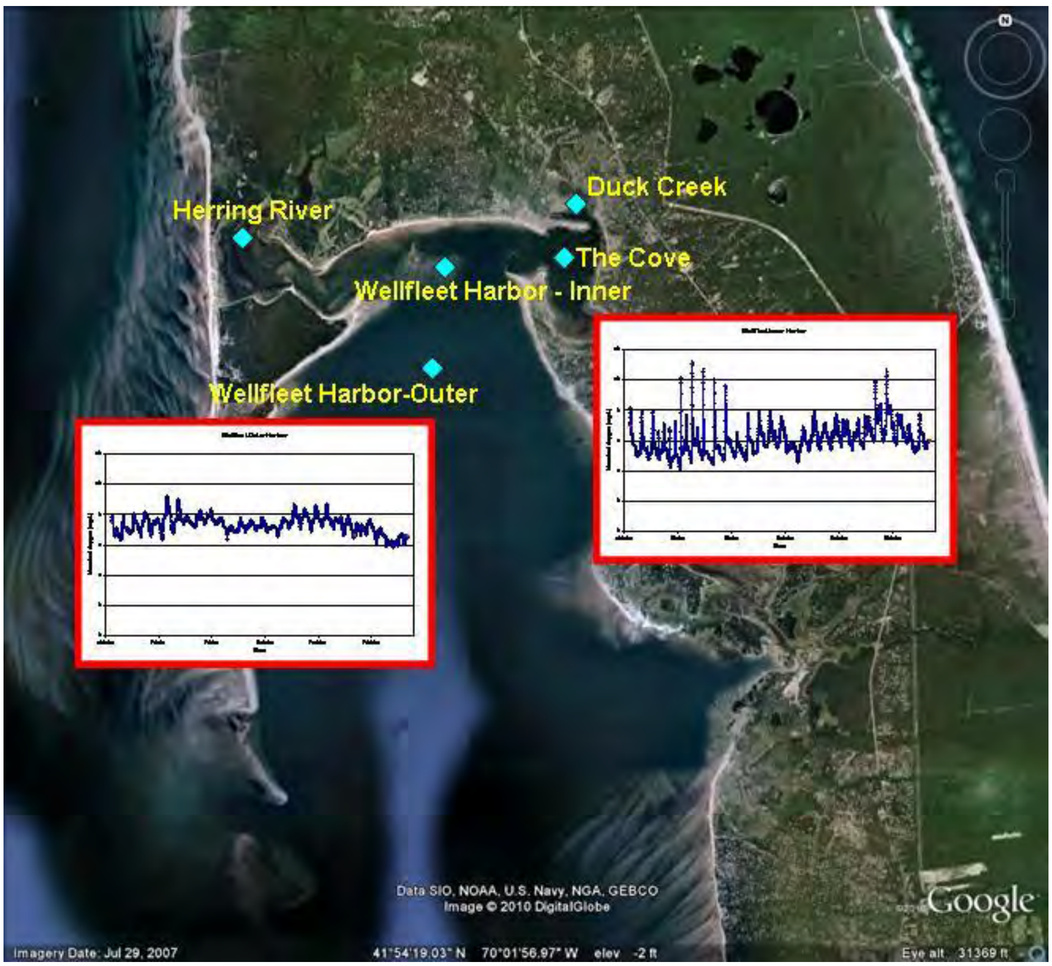
Massachusetts Estuaries Project

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



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

FINAL REPORT – March 2017

Massachusetts Estuaries Project

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

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Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Hummock Pond, Nantucket, Massachusetts

Executive Summary

1. Background

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Wellfleet Harbor embayment system, a coastal embayment of outer Cape Cod within the Town of Wellfleet, Massachusetts. Analyses of the Wellfleet Harbor embayment system was performed to assist the Town with up-coming nitrogen management decisions as well as wetland restoration, anadromous fish runs, shell fishery, and open-space 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/macroalgal 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 Wellfleet 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 Wellfleet 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 restoration of the Wellfleet 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 Wellfleet Harbor embayment system within the Town of Wellfleet is showing clear signs of eutrophication (over enrichment) from extremely limited tidal exchange with clean Cape Cod Bay water, atmospheric deposition, flux of nutrients from bottom sediments, as well as and to a lesser extent, enhanced nitrogen loads entering through groundwater from the gradually increasing development of the 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 relatively pristine nature of Wellfleet's nearshore, Harbor and pond waters has historically been a valuable asset to the region. However, concern over the potential degradation of Harbor water quality and the subsequent effect on the oyster aquaculture sector began to arise, which has resulted in monitoring, scientific investigations and management planning which continues to this day. While Wellfleet Harbor presently has a relatively low nitrogen load from its watershed, due to its moderately sized watershed and proportionally large undeveloped areas, it is still showing signs of impairment by nitrogen enrichment in the upper most reaches of the system (tributary basins) and is clearly eutrophic (e.g. Duck Creek). Overall, the estuary is showing some nitrogen related habitat impairment within some of its component basins, however, most of the system is supporting high quality to moderately impaired habitat, with regions of moderate to significant impairment found only in Duck Creek, which was significantly nitrogen enriched (0.93 mg L^{-1} tidally averaged TN) and is furthest from the systems tidal inlet. As such, nutrient management in the Wellfleet Harbor watershed is warranted.

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 and the Islands (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 Wellfleet Harbor embayment system by using site-specific data collected by the MEP and water quality data from the Water Quality Monitoring Program conducted by the Wellfleet Health and Conservation Department, with technical guidance from the Coastal Systems Program at SMAST (see Section II). Evaluation of upland nitrogen loading was conducted by the MEP. Estuaries Project staff obtained digital parcel and tax assessors data from the Town of Wellfleet Geographic Information Systems Department and watershed specific water use data from the Department of Public Works. The land-use data was used to determine watershed nitrogen loads within the Wellfleet Harbor embayment system and associated sub-embayments (current and build-out loads are summarized in Section IV). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Wellfleet Harbor embayment system. Once the hydrodynamic properties of the estuarine system was 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 bio-available and total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis while nitrogen entering the coastal embayment was quantified by direct measurement of stream nutrient concentrations and freshwater flow, predominantly groundwater, in streams discharging directly to the embayment. Boundary nutrient concentrations in the Cape Cod Bay source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Wellfleet 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 approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout and 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 Wellfleet 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 salt marsh and tidal flat 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 Wellfleet 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 Wellfleet in order to effectively examine the effect of load increases/reductions on water column nutrient concentrations.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Wellfleet Harbor system based upon available water quality monitoring data, distribution of macroalgae, time-series water column oxygen measurements, and benthic community structure. At present, eelgrass is not found within Wellfleet Harbor. Eelgrass surveys and analysis of historical data are a key part of the MEP Approach. Surveys of submerged aquatic vegetation were conducted in the Wellfleet Harbor Estuary, particularly within the shallow waters in the uppermost reaches of the system (mouth of Herring River, the Cove, Duck Creek) as well as the tidal flats around Lieutenants Island. Eelgrass surveying was also undertaken in the nearshore waters immediately east and west of the Great Island, Great Beach and the narrow barrier beach/sand spit that separates Wellfleet Harbor from Cape Cod Bay. The most recent survey was conducted in 2001, as part of the MEP program with an earlier survey conducted in 1995. Additional analysis of available aerial photographs from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed.

While there were no eelgrass beds within the Wellfleet Harbor Estuary in the MassDEP conducted 1995 and 2001 surveys (with the exception of the nearshore waters on the Cape Cod Bay side of the barrier beach spit extending southward from Great Island and Great Beach) and the recently lost small patch near the inlet, the MEP Technical Team also confirmed both the lack of eelgrass in the tidal flats areas around Lieutenants Island, as well as the shallow waters leading into the Herring River. The MEP Technical Team confirmed the lack of eelgrass throughout the Wellfleet Harbor system in 2004. Therefore, habitat restoration in this system should focus on infaunal habitat quality.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate significantly nutrient enriched waters within the innermost basins of the Wellfleet Harbor system (Section VII.2). The oxygen data are consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-*a*. The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follows the spatial pattern of total nitrogen levels in this system (Section VII), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

The oxygen records (both moorings and grab samples) collected from the Wellfleet Harbor system show that the inner most basins within the system (e.g. Wellfleet-inner, The Cove, Duck Creek, Herring River) have large daily oxygen excursions, indicative of nitrogen enrichment. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration indicates that the inner-most portions of the system are showing signs of nitrogen enrichment. Measured dissolved oxygen depletion from moored sensors and grab samples indicate that the much of the Wellfleet Harbor Estuary (e.g. Wellfleet-inner, The Cove, Duck Creek, Herring River, Drummers Cove/Loagy Bay and basin south of Lt. Island) with the exception of the lower main basin of Wellfleet Harbor, are exhibiting moderate to significant oxygen stress. The embayment specific results are presented in Section VII.2.

Quantitative sediment sampling was conducted at 21 locations within the Wellfleet Harbor Embayment System to characterize benthic animal communities as a indicator of habitat health/impairment. 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. It should be noted that, given the presence of macroalgae and the recent loss of eelgrass from near the inlet and periodic oxygen declines in some sub-basins to <4 mg L^{-1}, it appears that portions of Wellfleet Harbor Estuary are impaired by nutrient enrichment, such as Duck Creek, the Cove and the mouth of the Herring River where it joins the upper portion of Wellfleet Harbor. To the extent that these areas can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded).

Overall, the Infauna Survey indicated that certain basins comprising Wellfleet Harbor Estuary are presently supporting impaired benthic infaunal habitat (Section VII.3). However, none of the basins had benthic communities with significant numbers of stress indicator species (e.g. *tubificids, capitellids*), which are typically found in highly nutrient and organic matter enriched estuarine basins. These species, where they did occur, generally comprised <5% of the community and were always less than 12% of the individuals present. Generally the communities throughout the system were comprised of crustaceans, mollusks, and polychaetes, with some deep burrowers, indicative of a system supporting moderate to high quality benthic habitat.

3. Conclusions of the Analysis

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

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

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Town of Wellfleet, Wellfleet Harbor embayment system was comprised primarily of runoff from natural surfaces, load directly to the water body surface and nitrogen from wastewater. Land-use and wastewater analysis found that generally about 82% of the controllable watershed nitrogen load to the embayment was from wastewater and 8 percent each was from impervious surfaces and fertilized areas in the watershed.

A major finding of the MEP clearly indicates that a single total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of numerous MEP analyses such as the nearby Pleasant Bay and Nauset Harbor analyses as well as analyses conducted across Martha's Vineyard Nantucket and Cape Cod (e.g. Great, Green and Bournes Pond Systems, Popponesset Bay System, the Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay, the analysis of the Rushy Marsh system and the Namskaket Marsh, Little Namaskaket Marsh and Rock Harbor embayments associated with the Town of Orleans).

The threshold nitrogen level for the Wellfleet Harbor embayment system was determined as follows:

Wellfleet Harbor Threshold Nitrogen Concentrations

- The approach for determining nitrogen loading rates that will support acceptable habitat quality throughout an embayment system is to first identify a sentinel location within the embayment and secondly, to determine the nitrogen concentration within the water column that will restore the location to the desired habitat quality. The sentinel location for Wellfleet Harbor was selected such that the restoration of that one site (WH-5) will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined (Section VIII.2), the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved (Section VIII.3).

- The upper main basin, the Drummer Cove/Loagy Bay sub-basin, the basin south of Lt. Island and the Cove are currently showing low to moderate impairment of benthic animal communities. The uppermost basin or Duck Creek has the greatest impairment and Lower main basin and the mouth of Herring River do not show symptoms of nitrogen related impairment to benthic habitat. Tidally averaged TN levels at WH-5 (0.55 mg TN L^{-1}) is slightly higher than typically found in open water systems supporting healthy benthic animal habitat (0.50 mg TN L^{-1}). As this basin is showing only a low level of impairment lowering the TN level to 0.53 mg TN L^{-1} should reverse its impairment.

- It should be noted that the Cove is highly depositional and supports a community adapted to those conditions. Lowering the nitrogen level within that basin will improve the community, but the high rates of deposition are due significantly to its geomorphology and this physical constraint will limit the amount of reduction in TN level possible at this location. Similarly, Duck Creek, behind Shirttail Point, has reduced mixing and is also depositional. This combined basin, with its fringing salt marsh, is structurally nitrogen enriched. None-the-less, these basins will be significantly restored if the threshold is met at the sentinel station, particularly if the function of Duck Creek as a salt marsh dominated tidal creek is considered.

- With the sentinel station (WH-5) established and a threshold concentration selected (0.53 mg TN L^{-1}), the Linked Watershed-Embayment Model was used to sequentially adjust nitrogen loads from the Wellfleet Harbor estuary watershed until the targeted nitrogen concentration was achieved. The modeling simulations described in Section VIII-3 targeted the restoration of benthic animal habitat in the main basin, with secondary thresholds within the tributary Coves. The lowering of average TN levels within the upper main basin of the Wellfleet Harbor System will also simultaneously improve benthic animals throughout this estuarine system.

It is important to note that the analysis of future nitrogen loading to the Wellfleet Harbor estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. In the case of the Wellfleet Harbor watershed, these potential increases are likely to be slight due to large areas that are part of the National Seashore. Nevertheless, given the slightly over-loaded state of the system, watershed-estuarine nitrogen management should consider management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Wellfleet Harbor estuarine system is that restoration will necessitate a reduction in nutrient loads from the watershed. Reduction in the present nitrogen inputs and management options to negate additional future nitrogen inputs should be considered as flushing of the system is strong with clean Cape Cod Bay water.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Wellfleet Harbor system, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations. Loads to estuarine waters of the Wellfleet Harbor system include both upper watershed regions contributing to the major surface water inputs.

Sub-embayments	Natural (unaltered) 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)	Present Atmospheric Deposition[5] (kg/day)	Present Benthic Flux (kg/day)	Present Total Load[6] (kg/day)	Observed TN Conc.[7] (mg/L)	Threshold TN Conc.[8] (mg/L)
Herring River/The Gut	13.68	15.97	11.75	--	27.72	2.81	20.65	51.18	0.45-0.90	--
Duck Creek	0.35	1.16	4.24	--	5.40	-	19.82	25.22	0.62-1.09	--
The Cove	0.46	1.85	7.97	--	9.82	2.22	148.71	160.75	0.62-1.10	--
Drummer/Blackfish	0.43	1.56	5.80	--	7.36	1.66	7.31	16.33	0.51-0.80	--
Hatches Creek	0.73	2.16	7.30	--	9.46	0.15	-8.58	1.03	0.46-0.70	--
Wellfleet Harbor	0.99	3.85	13.68	177.00	17.53	64.72	47.51	129.76	0.38-0.72	0.53
Loagy Bay	0.19	0.52	1.93	--	2.45	0.99	9.75	13.19	--	--
System Total	**16.83**	**27.07**	**52.67**	**177.00**	**79.74**	**72.55**	**245.17**	**397.46**	**0.38-1.10**	**0.53**

[1] assumes entire watershed is forested (i.e., no anthropogenic sources)
[2] composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
[3] existing unattenuated wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings
[5] atmospheric deposition to embayment surface only.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of data collected between 2001 and 2006, ranges show the upper to lower regions (highest-lowest) of the indicated sub-embayment.
[8] threshold for sentinel site located at mid-point WQ monitoring station of the system.

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

Sub-embayments	Present[1] Watershed Load (kg/day)	Target[2] Threshold Watershed Load (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic[3] Flux Net (kg/day)	TMDL[4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
Herring River/The Gut	27.72	27.13	2.81	18.70	48.64	-2.13%
Duck Creek	5.40	1.80	-	17.88	19.68	-66.67%
The Cove	9.82	3.04	2.22	133.46	138.72	-69.04%
Drummer/Blackfish	7.36	3.59	1.66	6.47	11.72	-51.22%
Hatches Creek	9.46	9.46	0.15	-7.84	1.77	0.00%
Wellfleet Harbor	17.53	8.64	64.72	44.61	117.97	-50.71%
Loagy Bay	2.45	1.19	0.99	8.65	10.83	-51.43%
System Total	**79.74**	**54.85**	**72.55**	**221.93**	**349.33**	**-31.21%**

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

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 southeastern Massachusetts. Without the help of many staff and volunteers, it would not have been possible to complete the Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Wellfleet Harbor Embayment System. Without these stewards and their efforts, the Massachusetts Estuaries Project would not have been possible.

First and foremost we would like to recognize and applaud the significant time and effort in data collection and discussion spent by members of the Town of Wellfleet Health and Conservation Department, CWMP Committee, and MEP Committee, Town of Truro staff, and Town of Eastham staff. The Coastal Systems Program Technical Team would also like to take the opportunity to specifically thank: Hillary Greenberg-Lemos, Emily Beebe, Alex Hay, and Curt Felix from Wellfleet; Paul Gabriel from Environmental Partners, the late Rex Peterson and Charleen Greenhalgh from Truro; Jane Crowley and Gail McAleer from Eastham for organizational support and personal commitment to advancing environmental stewardship on Cape Cod and specifically in Wellfleet Harbor.

In addition to local contributions, technical, policy and regulatory support has been freely and graciously provided by Paul Niedzwiecki and Tom Cambareri of the Cape Cod Commission. We are also thankful for the long hours in the field and laboratory spent by technical staff (Jen Benson, Michael Bartlett, Sara Sampieri and Dahlia Medieros), interns and students within the Coastal Systems Program at SMAST-UMD.

Support for this project was provided by the Town of Wellfleet, Barnstable County and the MassDEP.

PROPER CITATION

Howes B.L., S. Kelley, J. S. Ramsey, E. Eichner, R.I. Samimy, D.R. Schlezinger, P. Detjens (2017). Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Wellfleet Harbor Embayment System, Town of Wellfleet, Massachusetts, Massachusetts Department of Environmental Protection. Boston, MA.

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I. INTRODUCTION

The Wellfleet Harbor embayment system is located within the Town of Wellfleet on Cape Cod Massachusetts. The system has an western shore bounded by a narrow barrier beach (the Gut extending southward past Great Island and ending at Jeremy Point) separating the Harbor from Cape Cod Bay, with which it exchanges tidal waters. The Wellfleet Harbor Estuary is one of the largest embayments on Cape Cod and is comprised of large open water areas (namely Wellfleet Harbor) as well as small tributary sub-embayments such as the mouth of Herring River at The Gut, Duck Creek, The Cove, Drummers Cove and Loagy Bay (Figure I-1). The watershed contributing nitrogen to the waters of the Wellfleet Harbor Estuary is contained primarily within the Town of Wellfleet with the exception of a small portion of the sub-watershed to Bound Brook which is a freshwater tributary to the Herring River. The uppermost portion of the Bound Brook sub-watershed extends into the Town of Truro. Restoration of degraded habitats within the estuary will depend mainly upon the efforts of the Town of Wellfleet and its citizens, however, depending on the level of nutrient management there may be the need for some coordination of efforts with the Town of Truro. In addition the National Seashore manages land within the watershed, but for the most part these areas are undeveloped and contribute little nitrogen load to the estuary.

The present configuration of the Wellfleet Harbor embayment system results from a combination of glacially dominated geologic processes including the deposition of glacial outwash deposits and tidal flooding of drowned river valleys (Herring River, Fresh Brook, Hatches Creek, Silver Spring) formed primarily by post-glacial rivers and enhancements to support human uses (e.g. tidal channel to Duck Creek). The major drowned-river valley components are found in The Herring River with its associated tributaries. The Cove in its present configuration appears to be formed as a small basin on the back side of a tombolo (Indian Neck) which was likely an island before being connected to the mainland. In the lower portion of the Wellfleet Harbor system, Fresh Brook, Silver Spring and Hatches Creek represent small drowned river valley systems with associated salt marsh and expansive tidal flats that are significantly exposed for lard portions of the ebb tide. Overall, the Wellfleet Harbor System is a composite or complex estuary comprised of the aforementioned drowned river valley sub-estuaries exchanging tidal waters with a large lagoonal estuary, Wellfleet Harbor, which is flushed by Cape Cod Bay. The large open water basin that is regarded as Wellfleet Harbor is oriented in a north-south manner with a central axis that runs parallel to the shore line and is bounded to the west by barrier beach and to the east by uplands of Cape Cod. The lagoon represents more than ¾ of the estuarine area and habitat. The lagoon was mainly formed by the depression created by the overlying Cape Cod Lobe of the glacier that occupied Cape Cod Bay during the last glacial period. During the retreat of the glaciers that formed Cape Cod, sea level gradually rose and drove erosion and sediment transport along the shores of Cape Cod. On the Atlantic Ocean side of the outer Cape sand was transported north to form the Provincetown Spit. The formation of the Provincelands prevented sediment transport to the Cape Cod bay beaches from the Atlantic. However, sediment from the eroding bay-side uplands of Cape Cod supplied sand to the bay side beaches by long shore drift. The sand moving south formed a spit of land off of the Wellfleet mainland. Eventually this spit connected to the northernmost island (Great Island) and successive small islands to the south. As the sand accumulated between the islands a barrier was formed providing protection from the waves of Cape Cod Bay thus forming the sheltered environment of Wellfleet Harbor with its associated salt marshes. The Wellfleet Harbor System is a relatively “young” estuary and 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.

Figure I-1. Study region proximal to the Wellfleet Harbor embayment system for the Massachusetts Estuaries Project nitrogen thresholds analysis. Tidal waters enter the system through one wide "inlet" to Cape Cod Bay. Freshwaters enter from the watershed primarily through 3 surface water discharges: Herring River, Fresh Brook and Hatches Creek, as well as direct groundwater discharge. The main basin constitutes Wellfleet Harbor.

Although erosional processes associated with post-glacial streams and rivers were fundamental to the formation of portions of this system, at present the streams are relatively small and discharge only a small portion of the aquifer recharge to the estuary. The biggest of the streams is the Herring River which discharges to uppermost portion of the harbor. Two small freshwater streams, Fresh Brook and Hatches Creek, discharge to the eastern side of the harbor through extensive salt marshes. Most freshwater from the watershed enters the Bay through direct groundwater seepage along the eastern shore.

As is typical of many other Cape Cod embayments (Nauset System and Pleasant Bay), Wellfleet Harbor is separated from the adjacent open waters by a barrier beach, which is heavily influenced by coastal storms. Within portions of Wellfleet Harbor, mainly the Herring River and the uppermost part of Duck Creek, the tide propagating through the wide opening of the Harbor is significantly attenuated by dikes which reduce flow up into these sub-basins. Whereas the mean tide range in Wellfleet Harbor is ~2.5 meters, up-gradient of the restriction of the Herring River dike the mean tide range drops to ~0.5 meters. Generally, all other areas of the Wellfleet Harbor system experience an undampened tide and are relatively well flushed.

The barrier beach that protects Wellfleet Harbor to the west is a very dynamic geomorphic feature, due to the strong influence of littoral transport processes. While the formation of the Wellfleet Harbor system was dependent upon coastal processes which formed the barrier beach to form the lagoon, the estuary continues to be affected by these same coastal processes as they alter both the length of the spit extending south from Great Island and the location of the tidal flats at the inlets to sub-components of the system such as the Herring River as well as Drummer Cove and Loagy Bay. The effect of these processes is no longer to significantly affect the geomorphology of the estuary and its basins, but to partially control the quality of the habitats within the estuary given how they maybe influenced by activities in the contributing watershed. Changes in hydrodynamics wrought by inlet and shoal dynamics is a key factor in determining the effects of watershed nitrogen loading on estuarine health (see Sections V & IX). To the extent that the small inlets to the sub-component basins of Wellfleet Harbor become restricted due to shifting shoals which reduce tidal flushing, nitrogen loading impacts will be magnified over present conditions.

Similar to the Nauset and Pleasant Bay embayment systems, Wellfleet Harbor is a shallow coastal estuary dominated by salt marsh and tidal flats, as well as being located within a watershed that includes glacial outwash plain (Wellfleet Outwash Plain) and marine deposits (beach/dune deposits and marsh deposits) consisting of material laid down after the retreat of the Cape Cod Lobe of the Laurentide Ice sheet ~15,000 years ago (Figure I-2, Oldale, 1992). The outwash material is highly permeable and varies in composition from well sorted medium sands to course pebble sands and gravels. As such, direct rainwater run-off is typically rather low for these coastal systems and therefore, most freshwater inflow to these estuarine waters is via groundwater discharge or groundwater fed surface water flow (e.g. Herring River, Fresh Brook, Hatches Creek). Wellfleet Harbor acts as a large mixing zone for terrestrial freshwater inflow and saline tidal flow from Cape Cod Bay, however, the salinity characteristics of the embayment system are mainly dominated by that of Cape Cod Bay with the exception of the uppermost reach of the Harbor in the immediate vicinity of the Herring River discharge and Duck Creek. Given the large tidal flows and volumetric exchange, there is presently only minor dilution of salinity throughout most of the estuary.

Wellfleet Harbor, along with its associated terminal sub-embayments which are dominated by salt marshes, constitutes an important component of the natural and cultural resources of Cape Cod and the Town of Wellfleet. As such the Town of Wellfleet, working with both the Coastal Systems Program at the University of Massachusetts School for Marine Science and Technology and the National Park Service (Cape Cod National Seashore) has undertaken comprehensive water quality monitoring of the Wellfleet Harbor system as well as a variety of studies to investigate the condition of the Herring River sub-system and its restoration.

The primary ecological threat to Wellfleet Harbor resources is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters has been greatly increased over the past few decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to this and other outer Cape embayment systems such as Pleasant Bay and the Nauset Estuary in the Town of Orleans, like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. The Town of Wellfleet has been steadily growing over the past two to three decades and does not have centralized wastewater treatment to process the increasing nitrogen loads resulting from the increased development. As existing and probable increasing levels of nutrients enter the waters of the Wellfleet Embayment System, water quality degradation will accelerate, with further harm to invaluable environmental resources of the Town and potentially affect a well established oyster aquaculture industry.

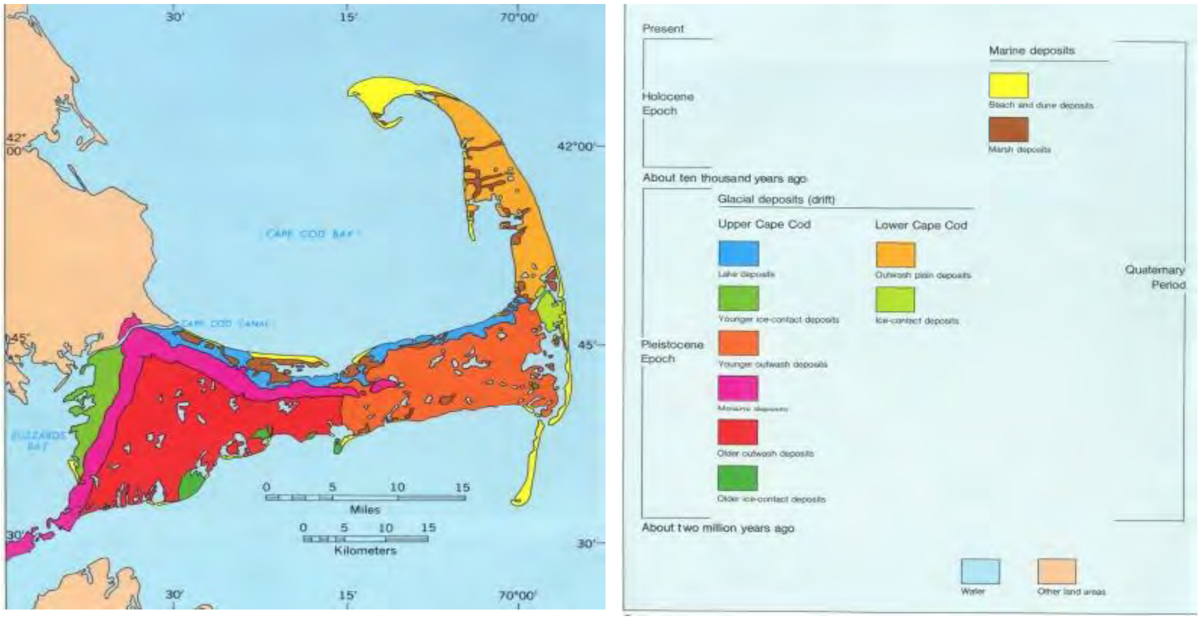

Figure I-2. Geologic map of Cape Cod (generalized from detailed mapping by K. F. Mather, R. P. Goldthwait, L. R. Theismeyer, J. H. Hartshorn, Carl Koteff, and R. N. Oldale).

