42-0.66 mg N L^{-1} (tidally averaged). Infaunal habitat health can further be confirmed when making an additional comparison to another similar marsh, Cockle Cove Creek (Chatham), which supports high quality habitats, both emergent marsh and creek bottom, at levels of 2 mg TN L^{-1}. Based upon all lines of evidence it appears that the Sandwich Harbor Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment. The lower TN levels in the Sandwich Harbor Estuary are predominantly the result of the high tidal flushing of this system on each tide with low nutrient waters of Cape Cod Bay (just offshore, 0.295 mg L^{-1}). Based upon all lines of evidence it appears that the Sandwich Harbor Estuary is presently supporting high quality infaunal habitat and appears to be well below its threshold nitrogen level for assimilating additional nitrogen without impairment.

Figure VII-10. Aerial photograph of the Sandwich Harbor Estuary showing location of benthic infaunal sampling stations (yellow symbols).

Table VII-3. Benthic infaunal community data for the Sandwich Harbor Estuary. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m2). Stations refer to map in Figure VII-10, (N) is the number of samples per site. Sediments within the Inlet Basin are coarse shifting sands, an unstable habitat for infaunal animals.

Sub-Embayment	Sta. I.D.*	Total Species	Total Individuals	#Species Calc @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Sandwich Harbor Estuary						
Mill Creek	**2,3**	**14**	**199**	**11**	**2.56**	**0.68**
Dock Creek	**5,6**	**15**	**2962**	**9**	**2.15**	**0.57**
Spring Hill Creek	**12**	**9**	**801**	**7**	**2.28**	**0.74**
Old Harbor Creek	**7,9,14**	**11**	**973**	**N/A**	**2.19**	**0.66**
Inlet Basin	**4**	**7**	**11**	**N/A**	**2.65**	**0.95**
* Station i.d.'s refer to Figure VII-10.						

Other Resource Characteristics:

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments, as developed by the Commonwealth and made available to the MEP Technical Team, were integrated into the habitat assessment portion of the MEP nutrient threshold development process. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the propagation of shellfish (Figure VII-11). As is the case with some systems on Cape Cod, all of the Sandwich Harbor Estuary is classified as prohibited (tributary creeks) or conditionally approved (main channel Old Harbor Creek) for the taking of shellfish at any time during the year. Sandwich Harbor upper estuarine reaches have reoccurring elevated numbers of indicator bacteria (fecal coliform). This is most likely due to bacterial inputs from wildlife and birds associated with the wetland and possibly from human activity (storm water or septic systems in the watershed). Despite the existing shellfish area classifications, the Sandwich Harbor Estuary is also classified as supportive of specific shellfish communities (Figure VII-12). The major shellfish species with potential habitat within the Sandwich Harbor Estuary are soft shell clams (*Mya*) in the lower portion of the main tidal channel of the system and Mill Creek and quahogs (*Mercenaria*) further up into Old Harbor Creek. The lowermost reach of Old Harbor Creek is suitable blue mussel habitat due to the hard substrates in that area.

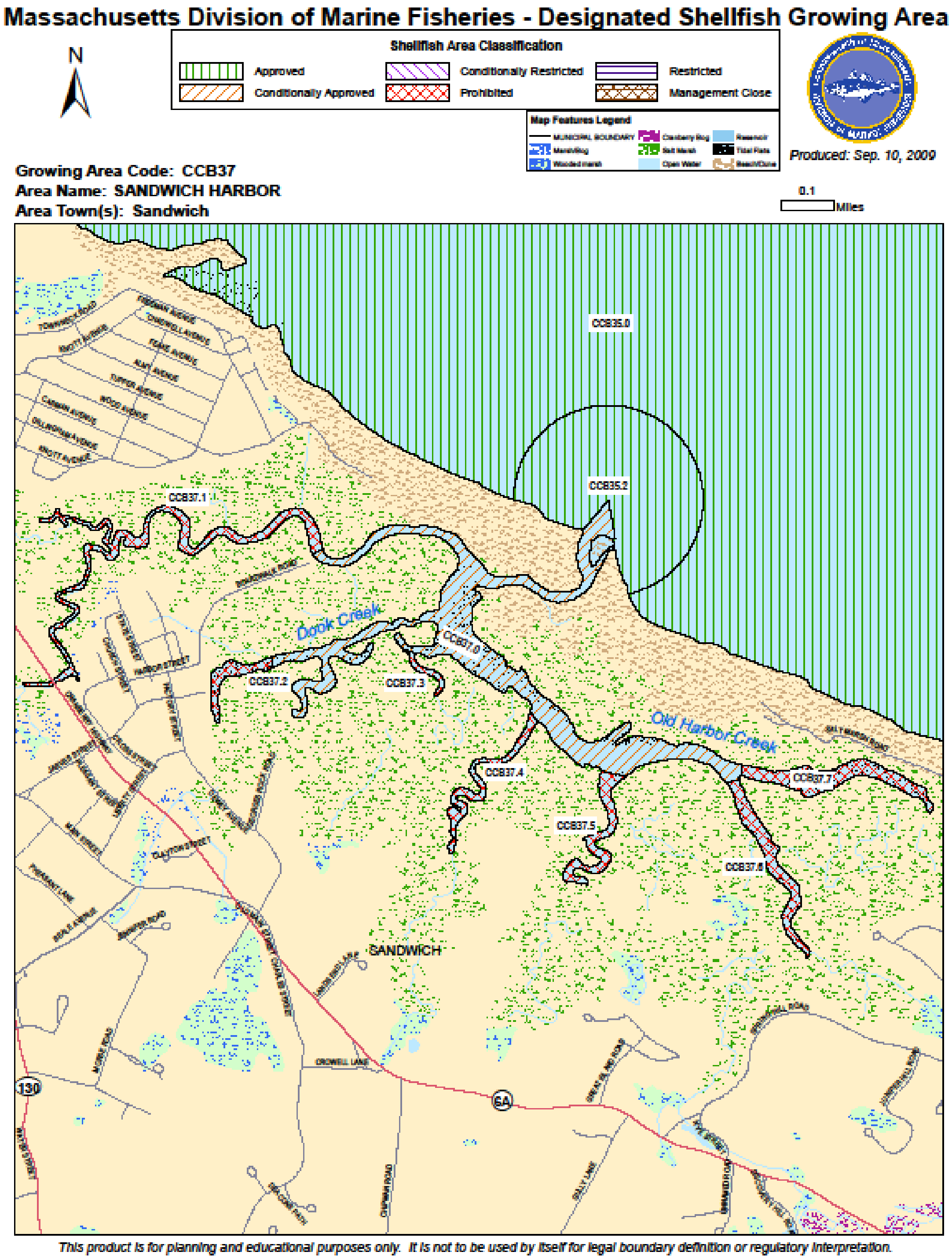

Figure VII-11. Location of shellfish growing areas in the Sandwich Harbor Estuary and the status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination from wildlife or human "activities", such as the location of marinas.