The large shoreline and numerous terminal sub-embayments greatly increases the potential for direct discharges from homes situated on the shore and decreases the travel time of groundwater from the watershed recharge areas to harbor regions of discharge. The nature of enclosed embayments in populous regions brings two opposing elements to bear: as protected marine shoreline they are popular regions for boating, recreation, and land development; as semi-enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shores. In particular, the more enclosed basin within the upper reaches of the Harbor (the Cove and the Gut), as well as terminal sub-embayments such as Drummer Cove and Loagy Bay along the Wellfleet Harbor eastern shoreline, are at risk of eutrophication from high nitrogen loads entering via direct groundwater seepage in addition to surface water inflows from adjacent sub-watersheds.

Given the value of the resource and concern over the problems associated with nutrient over-enrichment, in 1989 the Massachusetts Secretary of Environmental Affairs designated part of Wellfleet Harbor as an Area of Critical Environmental Concern (ACEC). The purpose of the ACEC program is to preserve, restore, and enhance critical environmental resource areas in the state. The designation is intended to encourage communities to steward the area's natural resources, but in practical terms it provides little regulatory oversight. It has therefore been necessary for the Town of Wellfleet to take the initiative to provide such oversight and clarity through amendment and revision to its own Environmental By-Law and take necessary steps to protect the Wellfleet Harbor resource consistent with the ACEC designation.

As the primary stakeholder to the Wellfleet Harbor Embayment System, the Town of Wellfleet was among the first communities to become concerned over perceived degradation of embayment health. The Town of Wellfleet (via the Health/Conservation Department) has long recognized the potential threat of nutrient over-enrichment of the Town's coastal embayment. As such, a comprehensive water quality monitoring program was developed to establish the current water quality conditions in the harbor and monitor for gradual changes in water quality over time. The common focus of the water quality monitoring efforts undertaken by the Town of Wellfleet has been to gather site-specific data on the current nitrogen related water quality throughout the Wellfleet Harbor system to ultimately 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 Wellfleet Water Quality Monitoring Program forms a 5 year baseline from which to gauge long-term changes as watershed nitrogen management moves forward. The quality of these data allowed the MEP to prioritize the Wellfleet Harbor System for this next step in the protection and management of the harbor as well as to gauge the impacts on the main basin of the restoration of specific tributaries to the overall system, such as the Herring River.

The MEP effort builds upon the efforts of the water quality monitoring programs, and previous hydrodynamic and water quality analyses, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Wellfleet Harbor embayment system, including all sub-embayments such as Herring River, Duck Creek, the Cove, Drummer Cove and Loagy Bay.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to undertake wastewater master planning and nitrogen management alternatives development which may be currently needed by the Town of Wellfleet. 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 to develop and evaluate the most cost effective nitrogen management alternatives to protect/restore this valuable coastal resource which is currently undergoing nitrogen enrichment.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

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 Wellfleet) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries.

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

The Massachusetts Estuaries Project represents the next generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (MassDEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts. The MEP approach was selected after extensive review by the MassDEP and USEPA and associated scientists and engineers. It has subsequently been applied to more than 60 estuaries and reviewed by other state agencies, municipalities, non-profit environmental organizations, engineering firms, scientists and private citizens. Over the course of the extensive reviews, the MEP approach has proven to be robust and capable of yielding quantitative results to support management of a wide variety of estuaries.

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

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

The major MEP nitrogen management goals are to:

- provide technical analysis and supporting documentation to Towns as a basis for sound nutrient management decision making towards embayment restoration
- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of 70 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment's model "alive" to address future municipal needs.

The core of the Massachusetts Estuaries Project analytical method is the Linked Watershed-Embayment Management Modeling Approach (Figure I-3). 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 of more than 60 embayments throughout southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach's greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing "what if" scenarios for evaluating watershed nitrogen management options. The MEP Technical Team, through SMAST-UMD, has conducted more than 200 scenarios to date.

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

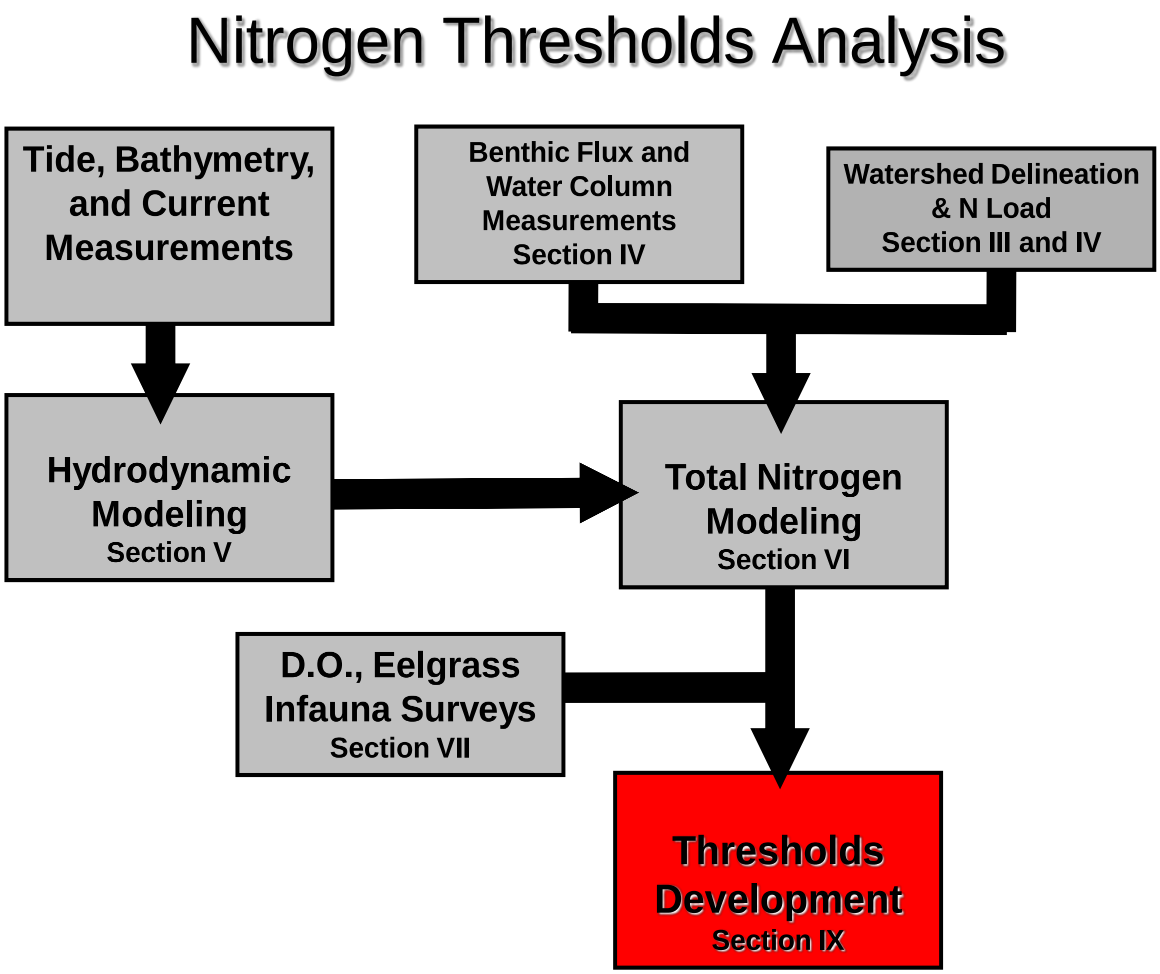

Figure I-3. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

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

- Watercolumn Monitoring - multi-year embayment nutrient sampling
- Hydrodynamics -
  - embayment bathymetry
  - site specific tidal record
  - current records (in complex systems only)
  - hydrodynamic model
- Watershed Nitrogen Loading
  - watershed delineation

  - stream flow (Q) and nitrogen load
  - land-use analysis (GIS)
  - watershed N model
- Embayment TMDL - Synthesis
  - linked Watershed-Embayment N Model
  - salinity surveys (for linked model validation)
  - rate of N recycling within embayment
  - D.O record
  - Macrophyte survey
  - Infaunal survey

As management alternatives are being developed and evaluated, it is important to note that nitrogen loading and tidal exchange within each sub-embayment is the primary factor controlling habitat health in that sub-basin. The quality of the inflowing waters from the main basin of Wellfleet Harbor is the other, although a slightly less critical controlling factor given the connectivity to low nutrient water from Cape Cod Bay. In addition the nitrogen loading to each sub-embayment affects the health of the receiving main basin of the System. Most of the nitrogen entering the lagoonal component, first passes through a sub-embayment. The result is that the restoration of nitrogen impaired tributary sub-embayments to the Wellfleet Harbor System require both "local" or contributing area specific nitrogen management, as well as management of nitrogen levels within the watershed of the larger "regional" main basin.

I.3 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 Wellfleet 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). Tidal reaches within Wellfleet Harbor system follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

Nutrient related water quality decline represents one of the most serious threats to the ecological health of 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 for assimilation without degradation (termed assimilative capacity) is exceeded and nutrient related water quality and aquatic resources decline. 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 we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout the Wellfleet Harbor System monitored by the Town of Wellfleet Water Quality Monitoring Programs 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.

In general, nutrient over-fertilization is termed "eutrophication" and when the nutrient loading is primarily from human activities, "cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to the Wellfleet Harbor system and contributed to a decline in ecological health, it is sometimes possible that eutrophication within the Wellfleet Harbor system could potentially occur without anthropogenic influence and must be considered in the nutrient threshold analysis. While this finding would not change the need for restoration, it would change the approach and potential targets for management. As part of future restoration efforts, it is important to understand that it may not be possible to turn each embayment into a "pristine" system.

I.4 WATER QUALITY MODELING

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

The MEP water quality evaluation examined the potential impacts of nitrogen loading into Wellfleet Harbor and all of its component sub-embayments. 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 system was 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 Monomoy model for sub-watershed areas designated by MEP. Almost all nitrogen entering the Wellfleet Harbor system is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Cape Cod Bay source waters and throughout the Wellfleet Harbor system was taken from the water quality monitoring program run by the Town of Wellfleet (associated with the Coastal Systems Program at SMAST). Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of the system were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Wellfleet Harbor System for the Town of Wellfleet. A review of existing studies related to habitat health or nutrient related water quality is provided in Section II with a more detailed review of prior hydrodynamic investigations in Section V. The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since 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 (Section IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission data and offshore water column nitrogen values were derived from an analysis of monitoring station data for an offshore station proximal to the “inlet” of the Harbor (Section IV and VI). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by the municipality) as discussed in Section VI. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of each embayment was performed that included a review of existing water quality information and the results of a benthic analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment in Section VIII.

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

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

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

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

A number of studies relating to development of the Town of Wellfleet and the management of its natural resources, hydrodynamics and habitat health (particularly the condition of the Herring River salt marsh) have been conducted within the Wellfleet Harbor System over the past three decades and are briefly summarized below.

***Local Comprehensive Plan**.* – Well before the Town's decision to engage in the Massachusetts Estuaries Project, a Local Comprehensive Plan was developed in 1995 for the Town of Wellfleet. The plan was undertaken to guide many aspects of development in the Town such that the community character would be maintained, much of which is dependent on the health of the local and regional natural resources (e.g. Wellfleet Harbor, Herring River). In 2008, an update to the 1995 Local Comprehensive Plan was completed by the Town of Wellfleet Planning Department. Of note in the 2008 update is the Towns commitment to protecting its natural resources and its recognition that the health of its estuarine resource is threatened by increased development and associated nutrient loading. It is stated explicitly in the 2008 update that "Wellfleet Harbor, like other coastal embayments throughout the US, has become nutrient enriched and is experiencing declines in ecological health. The primary cause of such eutrophication is an overabundance of nitrogen discharged within the watershed of the waterbody. For Wellfleet Harbor, the primary source of the contaminant nitrogen is wastewater. Stormwater, leaching lawn fertilizers and discharges from agricultural land uses also contribute varying quantities of nitrogen." In this context, Wellfleet entered into the Massachusetts Estuaries Project early on in the inception of the MEP specifically to explore approaches to better managing sanitary wastewater and obtain sound assessment of the quality of the Town's embayment and how to institute changes necessary to control sources of nitrogen and restore impaired water quality conditions. The MEP analysis of the Wellfleet Harbor system has proceed in a manner consistent with the needs of the Town the priorities of MassDEP for wastewater planning and its desire to abide by recommendations set forth in the 2008 Update of the Local Comprehensive Plan.

***2006 Wellfleet Harbor Management Plan* –** The 2006 Wellfleet Harbor Management Plan was developed as an update to the Harbor Management Plan (HMP) which was originally completed in 1995. The original HMP was in part developed to support the 1989 designation of Wellfleet Harbor as an Area of Critical Environmental Concern (ACEC). While the 2006 Harbor Management Plan indicates that the state of the Harbor is generally sound, it does also state that there are many signs that elicit concern and require attention and action. Some of these signs are specifically related to the potential effects of nutrients on estuarine water quality such as: 1) the last twenty-five years has seen explosive growth in the Town population, summer visitors, boaters, shellfish grants, etc., all of which leads to a more intensive use of the harbor with associated impacts, 2) closures of shellfish areas downstream of the Herring River dike are on-going, 3) high levels of nutrients, specifically nitrogen, were observed, especially in Duck Creek, the Marina area and Blackfish Creek, 4) the high levels of nutrients have resulted in elevated levels of chlorophyll (an indicator of increased biological activity) and declines in dissolved oxygen, 5) there is evidence for consequent losses in biological diversity in Wellfleet Harbor and sub-components of the overall harbor system, 6) shell fishermen have reported an increase in seaweeds (e.g. macroalgae) and algal blooms, 7) eelgrass once colonizing areas of Wellfleet Harbor has now disappeared; and 8) Duck Creek, and the marina, show a build-up of soft sulfidic bottom sediments. The harbor management plan is based on a few fundamental principles which are also supported by the objectives of the Massachusetts Estuaries Project analysis, mainly maintaining good water quality is critical to all uses of the harbor, ensuring multiple, traditional uses of the harbor, with opportunities for local employment and maintaining the biological diversity of the harbor, with its many habitats and species. A series of recommendations were set forth on a wide variety of aspects of harbor management including some which relate specifically to the MEP: 1) Map the subtidal bottoms in Wellfleet and inventory the basic fauna to follow the health of this environment and 2) Create an education program for citizens, board members and Town officials to increase knowledge about nitrogen overloads, the MEP process and likely outcomes.

Cape Cod Coastal Embayment Project. Eichner, E.M., T.C. Cambareri, K. Livingston, C. Lawrence, B. Smith and G. Prahm. 1998. 319 Final Project Report for MassDEP and USEPA. Cape Cod Commission. Barnstable, MA.

The Cape Cod Commission conducted watershed analysis on a series of Cape Cod embayments, including Wellfleet Harbor. The results are available in the Cape Cod Commission Coastal Embayment Project Report (1998) included an assessment of Wellfleet Harbor. This assessment included delineation of a watershed and selected subwatersheds, development of nitrogen loads based on existing and build-out land uses, and development of potential nitrogen loading limits based on residences times developed from a tidal flushing assessment (McSherry, 1993)[1]. It was noted at the time that water quality data should be compared to the estimated nitrogen loading limits especially for Drummer Cover/Blackfish Creek and that a review that was underway at the time by SMAST had indicated that internal loading by sediment regeneration in Duck Creek was also a concern. These data have been incorporated into the present MEP assessment.

Hydrodynamic and Salinity Modeling for Estuarine Habitat Restoration at Herring River, Wellfleet, Massachusetts (2001) – The focus of this study completed by scientists at the University of Rhode Island (Spaulding and Grilli, 2001) was the development of a calibrated and validated hydrodynamic model of the Herring River salt marsh system that discharges to the head of Wellfleet Harbor. Special attention was given to assessing the volumetric tidal flows though the dike.

Much attention has been dedicated to understanding the effects of the dike that was constructed in 1908 across the entrance to Herring River and the associated marsh system. The dike has restricted tidal flows, resulting in loss of salt marsh habitat within the Herring River. The restriction in flow imposed by the dike has resulted in the conversion of hundreds of hectares of the original inter-tidal, salt marshes into upland vegetation eliminating habitat for estuarine plants and animals, including fish and shellfish. In addition it has resulted in adverse impacts on water quality including acidification of river waters, leaching of metals from the sediments and episodic anoxia. It has also resulted in subsidence of the wetlands. Understanding the effects of the dike has become critical to the restoration efforts being undertaken in the Herring River marsh system.

Due to the significant changes that occurred to the salt marsh system over the past 100 years, the National Park Service (NPS), the Cape Cod National Seashore (CACO) managers, the public, and local and state environmental authorities over the past decade have turned their attention towards restoring the estuarine habitat in Herring River. As a first step towards the development of a restoration plan, the hydrodynamic study was undertaken to build a calibrated and validated hydrodynamic and salinity model. The model was developed to allow for the analysis of the impact of various restoration options, including various configurations of the sluice and tidal gates located in the dike and alterations to the opening in the dike, on the flows, sea surface elevations, and salinity distribution in the river. This hydrodynamic model was based on earlier simplified modeling studies and field data collection programs sponsored by NPS. Ultimately, the goals of the 2001 Spaulding-Grilli study were: (1) to apply state of the art models to predict the tidal flows and salinity in the Herring River system above the dike, (2) to collect field data for selected periods of time to validate and calibrate the models, and (3) to perform a series of simulations, using the validated model, to determine the impact of various modifications to the dike on the tidal flows and the tidal ranges and salinities in the river.

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[1] McSherry, T.R. 1993. Modeling of Wellfleet Harbor and Adjoining Tributaries. Woods Hole Oceanographic Institution. Woods Hole, MA.

To support model calibration and validation two separate field programs were performed. The first consisted of continuous time series measurements of sea surface elevation up and downstream of the dike for the period from June to October 2000. The second consisted of two intensive tidal cycle experiments, performed on July 25, 2000 and September 27, 2000, which directly characterized the currents and flows through the dike, sea surface elevations up and downstream of the dike, and salinity and temperature fields in the Herring River system and adjacent Wellfleet Harbor, over a lunar, semi-diurnal (M2) tidal cycle (period-12.42 hrs). In addition the flux of freshwater into the system was determined by gauging surface water inflows at key locations.

Sedimentation concerns associated with the proposed restoration of Herring River marsh, Wellfleet, MA. (2004) - Town officials and resources managers have been concerned over how sediment transport and deposition might change with the alteration of the tidal regime in Herring River as part of restoration. Of particular concern is potential increased sedimentation on shellfish beds seaward of the present dike. Therefore, a study was conducted by Dougherty (2004) to address sedimentation concerns related to the possible restoration of Herring River flows and to determine the effect of altering the tidal system on tidal flats used for oyster and hard clam culture in Wellfleet Harbor. This study used a two-step approach to examine potential changes in sedimentation associated with increasing tidal flow to the Herring River: 1) Solicitation of specific sedimentation questions from the community concerning the restoration of the Herring River, with special emphasis on the effects on shellfish grants and 2) Response to these questions using pertinent information from previous investigations augmented with new, site specific data and analyses. While this report is not directly related to the nutrient focus of the MEP it does offer some pertinent conclusions regarding down stream effects of dike removal/modification associated with restoration of the up-gradient Herring River marshlands. A few of the conclusions related specifically to potential sedimentation in the lower Herring River are as follows: 1) Geomorphic analysis of the inter-tidal area below the Herring River Dike shows almost no change over the past 155 years, with the exception of the formation of a small ebb- and larger flood-tidal delta. Otherwise, channel morphology below the present dike is the same today as before dike construction in 1909; hence the dike has had little effect on downstream sedimentation, 2) the predicted change in sedimentation, as a result of restoring tidal flow to the Herring River, would be minimal and proximal to the dike, 3) Data from both the 1960s breach of the dike and from Hatches Harbor sedimentation not only support this prediction of minimal down stream sedimentation effects, but also indicate that the resulting changes around the dike will purportedly improve sedimentary conditions for shellfish repopulation.

Wellfleet Harbor Comprehensive Water Quality Monitoring Program - The Town of Wellfleet through the Health Department, while being actively engaged in the study and management of municipal infrastructure and natural resources, committed early on to gathering baseline water quality monitoring data in support of the MEP analysis. For the Town of Wellfleet, the focus of the Wellfleet Harbor Water Quality Monitoring Program was the gathering of site-specific data on the current nitrogen related water quality throughout the estuary to support evaluations of water quality, assessment and modeling and information relative to habitat health. Water quality monitoring of the Wellfleet Harbor system on the Cape Cod Bay shore of Cape Cod was initiated and designed as a coordinated effort between the Town of Wellfleet Health Department and the Coastal Systems Program at SMAST-UMD. The water quality monitoring program was initiated in 2005 and has continued uninterrupted through the summer of 2011. After the first three years of monitoring, the sampling program was reduced in terms of the number of sampling events conducted each summer. In the first three years of monitoring, six sampling events undertaken each summer between June and early September. In subsequent years, only 4 events were completed from June to early September. The Water Quality Monitoring Program developed its baseline from sampling stations distributed throughout the harbor basin and Duck Creek as well as Drummer Cove and Loagy Bay. (Figure II-1). Additionally, as remediation plans for this system are implemented throughout the Town of Wellfleet, the continued monitoring is planned to provide quantitative information to the Town relative to the efficacy of remediation efforts relative to the Clean Water Act.

The joint Town of Wellfleet / CSP Water Quality Monitoring Program provided the quantitative water column nitrogen data (2005-2011) required for the implementation of the MEP's Linked Watershed-Embayment Management Modeling Approach. The MEP effort also builds upon previous watershed delineation and land-use analyses, the previous embayment hydrodynamic modeling work undertaken by others (Spaulding, 2001) and historical eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Wellfleet Harbor Estuarine System. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the Wellfleet Harbor System and to reduce costs to the Town of Wellfleet.

Regulatory Assessments of Wellfleet Harbor Resources - The Wellfleet Harbor Estuary contains a variety of natural resources of value to the citizens of Wellfleet and Truro as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these resources. The MEP gathers the available information on these resources as part of its assessment, and presents them here (Figures II-2 through II-7) for reference by those providing stewardship for this estuary. For the Wellfleet Harbor Estuary these include:

- Mouth of River designation – MassDEP (Figure II-2a, 2b, 2c)
- Designated Shellfish Growing Area – MassDMF (Figure II-3a, 3b)
- Shellfish Suitability Areas - MassDMF (Figure II-4)
- Anadromous Fish Runs - MassDMF (Figure II-5)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-6)
- Area of Critical Environmental Concern – ACEC (Figure II-7)

Implementation of the MEP's Linked Watershed-Embayment Approach incorporates the quantitative water column nitrogen data (2005-2011) gathered by the Water Quality Monitoring Program and watershed and embayment data collected by MEP staff. The MEP effort also builds upon previous watershed delineation and land-use analyses, the previous embayment hydrodynamic modeling (by MEP staff) and historical eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Wellfleet Harbor Estuarine System. The MEP has incorporated all appropriate data from previous studies to enhance the development of nitrogen thresholds for the Wellfleet Harbor System and to reduce costs of restoration for the Town of Wellfleet.

Figure II-1. Town of Wellfleet Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the Town and volunteers in conjunction with technical support from the Coastal Systems program - SMAST. Red symbols are stations sampled in years prior to 2005 but not included in current monitoring program (2005-2011)

Figure II-2a. Mouth of river designation (red line) by MassDEP, the Massachusetts Rivers Act.

Figure II-2b. Mouth of river designation (red line) by MassDEP, the Massachusetts Rivers Act.

Figure II-2c. Mouth of river designation (red line) by MassDEP, the Massachusetts Rivers Act.

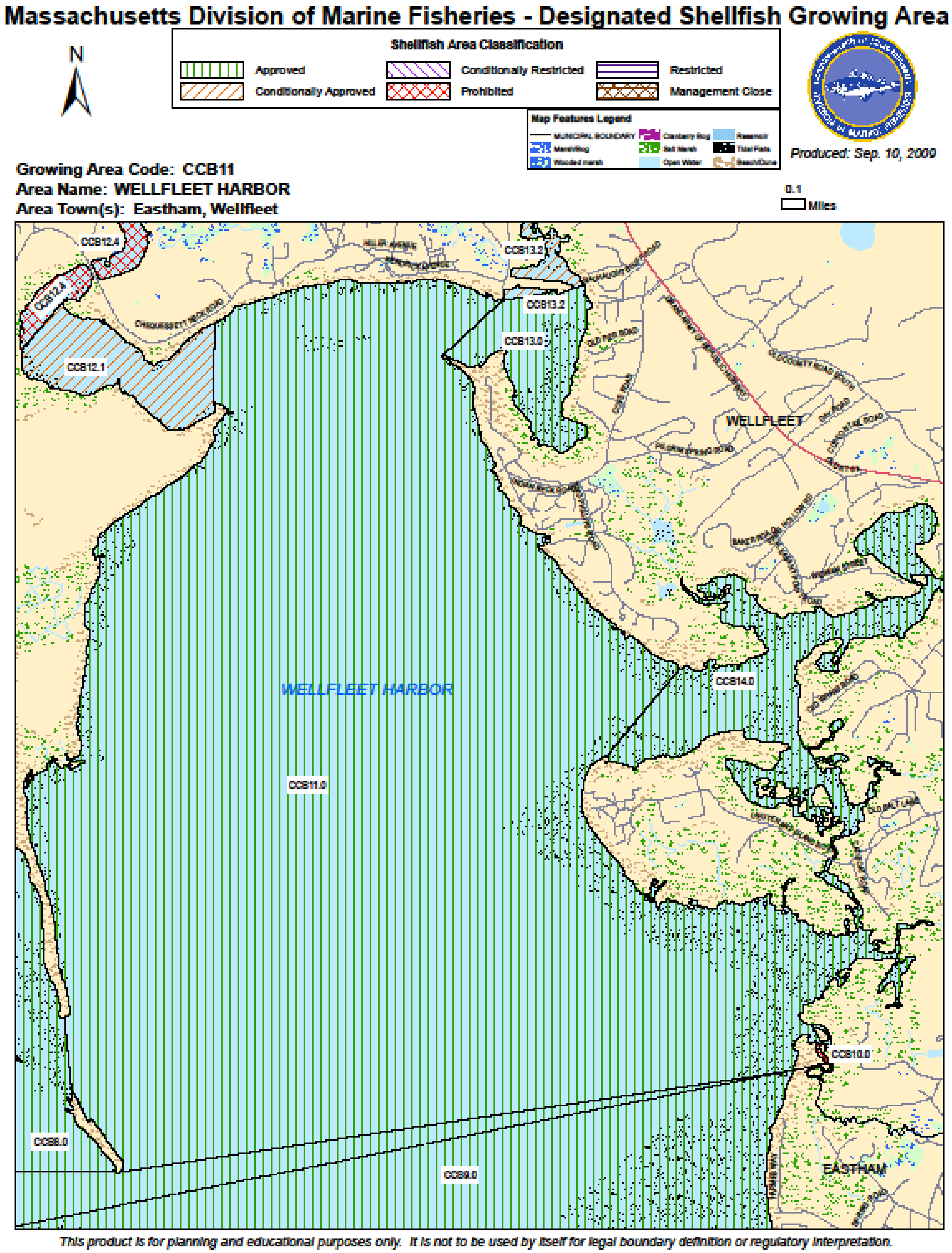


Figure II-3a. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas. Duck Creek and lower Herring River are conditionally approved due to bacterial contamination.