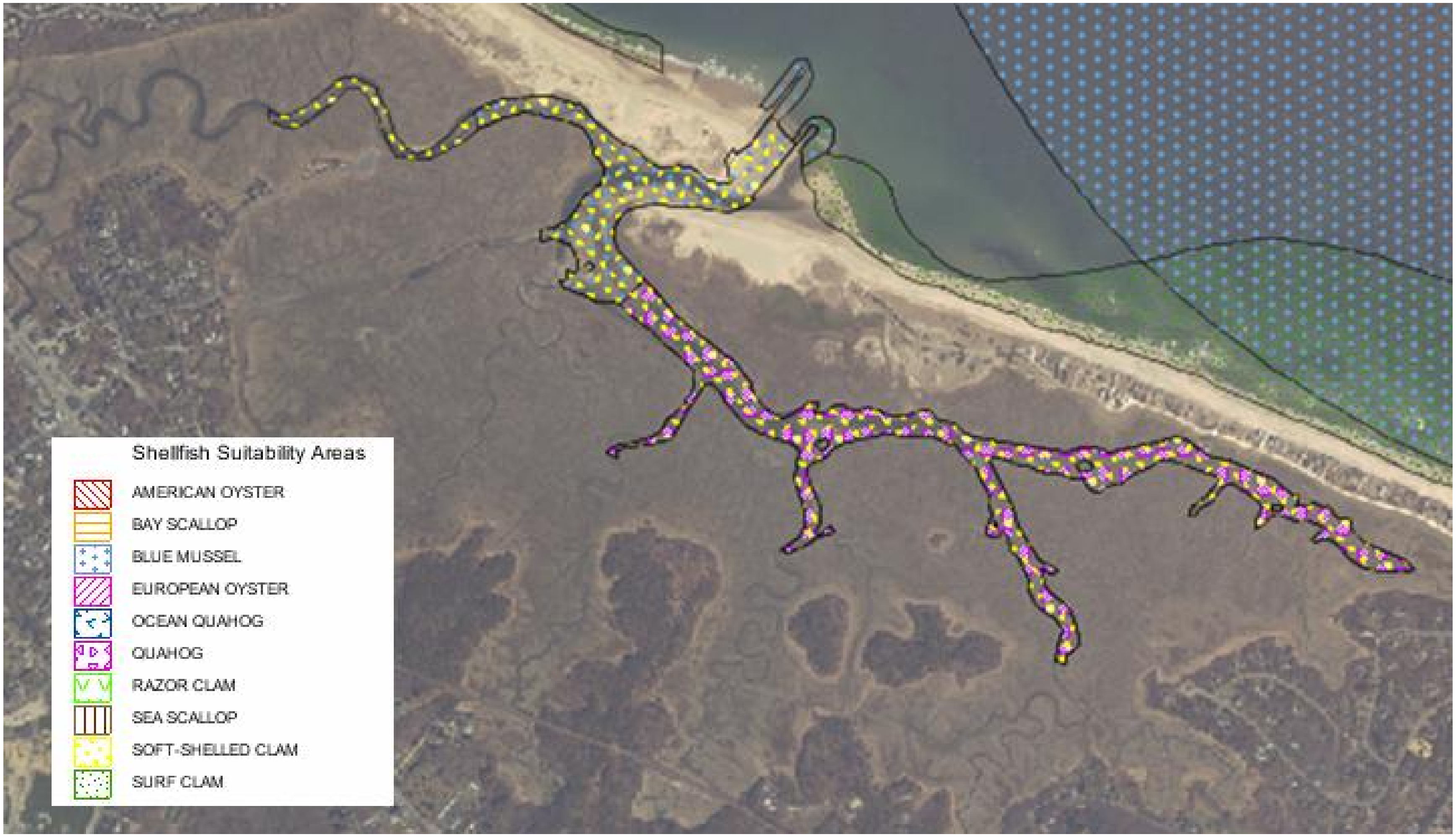

Figure VII-12. Location of shellfish suitability areas within the Sandwich Harbor Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence". The delineated areas generally coincide with creek bottoms dominated by fine and medium sands.

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll-*a*). Additional information on temporal changes within each sub-embayment and its watershed further strengthen the analysis. These data were collected to support threshold development for the Sandwich Harbor Estuary by the MEP and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the water quality monitoring baseline collected by the Town of Sandwich Water Quality Monitoring Program (2005-2007).

At present, the Sandwich Harbor Estuary is not showing nitrogen impairment of habitat throughout its tidal reaches. The estuary contains little open water and appears to be a fully functional tidal salt marsh with deeply incised narrow creeks surrounded by extensive emergent marsh separated from the adjacent Bay by a barrier beach. This is typical of New England "pocket" marshes, typically with a few large central creeks and smaller tidal creeks and a marsh plain dominated by low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) plant communities with patches of fringing brackish marsh vegetation (*Juncus, Phragmites*). Old Harbor Creek, is the main tidal creek within a large emergent vegetated marsh. The large central tidal creek has physically disturbed sediments near the tidal inlet due to the high tidal velocities (can be seen in the medium to coarse sands) and is also influenced by sand transport via nearshore coastal processes associated with adjacent Cape Cod Bay. These disturbances prevent establishment of stable infauna communities in its lowermost portion, but this effect is constrained as velocities are lower in the upper reach and tributaries, which support unimpaired infauna habitat. Plant communities are generally similar throughout the emergent marsh, except that there are some fringing brackish water species adjacent the upland and the marsh grades to barrier beach/dune vegetation near the Bay. The tide range in adjacent Cape Cod Bay is large, ~10 ft (Chapter V), and the salt marsh areas are regularly flooded at high tide and the salt marsh creeks drain nearly completely with each ebb tide.

While there is cyclical depletion of oxygen in the marsh creeks, there is typically no prolonged hypoxia. Chlorophyll levels are low in the tidally flushed marsh creeks (<6 ug L^{-1}), indicating low phytoplankton biomass. Macroalgal accumulations were not observed. The near complete flushing of the system with each tidal cycle prevents build-up of nitrogen and subsequent blooms from occurring within the marsh. The lack of nitrogen related impairment is supported by the general absence of surface algal mats and macroalgae, with only a few patches of very sparse *Ulva* being observed. The near absence of macroalgal accumulations is consistent with the relatively low total nitrogen levels (for a salt marsh) within this system, 0.38 mg N L^{-1} (long-term average), except in the uppermost regions nearest the upland freshwater discharge points at low tide.

The relatively low chlorophyll-*a* concentrations in the creek waters throughout the central marsh, 3 - 6 ug L^{-1} reflect the offshore waters, as the near complete exchange of tidal waters on each tide in the creeks does not allow for chlorophyll levels to build. The absence of a strong diurnal oxygen cycle for most of the record, indicative of nitrogen enriched embayments (due to stimulation of phytoplankton), supports the concept that the marsh processes are the primary control on oxygen dynamics at this site. In fact, the daily average dissolved oxygen concentration varied inversely with the tidal amplitude suggesting that longer residence time and greater areal submergence of the marsh was responsible for the lowest observed oxygen levels. Further evidence for the dominance of marsh processes is the lack of linkage between the observed variations in chlorophyll and the extent of oxygen depletion. In embayments, oxygen minima are typically observed as a bloom declines (senesces), a pattern not seen at this site. Consistent with this latter observation is that the tidally averaged TN level at the mooring sites in Old Harbor Creek of only 0.36 mg N L^{-1} and <0.38 mg L^{-1} throughout the tidally dominated creeks accounting for most of the marsh. Note that areas of freshwater discharge generally had higher TN levels at low tide when the creeks were nearly completely drained. By comparison, the tidally averaged TN level at the DO mooring site in Namskaket Marsh (Town of Orleans), a salt marsh system similar to the Sandwich Harbor system, was 0.488 mg N L^{-1}. Like Sandwich Harbor, dissolved oxygen and chlorophyll levels exhibited characteristics consistent with healthy salt marsh environments. In traditional embayment systems on Cape Cod, these TN levels typically do not result in the level of oxygen depletion found in the salt marsh creeks such as Sandwich Harbor, Scorton Creek or Namskaket and adjacent Little Namskaket Estuaries in the Town of Orleans. It is clear that internal processes associated with the organic rich sediments of the salt marsh are a predominant control of oxygen levels. It should be noted that the level of TN in Sandwich Harbor Estuary is quite low, as is the chlorophyll-*a*, due to the robust tidal flushing with low nitrogen Cape Cod Bay waters; the observed oxygen declines are typical of salt marsh creeks, and does not indicate impairment in that type of environment. These data support the contention that the Sandwich Harbor salt marshes are not nitrogen impaired.

All of the key indicators are consistent with the Sandwich Harbor Estuary, and particularly its tidal creeks, supporting high quality habitat, relative to its salt marsh structure and function (Chapter VII). Assessment of habitat quality must necessarily consider the natural function and tolerances of the specific estuarine ecosystem being evaluated. The lack of impairment of Sandwich Harbor Estuary is predictable from its low-moderate nitrogen levels and the greater tolerance of salt marshes to nitrogen loading than open water embayments.

Eelgrass:

Eelgrass surveys were not undertaken by the MassDEP Eelgrass Mapping Program (C. Costello) for the tidal creek that constitutes the Sandwich Harbor Estuary as this "basin" is the central tidal creek with large tributary creeks supporting an extensive salt marsh, similar to adjacent Scorton Creek or Ellisville Harbor. Salt marsh tidal creeks do not generally support eelgrass habitat, particularly when the creek drains nearly completely during each ebb tide, as is the case for the Sandwich Harbor Estuary (Mill Creek and Old Harbor Creek). In addition, the baseline 1951 analysis could not be performed by MassDEP due to the lack of adequate aerial photos. However, there is no evidence of eelgrass previously colonizing this system or similar marsh systems on Cape Cod. The MEP Technical Team did confirm the lack of eelgrass in the tidal creeks to the Sandwich Harbor System. The absence of eelgrass in the Sandwich Harbor Estuary was expected from the structure and function of the estuary, and does not indicate nor is it related to nutrient enrichment.

Based on the salt marsh function of the Scorton Creek Estuary, historical absence of eelgrass in all of the other salt marsh systems on Cape Cod that exchange waters with Cape Cod Bay and the similarity of Scorton Creek to Namskaket Creek and Little Namskaket Creek that have not historically supported eelgrass habitat, the MEP Technical Team concludes that the Sandwich Harbor Estuary has not supported eelgrass for many decades, if ever. Also, search of historic records has not revealed evidence of eelgrass beds in Sandwich Harbor or adjacent Scorton Creek. Based upon all available information, it appears that the Sandwich Harbor Estuary is not structured to support eelgrass habitat. Therefore, threshold development for protection/restoration of this system should focus on infaunal habitat quality. This is typical for New England salt marshes, which are naturally organic and nutrient rich and generally contain little water in the creeks at low tide. This conclusion has been confirmed in a wide range of salt marsh dominated basins throughout southeastern Massachusetts by the MEP Technical Team.

The lack of eelgrass data for the Namskaket, Little Namskaket and Scorton Creek estuaries are consistent with the lack of eelgrass for Sandwich Harbor as are the results of the benthic infauna analysis and the water quality data for this system (see below).

Infaunal Animal Communities:

The Sandwich Harbor Estuary tidal creeks are presently supporting a typical salt marsh infaunal habitat with high productivity. Infauna communities within the tidal creek were indicative of the organic rich environment typical of salt marshes and consistent with the observed levels of oxygen depletion and water column TN. The communities within the smaller tributary creeks to Old Harbor Creek generally had moderate to high numbers of individuals (200 - 3000 individuals per sample) with moderate numbers of species (9-15) and diversity (2.2 - 2.6). The main tidal creek (Old Harbor Creek) showed similar but slightly lower habitat metrics (1000 individuals/sample; 11 species; diversity 2.2) likely due to the high water velocities and swept sands. The observed communities were typical of New England salt marsh creek bottom environments in summer. The communities generally contained some organic enrichment tolerant species. However, species like *Capitella,* typically observed in impaired embayment habitats, like nearby Rock Harbor lower basin in the Town of Orleans, generally did not dominate and there were significant numbers of crustaceans and polychaetes. However, tubificids were important (not dominant) at some stations. Evenness was also moderate to high in the tributary creeks and lower estuary, which also had some deep burrowing organisms. The mid and lower reach of the main channel was found to have high water velocities which have winnowed the fines from the sediments and created a medium to coarse sand with shifting sediments. The result is similar to tidal inlets or Chatham Harbor's shifting sands which do not support extensive benthic habitat, being naturally disturbed. The observed communities were typical of New England salt marsh creek bottom environments in summer.

Overall, the infauna survey indicated that most areas within Sandwich Harbor Estuary are supporting infauna habitat typical of organic rich New England salt marshes, hence high quality relative to this estuarine ecosystem type. This is supported by the sparse presence of macroalgae (mainly drift) and the absence of algal mats within the creek bottoms, which can result if there is "excessive" external nitrogen loading. The near absence of macroalgal accumulations is consistent with the relatively low total nitrogen levels within this system, generally <0.35 throughout (tidally averaged), with higher TN levels at the uppermost regions of creeks strongly influenced by freshwater entry at low tide. The lower TN levels in the Sandwich Harbor Estuary are predominantly the result of the high tidal flushing of this system on each tide with low nutrient waters of Cape Cod Bay (just offshore, 0.295 mg L^{-1}). By comparison, in Namskaket Marsh a similar salt marsh system also fed by low nutrient waters from Cape Cod Bay, macroalgal accumulations were also absent with the relatively low total nitrogen levels of 0.42-0.66 mg N L^{-1} (tidally averaged), Infaunal habitat health can further be confirmed when making an additional comparison to another similar marsh, Cockle Cove Creek (Chatham), which supports high quality habitats, both emergent marsh and creek bottom, at levels as high as 2 mg TN L^{-1}. Based upon all lines of evidence it appears that the Sandwich Harbor Estuary is presently supporting high quality infaunal habitat (see summary Table VIII-1, below)and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Sandwich Harbor Estuary/ Salt Marsh on the Cape Cod Bay shore of the Town of Sandwich, MA, based upon assessment data presented in Chapter VII. The tidal reach of this estuary is a typical New England salt marsh with a large central tidal creek and as such it is nutrient and organic matter enriched. WQMP refers to the Water Quality Monitoring Program, 2005-2007.