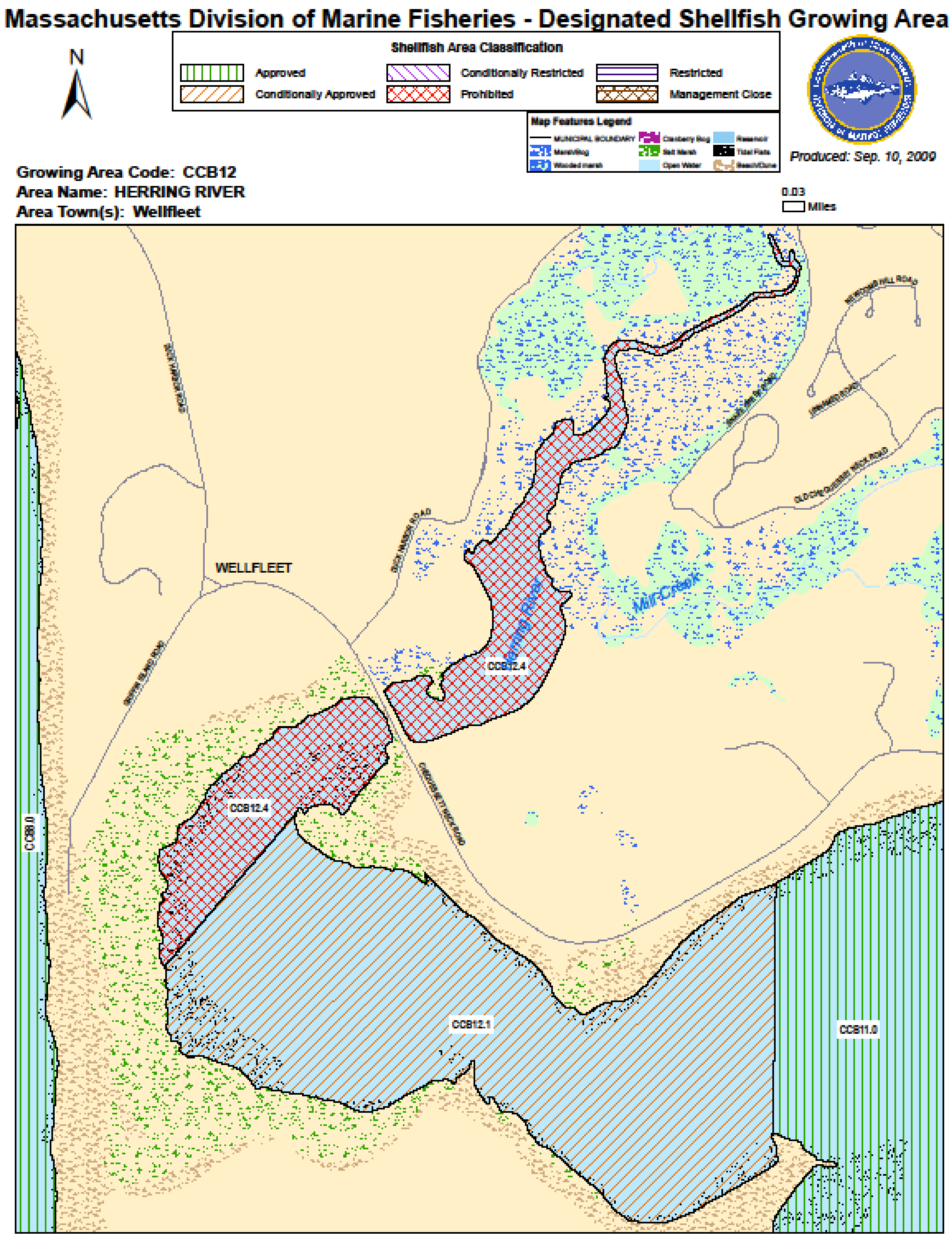


Figure II-3b. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas. The area above the dike is permanently closes

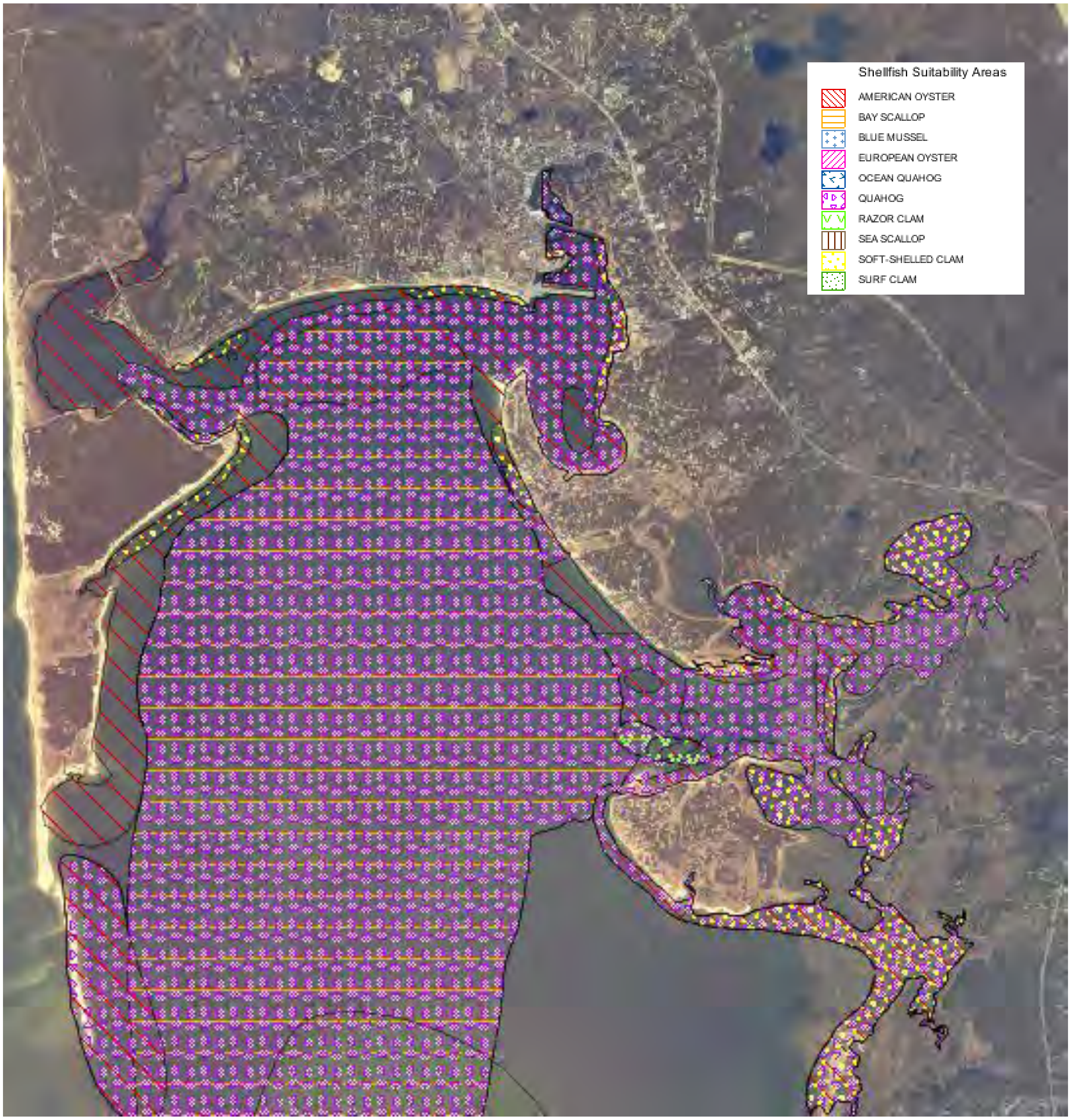


Figure II-4. Location of shellfish suitability areas within the Wellfleet Harbor Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean those shellfish are actually "present".

Figure II-5. Anadromous fish run within the Herring River portion of the Wellfleet Harbor Estuary as determined by Mass Division of Marine Fisheries. The red diamonds show areas where fish were observed. .

Figure II-6. Habitats designated as supportive of Rare Wildlife and State Protected Rare Species within the Wellfleet Harbor Estuary as determined by - NHESP. Designation only means the habitat is appropriate, not that the rare or protected species is actually present.

Figure II-7. Areas of Critical Environmental Concern (ACEC) associated with the Wellfleet Harbor Estuary.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). The USGS groundwater modelers were central to the development of the groundwater modeling approach used by the Estuaries Project. The USGS has a long history of developing regional models for the six-groundwater flow cells on Cape Cod. Through the years, advances in computing, lithologic information from well installations, water level monitoring, stream flow measurements, and reconstruction of glacial history have allowed the USGS to update and refine the groundwater models significantly improving their accuracy. 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 address a 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 the Wellfleet Harbor System. The Wellfleet Harbor Estuary is characterized by a large, open basin (lagoon) with a number of smaller tributary basins located along its margin (*e.g.*, Duck Creek, The Cove, Drummer Cove, and Loagy Bay) and is fed by a number of streams, including the Herring River, Fresh Brook, and Blackfish Creek. This estuary is situated along the eastern edge of Cape Cod and is bounded by Cape Cod Bay. The Wellfleet Harbor watershed includes portions of the Towns of Wellfleet, Eastham, and Truro, with areas within the bounds of the National Seashore.

In the present investigation, the USGS was responsible for the application of its regional groundwater model to define the watershed or contributing area to the Wellfleet Harbor estuarine system. The Wellfleet Harbor watershed is situated across the Chequesset groundwater lens and the northern margin of the Nauset groundwater lens. Both lenses are included in a regional groundwater model of the Lower Cape (Masterson, 2004). Watershed modeling was undertaken to sub-divide the overall watershed to the Wellfleet Harbor Estuary into functional sub-units based upon: (a) defining inputs from contributing areas to each major portion within the embayment system, (b) defining contributing areas to major freshwater aquatic systems which 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 the estuary. 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 Wellfleet Harbor watersheds was also used to evaluate the contributing areas to current and potential future public water supply wells throughout the Lower Cape.

The relatively transmissive sand and gravel deposits that comprise most of Cape Cod create a hydrologic environment where watershed boundaries are generally best 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 that discharges directly into an estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Wellfleet Harbor Estuary and its various subwatersheds, such as Herring River, Duck Creek, and Loagy Bay, were delineated using the regional groundwater model for the Lower Cape (Masterson, 2004). The USGS variable density groundwater model SEAWAT (Guo and Langevin, 2002) was used to model the groundwater lens. SEAWAT was used because the Lower Cape freshwater groundwater lenses float on salt water rather than having bedrock at their base like the Monomoy and Sagamore regional groundwater lenses. The USGS particle-tracking program MODPATH (Pollock, 1994), which uses output files from SEAWAT, was used to track the simulated movement of water in the aquifer and delineate the contributing areas to streams, ponds, and coastal water bodies. This approach was used to determine the contributing areas to the Wellfleet Harbor system and its subwatersheds and also to determine portions of recharged water that may flow through freshwater ponds and streams prior to discharging into the coastal water bodies.

The Lower Cape Flow Model extends across all four groundwater lenses of the outer Cape. The model grid consists of 320 rows, 110 columns and 23 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top layer extends to 5 feet below NGVD 29, the second layer extends to 20 feet below NGVD 29, and then layers are uniformly 20 feet thick down to 200 ft below NGVD 29. Below this level, layers are uniformly 25 ft thick with the bottom layer (#23) extending to 500 feet below NGVD 29, which is specified as a no-flow boundary in the model and is generally the top of the bedrock surface beneath the outer Cape (Masterson, 2004). SEAWAT allows the transient modeling of the freshwater/saltwater interface, which is generally important for defining groundwater discharge along the coast and specifically important for modeling potential impacts of municipal drinking water well withdrawals.

Direct rainwater run-off in Cape Cod aquifer materials is typically rather low. Lithological data used to determine hydraulic conductivities used in the regional groundwater model were obtained from a variety of sources including well logs from USGS, local Town records and data from previous investigations. Final aquifer parameters in the groundwater model were determined through calibration to measured water levels and stream flows. Hydrologic data used for Outer Cape model calibration included historic water-level data obtained from USGS records for the long-term monitoring network and three synoptic water table surveys in November 1975, June 2001, and May 2002 (Masterson, 2004).

The two groundwater lenses that are part of the Wellfleet Harbor watershed are generally within aquifers derived from two different sources of glacial sediments. The Lower Cape, except for Provincetown, is generally comprised of sediments deposited in three large braided river deltas flowing from retreating lobes of the continental ice sheet approximately 15,000 years ago (Oldale and O'Hara, 1984). These rivers flowed into a large glacial lake located in present Cape Cod Bay. Coarser sand and gravel were deposited closer to the ice sheet lobes with finer material closer to the lake. These former river deltas constitute the Eastham, Wellfleet, and Truro Plains Deposits (Oldale and Barlow, 1986). The majority of the Wellfleet Harbor watershed is part of the Wellfleet Plains Deposit, with a smaller, southern portion within the Eastham Plains Deposits. The Eastham Plains Deposits are the youngest of the outer Cape glacial deposits and were the furthest from the sediment source (*i.e.*, the glacier face), while the Wellfleet Plains Deposits are the oldest of the outer Cape deposits and were much closer to the glacier face. As such, the Eastham Plains Deposits tend to be composed of finer sands and are underlain by silts and clays, while the Wellfleet Plains Deposits tend to be composed of coarser sands and gravels (Masterson, 2004). Although these glacial materials vary, modeling and field measurements of contaminant transport at the Massachusetts Military Reservation have shown that groundwater flowpaths in these types of deposited materials are highly permeable (*e.g.*, Masterson, et al., 1996). Given their high permeability, recharge dominates and direct rainwater run-off is typically rather low within the watershed.

The construction of the Lower Cape regional groundwater model includes an average recharge rate of 24 inches/year. Since most of the Lower Cape relies on private on-site wells for drinking water and septic systems for wastewater treatment, water withdrawn and returned to the groundwater system typically occurs on the same lot and this is included in the construction of the USGS model. The only exception in the USGS modeling was associated with the Truro/Provincetown public water supplies where water is pumped in Truro and most is discharged within Provincetown (Masterson, 2004). The selected recharge rate is based on the most recent USGS analysis.

III.3 WELLFLEET HARBOR ESTUARY CONTRIBUTORY AREAS

The refined watershed and sub-watershed boundaries for the Wellfleet Harbor embayment system, including Duck Creek, Drummer Cove, Loagy Bay and other sub-basins (Figure III-1) were determined by the United States Geological Survey (USGS). Model outputs of the watershed boundaries were "smoothed" to: (a) correct for the artifacts of 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 developed as a collaborative effort between the USGS and the rest of the MEP Technical Team at the outset of the project and was used by the MEP technical team to refine the Wellfleet Harbor subwatersheds. The MEP sub-watershed delineation includes 10-yr time-of-travel boundaries. Including travel time, 43 sub-watershed areas were delineated within the Wellfleet Harbor study area, including watersheds to eight freshwater ponds and three MEP monitored stream gauges.

Table III-1 lists the daily freshwater discharge volumes for each of the subwatersheds to Wellfleet Harbor as determined from 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 directly measured surface water discharges. The overall estimated freshwater inflow into the Wellfleet Harbor Estuary from its MEP watersheds is 117,286 m^3/d. This flow includes corrections for outflow from selected ponds along the outer Wellfleet Harbor watershed boundary, including Great Pond in Truro and Long Pond in Wellfleet. Model output was compared to measured flow at MEP gauges, which collected streamflow measurements between 2003 and 2005 (see Section IV.2). The measured flows are also used for calibration of the estuarine water quality model.

The MEP watershed delineation is the second watershed delineation completed in recent years for the Wellfleet Harbor System. 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 developed based on 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 three versions of the Regional Policy Plan (CCC, 1996, 2001, and 2009).

The MEP watershed area for the Wellfleet Harbor system as a whole is approximately 4% smaller than the 1998 CCC delineation (17,353 acres vs. 18,002 acres, respectively). There are small differences in the location of the groundwater divide between Cape Cod Bay and the Atlantic Ocean, but most of the difference is in the northern portion of the watershed, where the CCC delineation extended further north than the MEP delineation. The MEP watershed delineation also includes much more refined interior sub-watersheds to various components of the Wellfleet Harbor system, such as selected ponds and gauged streams that were not included in the CCC delineation. These refinements allow estimation of portions of pond watershed flows that ultimately reach Wellfleet Harbor. For example, the MEP delineation refinements show that Long Pond in Wellfleet discharges groundwater to Gull Pond and the wetland system that discharges into Duck Harbor (see Figure III-1). Gull Pond predominantly discharges to a portion of the Chequesset groundwater lens that flows toward the Atlantic Ocean, while Duck Harbor is a portion of Wellfleet Harbor. These types of subwatershed refinements of flow/discharge allow better agreement with measured MEP streamflows and, ultimately, better targeting of nitrogen management strategies. These refinements are another benefit of the update of the USGS regional groundwater models.

The evolution of the watershed delineation for the Wellfleet Harbor System has allowed increasing accuracy as each new version adds new hydrologic data to that previously collected; the groundwater model allows all this data to be organized and to be brought into congruence with data from adjacent watersheds. The evaluation of older data and incorporation of new data during the development of the model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model 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 of the watershed. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the downgradient estuary. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the aquatic systems and ultimately to the estuarine waters of the Wellfleet Harbor estuary system (Section V.1).

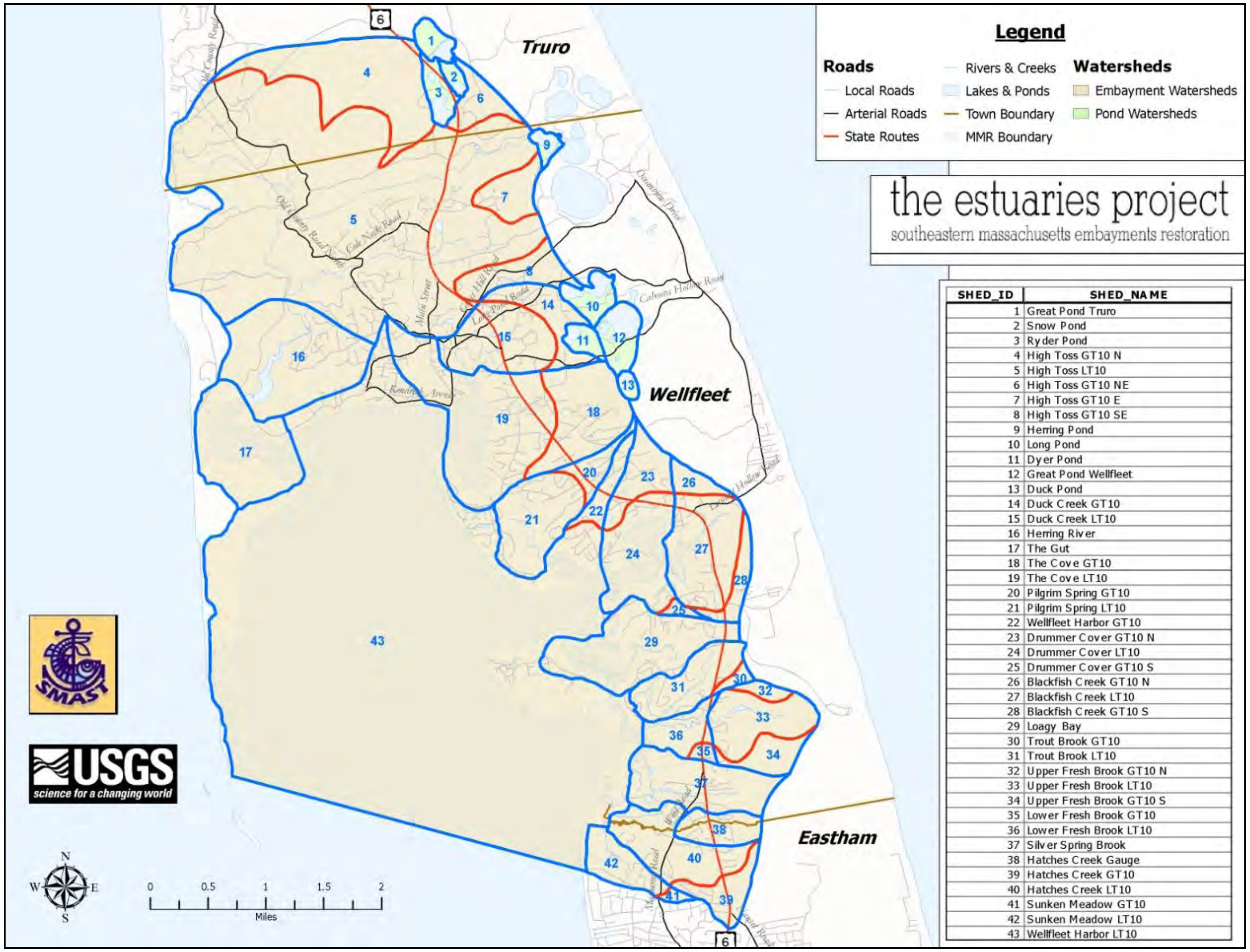


Figure III-1. Watershed delineation for the Wellfleet Harbor estuary used in the land-use analysis by the MEP. The Watershed includes portions of three Towns: Wellfleet, Eastham, and Truro. Subwatershed delineations are based on USGS groundwater model output with modifications to better address pond and estuary shorelines and MEP stream gauge measurements. Subwatersheds to estuarine sub-basins (*e.g.*, Duck Creek) were selected based upon functional estuarine sub-units in the water quality model (see Section VI). Ten-year time-of-travel delineations were produced for quality assurance purposes and are designated with a "LT10" or "GT10" in the watershed names.

Table III-1. Daily groundwater discharge from each of the sub-watersheds comprising the overall watershed to the Wellfleet Harbor Embayment System, as determined from the regional USGS groundwater model outputs.

Watershed	#	Watershed Area (acres)	Discharge	
			m^3/day	ft^3/day
Great Pond Truro	1	57	384	13,578
Snow Pond	2	28	192	6,779
Ryder Pond	3	72	485	17,130
High Toss GT10N	4	568	3,838	135,535
High Toss LT10	5	3,271	22,107	780,704
High Toss GT10NE	6	107	725	25,588
High Toss GT10E	7	123	834	29,462
High Toss GT10SE	8	157	1,063	37,538
Herring Pond	9	33	221	7,807
Long Pond	10	84	568	20,059
Dyer Pond	11	47	321	11,319
Great Pond Wellfleet	12	111	751	26,509
Duck Pond	13	22	148	5,216
Duck Creek GT10	14	155	1,051	37,108
Duck Creek LT10	15	313	2,113	74,606
Herring River	16	562	3,801	134,244
The Gut	17	221	1,491	52,661
The Cove GT10	18	340	2,296	81,084
The Cove LT10	19	537	3,631	128,215
Pilgrim Spring GT10	20	75	504	17,805
Pilgrim Spring LT10	21	308	2,080	73,450
Wellfleet Harbor GT10	22	80	540	19,081
Drummer Cove GT10N	23	153	1,033	36,493
Drummer Cove LT10	24	200	1,349	47,629
Drummer Cove GT10S	25	20	134	4,729
Blackfish Creek GT10N	26	57	385	13,583
Blackfish Creek LT10	27	342	2,313	81,685
Blackfish Creek GT10S	28	81	546	19,289
Loagy Bay	29	385	2,603	91,921
Trout Brook GT10	30	24	159	5,620
Trout Brook LT10	31	219	1,481	52,299
Upper Fresh Brook GT10N	32	35	235	8,284
Upper Fresh Brook LT10	33	241	1,626	57,409
Upper Fresh Brook GT10S	34	101	686	24,212
Lower Fresh Brook GT10	35	20	132	4,664
Lower Fresh Brook LT10	36	110	743	26,246
Silver Spring Brook	37	336	2,269	80,119
Hatches Creek Gauge	38	124	836	29,534

Table III-1 (continued).
Daily groundwater discharge from each of the sub-watersheds in the watershed to the Wellfleet Harbor system estuary, as determined from the regional USGS groundwater model outputs.

Watershed	#	Watershed Area (acres)	Discharge	
			m3/day	ft3/day
Hatches Creek GT10	39	117	792	27,974
Hatches Creek LT10	40	299	2,023	71,458
Sunken Meadow GT10	41	15	104	3,667
Sunken Meadow LT10	42	136	921	32,519
Wellfleet Harbor LT10	43	1,027	6,944	245,234
TOTALS		11,312	76,457	2,700,043
WELLFLEET HARBOR TOTALS			75,022	2,649,366

Notes:
1) discharge volumes are based on 24 in/yr of recharge on adjusted watershed areas (total watershed areas are shown);
2) listed flows do not include precipitation on the surface of the estuary;
3) upgradient ponds often discharge to multiple downgradient subwatersheds, percentage of outflow is determined by length of downgradient shoreline going to each subwatershed; these corrections are included in the Wellfleet Harbor totals;
4) totals may not match exactly due to rounding.

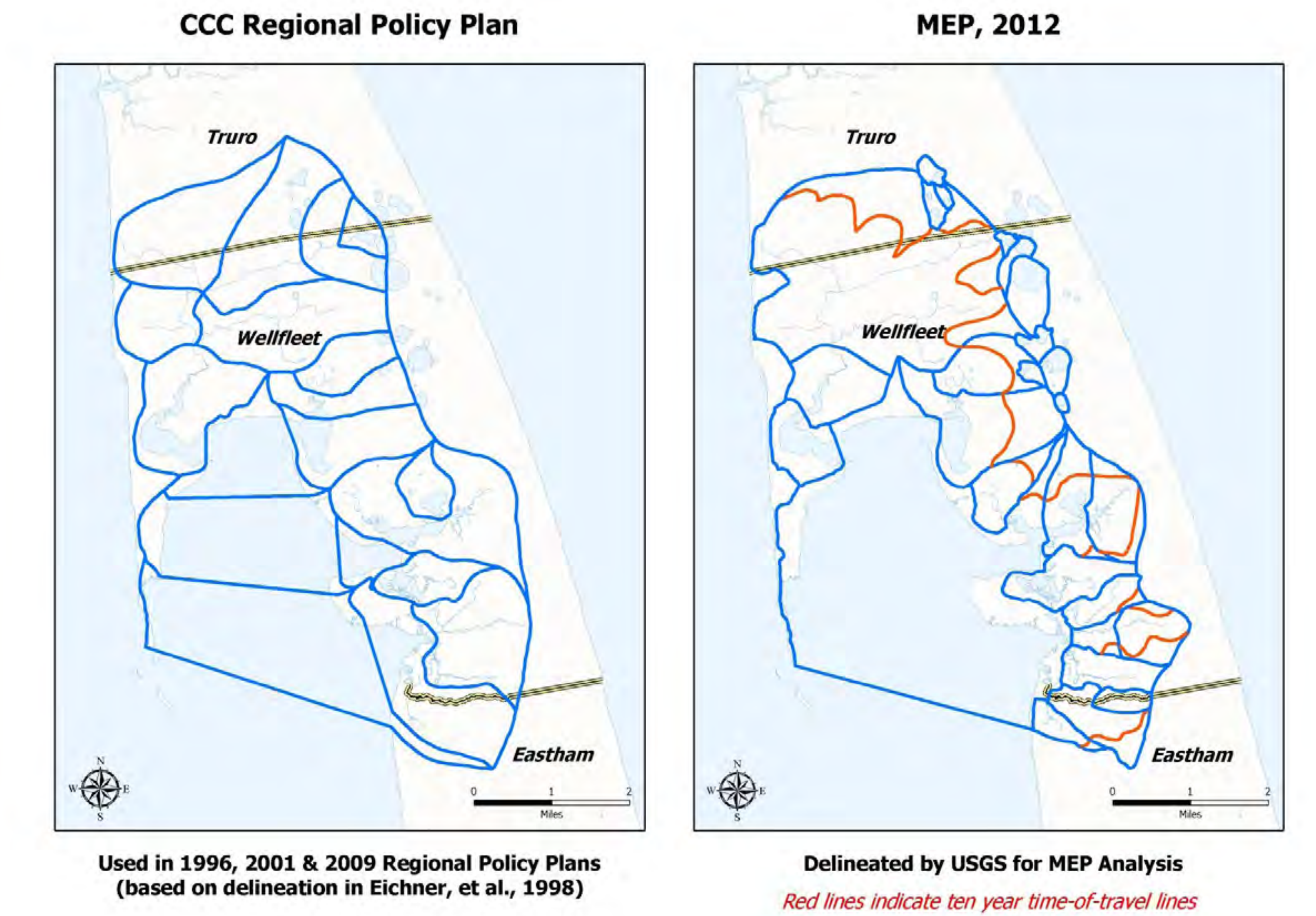


Figure III-2. Comparison of MEP Wellfleet Harbor watershed and subwatershed delineations produced by the USGS groundwater modeling for the current assessment and the earlier Cape Cod Commission delineation (Eichner, *et al.*, 1998), which has been used in three Barnstable County Regional Policy Plans (CCC, 1996, 2001, and 2009). The MEP watershed area for the Wellfleet Harbor estuary system as a whole is only 4% smaller than the CCC delineation.