	Sandwich Harbor Estuary			
Health Indicator	**Mill Creek Salt Marsh**	**Dock Creek Salt Marsh**	**Spring Hill Salt Marsh**	**Old Harbor Salt Marsh**
Dissolved Oxygen	H[1,4]	H[1,4]	H[1,3]	H[1,2,3]
Chlorophyll	H[5]	H[6]	H[7]	H[8]
Macroalgae	H[9]	H[9]	H[9]	H[9]
Eelgrass	--[10]	--[10]	--[10]	--[10]
Infaunal Animals	H[11]	H[11]	H[11]	H[11]
Overall:	**H[12]**	**H[12]**	**H[12]**	**H[12]**

1 -- oxygen dynamics consistent with a naturally organic matter and nutrient rich New England salt marsh, oxygen depletions are typical of pristine salt marsh creeks on Cape Cod and elsewhere.
2-- Oxygen depletion to 4 mg L-1, but multi-tidal cycle hypoxia rare, typical of upper salt marsh creek
3-- Relatively high oxygen for a salt marsh, D.O. >4 mg L-1 for 98% of record (lower creek) and 91% of record (upper creek). WQMP N=84, <4 mg/L = 3%; >6 mg/L = 87%; SDH-13 typically >6 mg/L
4-- Cyclical depletions briefly to 4 and 2 mg L-1 (WQMP=46% of dates), no prolonged or even full tidal cycle depletion.
5-- low-moderate chlorophyll-*a*, time-series mean= 5.6 ug/L, WQMP upper 5.0 ug L^{-1}, lower 5.7 ugL^{-1}.
6 -- very low chlorophyll-*a* levels, similar to main creek averaging upper 4.7 ug L^{-1}, lower 2.7 ugL^{-1}.
7 -- low chlorophyll-*a* levels, WQMP 3.1 to 7.2 ug L-1, for Spring Hill Creek and 3.1 to 6.2 ug L^{-1} adjacent creek, respectively.
8 – low chlorophyll-*a* levels, throughout main creek mean= upper 4.1 ug L^{-1}, mid 3.1, lower 2.7 ugL^{-1}.
9 – *Ulva* and drift algae and surface algal mats very sparse to absent, consistent with high tidal velocity
10 – no evidence that this estuarine reach is supportive of eelgrass. Area is a salt marsh tidal creek, which drains at low tide and has deeply incised tidal creeks.
11 – high numbers of individuals (200 - 3000), moderate numbers of species (9-15) and diversity (2.2 - 2.6) and Evenness (0.6 - 0.74) with some deep burrowers (Table VII-3). Indicative of non-nutrient impaired benthic habitat.
12 -- near absence of macroalgae and low chlorophyll-*a*, consistent with the relatively low total nitrogen levels, generally <0.39 throughout (tidally averaged), with higher TN levels at the uppermost regions of creeks strongly influenced by freshwater entry at low tide; oxygen generally high to moderately depleted and benthic animal communities that are diverse and productive..
**–Sandwich Harbor Inlet: high water velocities have winnowed the fines from the sediments and created a medium to coarse sand with shifting sediments a natural physical disturbance similar to tidal inlets or Chatham Harbor's shifting sands which do not support extensive benthic habitat.

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

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout an embayment system, is to first identify a sentinel location within the estuary and second, to determine the nitrogen concentration within the water column which will restore or maintain the desired habitat quality. The sentinel location is selected such that the restoration or protection 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.

Sandwich Harbor Estuary functions wholly as a large tidal salt marsh with large deeply incised creeks and high rate of flushing, with the creeks generally empting at low tide. As a result, the Estuary does not support eelgrass habitat, similar to other Cape Cod Bay salt marshes, like Namskaket and Little Namskaket Marshes (Town of Orleans). MEP assessment of the other habitat metrics for Sandwich Harbor Estuary do not indicate nitrogen related habitat impairments (Table VIII-1). As a result, threshold development for this estuary targets its protection and focuses on sustaining infaunal habitat quality. The primary mechanism for nitrogen related infaunal habitat quality decline in salt marsh creeks of this type is through stimulation of macroalgal production and accumulation, which smothers benthic animals and at higher levels can negatively impact creek bank vegetation.

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Sandwich Harbor Estuary is based primarily upon: 1) the systems structure and function as a salt marsh, 2) macroalgal distribution, 3) current benthic community indicators and 4) nitrogen levels. Given the database it is possible to develop a site-specific threshold, which is a refinement upon general threshold analysis frequently employed. It should be noted that nitrogen levels (tidally averaged) within the Sandwich Harbor Estuary are generally quite low at present compared to other marshes and even the more sensitive embayment systems of Cape Cod. Salt marshes are tolerant of much higher nitrogen enrichment and associated chlorophyll-*a* and oxygen declines. Salt marshes, due to their organic nature typically show periodic oxygen declines in summer due to their naturally organic rich sediments and high productivity. However, unlike embayments, the organisms within salt marshes have evolved to exploit these habitats. In Sandwich Harbor marshes some reaches periodically became hypoxic for brief periods, but anoxia was not observed, again consistent with the productive infauna communities observed.

This is similar to the Namskaket Estuary which is also presently supportive of high quality salt marsh infaunal habitat throughout its tidal reaches. While there is periodic summertime oxygen depletion of creek waters, the levels are consistent with unimpaired New England salt marsh systems. At present, significant (or even modest) macroalgal accumulations do not occur within this macro-tidal estuary at long term ebb tide concentrations of 0.677 mg N L^{-1} (headwaters) to 0.323 mg N L^{-1} (near tidal inlet). The inflowing water at the head of the marsh, "freshwater" (average salinity of 1.3 ppt), has the highest TN level at 0.989 mg TN L^{-1}, with tidal waters averaging total nitrogen levels of 0.662 mg N L^{-1} (headwaters) to 0.421 mg N L^{-1} (tidal inlet).

Since Sandwich Harbor marshes are presently below the level of nitrogen loading that would cause impairment to its infaunal habitats (i.e. below its nitrogen threshold level), a conservative estimate of the threshold was established. The threshold was based upon the site-specific data mentioned above and comparison to other similar systems on Cape Cod where detailed nitrogen threshold studies have been completed. This inter-estuarine comparison focused upon similar salt marshes which are presently experiencing higher nitrogen levels, with and without impairment.

The near complete absence of macroalgal accumulations is consistent with the relatively low total nitrogen levels within this system, 0.32-0.38 mg N L^{-1} with freshwater influenced areas (long-term average) generally <0.5 mg N L^{-1}. By comparison, in Scorton Creek and Namskaket Marsh, two similar salt marsh systems also fed by low nutrient waters from Cape Cod Bay, macroalgal accumulations were also absent with similarly low total nitrogen levels of 0.32-0.38 mg N L^{-1} and 0.42-0.66 mg N L^{-1}, respectively. Infaunal habitat health status can further be confirmed when making an additional comparison to another similar marsh, Cockle Cove Creek (Town of Chatham, SMAST 2006), which supports high quality habitats, both emergent marsh and creek bottom, at levels of 2 mg TN L^{-1}. In addition to having a similar structure, Cockle Cove Creek also supports similar benthic communities, sparse (to absent) macroalgal accumulations and tidal velocities within the central creek are similar. In addition, the infaunal habitats within Namskaket and Cockle Cove Marsh are similar in composition and diversity (dominated by polychaetes and crustaceans, with some mollusks). Some of the key species (*Leptocheirus, Paranais*) were also observed in a study of a healthy salt marsh, Great Sippewisset Marsh on Cape Cod (Wiltse 1984). Sandwich Harbor, Scorton Creek and Namskaket Creek all support benthic infauna habitat unimpaired by nitrogen enrichment and habitat typical of organic rich New England salt marshes, hence high quality relative to this estuarine ecosystem type. This is supported by the absence of macroalgal accumulations and algal mats within the creek bottoms, which can result if there is "excessive" external nitrogen loading. The absence of macroalgal accumulations in these systems is consistent with their relatively low total nitrogen levels.