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 Wellfleet Harbor estuary system. Determination of watershed nitrogen inputs to this embayment system requires: (a) identification and quantification of the nutrient sources and their loading rates to the land or aquifer, (b) confirmation that a groundwater transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes prior to reaching the estuary. This latter natural attenuation process 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 estuarine 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 Wellfleet Harbor estuarine system, the MEP Technical Team developed nitrogen-loading rates (Section IV.1) to each component basin of the estuary and its upland contributing area (Section III). The Wellfleet Harbor watershed was sub-divided to define contributing areas or subwatersheds to each of the major inland freshwater systems and to each major portion of the estuary. Further sub-divisions were made to identify watershed areas where groundwater travel time transports a nitrogen discharge to estuary waters in less than 10 years or greater than 10 years. A total of 43 subwatersheds were delineated in the overall Wellfleet Harbor watershed, including watersheds to eight fresh water ponds and the three MEP gauged streams (see Section III). The nitrogen loading effort also involved further refinement of watershed boundaries to accurately reflect shoreline areas to freshwater ponds and each portion of the estuary.

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 Wellfleet Harbor watershed have been delineated for ponds, streams and the estuary itself. Review of less than and greater than 10 year time of travel watersheds indicates that 83% of the unattenuated nitrogen load from the whole watershed reaches the estuary in less than 10 years from its discharge to the watershed (Table IV-1). This review does not include refinements for flow leaving the watershed from ponds along its outer boundary; if these are included the less than 10 year time-of-travel percentage increases to 84%. If direct nitrogen input (precipitation) on the estuary surfaces is included, the less than 10 year time-of-travel percentage of total nitrogen load increases to 91%. The overall result of this analysis of timing of nitrogen loads relative to groundwater travel times is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuary and that the distinction between groundwater time of travel in the subwatersheds is not important for modeling existing conditions. Overall and based on the review of all this information, it was determined that the Wellfleet Harbor estuary is currently in balance with its watershed load.

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other detailed 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 Wellfleet Harbor Embayment System, the model used parcel based land-use data from the Towns of Wellfleet, Truro, and Eastham which was transformed into nitrogen loads using both regional nitrogen loading factors and local watershed-specific data (such as parcel-by-parcel water use and alternative septic system monitoring). Determination of the nitrogen loads required obtaining watershed-specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the “potential” or unattenuated nitrogen load to each receiving embayment, since attenuation within surface waters is included at a later stage.

Natural attenuation of nitrogen during transport from land-to-sea within the Wellfleet Harbor watershed was determined based upon site-specific studies of streamflow and assumed attenuation in the upgradient freshwater ponds. Streamflow was characterized at High Toss Road crossing the Herring River, at Route 6 crossing Fresh Brook, and at Massasoit Road/West Road crossing of Hatches Creek. 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%, as determined from Cape Cod wide surveys, unless available monitoring and pond physical data is reliable enough to calculate a pond-specific attenuation factor. Streamflow and attenuation data is presented in Section IV.2.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. In the present effort, eight freshwater ponds have delineated subwatersheds within the Wellfleet Harbor watershed. 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 Wellfleet Harbor.

WATERSHED		LT10	GT10	TOTAL	%LT10
Name		kg/yr	kg/yr	kg/yr	

Great Pond Truro	1		94	94	0%
Snow Pond	2		42	42	0%
Ryder Pond	3		157	157	0%
High Toss GT10N	4		157	157	0%
High Toss LT10	5	8,151		8,151	100%
High Toss GT10NE	6		51	51	0%
High Toss GT10E	7		165	165	0%
High Toss GT10SE	8		463	463	0%
Herring Pond	9	88		88	100%
Long Pond	10		204	204	0%
Dyer Pond	11		55	55	0%
Great Pond Wellfleet	12		230	230	0%
Duck Pond	13		54	54	0%
Duck Creek GT10	14		359	359	0%
Duck Creek LT10	15	1,573		1,573	100%
Herring River	16	1,539		1,539	100%
The Gut	17	167		167	100%
The Cove GT10	18		739	739	0%
The Cove LT10	19	2,840		2,840	100%
Pilgrim Spring GT10	20		516	516	0%
Pilgrim Spring LT10	21	952		952	100%
Wellfleet Harbor GT10	22		330	330	0%
Drummer Cove GT10N	23		493	493	0%
Drummer Cove LT10	24	1,038		1,038	100%
Drummer Cove GT10S	25		110	110	0%
Blackfish Creek GT10N	26		64	64	0%
Blackfish Creek LT10	27	884		884	100%
Blackfish Creek GT10S	28		98	98	0%
Loagy Bay	29	894		894	100%
Trout Brook GT10	30		42	42	0%
Trout Brook LT10	31	560		560	100%
Upper Fresh Brook GT10N	32		6	6	0%
Upper Fresh Brook LT10	33	442		442	100%
Upper Fresh Brook GT10S	34		77	77	0%
Lower Fresh Brook GT10	35		45	45	0%
Lower Fresh Brook LT10	36	213		213	100%
Silver Spring Brook	37	266		266	100%
Hatches Creek Gauge	38	540		540	100%
Hatches Creek GT10	39		532	532	0%
Hatches Creek LT10	40	1,037		1,037	100%
Sunken Meadow GT10	41		128	128	0%
Sunken Meadow LT10	42	635		635	100%
Wellfleet Harbor LT10	43	3,571		3,571	100%
Wellfleet Harbor Whole System		25,387	5212	30,599	83%

Notes:

a) loads exclude atmospheric loading on the estuary surface waters; if these are included the percentage of total load within a less than 10 year time-of-travel increases to 91%

b) loads are unattenuated and do not include corrections to exclude nitrogen loads that are discharged outside of the watershed to the Wellfleet Harbor System from ponds or wellhead protection areas on the system watershed boundaries

c) whole system totals may not add due to rounding.

Based upon the land-use evaluation of the watershed, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the subwatersheds that directly discharge 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 Wellfleet Harbor Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Since the watershed to Wellfleet Harbor extends over three towns (Wellfleet, Truro, and Eastham), Estuaries Project staff obtained digital parcel and tax assessor's data from the towns to serve as a base for the watershed nitrogen loading model. Digital parcels and land use/assessors data from the three towns are from 2010. Using GIS techniques, this data was linked to available measured water use for the limited number of properties connected to the Wellfleet public water supply system (water use from 2008-2010). The remainder of developed properties were assumed to utilize on-site wells for drinking water. This unified database also contains traditional information regarding land use classifications (MassDOR, 2012) plus additional information developed by the towns. It is also the database that the town is using for its current wastewater planning effort (Environmental Partners, 2012). 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 Wellfleet Harbor estuary watershed. Land uses in the study area are grouped into seven land use categories plus freshwater ponds: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) undeveloped, 6) public service/government, including road rights-of-way, and 7) properties without land use codes assigned by town assessors. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2012). "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (*e.g.*, schools, open space, roads) and private groups like churches and colleges.

Public service land uses are the dominant land use type in the overall Wellfleet Harbor watershed and occupy 52% of the watershed area (Figure IV-2). Examples of these land uses are lands owned by town, state, and federal government (including conservation lands, schools, and landfills), housing authorities, and churches. Residential land uses occupy the second largest area with 29% of the overall watershed area. It is notable that land classified by the town assessor as undeveloped is 7% of the overall watershed area. The majority of the public service lands in the Wellfleet Harbor watershed are parts of Cape Cod National Seashore. There is also a large portion of the National Seashore within the Town of Truro that is not classified by the town assessor. These lands make up the majority of the 16% of the area of the Herring River subwatershed and the 8% of the overall Wellfleet Harbor watershed that are listed as unclassified.

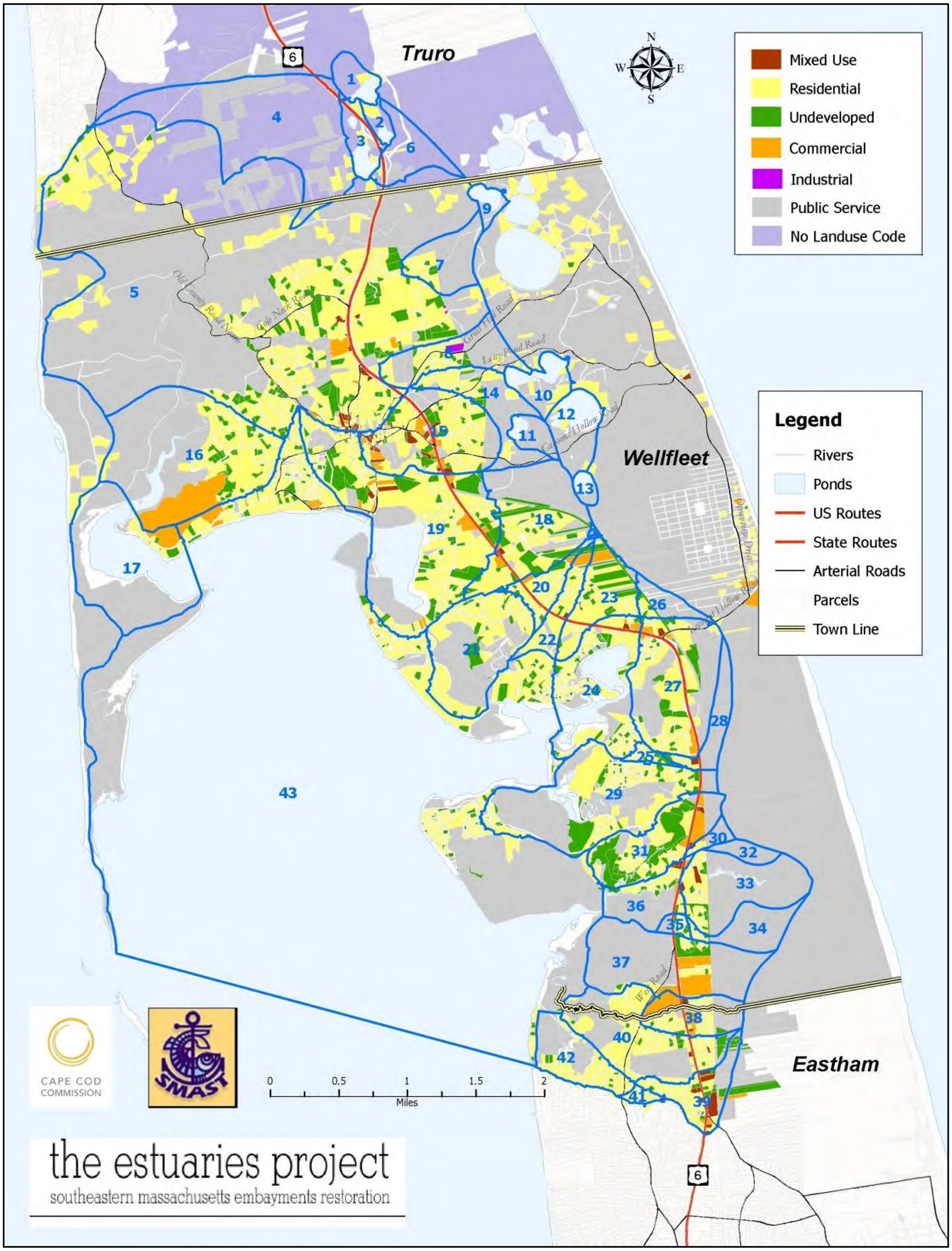


Figure IV-1. Land-use in the Wellfleet Harbor Embayment System watershed and subwatersheds. Most of the watershed is within the Town of Wellfleet, but also includes portions of the towns of Eastham and Truro. Land use classifications are based on town assessor classifications and MADOR (2012) categories. Base assessor and parcel data for all three towns are from the year 2010.

Although the majority of the watershed area is public service land uses, the dominant parcel type in all the major subwatershed groupings is residential land uses. Residential parcels range from 62% to 75% of the total number of parcels in the watershed groupings in Figure IV-2 and are 70% of all parcels in the whole Wellfleet Harbor watershed. Single-family residences (MassDOR land use code 101) are the dominant type of residential parcel; these represent 91% of the residential parcel count and 84% of the residential parcel area throughout the Wellfleet Harbor system watershed.

Typically, in MEP analyses, project staff obtains parcel-by-parcel water use information to be used as a proxy for wastewater generation. In this watershed, this type of information was generally not available, but it is incorporated into the MEP watershed nitrogen loading model where it is available. The Town of Wellfleet has a limited public water supply area, primarily located within the main village center. Three years of water use (2008-2010) was available for these properties (personal communication, Paul Gabriel, Environmental Partners) and this information was incorporated into the MEP watershed nitrogen loading model. The remainder of the Town of Wellfleet and portions of the Towns of Truro and Eastham inside the Wellfleet Harbor watershed do not have public water available. MEP staff reviewed the available water use information, US Census data, and water use data from similar nearby communities to determine water use factors within the Wellfleet Harbor watershed. The development of these factors is discussed below.

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 generally 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 down gradient surface water aquatic receptors.

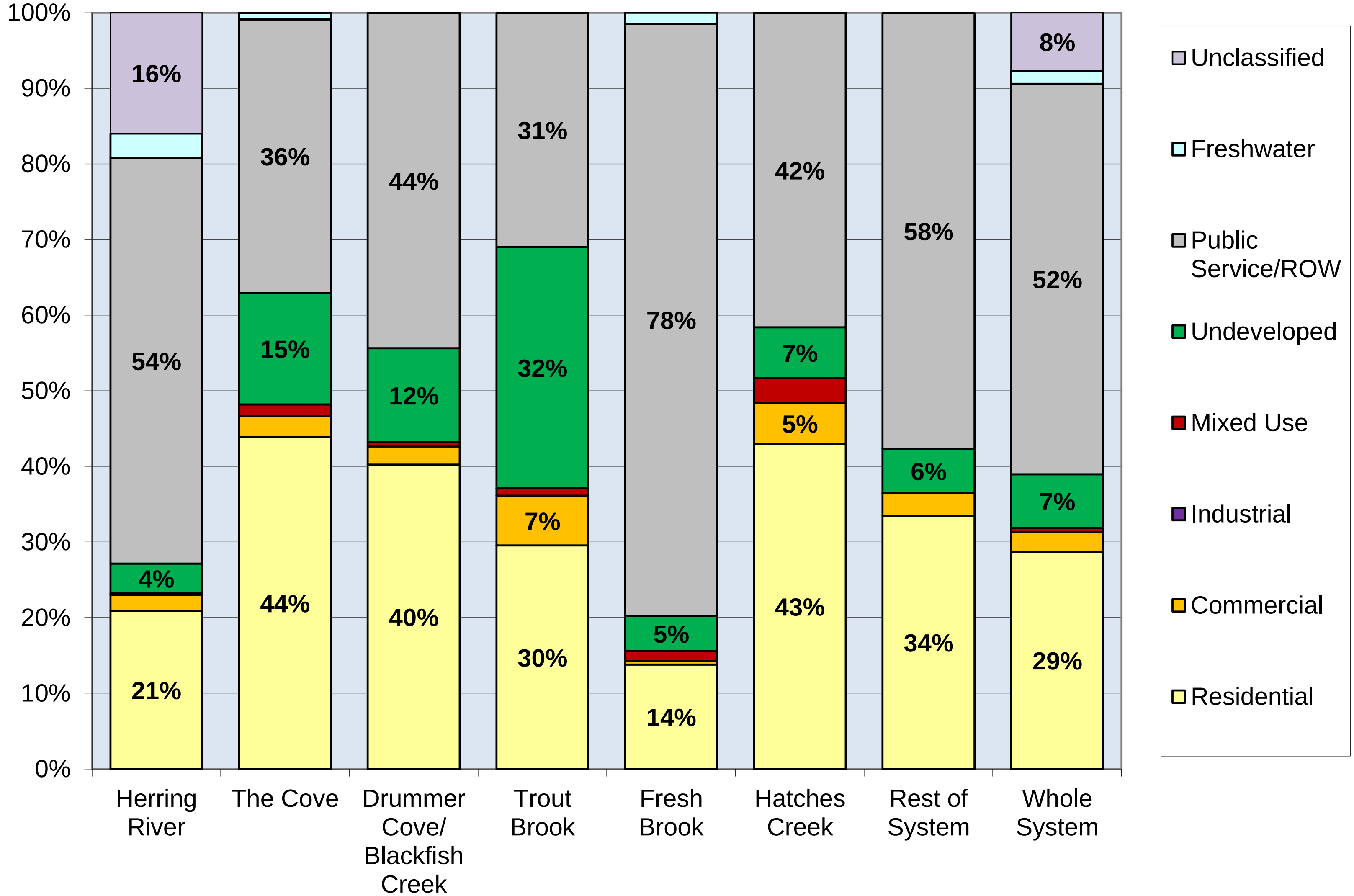


Figure IV-2. Distribution of land-uses by area within the Wellfleet Harbor system watershed and seven component subwatersheds. Land use categories are generally based on town assessor's land use classification and groupings recommended by MADOR (2012). Unclassified parcels do not have an assigned land use code in the town assessor's databases. Only percentages greater than or equal to 4% are shown.

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, 2013).

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

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

The independent validation of the water quality model (Section VI) and the reasonableness of the freshwater attenuation (Section IV.2) add additional weight to the nitrogen loading coefficients used in the MEP analyses and a variety of other MEP embayments. While the MEP septic system nitrogen load is the best estimate possible, to the extent that it may underestimate the nitrogen load from this source reaching receiving waters provides a safety factor relative to other higher loads that are generally used for septic systems in regulatory situations. The lower concentration results in slightly higher amounts of nitrogen mitigation (estimated at 1% to 5%) needed to lower embayment nitrogen levels to a nitrogen target (*e.g.*, nitrogen threshold, cf. Section VIII). The additional nitrogen removal is not proportional to the septic system nitrogen level, but is related to the how the septic system nitrogen mass compares to the nitrogen loads from all other sources that reach the estuary (i.e. attenuated loads).

In order to estimate wastewater flows within the Wellfleet Harbor watershed, MEP staff also obtained parcel-by-parcel water use data from the small public supply area concentrated around the village center in Wellfleet (personal communication, Paul Gabriel, Environmental Partners). At the time of the MEP assessment, there were only 37 residential parcels connected to the supply system. The average water use for these parcels was 108 gpd. These measured water uses were assigned to each of the respective parcels, but based on the average occupancy in Wellfleet and seasonal population estimates, this flow seemed to be too low for average usage in the watershed. Project staff reviewed metered water use data from previous nearby MEP assessments and found the following averages: 142 gpd for Rock Harbor (Howes, et al., 2008) and 148 gpd for Pleasant Bay (Howes, et al., 2006). Staff also reviewed average 2000 US Census occupancy for Orleans, which best matches the time period of the meter water, and found that it closely approximated the 2010 Wellfleet occupancy (2.05 people per residential unit versus 2.01 people per residential unit, respectively). Given this review, MEP staff selected a 145 gpd average water use for single-family residential units within the Wellfleet Harbor watershed, as well as commercial development. Water use for multi-family dwellings (e.g., land use codes 109 or 111) was conservatively assumed to be double the single-family rate. The final wastewater nitrogen load for each parcel is based upon the measured or assumed 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.

Harborside Trailer Park Wastewater Treatment Facility

When developing watershed nitrogen loading information, MEP project staff typically seek 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 whether large wastewater treatment facilities discharge within the Wellfleet Harbor watershed. One state Groundwater Discharge Permit (GWDP) is listed within the Wellfleet Harbor watershed: Harborside Trailer Park (personal communication, Brian Dudley, MassDEP, 2/12). MEP staff generally request at least three years-worth of monitoring data and received monthly flow and TN effluent data for 2007, 2008, 2009 and 2010. A GWDP is required under MassDEP regulations for wastewater treatment systems with design flows greater than 10,000 gallons per day. Harborside Trailer Park had an average annual flow of 7,525 gpd with an average TN effluent concentration of 19 mg/L and an average annual nitrogen load of 177 kg/yr. This load was incorporated into the watershed nitrogen loading model.

Alternative Septic Systems

There are 49 alternative, on-site denitrifying septic systems in the Wellfleet Harbor watershed that have total nitrogen effluent data in the Barnstable County Department of Health and the Environment database (personal communication, Brian Baumgaertel, 1/11). Wellfleet has 47 of these systems, Eastham has two and there are none in Truro. These systems utilize a variety of technologies. Individual systems have been sampled 3 to 89 times with average total nitrogen concentrations ranging between 3.5 and 80.6 mg/L. Project staff used the available monitoring data with the assumed water uses to calculate average annual wastewater loads from each of these individual sites. These loads were incorporated into the subwatershed and overall system nitrogen loading for Wellfleet Harbor.

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 Wellfleet Harbor system, MEP staff reviewed available regional information about residential lawn fertilizing practices and incorporated site-specific information for the Chequessett Yacht and Country Club. An estimated nitrogen load is also included for agricultural uses in the watershed, including farm animals.

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

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. This assessment, which was completed prior to the start of the MEP, 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. MEP staff obtained course- and turf-specific, nitrogen fertilizer application information for the Chequessett Yacht and Country Club (personal communication, Dave Stott, Golf Course Superintendent, 4/11). Golf courses usually have different fertilizer application rates for different turf areas, usually higher annual application rates for tees and greens (~3 to 4 pounds per 1,000 square feet) and lower rates for fairways and roughs (~2 to 3.5 pounds per 1,000 square feet). As has been done in all MEP reviews, MEP staff reviewed the layout of the golf course from aerial photographs, classified the various turf types, and, using GIS tools, assigned these areas to the appropriate subwatersheds. The golf course-specific nitrogen application rates were then applied to the respective turf areas, a standard MEP 20% leaching rate was applied, and annual load for the portion of each golf course within each subwatershed was calculated.

Nitrogen loads were also added for site-specific agricultural land uses. MEP staff discussed agricultural issues with town staff (personal communication, Hillary Greenberg, Wellfleet Health Department, 1/11). Based on town staff observations, there is no extensive crop production in Wellfleet, but there are farm animals (mostly horses and chickens) that are housed within the Wellfleet 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 lots based on the town-provided animal counts.

Nitrogen Loading Input Factors: Town of Wellfleet Landfill

MEP staff reviewed MassDEP's solid waste database and identified one solid waste site within the Wellfleet Harbor watershed: the Town of Wellfleet Landfill. Project staff contacted town staff, who authorized the release of landfill monitoring data (personal communication, Paul Gabriel, Environmental Partners, 1/11). Using the available monitoring information, MEP staff developed a nitrogen load for the landfill site.

The Town landfill is located north of Coles Neck Road and north of Route 6 within the High Toss Road LT10 subwatershed (subwatershed #5). According to MassDEP records, the landfill is unlined, was closed in 1992 and capped in 2008. Monitoring and water level data are collected twice a year from eight wells located around the landfill. The eight wells are located at six monitoring sites; four of the wells are installed as shallow and deep couplets. Data from August 2007 to August 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 Wellfleet 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 (NH4-N = 0.0352*ALK - 0.3565; r2 = 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 7 available sampling runs showed that wells MW-1 and CSAW-1D had the highest average alkalinity concentrations (177 and 264 mg/L $CaCO_3$, respectively). The estimated average TN concentration of the two wells is 8.4 mg/L. Based on a review of groundwater elevations and contaminant concentrations, MEP staff also determined that CSAW-4S was appropriate for use as an upgradient or cross-gradient well that was largely unimpacted by the landfill (*e.g.*, average alkalinity concentration of 9 mg/L $CaCO_3$). Using the estimated TN concentration from the most impacted wells and subtracting the estimated TN concentration for the unimpacted well, MEP staff determined a DIN/TN concentration addition for the landfill. Using this concentration, the area of solid waste, and the MEP recharge rate for the area, MEP staff estimated an annual total nitrogen load of 97 kg from the Wellfleet landfill and included this in the MEP watershed nitrogen load. If the upgradient correction is not included, the annual nitrogen load from the landfill will increase to 138 kg.

It is acknowledged that this approach for estimating a nitrogen load from the Wellfleet 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 Wellfleet 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 Wellfleet Harbor watershed are summarized in Table IV-2.

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 Wellfleet Assessor's database includes building footprint data for individual parcels. This information was used to determine roof areas which were combined other MEP nitrogen loading factors to determine nitrogen loads from these impervious surfaces. The towns of Truro and Eastham did not have similar data available in their town databases, so building areas in these portions of the Wellfleet Harbor watershed were determined based on averages from the Town of Wellfleet data.

Table IV-2. Primary Nitrogen Loading Factors used in the Wellfleet Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from watershed-specific data or comparable data within the overall MEP study area.

Nitrogen Concentrations:	**mg/l**	**Recharge Rates:**	**in/yr**
Road Run-off	1.5	Impervious Surfaces	37.8
Roof Run-off	0.75	Natural and Lawn Areas	24
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:	145 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[4]
Residential Watershed Nitrogen Rate (lbs/lawn)[1]	1.08	Commercial and Industrial Buildings without/WU and buildout additions	
Leaching rate	20%	Commercial	
Nitrogen Fertilizer Rate for one golf course in watershed determined from site-specific information; other areas assumed to utilize residential application rate; farm animal nitrogen loads based on loads determined in other MEP assessments[3]		Wastewater flow (gpd/1,000 ft2 of building):[5]	180
		Building coverage:[6]	11%
		Industrial	
		Wastewater flow (gpd/1,000 ft2 of building):[5]	44
		Building coverage:[6]	5%
		Average Single Family Residence Building Size from watershed data (sq ft)	1,325[7]

Notes:

1) Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.
2) Estimated flow developed for Wellfleet Harbor, based on measured flow for similar properties in Town of Orleans
3) Golf course fertilizer application rate information supplied by Dave Stott, Golf Course Superintendent, Chequessett Yacht and Country Club. Farm animal counts supplied by Hillary Greenberg, Health and Conservation Agent, Town of Wellfleet.
4) Public municipal water supply was only available to 37 properties concentrated in Wellfleet village center
5) Wastewater flow for commercial and industrial properties is based on town-wide averages from the Town of Falmouth
6) Commercial building coverage is based on town-wide average for Wellfleet; industrial building coverage is based on town-wide average for Falmouth (Wellfleet had only 1 industrial property).
7) Average single family residence area is developed from data in the Town of Wellfleet assessor's database; Truro and Eastham do not have similar data in their databases.

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 Town of Wellfleet Assessor’s database. Project staff used the average single-family residence building footprint based on available properties in the MEP study area (1,325 sq ft) for any residential units without footprint information, including those in Eastham and Truro. 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 Wellfleet Harbor estuarine waters. The assignment effort is undertaken to better define nitrogen loads to each component sub-basin 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 43 subwatersheds in the Wellfleet Harbor study area. These subwatershed modules summarize, among other things: water use (as available), parcel areas, frequency of land use types, private wells, and road areas. All relevant nitrogen loading data is assigned to each subwatershed. Individual sub-watershed information is then integrated to create the Wellfleet Harbor Watershed Nitrogen Loading module with summaries for each of the individual 43 subwatersheds. The subwatersheds are generally paired with functional embayment/estuary units for the Linked Watershed-Embayment Model’s water quality component.

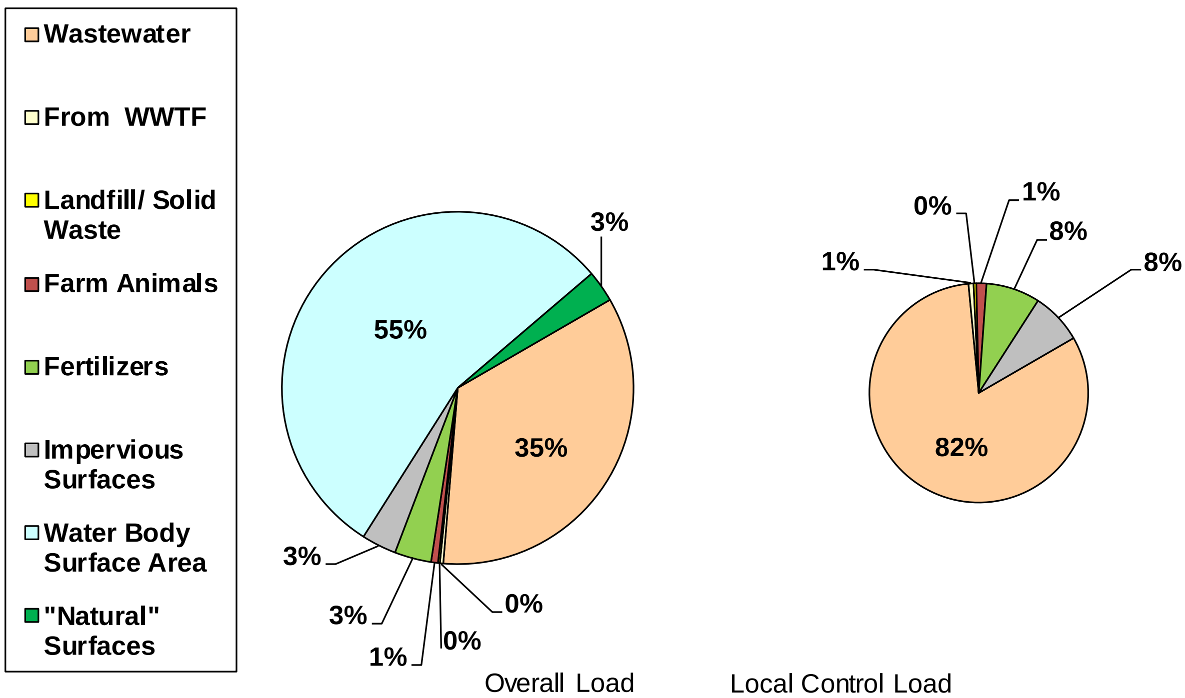
For management purposes, the aggregated estuary watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Wellfleet Harbor study area, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), landfills, wastewater treatment facilities, farm animals, fertilizers (including contributions from golf courses), impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-3). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-3). In general, the annual nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine waters before use in the embayment water quality sub-model.

Table IV-3(a). Wellfleet Harbor Watershed Nitrogen Loads. Unattenuated nitrogen loads are a sum of all sources within the watershed without including natural nitrogen attenuation during transport through surface freshwater systems. 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), while pond attenuation factors are assigned a standard MEP nitrogen attenuation of 50% attenuation based on MEP data review, including water quality monitoring from the Cape Cod Pond and Lake Stewards program. All nitrogen loads are kg N yr^{-1}.

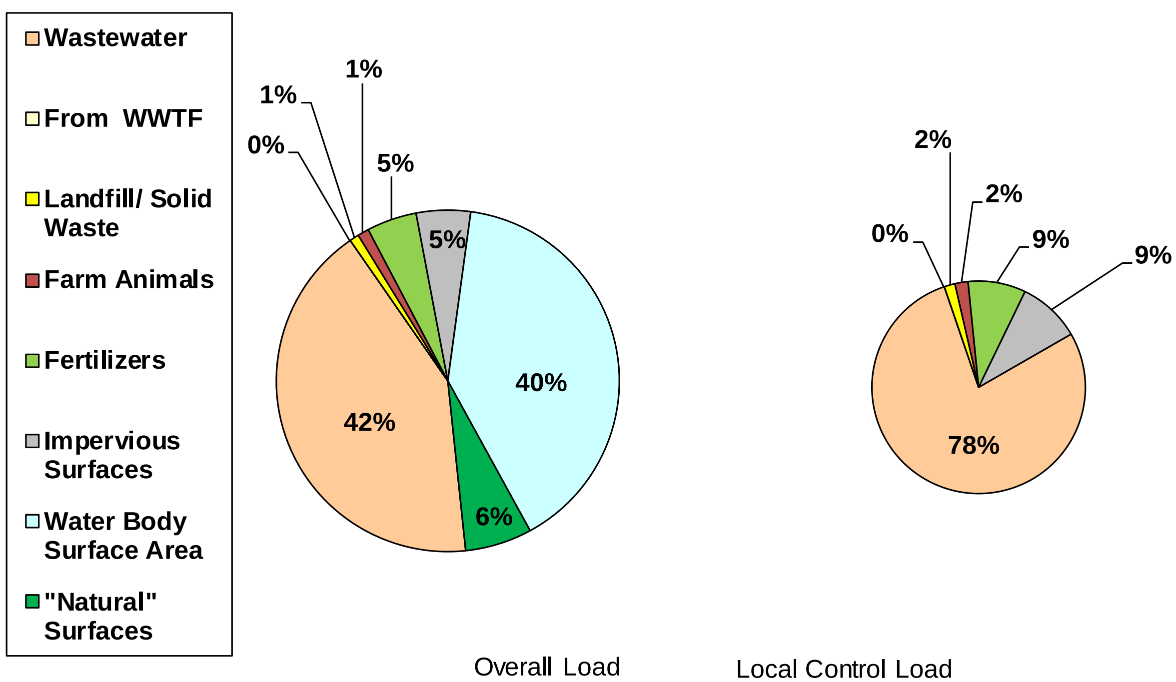
		Wellfleet Harbor N Loads by Input (kg/y):											***Present N Loads***			***Buildout N Loads***			***Alt Buildout N Loads***		
Watershed Name	**shed ID#**	**Wastewater**	**From WWTF**	**Landfill/ Solid Waste**	**Farm Animals**	**Fertilizers**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**Alt Buildout**	**% of Pond Outflow**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Wellfleet Harbor System		**19,613**	**177**	**97**	**358**	**1,911**	**1,812**	**31,007**	**1,637**	**11,779**	**1,432**		**56,612**		**55,584**	**68,390**		**67,121**	**58,044**		**56,989**
Pilgrim Spring GT10	20	438	0	0	0	40	28	-	11	119	5		516		516	635	0%	635	522	0%	522
Pilgrim Spring LT10	21	727	0	0	56	69	49	-	50	226	38		952		952	1,178	0%	1,178	989	0%	989
Wellfleet Harbor GT10	22	270	0	0	0	26	22	-	12	97	11		330		330	427	0%	427	341	0%	341
Loagy Bay	29	703	0	0	0	72	55	-	63	635	38		894		894	1,528	0%	1,528	931	0%	931
Silver Spring Brook	37	156	0	0	0	13	39	-	58	889	5		266		266	1,155	0%	1,155	271	0%	271
Sunken Meadow GT10	41	109	0	0	0	11	6	-	2	-	-		128		128	128	0%	128	128	0%	128
Sunken Meadow LT10	42	516	0	0	0	53	46	-	20	22	22		635		635	657	0%	657	657	0%	657
Wellfleet Harbor LT10	43	2776	177	0	0	268	186	-	164	689	108		3,571		3,571	4,260	0%	4,260	3,679	0%	3,679
Herring River Total		4,646	-	97	118	520	565	4,409	696	3,300	287		11,053		10,117	14,353	0%	13,185	20,950	0%	10,377
The Gut	17	80	0	0	0	28	18	4	38	11	16		167		167	178	0%	178	184	0%	184
Herring River Dike		4,566	-	97	118	492	548	4,405	659	3,289	271		10,885		9,949	14,175	0%	13,007	20,668	0%	10,193
Herring River	16	659	0	0	0	129	57	626	67	464	16		1,539		1,539	2,003	0%	2,003	1,555	0%	1,555
High Toss Road Total		3,906	-	97	118	363	491	3,779	591	2,826	255		9,347	8%	8,410	12,172	8%	11,004	17,770	8%	8,638
High Toss GT10N	4	38	-	-	-	3	16	-	100	5	-		157		157	162	0%	162	157	0%	157
High Toss LT10	5	3,323	-	97	118	306	386	3,514	407	2,696	221		8,151		8,151	10,847	0%	10,847	8,372	0%	8,372
High Toss GT10NE	6	14	-	-	-	1	17	-	18	-	-		51		51	51	0%	51	51	0%	51
High Toss GT10E	7	114	-	-	-	12	18	-	21	38	5		165		165	202	0%	202	170	0%	170
High Toss GT10SE	8	368	-	-	-	37	33	-	25	76	16		463		463	539	0%	539	479	0%	479
Ryder Pond Total	RP	34	-	-	-	3	19	142	12	5	5	100%	210	50%	90	215	50%	91	215	50%	91
Snow Pond Total	SP	5	-	-	-	1	0	37	4	6	6	57%	46	50%	17	52	50%	20	52	50%	20
Herring Pond	9	-	-	-	-	-	-	28	1	-	-	32%	28	50%	14	28	50%	14	28	50%	14
Long Pond Total	LP	12	-	-	-	1	1	59	3	-	2	29%	75	50%	34	75	50%	34	77	50%	34
The Cove Total		4,463	-	-	87	384	371	84	217	2,534	184		5,605		5,556	8,139	0%	8,090	5,789	0%	5,740
The Cove GT10	18	555	-	-	32	55	42	-	56	550	22		739		739	1,289	0%	1,289	761	0%	761
The Cove LT10	19	2355	0	0	29	197	178	-	80	1,273	124		2,840		2,840	4,113	0%	4,113	2,964	0%	2,964
Duck Pond	13	0	0	0	0	0	0	10	0	0	0	19%	10	50%	5	10	50%	5	10	50%	5
Duck Creek Total		1,554	-	-	26	132	151	74	80	711	38		2,016		1,972	2,728	0%	2,684	2,054	0%	2,010
Duck Creek GT10	14	279	-	-	-	28	26	-	26	43	5		359		359	402	0%	402	364	0%	364
Duck Creek LT10	15	1270	0	0	26	103	124	3	46	668	32		1,573		1,573	2,241	0%	2,241	1,605	0%	1,605
Dyer Pond	11	0	0	0	0	0	1	48	6	0	0	100%	55	50%	28	55	50%	28	55	50%	28
Long Pond Total	LP	5	-	-	-	0	0	23	1	-	1	12%	29	50%	13	29	50%	13	30	50%	13

Table IV-3(b). Wellfleet Harbor Watershed Nitrogen Loads. Unattenuated nitrogen loads are a sum of all sources within the watershed without including natural nitrogen attenuation during transport through surface freshwater systems. 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), while pond attenuation factors are assigned a standard MEP nitrogen attenuation of 50% attenuation based on MEP data review, including water quality monitoring from the Cape Cod Pond and Lake Stewards program. All nitrogen loads are kg N yr^{-1}.

		Wellfleet Harbor N Loads by Input (kg/y):											*Present N Loads*			*Buildout N Loads*			*Alt Buildout N Loads*		
Watershed Name	shed ID#	Wastewater	From WWTF	Landfill/ Solid Waste	Farm Animals	Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout	Alt Buildout	% of Pond Outflow	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Drummer Cove/Blackfish Creek Total		2,117	-	-	45	194	196	-	136	1,301	92		2,687		2,687	3,988		3,988	2,779		2,779
Drummer Cove Total		1315	0	0	43	124	102	0	57	734	49		1,641		1,641	2,376	0%	2,376	1,690	0%	1,690
Drummer Cove GT10N	23	355	0	0	43	32	39	-	24	458	11		493		493	952	0%	952	504	0%	504
Drummer Cove LT10	24	869	0	0	0	83	56	-	30	265	38		1,038		1,038	1,303	0%	1,303	1,075	0%	1,075
Drummer Cove GT10S	25	91	0	0	0	10	6	-	3	11	-		110		110	121	0%	121	110	0%	110
Blackfish Creek Total		801	0	0	2	69	95	0	79	566	43		1,046		1,046	1,612	0%	1,612	1,089	0%	1,089
Blackfish Creek GT10N	26	47	0	0	0	4	3	-	10	11	-		64		64	75	0%	75	64	0%	64
Blackfish Creek LT10	27	688	0	0	2	59	79	-	55	555	43		884		884	1,439	0%	1,439	927	0%	927
Blackfish Creek GT10S	28	66	0	0	0	6	13	-	14	-	-		98		98	98	0%	98	98	0%	98
Trout Brook Total		469	0	0	0	44	50	0	39	505	32		602		602	1,107		1107	634		634
Trout Brook GT10	30	33	0	0	0	3	2	-	4	-	-		42		42	42	0%	42	42	0%	42
Trout Brook LT10	31	435	0	0	0	41	48	-	35	505	32		560		560	1,064	0%	1,064	592	0%	592
Fresh Brook Total		524	0	0	52	52	38	31	85	166	22		783		741	949		897	804		762
Upper Fresh Brook Total		330	0	0	52	33	15	31	64	123	5		525	8%	483	648	8%	596	530	8%	488
Upper Fresh Brook GT10N	32	0	0	0	0	0	0	-	6	-	-		6		6	6	0%	6	6	0%	6
Upper Fresh Brook LT10	33	278	0	0	52	27	13	31	40	117	5		442		442	559	0%	559	447	0%	447
Upper Fresh Brook GT10S	34	52	0	0	0	5	2	-	18	5	-		77		77	83	0%	83	77	0%	77
Lower Fresh Brook Total		194	0	0	0	20	23	0	21	43	16		258		258	301	0%	301	274	0%	274
Lower Fresh Brook GT10	35	33	0	0	0	3	5	-	3	5	-		45		45	51	0%	51	45	0%	45
Lower Fresh Brook LT10	36	161	0	0	0	16	17	-	18	38	16		213		213	250	0%	250	229	0%	229
Hatches Creek Total		1699	0	0	0	166	160	2	83	1297	589		2,109		2,109	3,406	0%	3,406	2,698	0%	2,698
Hatches Creek Gauge	38	435	0	0	0	45	40	2	18	700	149		540		540	1,241	0%	1,241	689	0%	689
Hatches Creek GT10	39	426	0	0	0	41	47	-	17	283	283		532		532	815	0%	815	815	0%	815
Hatches Creek LT10	40	838	0	0	0	80	72	-	47	313	156		1,037		1,037	1,350	0%	1,350	1,193	0%	1,193
Estuary Surfaces																					
Duck Creek LT10	15							0					0		0	0		0	0		0
Herring River	16							126					126		126	126		126	126		126
The Gut	17							899					899		899	899		899	899		899
The Cove LT10	19							809					809		809	809		809	809		809
Pilgrim Spring LT10	21							3					3		3	3		3	3		3
Drummer Cove LT10	24							543					543		543	543		543	543		543
Blackfish Creek LT10	27							63					63		63	63		63	63		63
Loagy Bay	29							361					361		361	361		361	361		361
Trout Brook LT10	31							16					16		16	16		16	16		16
Lower Fresh Brook LT10	36							35					35		35	35		35	35		35
Silver Spring Brook	37							24					24		24	24		24	24		24
Hatches Creek LT10	40							4					4		4	4		4	4		4
Sunken Meadow LT10	42							22					22		22	22		22	22		22
Wellfleet Harbor LT10	43							23,575					23,575		23,575	23,575		23,575	23,575		23,575

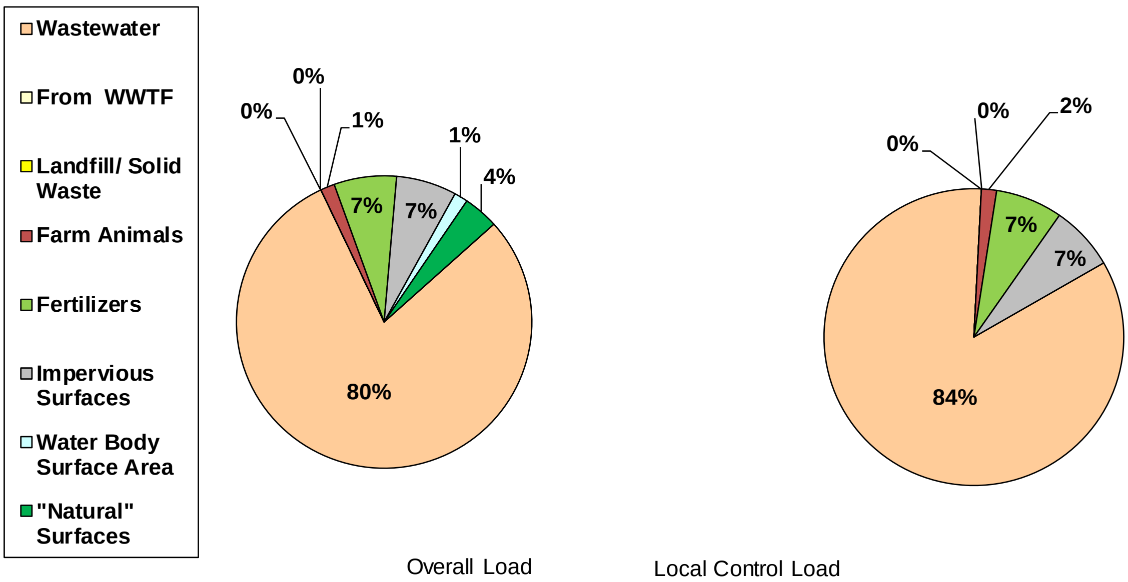


a. Whole Wellfleet Harbor System

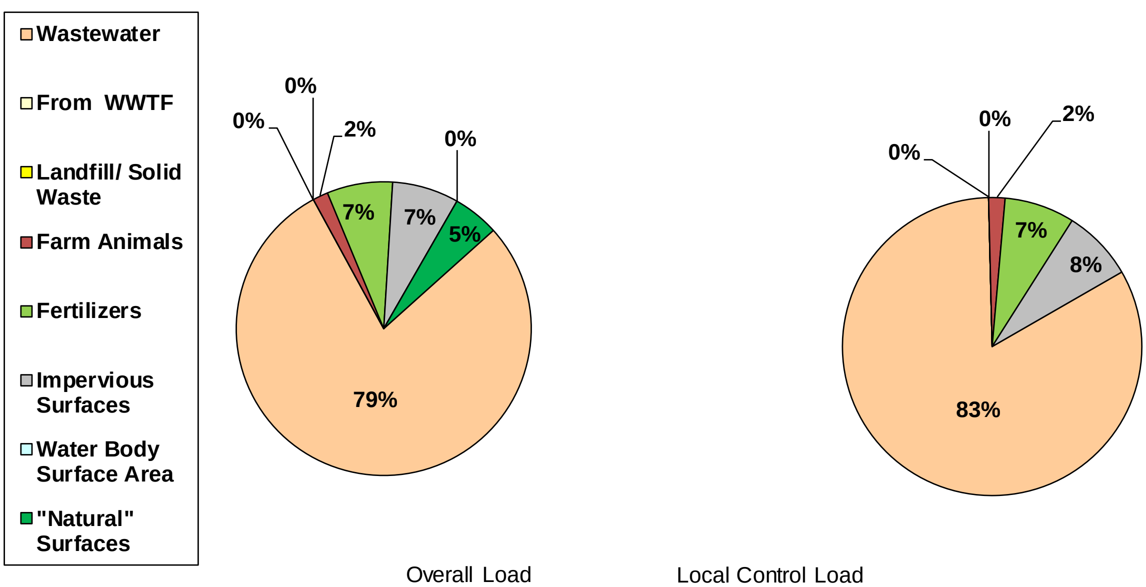


b. Herring River Total

Figure IV-3 (a, b). Land use-specific unattenuated nitrogen loads (by percent) to the a) whole Wellfleet Harbor watershed, b) Herring River subwatershed, c) the Cove subwatershed, and d) Drummer Cove/Blackfish Creek subwatershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.



C. The Cove Total



d. Drummer Cove/Blackfish Creek Total

Figure IV-3 (c, d). Land use-specific unattenuated nitrogen loads (by percent) to the a) whole Wellfleet Harbor watershed, b) Herring River subwatershed, c) the Cove subwatershed, and d) Drummer Cove/Blackfish Creek subwatershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.

Freshwater Pond Nitrogen Loads

Freshwater ponds on Cape Cod are generally 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. 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, retain some nitrogen in the sediments, and change the nitrogen among its various oxidized and reduced forms. As result of these interactions, some of the nitrogen in the pond watershed is removed from the estuary watershed system, 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 embayment 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, watershed hydrology, 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.

In addition to bathymetry, temperature and dissolved profiles are useful to help understand whether temperature stratification is occurring in a pond and whether sediment regeneration may be impacting measured nitrogen concentrations. 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 all portions of 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, summer-long pond sampling programs in many communities on Cape Cod and southeastern Massachusetts. 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 site-specific nitrogen attenuation rates can be reliably assigned to freshwater ponds.

Within the Wellfleet Harbor study area, there are eight freshwater ponds with delineated watersheds: a) Great, Ryder, and Snow in Truro and b) Duck, Dyer, Great, Herring, and Long in Wellfleet. Of these eight ponds, two have available bathymetry (Duck and Long) according to the Cape Cod Pond and Lake Atlas (Eichner, *et al.*, 2003). PALS water quality sampling shows all of these ponds have been sampled; number of sampling runs in the 13 years of PALS sampling range between 3 (Dyer) and 12 (Great – Truro). For the two ponds with both bathymetry and water quality sampling data, neither has had sufficient sampling outside of the PALS Snapshots to assign a pond-specific nitrogen attenuation rate. This data review supports the use of the standard MEP pond 50% nitrogen attenuation rate for all ponds in within the Wellfleet Harbor study area.

Although available data was insufficient to assign a pond nitrogen attenuation rate different from the standard MEP 50%, the overall nitrogen load to Wellfleet Harbor is relatively insensitive to changes in this rate. A decrease or increase of the attenuation rate by 10% (*i.e.*, to 40% or 60%) for all the ponds in the Wellfleet Harbor watershed results in a 0.08% change in the overall attenuated system load. The overall load is relatively insensitive because of the comparatively small amounts of development in the pond watersheds and their accompanying small nitrogen loads.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment 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 are 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 density developments, 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 Wellfleet, Truro or Eastham 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 Wellfleet Harbor watersheds, MEP staff reviewed the results with town officials. MEP staff reviewed the preliminary watershed buildout results with representatives from all the towns in the watershed including the following representatives: a) Wellfleet: Hillary Greenberg-Lemos, Health and Conservation Agent, Paul Gabriel, Environmental Partners, Alex Hay, and Curt Felix, Comprehensive Wastewater Management Planning Committee; b) Truro: Rex Peterson, Town Administrator and Charleen Greenhalgh, Assistant Town Administrator/Town Planner; and c) Eastham: Jane Crowley, Health Agent and Gail McAleer, Deputy Assessor. All suggested changes from town reviews of the initial buildout were incorporated into the final buildout for Wellfleet Harbor.

All the parcels with additional buildout potential within the Wellfleet 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 Wellfleet Harbor watersheds will increase the unattenuated watershed nitrogen loading rate by 21%.

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 relative to the tidal flushing and nitrogen cycling within the embayment basins. 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 Wellfleet Harbor System being investigated under this nutrient threshold analysis were based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1).

If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such being the case in the developed region of southeastern Massachusetts, particularly on Cape Cod). 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) can be 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 to the Wellfleet Harbor embayment system, a portion of the freshwater flow and transported nitrogen passes through several surface water systems of varying sizes (e.g. the Herring River discharging to the head of the harbor from the up-gradient wetland area, Fresh Brook discharging to the tidal flats immediately south of Lieutenants' Island and Hatches Creek also discharging to the tidal flats south of Lieutenants' Island) prior to entering the estuary, producing the opportunity for potential nitrogen attenuation.

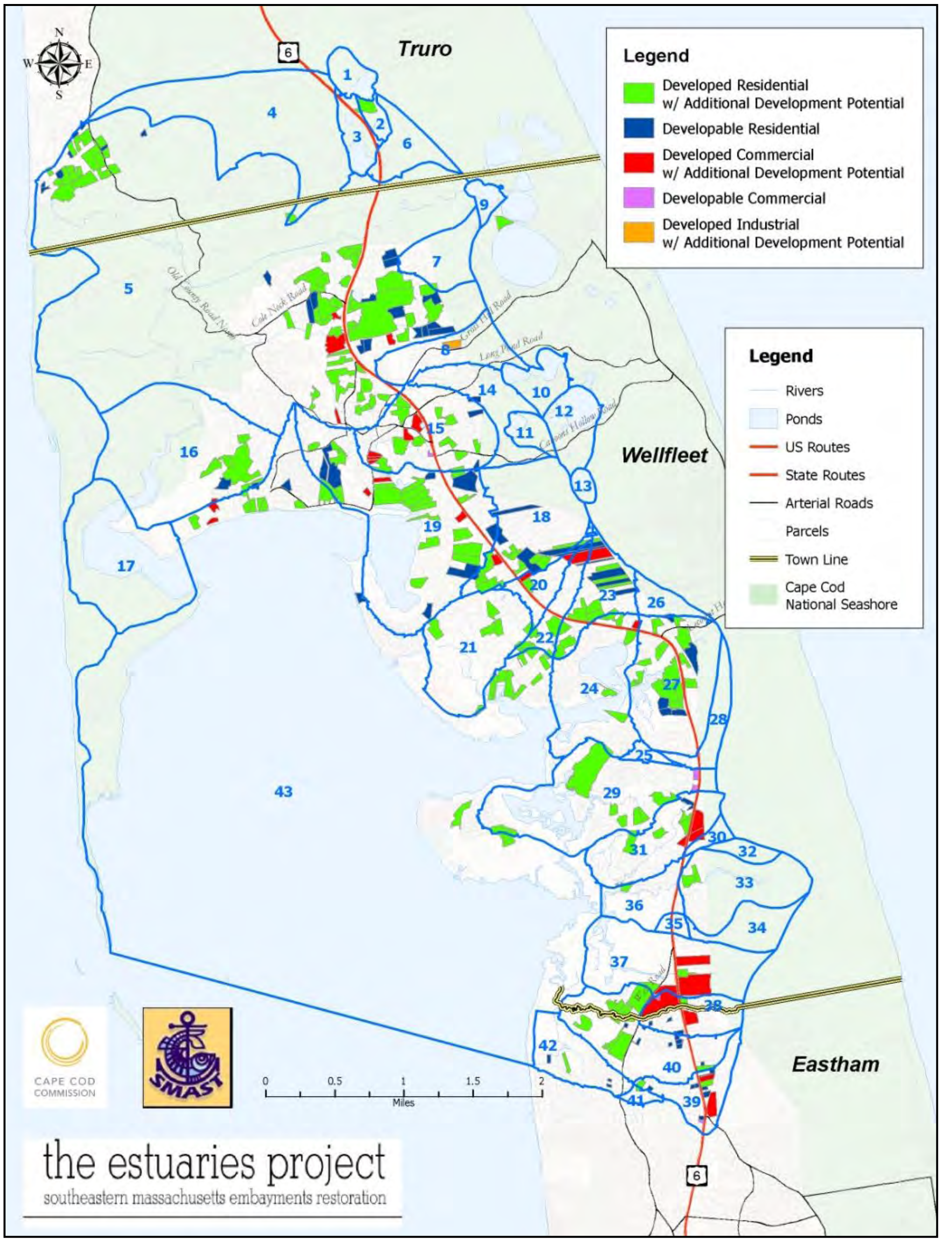


Figure IV-4. Developable Parcels in the Wellfleet Harbor watershed. Parcels colored green, red, and orange are developed parcels (residential, commercial and industrial, respectively) with additional development potential based on current zoning, while parcel colored blue and light purple are undeveloped residential and commercial parcels classified as developable by the town assessor. There are no undeveloped industrial parcels in the watershed. 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 town zoning; these parcels are assigned nitrogen loads in MEP buildout calculations. All initial buildout results were reviewed with officials in each town and any corrections were incorporated into the final buildout nitrogen loads.

Failure to determine the attenuation of watershed derived nitrogen can cause overestimation of 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 (Town of Falmouth, Cape Cod) indicated 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. Therefore, 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 Wellfleet Harbor embayment system. MEP conducted long-term measurements of natural attenuation relating to the surface water discharges to the estuary in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). These additional site-specific studies were conducted in the 3 major surface water flow systems in the Wellfleet Harbor watershed, 1) Herring River at High Toss Road discharging from the wetlands to the head of the harbor system, 2) Fresh Brook discharging from upland to the tidal flats south of Lieutenants' Island and 3) Hatches Creek discharging from upland to the tidal flats south of Lieutenants' Island (Figures IV-5,6,7).