Based on MEP analysis, it was ascertained that the major infaunal habitat issue related to nitrogen levels in salt marshes (e.g. Sandwich Harbor, Scorton Creek, Namskaket Marsh and Cockle Cove) was associated with the potential accumulation of macroalgae within the tidal creek bottom. Accumulations of macroalgae have been observed in a variety of nitrogen enriched salt marsh systems, For example Mashapaquit Marsh, West Falmouth Harbor and Aucoot Cove salt marsh (Town of Falmouth and Marion respectively). These marshes differ from Namskaket and Cockle Cove Creek, in that they do not empty at low tide and they support broad creeks with low tidal velocities. These geomorphic differences allow these systems to grow and accumulate opportunistic drift algae (*Ulva*), which can then "smother" benthic communities. The MEP Technical Team assessed tidal velocities of these systems using a numerical hydrodynamic model. Cockle Cove Creek, Namskaket Creek and adjacent Little Namskaket Creek were found to have similar tidal velocities (1.1 ft sec^{-1},1.24 sec^{-1},1.13 ft sec^{-1}, respectively), but lower than the maximum velocities in the main channel of Sandwich Harbor (see Section V) which reaches velocities of >2.0 ft sec^{-1} and has maximum velocities of >1 ft sec^{-1} throughout much of its tidal reaches. None of these systems have macroalgal accumulations. In contrast, Mashapaquit and Aucoot Marshes had much lower tidal velocities (<0.5 ft sec^{-1}) and macroalgal accumulations. Algal accumulation did not appear to be controlled by nitrogen level alone, as Cockle Cove Creek had nitrogen levels 3-5 fold higher than the other systems, predominantly in plant available forms (nitrate, ammonium). The velocity data relates to the inability of drift algae to accumulate if there is no basin or low velocity areas to allow for settling. This is the case in the Sandwich Harbor Estuary.

A principal component of the high tolerance of salt marsh systems to nitrogen inputs from groundwater and surface water inflows is that unlike embayments, creek waters cannot accumulate nutrients over multiple tidal cycles as embayments do. In addition, increasing the nitrogen concentration in the tidal waters that flood the marsh plain will have a negligible or possibly a stimulatory effect on marsh primary and likely secondary production (i.e. an enhancement of habitat). In addition, since the inflowing fresh waters flow down gradient through the marsh creek and out to the Cape Cod Bay, the nitrogen level will never exceed the inflowing freshwater nitrogen level.

For the Cockle Cove Creek system, it was determined that a highly conservative nitrogen threshold would yield a total nitrogen level of $\leq$2 mg N L^{-1} throughout the salt marsh, e.g. from headwaters to tidal inlet. As this system resembles the structure and hydrodynamics of Sandwich Harbor, this threshold level appears to be appropriate for Sandwich Harbor as well (as for Scorton Creek). It should be noted that the upper most marsh reach of Cockle Cove is currently exposed to 2-3 mg N L^{-1} and Little Namskaket Marsh the range is 1.044 - 0.604 mg N L^{-1}., without discernible habitat impairment. Also, it is important to note that since the creek bottom sediments remove nitrate during transport, the TN concentration declines along the tidal reach. As such, the lower tidal reach has a significantly lower tidally averaged concentration compared to the headwaters. This can be seen in the existing TN gradient, where average TN in Sandwich Harbor Estuary headwaters are 0.5 - 0.9 mg N L^{-1} and 0.32 mg N L^{-1} near the inlet. It should be noted that the high flushing rates in Sandwich Harbor and Scorton Creek Estuaries make them more tolerant of nitrogen inputs than the Cockle Cove and Namskaket Marshes.

Putting all the assessment elements together, it appears that for the Sandwich Harbor Estuary, the critical values are a total nitrogen level of 2 mg N L^{-1} in the headwater stations (SH-5,7,9,15) and a level of 1 mg N L^{-1} in the mid upper reach main channel (check Station SH-11, currently 0.345 mg N L^{-1}). This latter "check" station is not used to set the threshold but serves as a "check" associated with the upper marsh infauna habitat, not significantly diluted by direct freshwater inflows. It should be noted that the tidally averaged total nitrogen level at the middle marsh station in Cockle Cove Creek is currently 1.378 mg N L^{-1} and the tidal inlet station shows concentrations of 0.472 mg N L^{-1}, consistent with the 1 mg N L^{-1} mid marsh station in Namskaket Marsh.

A more conservative approach was used in setting the threshold for the Sandwich Harbor Estuary. The threshold was based on not exceeding 2 mg L^{-1} overall in the freshwater influenced uppermost tidal reaches of the main creeks. As there are multiple creeks originating at the upland border, the average of the major creek sites was used (SH-5, SH-7, SH-9 and SH-15). The present tidally averaged value for this composite sentinel station is 0.819 mg L^{-1} with a minimum and maximum of 0.627 and 0.952 mg L^{-1}, respectively, well below the threshold. The threshold applies as long as the tidal creek maintains its present hydrodynamic characteristics (flushing and velocity). The nitrogen threshold for Sandwich Harbor Creek is intentionally conservative based upon all available data from comparable systems. While not intuitive, the threshold in Sandwich Harbor Estuary is more restrictive of nitrogen loading than for Namskaket Marsh, since the sentinel stations are farther upgradient in the system and capture higher concentrations than in Namskaket Marsh. In all cases the sentinel station values and check station values are much lower than the threshold targets, indicating that additional nitrogen may enter this system without impairment of its habitat quality throughout the estuary. The nitrogen loads associated with the threshold concentration at the sentinel location are discussed in Section VIII.3, below.

VIII.3 DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for protection of infaunal habitats in the

Sandwich Harbor system. Total nitrogen thresholds developed in Section VIII.1 were used to adjust the calibrated constituent transport model described in Section VI. Contrary to typical estuarine systems evaluated as part MEP, the threshold concentration was set higher than present conditions, meaning that the system would be allowed to have a higher load than present and still be able to meet the threshold. Therefore, watershed nitrogen loads were sequentially raised in the model until the nitrogen levels reached the ensemble average of the selected sentinel stations (SH-5, SH-7, SH-9 and SH-15) chosen for Sandwich Harbor Estuary. It is important to note that load increases could be produced by increasing of any or all sources of nitrogen to the system. The load increases presented below represent only one of a suite of potential approaches that could be evaluated by the Town. This presentation is to establish the general degree and spatial pattern of loading that will be allowable for this system. A comparison between present septic and total watershed loading and the loadings for the modeled threshold scenario is provided in Tables VIII-2 and VIII-3, respectively.

As shown in Table VIII-3, the threshold set for this system would allow up to a 137% increase in the total watershed loading. In this particular scenario run, the watershed increase is achieved solely by increasing the total septic load to the system by 200% (three times the septic load for present conditions). The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

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 modified from existing conditions based on the load increase and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Cape Cod Bay, as discussed in Section VI.

The comparison between model results of existing loading conditions and the selected loading scenario to achieve the target TN concentrations is shown in Table VIII-5. To achieve the allowable ensemble threshold nitrogen concentration, increases in average TN concentrations of typically greater than 200% occur in the system, between the main harbor creek and the upper portions of the subsidiary marsh creeks.

Although the above modeling results provide one manner of achieving the selected threshold level for the system, the specific example does not represent the only method for achieving this goal. However, this example provides a general sense of what could be possible when considering future N loading increases to the Harbor.

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Mill Creek	11.205	33.616	+200.0%
Dock Creek	3.836	11.507	+200.0%
Old Harbor Creek	12.641	37.923	+200.0%
System Total	27.682	83.047	+200.0%

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Mill Creek	17.559	39.970	+127.6%
Dock Creek	6.200	13.871	+123.7%
Old Harbor Creek	16.622	41.904	+152.1%
System Total	40.381	95.745	+137.1%

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Mill Creek	39.970	0.121	3.870
Dock Creek	13.871	0.359	0.250
Old Harbor Creek	41.904	0.433	-4.051
System Total	95.745	0.912	0.069

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold loading scenario, with percent change over background in Cape Cod Bay (0.295 mg/L), for the Sandwich Harbor system. The stations used to determine the threshold N concentration are shown in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Inlet basin	SH-2	0.310	0.348	+251.7%
Lower Dock Creek	SH-3	0.327	0.411	+266.7%
Lower Mill Creek	SH-4	0.332	0.477	+387.7%
Upper Mill Creek	**SH-5**	**0.627**	**1.325**	**+210.6%**
Lower Old Harbor Creek	SH-6	0.310	0.350	+261.2%
Upper Dock Creek	**SH-7**	**0.891**	**1.820**	**+155.7%**
Sandwich Harbor	SH-8	0.343	0.449	+217.4%
Sandwich Harbor	**SH-9**	**0.952**	**2.270**	**+200.7%**
Sandwich Harbor	SH-10	0.313	0.361	+259.2%
Mid Old Harbor Creek	SH-11	0.312	0.363	+287.9%
Lower Spring Hill Creek	SH-12	0.315	0.374	+300.5%
Upper Spring Hill Creek	SH-13	0.385	0.874	+542.2%
Upper Old Harbor Creek	SH-14	0.361	0.525	+250.5%
Upper Old Harbor Creek	**SH-15**	**0.806**	**1.996**	**+232.5%**

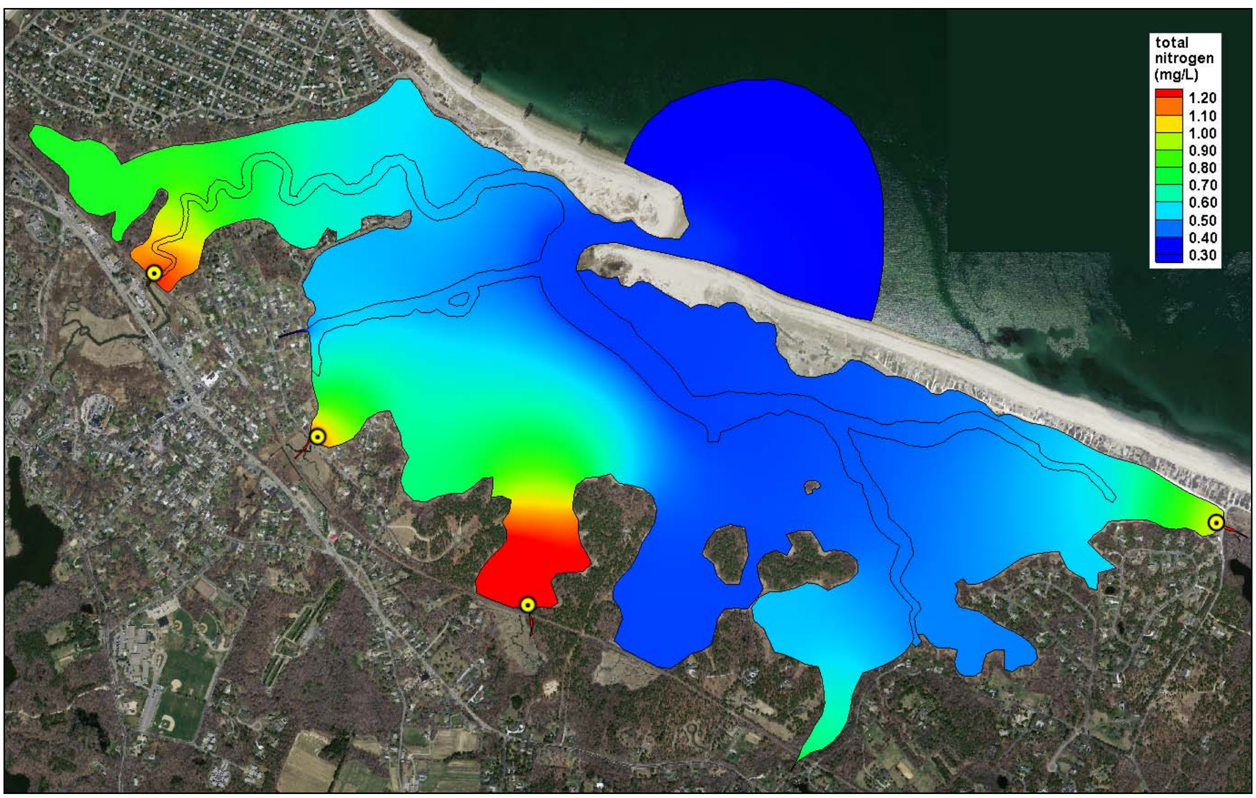

Figure VIII-1. Contour plot of tidally averaged modeled total nitrogen concentrations (mg/L) in the Sandwich Harbor system, for threshold. Yellow markers indicates sentinel stations used to determine the threshold station ensemble average.

IX. MANAGEMENT SCENARIO

IX.1 BACKGROUND

In 2012, the Town of Sandwich wastewater consultants, Wright-Pierce, created a Needs Assessment for the town's Comprehensive Water Resource Management Plan (CWRMP) (WP, 2012). As part of guidance from the Massachusetts Department of Environmental Protection (MassDEP) community-based wastewater planning activities, a needs assessment identifies the wastewater needs in a town and is followed sequentially by: a) development and screening of alternatives to meet the identified needs and b) development of a comprehensive plan including details for all resulting preferred alternatives. The plan usually goes through state (MEPA) and county (DRI) regulatory review.

MEP assessments are usually a key for determining whether there are ecosystem and water quality problems or identified needs in target estuaries. If the MEP assessment indicates that a system is impaired, the MEP report will include a recommended nitrogen threshold concentration. If this threshold concentration is attained at one or more select "sentinel" stations, the system will be restored. These recommended nitrogen thresholds are typically adopted as Total Maximum Daily Loads (TMDLs) by MassDEP and EPA and, thus, are established as regulatory thresholds or restoration targets under the Clean Water Act. If an estuary is identified as impaired in a MEP report, MEP staff typically evaluates two options or scenarios to meet the N threshold: 1) review of inlet restrictions if collected MEP data indicates there is dampening of the tidal signal at the inlet and 2) development of one watershed nitrogen loading reduction strategy that attains the threshold concentration. This second scenario, which is called the threshold scenario, typically involves sequential reductions in wastewater loads within MEP subwatersheds until the threshold is just attained. This threshold scenario option is only one example to show that the threshold can be attained, but is not informed by either the cost or advisability of sewering. Other alternative options could also attain the threshold and often communities choose to evaluate a variety of options to attain the threshold after a MEP report is completed.