Quantification of watershed based nitrogen attenuation is contingent upon being able to compare nitrogen load to the embayment system directly measured in freshwater stream flow (or in tidal marshes, net tidal outflow) to nitrogen load as derived from the detailed land use analysis (Section IV.1). Measurement of the flow and nutrient load associated with the freshwater streams discharging to the estuary provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up-gradient from the various gauging sites. Flow and nitrogen load were measured at the gauges in each freshwater stream for between 16 and 24 months of record depending on the stream gauging location (Figures IV-5, 6 and 7). During each study period, velocity profiles were completed on each surface water inflow every month to two months. The summation of the products of stream subsection areas of the stream cross-section and the respective measured velocities represent the computation of instantaneous stream flow (Q).

Figure IV-5. Location of Stream gauge (red symbol) on Herring River discharging to the Wellfleet Harbor Embayment System. Gauge was located at the culvert passing under High Toss Road.

Figure IV-6. Location of Stream gauge (red diamonds) on Hatches Creek discharging to the Wellfleet Harbor Embayment System, south of Lieutenant's Island.

Determination of stream flow at each gauge was calculated based on the measured values obtained for stream cross sectional area and velocity. Stream discharge was represented by the summation of individual discharge calculations for each stream subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire stream cross section were not averaged and applied to the total stream cross sectional area. Instead, each individual component area of the cross-section had a measured instantaneous discharge, which when all components are summed equals the total instantaneous cross-sectional volumetric discharge.

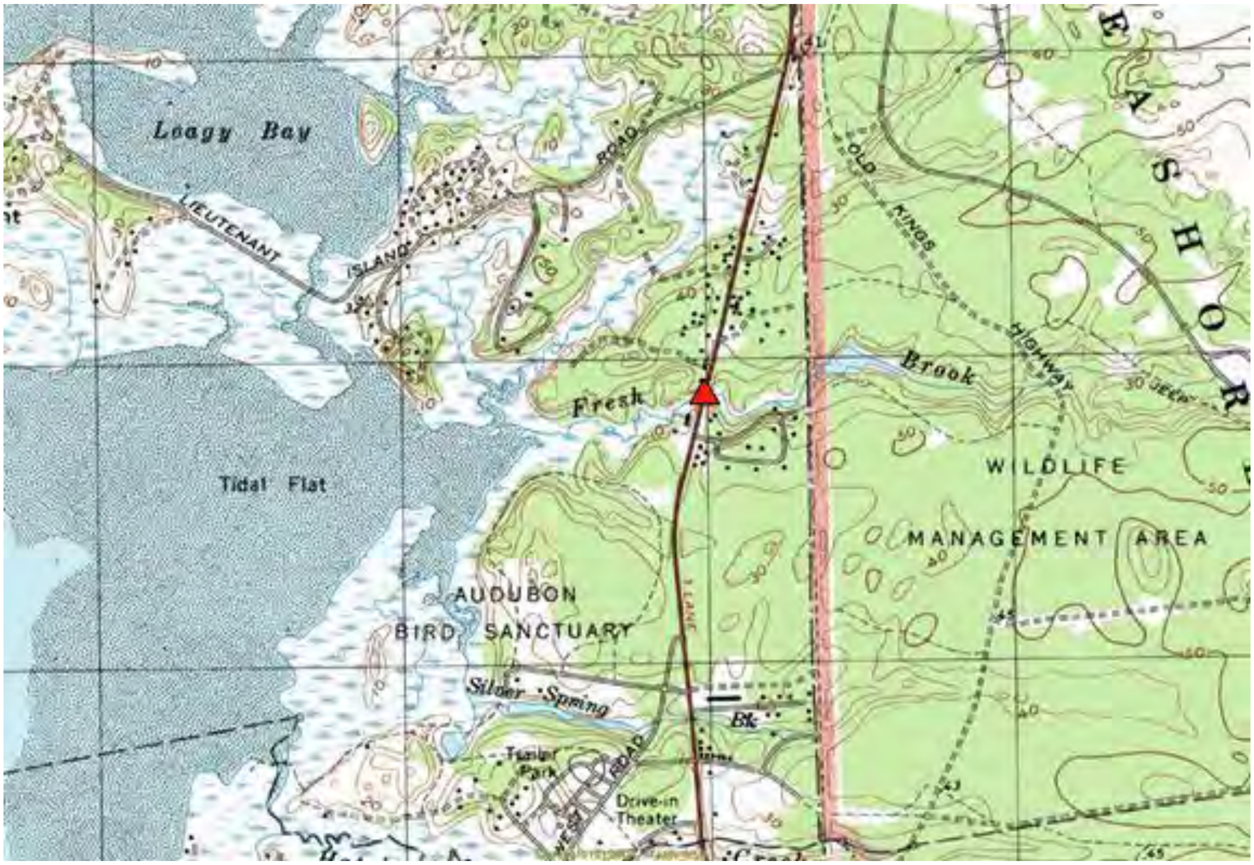


Figure IV-7. Location of Stream gauge (red symbol) on Fresh Brook discharging to the Wellfleet Harbor Embayment System from the Cape Cod National Seashore.

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 detailed record of stage measured by the continuously recording stream gauges. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given river/stream/creek/brook. These hourly stage values were then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. In the case of tidal influence on stream stage, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of strictly freshwater flow. The lowest low tide stage values for any given day were utilized in the stage – discharge relation in order to compute daily flow as this stage value is most representative of freshwater flow. A complete annual record of stream flow (365 days) was generated for each of the major surface water discharges flowing into the Wellfleet Harbor embayment system.

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

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Herring River at High Toss Rd. Discharge to the Wellfleet Harbor Estuary

Unlike most surface water features in the MEP study region that typically emanate from a specific pond, the Herring River, which discharges into the head of the Wellfleet Harbor Estuary, does not have a significant up-gradient lake from which the river discharges. Rather the Herring River discharges from a large fresh to brackish water marsh with significant groundwater inflow. Additionally, the Herring River is a complex network of tributary wetlands with associated drainage ditches and creeks, all of which come together to form what is commonly considered the Herring River. Collectively, the generally freshwater wetland area above the stream gauge at High Toss Road can provide significant potential for nitrogen attenuation under the correct conditions, however, these wetland areas can also be biogeochemical sources of nitrogen as well. Both possibilities must be considered for accurate determination of the nitrogen load to the Wellfleet Harbor estuarine waters from the Herring River. Based on numerous previous studies completed by the MEP on other systems in southeastern Massachusetts, the outflow from the wetlands and the wooded areas up-gradient of the Herring River gauge at High Toss Road can potentially contribute to the attenuation of nitrogen and also provides for a direct measurement of the nitrogen attenuation. The combined rate of nitrogen attenuation by the biological processes that occur in the various surface water features was determined by comparing the present predicted (calculated from land use analysis) nitrogen loading to the sub-watershed region contributing to the wetlands and wooded areas above the gauge site and the measured annual discharge of nitrogen to the Wellfleet Harbor Embayment System from the freshwater portion of the Herring River, Figure IV-9.

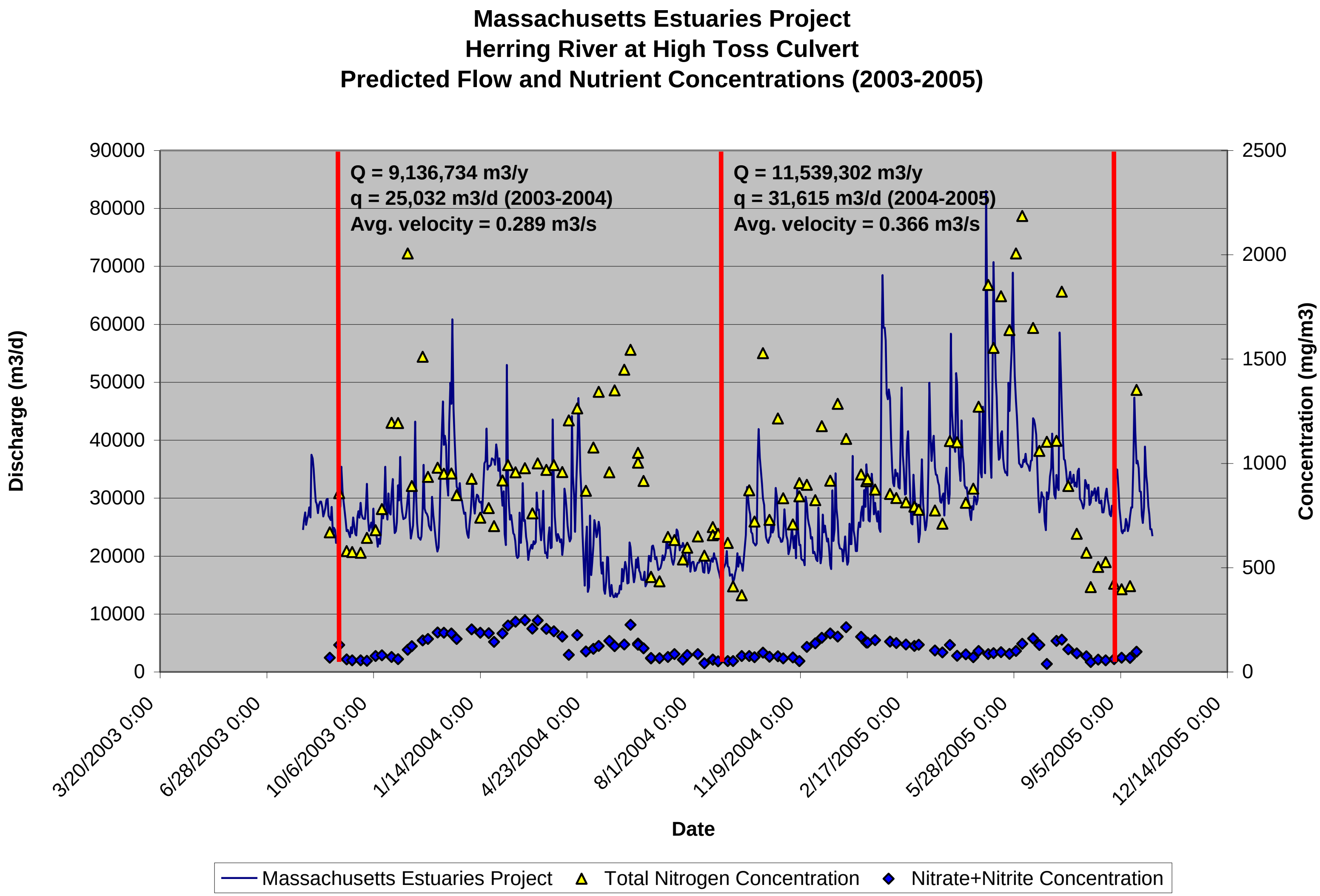


Figure IV-9. Discharge from Herring River freshwater reach (solid blue line), total nitrogen (yellow symbols) and NOx (blue symbols) concentrations for determination of annual volumetric discharge and nitrogen load from the sub-watershed of the Herring River at the High Toss Road culvert discharging to the head of the Wellfleet Harbor Estuary (Table IV-4).

At the Herring River gauge site (established at the culvert passing under High Toss Road), a continuously recording vented calibrated water level gauge was installed to yield the level of water in the channel that carries the flow and associated nitrogen load to the head of the Wellfleet Harbor Estuary. As the lower reach of the Herring River is tidally influenced, the stage record from the gauge was checked to make sure there was no tidal influence in the record at low tide. To confirm that freshwater was being measured at low tide, the stage record was analyzed for any semi-diurnal variations indicative of tidal influence and salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average salinity of the water samples taken from the Herring River at High Toss Road at low tide was determined to be 0.2 ppt. Therefore, the gauge location was deemed acceptable for making freshwater flow measurements at low tide. Calibration of the gauge was checked monthly. The gauge on the Herring River at High Toss Road was installed on July 31, 2003 and was set to operate continuously for 16 months such that a complete hydrologic year would be captured in the flow record. Stage data collection continued until October 4, 2005 for a total deployment of approximately 26 months.

Surface freshwater flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Herring River (High Toss Road gauge site) based upon these flow measurements and measured water levels from the gauge. The rating curve was then used for conversion of the continuously measured stage data to daily freshwater volumetric flow. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge from the freshwater portion of the Herring River to the head of the Wellfleet Harbor estuarine reach and reflective of the biological processes occurring in the stream channel and extensive network of wetlands and wooded area potentially contributing to nitrogen attenuation (Figure IV-9 and Table IV-4 and IV-5). In addition, a water balance was constructed based upon the U.S. Geological Survey/MEP defined watershed delineations to determine long-term average freshwater discharge expected at each gauge site based on area and average recharge.

The annual freshwater flow record (2-year average) for the Herring River as measured between 2003 and 2005 by the MEP was compared to the long-term average flows determined by the USGS/MEP modeling effort (Table III-1). The measured freshwater discharge from the Herring River at the High Toss Road gauge location was virtually the same as the long-term average modeled flows (only 5% lower). The average daily flow based on the MEP measured flow data for two hydrologic years beginning September 2003 and ending in August 2005 (low flow to low flow) was 28,323 m^3/day compared to the long term average flows determined by the watershed modeling effort (29,768 m^3/day). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in the Herring River discharging from the sub-watershed indicate that the Herring River is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Herring River outflow at High Toss Road were moderate to high, 1.002 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 28.39 kg/day and a measured total annual TN load of 10,361 kg/yr. In the Herring River at High Toss Road, nitrate made up a small fraction of the total nitrogen pool (8%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the wetland areas up gradient of the gauge was being transformed from inorganic to organic forms by plants within these different aquatic systems as well as the stream ecosystems. PON+DON represented 80% of the total nitrogen pool.

Table IV-4. Comparison of water flow and nitrogen load discharged by surface waters (freshwater) to the Wellfleet Harbor Estuary. The "Stream" data are from the MEP stream gaging effort. Watershed data are based upon the MEP watershed modeling effort (Section IV.1) and the USGS watershed delineations. Delineations were reviewed by MEP Technical Team Members and sub-watershed delineations were developed by the MEP (Section III).

Stream Discharge Parameter	Stream Discharge to Wellfleet Harbor			Data Source
	Herring River Discharge[a]	Fresh Brook Discharge[a]	Hatches Creek Discharge[a]	
Total Days of Record	365[b]	365[b]	365[b]	(1)
Flow Characteristics				
Stream Average Discharge (m3/day) **	28323	2344	743	(1)
Contributing Area Average Discharge (m3/day)	29768	2546	836	(2)
Discharge Stream 2003-05 vs. Long-term Discharge	-5%	-9%	-13%	
Nitrogen Characteristics				
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.076	0.223	1.92	(1)
Stream Average Total N Concentration (mg N/L)	1.002	0.561	2.613	(1)
Nitrate + Nitrite as Percent of Total N (%)	8%	40%	73%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	28.39	1.32	2.16	(1)
TN Average Contributing UN-attenuated Load (kg/day)	25.05	1.44	1.48	(3)
Attenuation of Nitrogen in Pond/Stream (%)	0%	8%	0%	(4)

(a) Flow and N load to streams discharging to Wellfleet Harbor Estuary includes apportionments of Pond contributing area.
(b) September 1, 2004 to August 31, 2005.
** Flow in the Herring River is average of annual flow for 2003-2005 (two year average, 2003-2004 and 2004-2005)

(1) MEP gage site data
(2) Calculated from MEP watershed delineations to ponds upgradient of specific gages;
the fractional flow path from each sub-watershed which contribute to the flow in the Wellfleet Harbor Estuary;
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.

Table IV-5. Summary of annual volumetric discharge and nitrogen load from the three major surface water discharges to the Wellfleet Harbor Estuarine System (based upon the data presented in Figures IV-9 through IV-10 and Table IV-4.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Herring River at High Toss Rd. (MEP)	**September 1, 2003 to August 31, 2004** **September 1, 2004 to August 31, 2005** **Average 2003 - 2005**	9136734 11539302 **10338018**	872 704 **788**	8405 12316 **10361**
Herring River at High Toss Rd. (CCC)	Based on Watershed Area and Recharge		--	--
Fresh Brook (MEP)	**September 1, 2004 to August 31, 2005**	**855458**	**191**	**480**
Fresh Brook (CCC)	Based on Watershed Area and Recharge		**--**	**--**
Hatches Creek (MEP)	**September 1, 2004 to August 31, 2005**	**271309**	**521**	**709**
Hatches Creek (CCC)	Based on Watershed Area and Recharge		**--**	**--**

From the measured nitrogen load discharged by the Herring River at High Toss Road and the nitrogen load determined from the watershed based land use analysis, it appears that there is little nitrogen attenuation of watershed derived nitrogen during transport through the wetlands to the head of the Harbor. Based upon the measured total nitrogen load (10,361 kg yr^{-1}) discharged at High Toss Road compared to that added by the various land-uses to the associated watershed (8,151 kg yr^{-1}), the integrated attenuation in passage through the freshwater wetlands prior to discharge to the estuary is 0%. This lack of attenuation compared to other streams evaluated under the MEP is expected given the nature of the upgradient bog/wetland areas capable of converting inorganic forms of nitrogen and generating high levels of particulate and dissolved organic nitrogen rather than denitrifying TN loads. In addition, large wetland systems have been found in some cases to export nitrogen to downgradient waters rather than show significant nitrogen removal through net burial and denitrification. The low attenuation/net export of nitrogen observed in the Herring River freshwater wetland reach is similar to other wetland dominated watersheds in the MEP study region such as in the Westport River watershed, particularly those watersheds that have few to no ponds that can serve as effective attenuators of nitrogen. Given the relatively low levels of remaining nitrate in the stream discharge, the possibility for enhancing nitrogen removal is be limited. The directly measured nitrogen load from the Herring River was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Hatches Creek Discharge to Wellfleet Harbor

Unlike most surface water features in the MEP study region that typically emanate from a specific pond, Hatches Creek, which discharges into the eastern portion of the Wellfleet Harbor System immediately south of Lieutenants'' Island, does not have an up-gradient pond from which that creek discharges. Rather, this small stream appears to be groundwater fed and emanates from a wooded area that extends into the National Seashore up-gradient of Route 6. The stream and associated wooded area up gradient of the gauge located at the Massasoit Road crossing of Hatches Creek may serve to contribute to the attenuation of nitrogen that passes through it. Measurements of flow and nitrogen concentration at the gauge provides for a direct measurement of nitrogen load and nitrogen attenuation. The combined rate of nitrogen attenuation by the biological processes occurring as the water in Hatches Creek flows to the estuary was determined by comparing the present predicted nitrogen loading to the sub-watershed contributing to the wooded areas above the gauge and the measured annual discharge of nitrogen to the tidal flats south of Lieutenants' Island on the eastern shore of the Wellfleet Harbor estuary, Figure IV-7.

The freshwater flow carried by Hatches Creek to the estuarine waters of the Wellfleet Harbor system was determined using a continuously recording vented calibrated water level gauge. As this surface water system was potentially tidally influenced, the creek discharge was checked to confirm the extent of tidal influence and whether freshwater flow could be measured at low tide in the estuary. To confirm that freshwater was being measured, salinity measurements were conducted on weekly water quality samples collected from the gauge site. Average measured sample salinity over the project period was 0.2 ppt, so flow at the site was freshwater. As such, an adjustment for tidal influence was not necessary in order to determine daily flows using the MEP developed stage-discharge relation. Based on the data, the Hatches Creek gauge location was deemed acceptable for making flow and nitrogen measurements and obtaining an estimate of annual freshwater flow and transported nitrogen load. Calibration of the gauge was checked monthly. The gauge was installed on July 31, 2003 and was set to operate continuously for 16 months such that at least one summer season would be captured in the flow record. Stage data collection continued until July 11, 2005 for a total deployment of 24 months.

Stream 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 the water levels measured by the gauge. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge by Hatches Creek from above the gauge to Wellfleet Harbor. Nitrogen levels are reflective of the nitrogen input from the watershed and biological processes occurring in the stream channel and associated areas contributing to nitrogen attenuation (Figure IV-10 and Table IV-4 and IV-5).

In addition, the MEP annual volumetric discharge was compared to a water balance constructed based upon the U.S. Geological Survey/MEP defined watershed delineations to determine long-term average freshwater discharge expected at the Hatches Creek gauge site based on area and average recharge Both estimates showed similar low flows. (Table III-1). The measured freshwater discharge from Hatches Creek at the Massasoit Road gauge location was slightly less than (11%) the long-term average modeled flows. The average daily flow based on the MEP measured flow data for the hydrologic year beginning September 2003 and ending in August 2004 (low flow to low flow) was 743 m^3/day compared to the long term average flows determined by the watershed delineation and water balance, 836 m^3/day. The small difference between these flow estimates in Hatches Creek indicate that the Creek is capturing the upgradient recharge (and loads) accurately.

Total nitrogen concentrations within the Hatches Creek outflow were high, 2.613 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 2.16 kg/day and a measured total annual TN load of 709 kg/yr. In the Hatches Creek flow, nitrate made up more than half of the total nitrogen pool (73%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the creek up-gradient of the gauge was not significantly taken up by plants in the up-gradient riparian zone, consistent with the lack of notable extensive wetland and bog features upgradient of the Hatches Creek gauge. Given the relatively high levels of remaining nitrate in the stream discharge, the possibility for additional uptake by constructed wetland/pond areas may be possible. However, the cost and effectiveness of trying to enhance natural attenuation in this creek system should be considered relative to the relatively small nitrogen load the creek contributes to the overall Wellfleet Harbor estuary.

From the measured nitrogen load discharged by Hatches Creek and the nitrogen load determined from the watershed based land use analysis, it appears that there is no significant nitrogen attenuation of watershed derived nitrogen during transport through the biologic systems associated with Hatches Creek. Based upon the measured total nitrogen load (709 kg yr^{-1}) discharged from Hatches Creek at Massasoit Road compared to that added by the various land-uses to the associated watershed (540 kg yr^{-1}), the integrated attenuation in passage through the stream prior to discharge to the estuary was set at 0%. This lack of attenuation is consistent with measurements on other streams evaluated under the MEP that emanate from a wooded watershed with no other surface water aquatic systems (wetlands, bogs, ponds) that serve as attenuators of nitrogen (e.g. Kirby Brook and Snell Creek discharging to the East Branch of the Westport River estuary). The directly measured nitrogen load from Hatches Creek was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

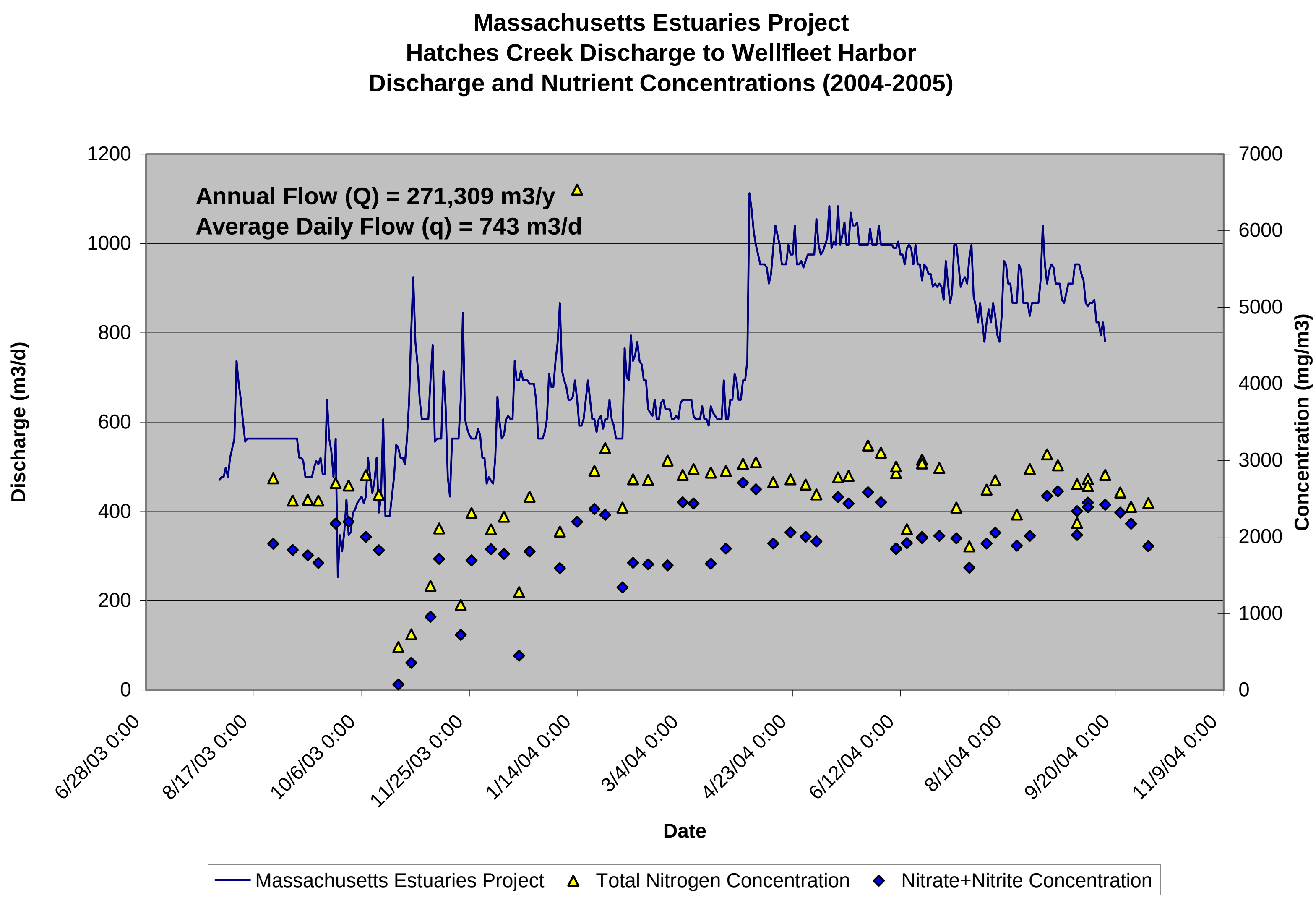


Figure IV-10. Discharge from Hatches Creek (solid blue line), total nitrogen (yellow symbols) and NOx (blue symbols) concentrations for determination of annual volumetric discharge and nitrogen load from the sub-watershed of Hatches Creek discharging to the eastern-outer portion of the Wellfleet Harbor system (Table IV-4).

IV.2.4 Surface water Discharge and Attenuation of Watershed Nitrogen: Fresh Brook Discharge to the Herring River Estuary

Unlike most surface water features in the MEP study region that typically emanate from a specific pond, Fresh Brook, which discharges to the eastern shore of the Wellfleet Harbor system just south of Lieutenants Island, does not have a significant up-gradient pond from which that brook discharges. Rather, this small brook appears to be groundwater fed and emanates from a small impoundment in a generally wooded area up-gradient of Route 6. The outflow leaving the wooded areas up gradient of Route 6 travels through an upland environment just prior to discharging directly into the head of a salt marsh along the eastern shore of the estuary. Transport through the small impoundment and the wooded area up gradient of the gauge may provide contact with biological systems that attenuate nitrogen. Measurements at the gauge can be used to derive a direct measurement of the nitrogen attenuation in this stream system. The combined rate of nitrogen attenuation by the biological processes occurring as the water in Fresh Brook flows to the estuary was determined by comparing the present predicted nitrogen loading to the gauge location and the measured annual discharge of nitrogen to the estuary relative to the Fresh Brook gauge, Figure IV-7.

The freshwater flow carried by Fresh Brook to the estuarine waters of the Wellfleet Harbor estuary was determined using a continuously recording vented calibrated water level gauge. Calibration of the gauge was checked monthly. As this surface water system was potentially tidally influenced, the discharge from the brook was checked to confirm the extent of tidal influence and whether freshwater flow to the estuary could be measured during low tide. To confirm that freshwater was being measured, salinity measurements were conducted on weekly water quality samples collected from the gauge site. Average measured sample salinity was 0.9 ppt, indication of a negligible tidal influence. As such, a salinity adjustment was not necessary in order to determine daily flows using the MEP developed stage-discharge relation and the Fresh Brook gauge location was deemed acceptable for making flow measurements and obtaining an estimate of annual freshwater flow. The gauge was installed on December 30, 2003 and was set to operate continuously for 16 months such that at least one summer season would be captured in the flow record. Stage data collection continued until October 30,2005 for a total deployment of 22 months.