Because the MEP report for the Sandwich Harbor estuary was not available at the time the Sandwich CWRMP was being prepared, Wright-Pierce incorporated a number of assumptions about Sandwich Harbor, including that it was impaired and required nitrogen reductions within its watershed to meet a prospective TMDL. Wright-Pierce proceeded with an analysis in the CWRMP that utilized the Cape Cod Commission watershed to Sandwich Harbor and a required 40% nitrogen reduction within the Sandwich Harbor watershed.

As indicated above, the MEP assessment has provided refinements that counter the assumptions in the CWRMP analysis. The MEP watersheds to Sandwich Harbor (see Figure III-2) provide a more refined watershed delineation that includes validation through the collection of streamflow data (see Section IV). In addition, and more importantly, the MEP analysis indicates that Sandwich Harbor is a healthy ecosystem and with excess capacity available for additional nitrogen loading. This capacity means that there should be no required reductions in nitrogen loading within the Sandwich Harbor watershed. It also means that additional nitrogen could be added to the watershed and the Sandwich Harbor ecosystem would remain healthy.

With the excess nitrogen loading capacity established, MEP staff were requested by the town and Wright-Pierce to complete a simple scenario that involved the following:

- 250,000 gpd effluent discharge at Parcel 43-5 (Wing School)

- 250,000 gpd effluent discharge to a portion of Parcel 99-1 (Shawme-Crowell State Forest)
- All effluent discharge at 8 mg/L TN
- All effluent imported into the Sandwich Harbor watershed

Parcel 43-5 (Wing School) is located within the Dock Creek LT10 subwatershed (subwatershed #9), while the proposed discharge site within the Shawme-Crowell State Forest parcel (parcel 99-1) straddles the subwatershed boundary between Shawme Lake LT10 (subwatershed #4) and Mill Creek LT10 (subwatershed #2) (Figure IX-1). Since the proposed discharge area within Shawme-Crowell State Forest straddles the subwatershed boundary, the proposed effluent volume was divided among the two subwatersheds based on the percentage of the discharge area within each subwatershed. Also as indicated in Section IV, Shawme Lake has an 11% nitrogen attenuation rate based on the measured load at the MEP gauge at its outlet. For the purposes of this scenario, this attenuation is maintained.

IX.2 SCENARIO RESULTS

A breakdown of the total nitrogen load entering each system subdivision for the loading scenario is shown in Table IX-1. The benthic flux input to each system subdivision was increased (i.e., absolute value of negative fluxes was made larger) based on the increase in the watershed load (as discussed in Section VI.2.6.1). The comparison of present and scenario total watershed loads is presented in Table IX-2. The largest increase in N loading based both on magnitude and percent change occurs for the Dock Creek watershed, where the N load increase is 11.2 kg/day, which is a 180% increase over existing loading conditions. Overall, the total watershed loading of the whole Sandwich Harbor system increases 26.3 kg/day, which is more than a 65% increase compared to present loading.

Table IX-1. Scenario loading sub-embayment and surface water loads used for total nitrogen modeling of the Sandwich Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux

Station Location	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Mill Creek	26.808	0.121	3.188
Dock Creek	17.395	0.359	0.265
Old Harbor Creek	22.512	0.433	-3.207
System Total	66.715	0.912	0.246

Table IX-2. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and the modeled loading scenario of the Sandwich Harbor system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	scenario % change
Mill Creek	17.559	26.808	+52.7%
Dock Creek	6.200	17.395	+180.6%
Old Harbor Creek	16.622	22.512	+35.4%
System Total	40.381	66.715	+65.2%

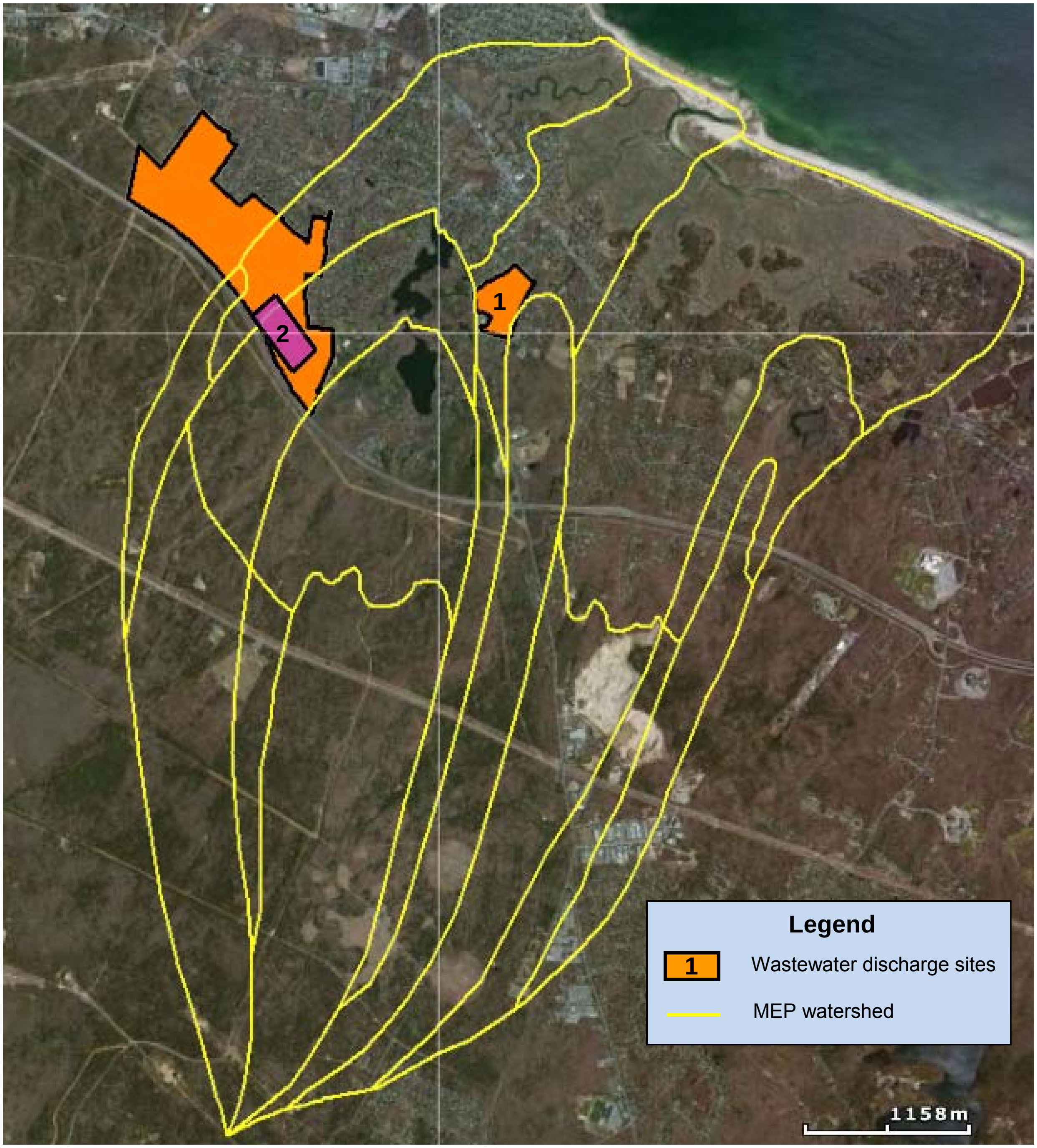

Figure IX-1. Scenario wastewater effluent discharge sites. Orange sites are effluent discharge sites selected in a scenario developed by Wright-Pierce and the town. Site 1 (Parcel 43-5, Wing School) is located within the Dock Creek LT10 subwatershed (subwatershed #9), while the discharge area (indicated in purple) within Site 2 (Parcel 99-1; Shawme Crowell State Forest) straddles the subwatershed boundary between Shawme Lake LT10 (subwatershed #4) and Mill Creek LT10 (subwatershed #2). Total effluent discharge for both sites is 0.5 million gallons per day with an effluent total nitrogen concentration of 8 mg/L.