Flow in the creek (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 the measured water levels by the gauge. The rating curve was then used to convert the continuously measured stage data to daily freshwater flow volume. Integrating the flow and nitrogen concentration datasets allows for the determination of nitrogen mass discharge to the head of the salt marsh. This measured load includes the effects of biological processes occurring in the stream channel and associated surface water systems and the small impoundment and the wooded areas potentially contributing to nitrogen attenuation (Figure IV-11 and Table IV-4 and IV-5).

The gauge flows were compared to a water balance that was constructed based upon the U.S. Geological Survey/MEP defined watershed delineations to determine long-term average freshwater discharge expected at the Fresh Brook gauge site based on contributing area and average recharge (Table III-1). The measured freshwater discharge at the gauge location was similar to the long-term average modeled flows (within 8%). The average daily flow based on the MEP measured flow data for the hydrologic year beginning September 2004 and ending in

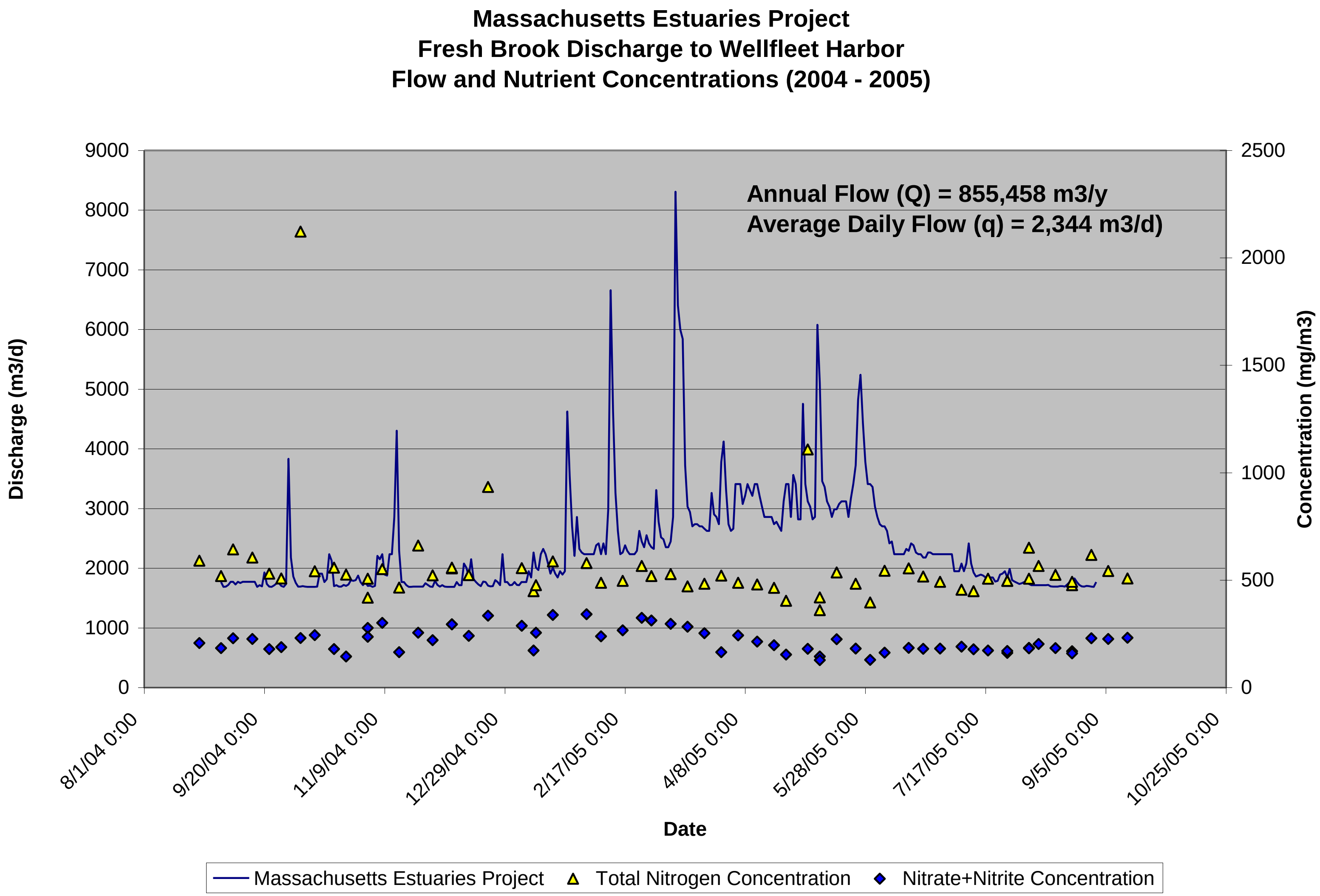


Figure IV-11. Discharge from Fresh Brook (solid blue line), total nitrogen (yellow symbols) and NOx (blue symbols) concentrations for determination of annual volumetric discharge and nitrogen load from the sub-watershed of Fresh Brook discharging from the Cape Cod National Seashore to the eastern outer portion of the Wellfleet Harbor Estuary (Table IV-4).

August 2005 (low flow to low flow) was 2,344 m^3/day compared to the long term average flows determined by the watershed modeling effort (2,546 m^3/day). The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Fresh Brook discharging from the sub-watershed indicate that the brook is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Fresh Brook outflow were relatively low, 0.561 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 1.32 kg/day and a measured total annual TN load of 480 kg/yr. In the Fresh Brook outflow, nitrate made up approximately half of the total nitrogen pool (40%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the wetland areas and stream bed up gradient of the gauge is being only partially taken up by plants within the impoundment and channel bed of the brook and converted to organic forms. Given the low levels of remaining nitrate in the creek discharge, there is only a low possibility for additional uptake by freshwater systems even if constructed wetlands or pond were introduced. However, modifying the impoundment upgradient of the gauge to enhance natural attenuation would likely lower the small N load, but given the size of the potential reduction versus the total nutrient load to the harbor it may not be a cost effective option.

From the measured nitrogen load discharged by Fresh Brook to the tidal reaches of Wellfleet Harbor and the nitrogen load determined from the watershed based land use analysis, it appears that there is only a small amount of nitrogen attenuation of upper watershed derived nitrogen during transport through Fresh Brook to estuarine receiving waters. Based upon lower total nitrogen load (480 kg yr^{-1}) discharged from Fresh Brook compared to that added by the various land-uses to the associated watershed (525 kg yr^{-1}), the integrated attenuation in passage through the small impoundment and the small brook prior to discharge to the estuary is 8% (i.e. 8% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams/creeks evaluated under the MEP is expected given the limited surface water systems in the watershed that typically remove nitrogen. The directly measured nitrogen load from Fresh Brook was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the benthic nutrient flux surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters throughout the Wellfleet Harbor Embayment System. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

As stated in above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the Wellfleet Harbor Estuary predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate.

This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the water column for sufficient time to be flushed out to a down gradient larger water body (like Nantucket Sound). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom sediments. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with associated nitrogen “load” become incorporated into the surficial sediments of the system.

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

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, such as found within much of the bordering region to the Lewis Bay main basin in the Town of Barnstable, Cape Cod. In contrast, regions of high deposition like Hyannis Inner Harbor, also part of the Lewis Bay system but essentially a dredged boat basin, typically support anoxic sediments with elevated rates of nitrogen release during summer months. This latter pattern has been previously observed in the Duck Creek/Cove region of Wellfleet Harbor as well. The consequence of this deposition is that these basin sediments are unconsolidated, organic rich and of a 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 Wellfleet Harbor Estuary. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for determining sediment-watercolumn nitrogen exchange

For the Wellfleet 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. Sediment samples were collected from a total of 32 sites in the Wellfleet Harbor Embayment System. Cores were spatially distributed throughout both the main basin and its tributary basins. All the sediment cores for this system were collected in July-August 2004. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shoreside lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from core sites to replace the headspace water of each core prior to incubation. The number of core samples from each estuarine component (Figure IV-11) are as follows:

Wellfleet Harbor Benthic Nutrient Regeneration Cores

- WHrb-1 1 core (Duck Creek)
- WHrb -2 1 core (Duck Creek)
- WHrb -3 1 core (Cove)
- WHrb -4 1 core (Cove)
- WHrb -5/6 2 core (Cove)
- WHrb -7 1 core (Herring River-mouth)
- WHrb -8 1 core (Herring River-mouth)
- WHrb -9 1 core (Cove)
- WHrb -10 1 core (Main Basin-Upper)
- WHrb -11 1 core (Main Basin-Upper)
- WHrb -12 1 core (Main Basin-Upper)
- WHrb -13 1 cores (Main Basin-Upper)
- WHrb -14 1 core (Main Basin-Middle Upper)
- WHrb -15 1 core (Main Basin-Middle Upper)
- WHrb -16 1 core (Main Basin-Middle Upper)
- WHrb -17 1 core (Main Basin-Middle Upper)
- WHrb -18 1 core (Main Basin-Middle Upper)
- WHrb -19 1 core (Drummer Cove-Loagy Bay)
- WHrb -20 1 core (Drummer Cove-Loagy Bay)
- WHrb -21 1 core (Drummer Cove-Loagy Bay)
- WHrb -22 1 core (Drummer Cove-Loagy Bay)
- WHrb -23 1 core (Drummer Cove-Loagy Bay)
- WHrb -24 1 core (Drummer Cove-Loagy Bay)
- WHrb -25 1 core (Main Basin-Middle Lower)
- WHrb -2 1 core (Main Basin-Middle Lower)
- WHrb -7 1 core (Main Basin-Middle Lower)
- WHrb -28 1 core (Main Basin-Middle Lower)
- WHrb -29 1 core (Main Basin-Middle Lower)
- WHrb -30 1 core (Main Basin-Lower)
- WHrb -31 1 core (Main Basin-Lower)
- WHrb -32 1 core (Main Basin-Lower)

Sampling was distributed throughout the primary component basins of the Wellfleet Harbor Estuary and the results were used for calculating the net nitrogen regeneration rates for the water quality modeling effort.

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

Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA. (508-910-6325 or d1white@umassd.edu). The laboratory follows standard methods for saltwater analysis and sediment geochemistry.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

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

Figure IV-11. Wellfleet Harbor Embayment System sediment sampling sites (yellow symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above.

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

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

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

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-12).

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

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

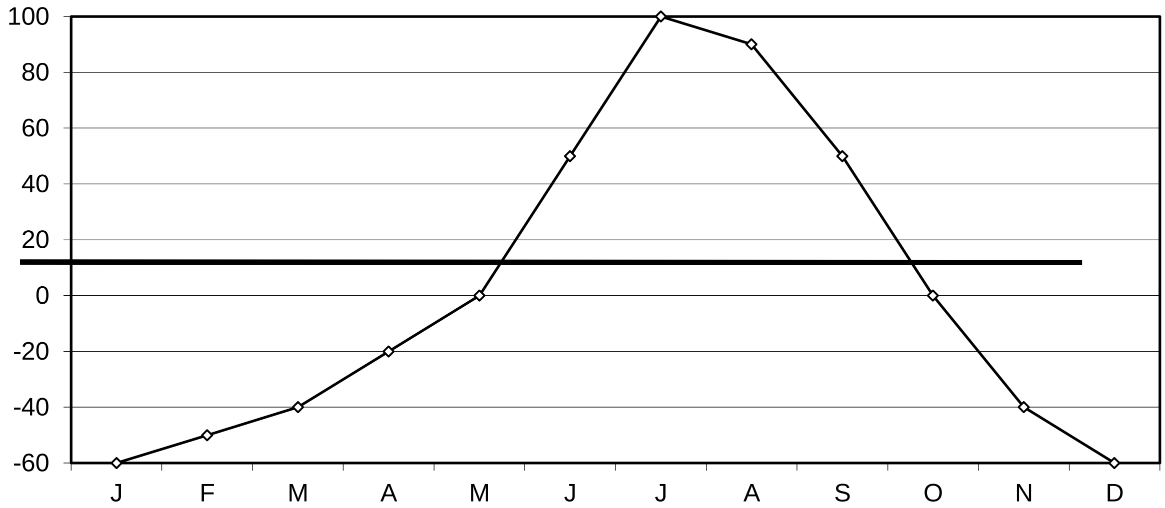


Figure IV-12. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Sediment sampling was conducted throughout the primary component basins (e.g. tidal reaches of the Main Basin, Duck Creek, Cove, Drummer Cove/Loagy Bay) which comprise the Wellfleet Harbor Estuary in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores in each sub-basin, harbor and cove was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

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

Net nitrogen release or uptake from the sediments within the Wellfleet Harbor Embayment System were comparable to other similar embayments with similar configuration and flushing rates in southeastern Massachusetts. In addition, the spatial pattern of sediment N release was also similar to other systems, with the high depositional anoxic sediments of the upper tidal reaches (Duck Creek, Cove) showing high net nitrogen release, the large open embayment depositional basins with oxidized surficial sediments showing low rates of net nitrogen release with net nitrogen uptake in deeper areas.

Sediment nitrogen release rates were highest in the semi-enclosed high depositional upper basins with soft organic rich mud with a thin oxidized or anoxic surface layer. These basins comprising the Duck Creek (173 mg N $m^{-2}d^{-1}$) and Cove (140 mg N $m^{-2}d^{-1}$) region of the Harbor are partially dredged, enhancing the deposition of organic matter and nitrogen release rates. The geomorphology, sedimentology and biogeochemistry of this region is nearly identical to that of Hyannis Inner Harbor (Lewis Bay) which show a similar net nitrogen release, 144 mg N $m^{-2}d^{-1}$. Analogous depositional basins also show similar net nitrogen release rates, for example, the depositional main basin of East Bay (Centerville River Estuary) and the lower basin of Rock Harbor (Orleans/Eastham), both of which support benthic regeneration rates of 59.1 mg N m^{-2} d^{-1} and 80.8 mg N m^{-2} d^{-1}, respectively. Additionally, the drowned kettle basins within Pleasant Bay, Meetinghouse Pond (79.5 mg N m^{-2} d^{-1}), Areys Pond (107.3 mg N m^{-2} d^{-1}), Quanset Pond (98.0 mg N m^{-2} d^{-1}), and Paw Wah Pond (120.7 mg N m^{-2} d^{-1}) also have similar basins and net rates of nitrogen release. The main basin and Drummer Cove and the mouth of Herring River showed lower net nitrogen release rates as typical of more open water basins with low/moderate rates of deposition and moderate to high rates of tidal exchange 2.2 to 10.2 mg N $m^{-2}d^{-1}$, with slightly higher rates in the ebb tidal delta areas of Herring River (18 mg N $m^{-2}d^{-1}$). Also similar to other estuaries in southeastern Massachusetts, the lower open water basin of the main Harbor which supports oxidized, generally coarse grained sediments, showed a low net nitrogen uptake, due primarily to in situ denitrification or remineralized N (5-15 mg N $m^{-2}d^{-1}$). The similarly situated Main Basins of Nasketucket Bay (-20 mg N $m^{-2}d^{-1}$), Pleasant Bay and Chatham Harbor (-7 and -9 mg N $m^{-2}d^{-1}$, respectively), Westport Harbor (-16 mg N $m^{-2}d^{-1}$) and Megansett Harbor (-5 mg N $m^{-2}d^{-1}$) all show similar sediments, water depths and nitrogen uptake rates. Overall, it is clear that the multiple component basins of Wellfleet Harbor Estuary presently support rates of summertime sediment nitrogen release/uptake typical of these types of basins in other estuaries, with similar structure and sediment characteristics, throughout the region.

Net nitrogen release rates for use in the water quality modeling effort for the main basins of the Wellfleet Harbor Embayment System (Section VI) are presented in Table IV-6. There was a clear spatial pattern of sediment nitrogen flux, with high net release of nitrogen in the upper organic rich, sulfidic, depositional basins and low/moderate release in the open water shallow main basins and a small net uptake of nitrogen within the open water deeper lower basin areas furthest from the sources of watershed nitrogen loading. The sediments within the Wellfleet Harbor Embayment System showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and are consistent with the level of nitrogen loading to this system and its rates of tidal flushing.

Table IV-6. Rates of net nitrogen return from sediments to the overlying waters of component basins comprising the Wellfleet Harbor Estuarine System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July - August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			Station I.D. *
	Mean	S.E.	# sites	WHbr-#
Wellfleet Harbor Estuary - Component Basins				
Main Basin - Upper	**2.2**	**5.9**	**4**	10,11,12,13
Main Basin - Middle Upper	**10.2**	**20.5**	**4**	14,15,16,17,18
Main Basin - Middle Lower	**-15.5**	**3.0**	**4**	25,26,27,28,29
Main Basin - Lower	**-5.1**	**4.1**	**3**	30,31,32
Duck Creek	**172.8**	**6.9**	**2**	1,2
Cove	**139.5**	**34.2**	**5**	3,4,5,6,9
Herring River Mouth	**18.0**	**5.5**	**2**	7,8
Drummer Cove - Loagy Bay	**3.5**	**8.1**	**6**	19,20,21,22,23,24

* Station numbers refer to Figure IV-11

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This hydrodynamic study was performed for Wellfleet Harbor, located on the Cape Cod Bay facing shoreline of Wellfleet , Massachusetts, in the lower Cape. 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. Wellfleet Harbor is an open embayment with a broad inlet to Cape Cod Bay. The lowest elevations of the system exist in the natural channel of the main Harbor Basin, where maximum depths of approximately -24 feet NAVD occur. The total surface coverage of the Wellfleet Harbor system is approximately 6,800 total acres, not including the area impounded by the Herring River dam.

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

Tidal exchange with Cape Cod Bay dominates circulation in the Harbor. From measurements made over the course of this study, the average offshore tide range is 9.6 feet. As indicated by the lack of attenuation of high tide elevations across the inland extents of the tributary creeks of the Harbor, tidal flushing appears very efficient throughout the tidal reaches of the system. This system has three main sub-embayment branches: 1) Blackfish Creek, 2) the inner harbor area at the town pier (including the embayment area known as “The Cove”), and 3) Herring River.

The hydrodynamic study of the Wellfleet 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 Wellfleet Harbor was performed to determine the variation of depths throughout the main sub-embayment areas of the system. This survey addressed the previous lack of adequate bathymetry data for these areas. In addition to the bathymetry survey, tides were recorded at five stations within the Harbor system for 31 days. These tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of Wellfleet 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 Wellfleet Harbor is an integral piece of the water quality model developed in Section VI 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 Wellfleet 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 model performance.

V.2.1 Bathymetry Data

Bathymetric data was collected in the northern reaches of the Harbor (including the inner harbor and Herring River) and the areas around Lieutenants Island (including Blackfish Creek). The survey employed a boat-mounted fathometer. Positioning data were collected using a differential GPS. Where practical, predetermined survey transects were followed at regular intervals. 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 bathymetric data was gathered from NOAA’s GEODAS database of historical hydrographic survey data. The GEODAS data were used for the main Harbor basin. The complied elevation dataset, including elevations from the bathymetry survey, is shown in Figure V-2.

V.2.2 Tide Data Collection and Analysis

Tide data records were collected concurrently at five gauging stations shown in Figure V-2, located at the opening to Cape Cod Bay (W-1), in Blackfish Creek (W-2), at the town pier in The Cove (W-3), Duck Creek upstream of Uncle Tim’s Bridge (W-4) and downstream of the Herring Creek dam (W-5). The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 61-day period between August 24 and October 24, 2005. 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.

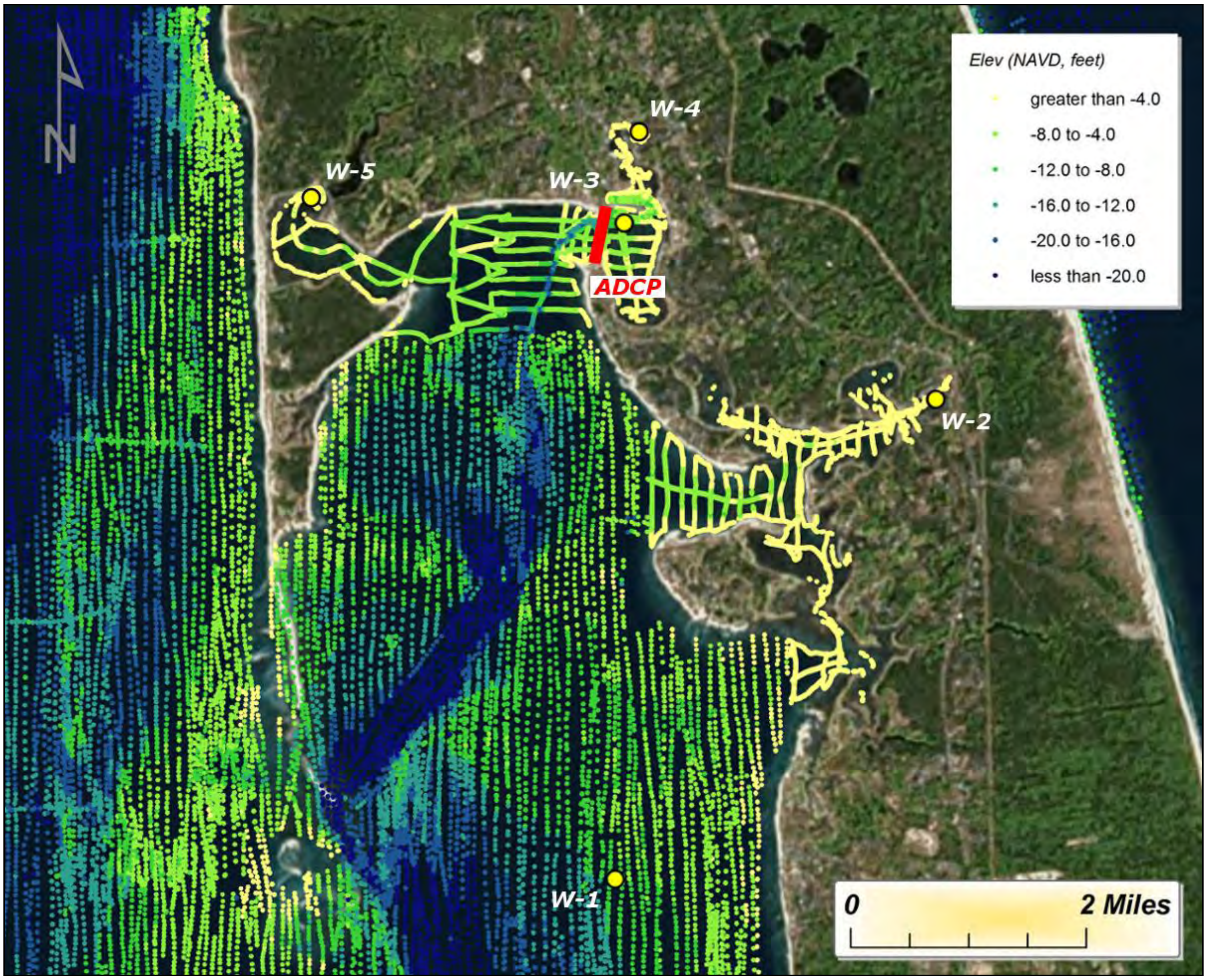


Figure V-2. Bathymetric data used to develop the RMA-2 hydrodynamic model. Points are colored to represent the bottom elevation relative to NAVD. The data sources used to develop the grid mesh are the 2005 bathymetry survey, and NOAA hydrographic data from their GEODAS database. Location of tide gauges and ADCP transect are also indicated.

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 five gauges are shown in Figure V-3 for the entire 31-day deployment. The spring-to-neap variation in tide range is easily discernible in these plots. The data record begins during a transitional period from spring to neap tides. Around September 18 there is a period of spring tides, which occurs around the time of the new moon of September 17. Following this spring tide is a continuing cycle of neap and spring tides. The minimum neap tide range in the offshore record is only 6.2 feet (September 26), while the maximum spring tide rage (occurring about a week earlier) is 13.5 feet (September 18).

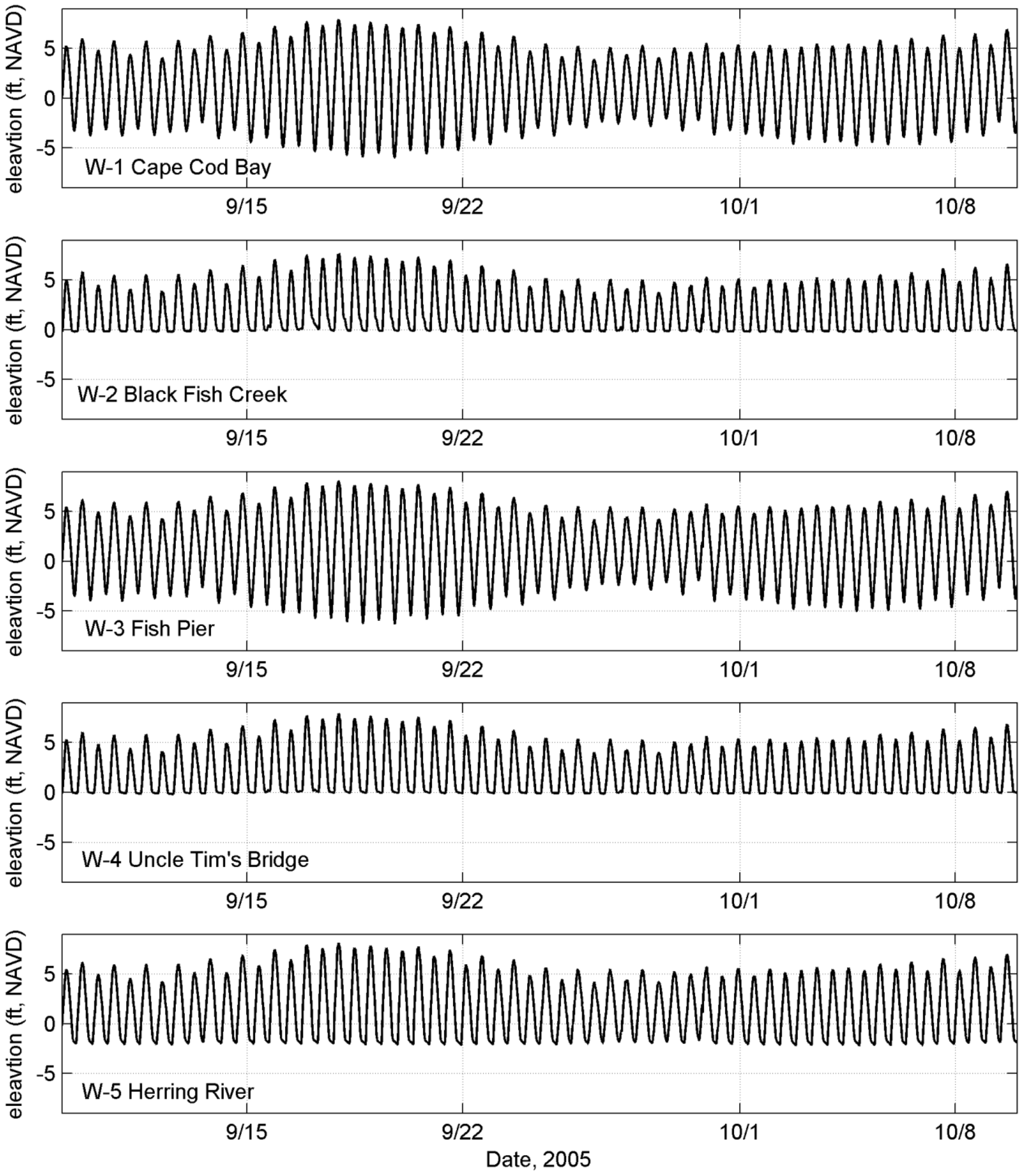


Figure V-3. Plots of observed tides for stations in Wellfleet Harbor, for the 31-day period between September 9 and October 10, 2005. All water levels are referenced to the NAVD vertical datum.

A visual comparison between tide elevations offshore and at the different stations in the system shows that the tide amplitude in the upper reaches is controlled by the bottom elevation of these areas. There is only a minor reduction of the water elevation at times of high tide (about 6 inches) between the offshore and inshore areas. Low tide elevations are highest at the Blackfish Creek and the Uncle Tim's Bridge gauges, where tide flats control the minimum water levels. For these areas, the low tide elevation during spring tides is nearly 6 feet higher than offshore in Cape Cod Bay.

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.