Following development of the nitrogen loading estimates for this alternative loading scenario, the water quality model was run to determine nitrogen concentrations at each monitoring station. The comparison of present loading and the modeled loading scenario is presented in Table IX-3. Again, total nitrogen concentrations in the receiving waters (i.e., Cape Cod Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from the modeled loading scenario was large, with all areas of the system experiencing increases (compared to the background concentration of 0.295 mg/L in Cape Cod Bay) greater than the modeled build out scenario of Chapter VI, but still less than the proposed system loading threshold presented in Section VIII. A contour plot showing tidally averaged TN concentrations throughout the system resulting from the N loading scenario is presented in Figure IX-2.

Table IX-3. Comparison of model average total N concentrations from present loading and the modeled loading scenario, with percent change over background in Cape Cod Bay (0.295 mg/L), for the Sandwich Harbor system.

Station Location	monitoring station (MEP ID)	present (mg/L)	scenario (mg/L)	% change
Inlet basin	SH-2	0.310	0.328	+115.2%
Lower Dock Creek	SH-3	0.327	0.387	+192.1%
Lower Mill Creek	SH-4	0.332	0.481	+399.7%
Upper Mill Creek	SH-5	0.627	0.916	+87.2%
Lower Old Harbor Creek	SH-6	0.310	0.324	+92.1%
Upper Dock Creek	SH-7	0.891	2.220	+222.8%
Sandwich Harbor	SH-8	0.343	0.379	+72.5%
Sandwich Harbor	SH-9	0.952	1.291	+51.6%
Sandwich Harbor	SH-10	0.313	0.329	+85.3%
Mid Old Harbor Creek	SH-11	0.312	0.328	+92.0%
Lower Spring Hill Creek	SH-12	0.315	0.333	+89.9%
Upper Spring Hill Creek	SH-13	0.385	0.422	+41.3%
Upper Old Harbor Creek	SH-14	0.361	0.407	+70.4%
Upper Old Harbor Creek	SH-15	0.806	1.106	+58.6%

These scenario results do not account for potential subwatershed changes as a result of discharging the selected effluent volumes. The selected volumes of discharge at both sites may have the potential to alter the groundwater flow paths near them enough to alter the subwatershed delineations. Site 1 is adjacent to a number of subwatershed boundaries, while Site 2 straddles a subwatershed boundary. Groundwater modeling would be necessary to fully evaluate these changes and this is beyond the scope of the MEP.

In addition, these scenario results do not account for the potential impact of increased phosphorus discharge at Site 2 within the Shawme Pond subwatershed. Water quality in freshwater ponds tends to be determined by the amount of phosphorus, which is usually added from both their watershed and internally from their sediments. According to WRS analysis in the CWRMP, Shawme Pond already has impaired ecosystem conditions, including excessive phosphorus and dense macrophyte growth (WP, 2012). These impaired conditions have been acknowledged by MassDEP, which has classified Shawme Pond as Category 5 waters requiring development of a TMDL (MassDEP, 2013). More refined characterization of the pond, including updated bathymetry, sediment phosphorus regeneration, and summer water quality data, would be necessary to determine the level of concern associated with the potential additional watershed phosphorus loads from the proposed Site 2 discharge.

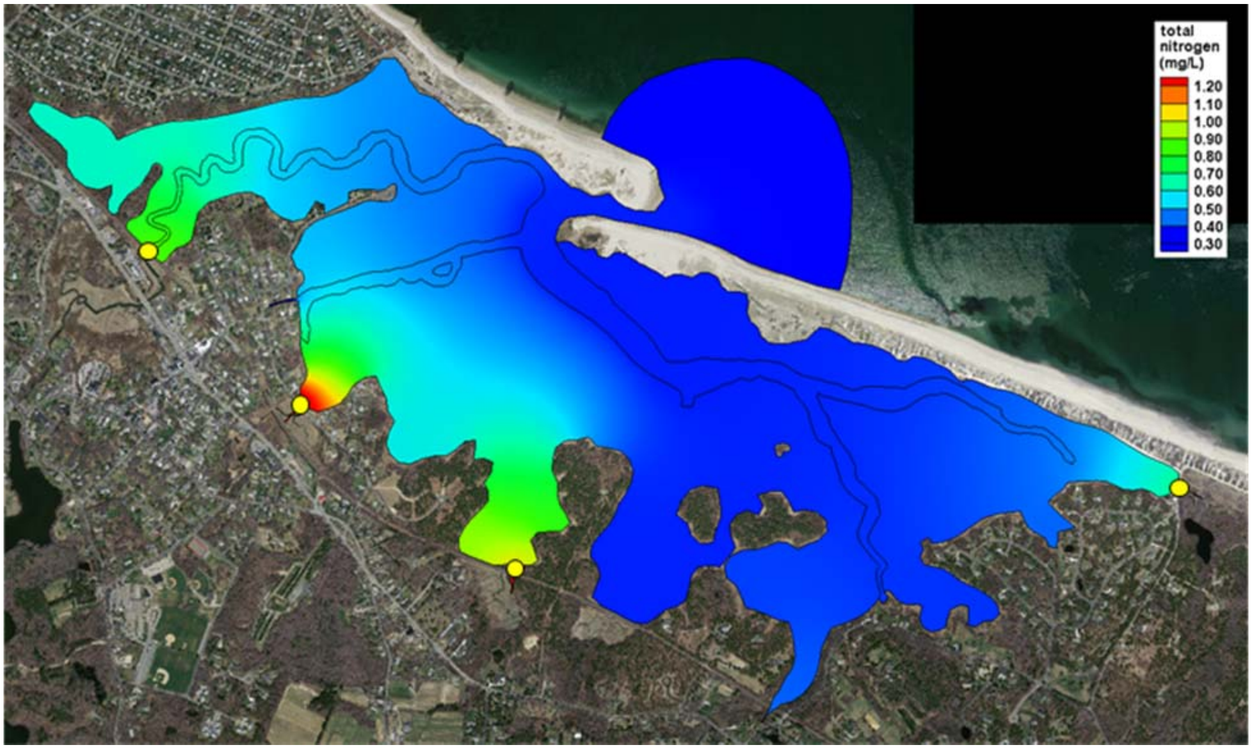

Figure XI-2. Contour plot of modeled total nitrogen concentrations (mg/L) in Sandwich Harbor, for the modeled loading scenario.

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