Tidal damping in the upper reaches of the Harbor system is manifest by the elevated levels of the low water datums, as presented in Table V-1. For example, MLW at the Uncle Tim's Bridge station is four feet higher than it is at the town pier. Though the tide range is truncated in these inner areas, the tidal flows are conveyed throughout the main sub-embayment areas of the system very efficiently, as can be seen by the small difference in elevation of high tide at all gauging stations. This is the case at the Uncle Tim's Bridge gauging station again, where MHW is only 0.2 feet less than it is a short distance downstream at the town pier.

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 Wellfleet 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 4.5 feet. The total range of the M_2 tide is twice the amplitude, or 9.0 feet.

The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.4 feet and 0.5 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 0.9 feet and 1.1 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.

Table V-1. Tide datums computed from 30-day records collected offshore and in the Wellfleet Harbor system in September and October 2005. Datum elevations are given relative to NAVD vertical datum.

Tide Datum	Cape Cod Bay	Town Pier	Duck Creek	Herring River	Blackfish Creek
Maximum Tide	7.9	8.0	7.9	8.1	7.7
MHHW	6.2	6.4	6.2	6.4	5.9
MHW	5.7	5.9	5.7	5.9	5.5
MTL	0.9	0.9	2.8	2.0	2.7
MLW	-3.9	-4.1	-0.1	-2.0	-0.1
MLLW	-4.2	-4.4	-0.1	-2.1	-0.2
Minimum Tide	-6.0	-6.3	-0.2	-2.2	-0.2
Mean Range	9.6	10.0	4.8	3.9	5.3

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 located at its inner reaches.

Together with the change in constituent amplitude across the 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 Wellfleet Harbor system, relative to the timing of the M_2 constituent in Cape Cod Bay, at the harbor entrance. The largest delay occurs at the Uncle Tim's Bridge station, where the M_2 phase is offset by one-and-one-half hours. Even with this large phase delay in the M_2 constituent (1.5 hours being 12% of the period of the M_2), the effect on the observed timing of high tide is minimal (as seen in Figure V-4).

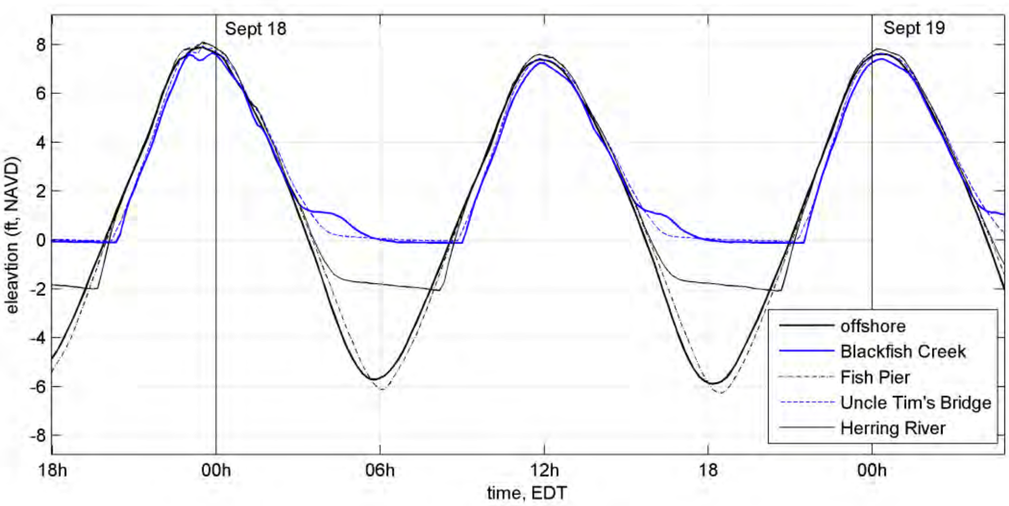


Figure V-4. Four-day tide plot showing tides measured in Cape Cod Bay and at stations in the Wellfleet Harbor system. .

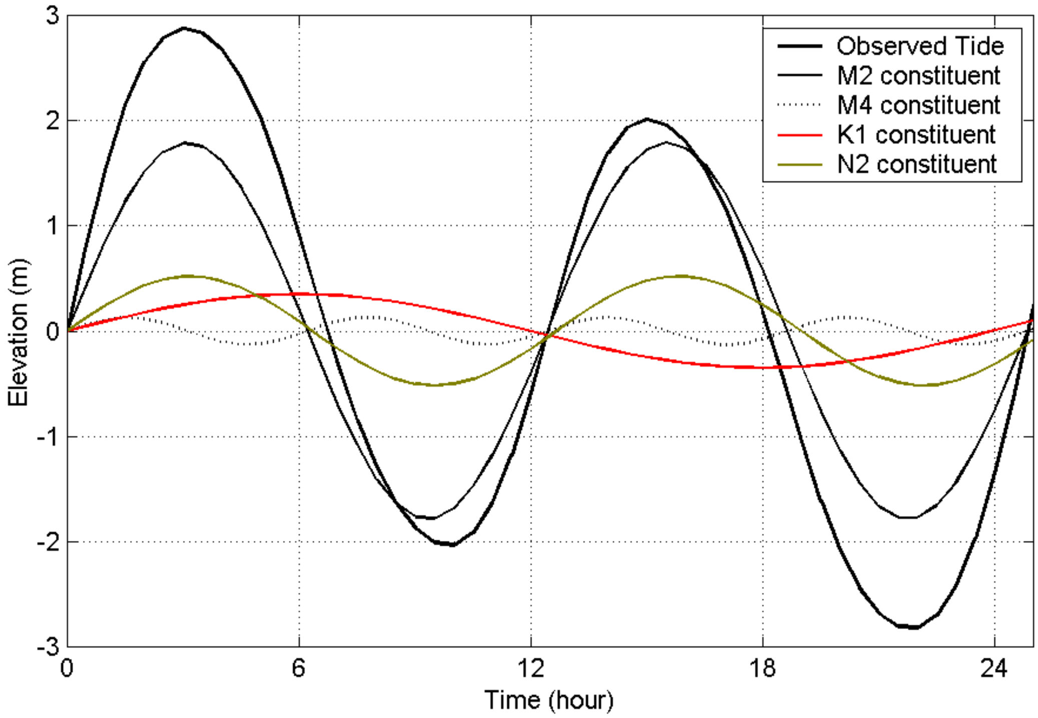


Figure V-5. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-2. Tidal Constituents computed for tide stations in the Wellfleet Harbor system and offshore in Cape Cod Bay, September to October, 2005.

	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	4.47	0.11	0.19	0.93	1.05	0.36	0.47
Town Pier	4.56	0.17	0.22	0.95	1.06	0.37	0.47
Uncle Tim's Bridge	2.80	0.77	0.14	0.48	0.66	0.29	0.33
Herring River	3.84	0.42	0.10	0.66	0.84	0.34	0.39
Blackfish Creek	2.65	0.82	0.11	0.46	0.61	0.30	0.33

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 Wellfleet Harbor compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 21 constituents determined by the harmonic analysis) is presented in Table V-4. Subtracting the tidal signal from the original elevation time series resulted 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.

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 Wellfleet 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 Blackfish Creek.

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

Station	Delay (minutes)
Blackfish Creek	83.7
Town Pier	33.1
Uncle Tim’s bridge	91.5
Herring River	57.7

Table V-4. Percentages of Tidal versus Non-Tidal Energy for stations in the Wellfleet Harbor system and Cape Cod Bay, September and October, 2005.

TDR Location	Total Variance (ft^2)	Tidal (%)	Non-tidal (%)
Cape Cod Bay	11.15	99.1	0.9
Blackfish Creek	4.41	96.0	4.0
Town Pier	11.58	99.0	1.0
Duck Creek	4.80	96.9	3.1
Herring River	8.27	98.1	1.9

V.2.2.a Tide Flood and Ebb Dominance

An investigation of the flood or ebb dominance of different areas in the Wellfleet Harbor system was performed using the measured tide data. Estuaries and sub-embayments that are flood dominant are typically areas that collect sediment over time since they have maximum flood tide velocities that are greater than the maximum velocities that occur during the ebb portion of the tide. Salt marshes tend to be flood dominant, as this condition allows them to collect material that is required to maintain healthy marsh resources.

Flood or ebb dominance in channels of a tidal system can be determined by utilizing the results of the harmonic analysis of tidal elevations, or by performing a similar analysis on a time series of tidal currents. 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.

For constituents based on tidal elevations, 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 ($0<\Phi<180$), 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 ($180<\Phi<360$), 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.

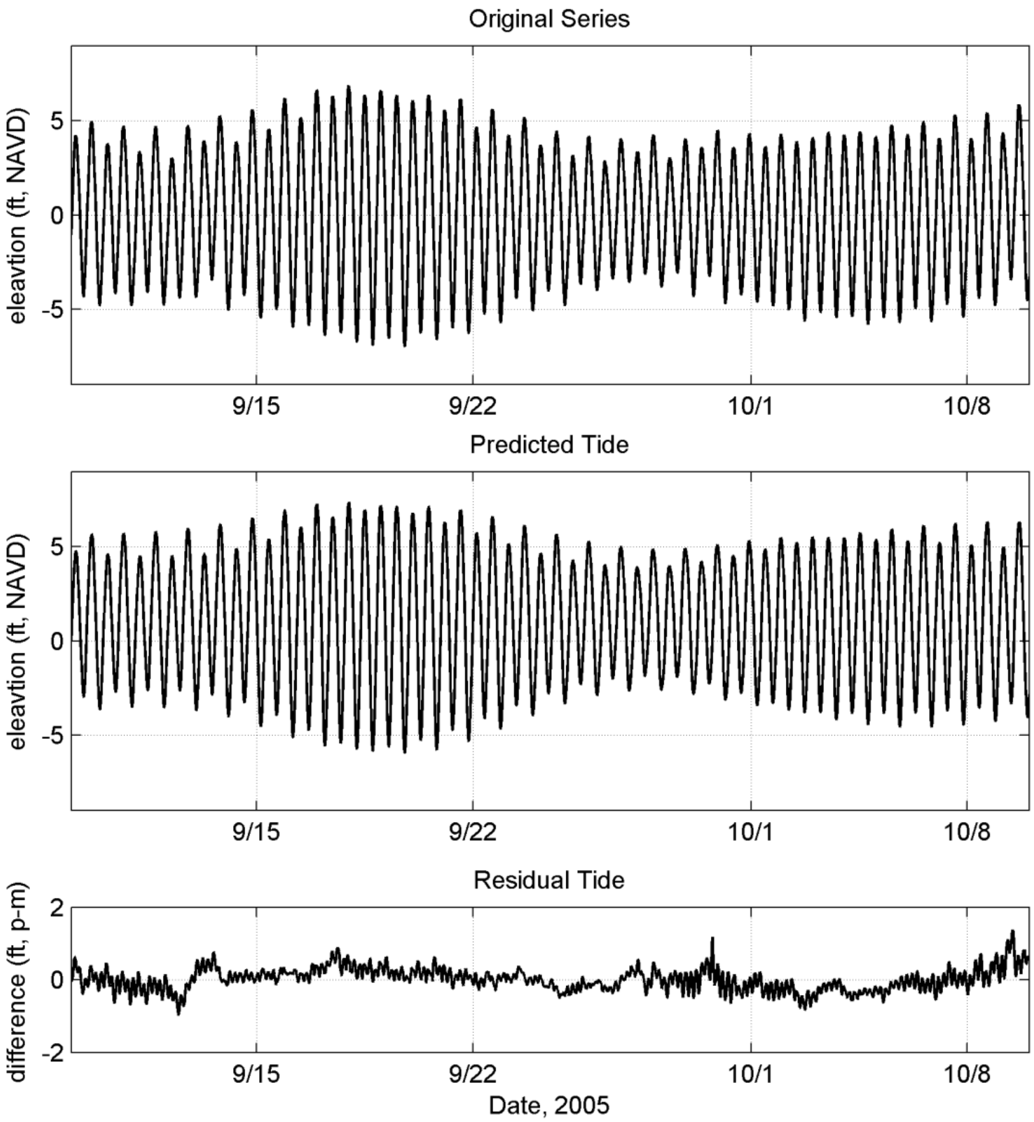


Figure V-6. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 21 individual tide constituents determine in the harmonic analysis of the Cape Cod Bay gauge data, collected offshore Wellfleet Harbor. The residual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

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 (W-1 in Cape Cod Bay) through to the upper reaches of the main tidal creeks (e.g., W-4, upstream of Uncle Tim's Bridge). The results of this velocity analysis of the Wellfleet Harbor measured tide data show that although the offshore gauge is ebb dominant, all interior gauge stations indicate flood dominant. The computed values of $2M_2$-M_4 are presented in Table V-5.

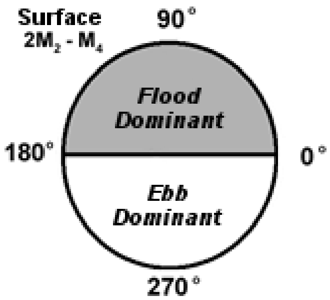


Figure V-7. Relative velocity phase relationship of M2 and M4 tidal elevation constituents and characteristic dominance, indicated on the unit circle. Relative phase is computed as the difference of two times the M2 phase and the M4 phase (2M2-M4). A relative phase of exactly 90 or 270 degrees indicates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

Table V-5. Wellfleet 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, W-1	195.1	Moderate Ebb
Blackfish Creek, W-2	14.1	Moderate Flood
Town Pier, W-3	158.0	Moderate Flood
Duck Creek, W-4	13.1	Moderate Flood
Herring River, W-5	29.0	Moderate Flood

V.2.3 ADCP Data Analysis

Tidal velocity measurements were surveyed through a complete tidal cycle in the Wellfleet Harbor system on October 6, 2005 to resolve spatial and temporal variations in tidal current patterns. The survey was designed to observe tidal flow across a cross-channel transect at hourly intervals. This transect was run between the western base of the town pier and the base of the inner harbor jetty. In total, 28 runs of the jetty transect were made during the 12.5-hour long survey. The data collected during this survey provided information that was necessary to properly validate the hydrodynamic model of the Wellfleet Harbor system.

Figures V-8 and V-9 show color contours of the current measurements observed during the period of maximum flood and ebb tide currents. Positive along-channel currents (top panel of these figures) indicate the flow is moving into the inner harbor area, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel (i.e., south toward the harbor jetty). In the lower left panels of these figures, depth-averaged currents at the channel transect are projected onto an aerial photograph of the inlet vicinity. The lower right panel of both figures indicates the stage of the tide that the survey transect was taken by a vertical line through the water elevation curve.

Along the ADCP transect maximum measured currents in the water column were 0.8 ft/sec (0.5 kts). The average velocity across the entire transect during both peak ebb and flood currents was 0.4 ft/sec (0.2 kts). Maximum flood flows in the morning of October 6 were 5,660 ft^3/sec. In the afternoon, maximum ebb flows were 5,040 ft^3/sec.

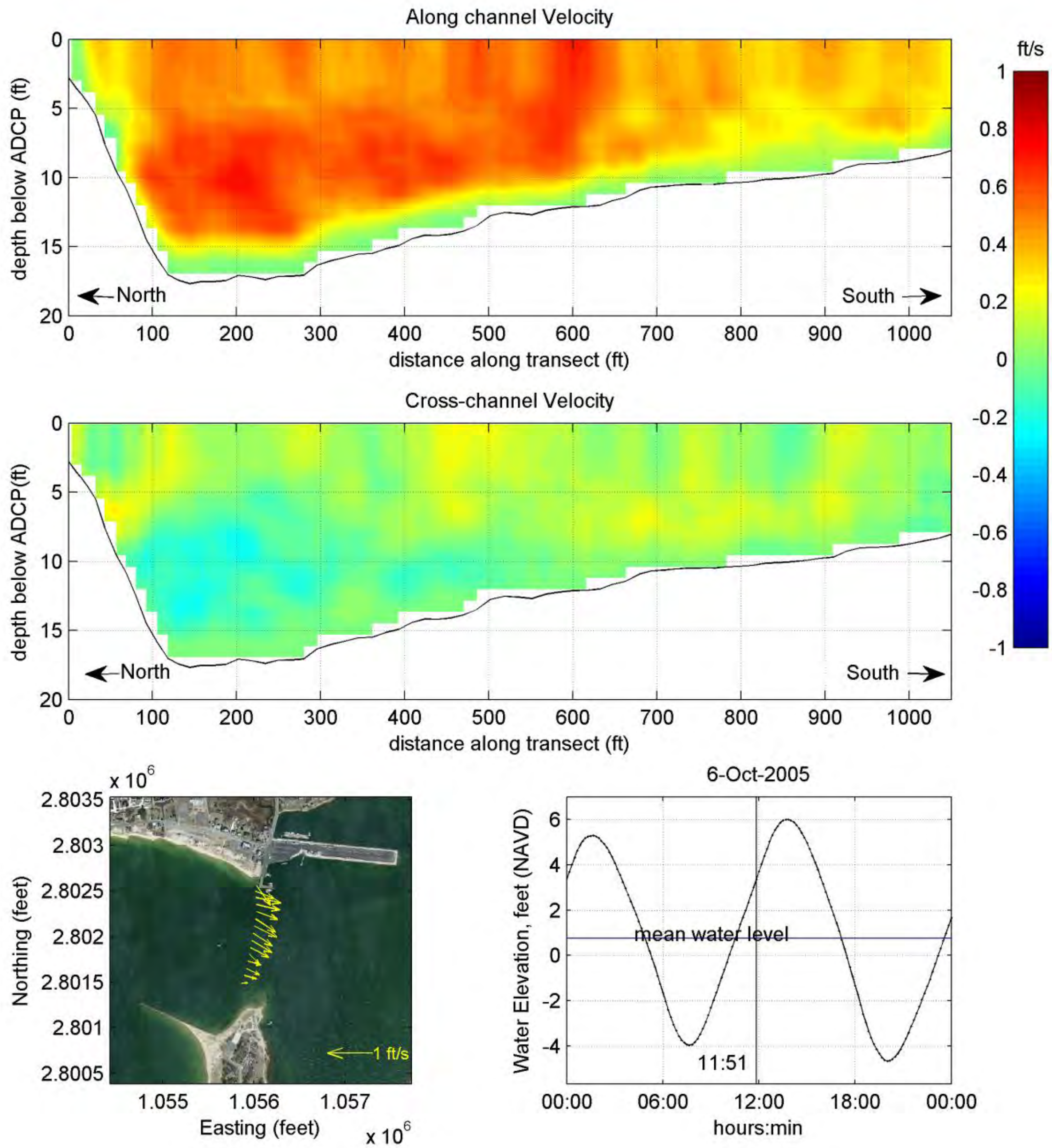


Figure V-8. Color contour plots of along-channel and cross-channel velocity components for transect line run at the entrance to inner Wellfleet Harbor, near the harbor jetty, measured at 11:51 on October 6, 2005 during the period of maximum flood tide currents. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Lower left plot shows scaled velocity vectors projected onto a 2009 aerial photo (MASS GIS) of the survey area. A tide plot for the survey day is also given.

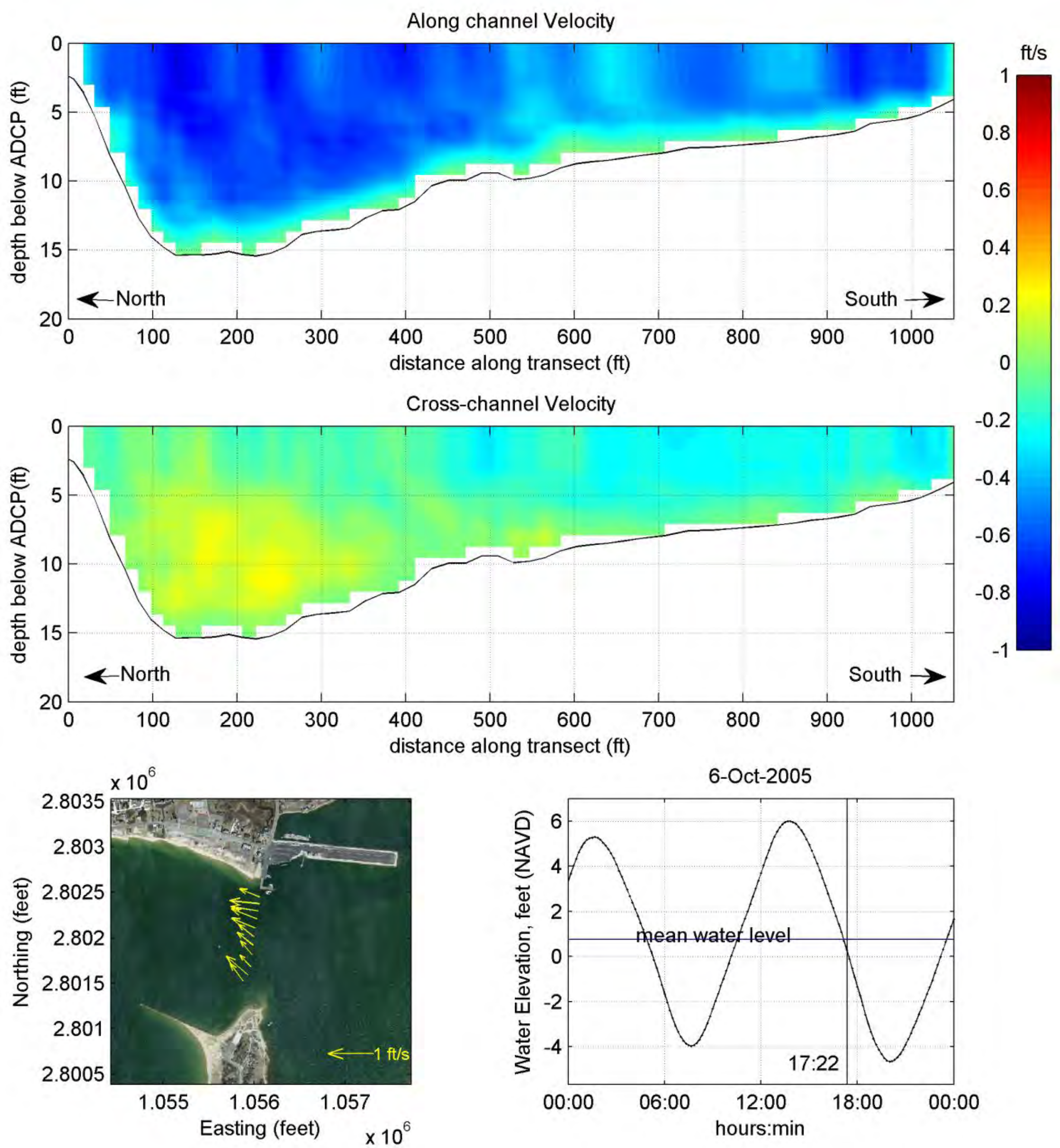


Figure V-9. Color contour plots of along-channel and cross-channel velocity components for transect line run at the entrance to inner Wellfleet Harbor, near the harbor jetty, measured at 17:22 on October 6, 2005 during the period of maximum ebb tide currents. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. Lower left plot shows scaled velocity vectors projected onto a 2009 aerial photo (MASS GIS) of the survey area. A tide plot for the survey day is also given.

V.3 HYDRODYNAMIC MODELING

For the modeling of the Wellfleet 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 Sandwich Harbor, 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 Wellfleet 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 10,533 nodes, which describe 3,858 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth is -27ft (NGVD) in the natural channel of the harbor. The completed grid mesh of the Wellfleet Harbor system is shown in Figure V-10.

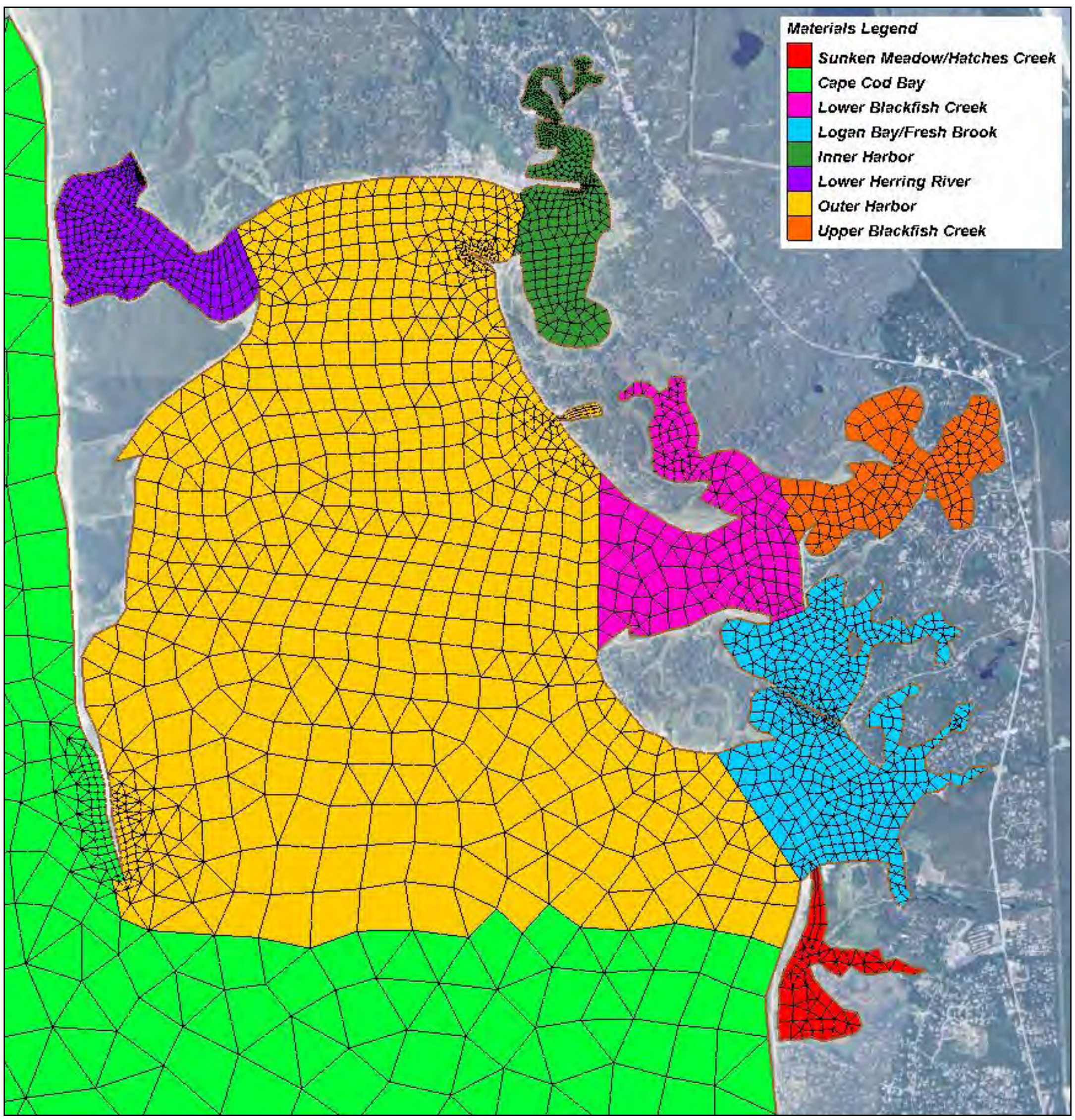


Figure V-10. Plot of hydrodynamic model grid mesh for Wellfleet Harbor. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Wellfleet Harbor. Areas of marsh were included in the model. 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 Wellfleet 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 collected at the offshore 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 Wellfleet Harbor grid every model time step. The model runs of the Harbor used a 10-minute time step, which was 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 Section VI.

V.3.2.3 Calibration

After developing the finite element grids, and specifying boundary conditions, the model for the Wellfleet 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 September 15, 2005 at 0910 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 using the ADCP dataset of tidal velocities measured on October 6, 2005.

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, a Manning's friction coefficient value of 0.020 was 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 Wellfleet 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
Inner Harbor	0.030	80
Loagy Bay/Fresh Brook	0.030	80
Blackfish Creek - lower	0.030	80
Blackfish Creek - upper	0.030	80
Herring River	0.025	50
Sunken Meadow	0.030	80
Wellfleet Harbor – main basin	0.030	100

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 in the main harbor basin.

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 Wellfleet Harbor system. Cyclically wet/dry areas of the marsh will tend to store water 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 and tide flats. 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-11 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.

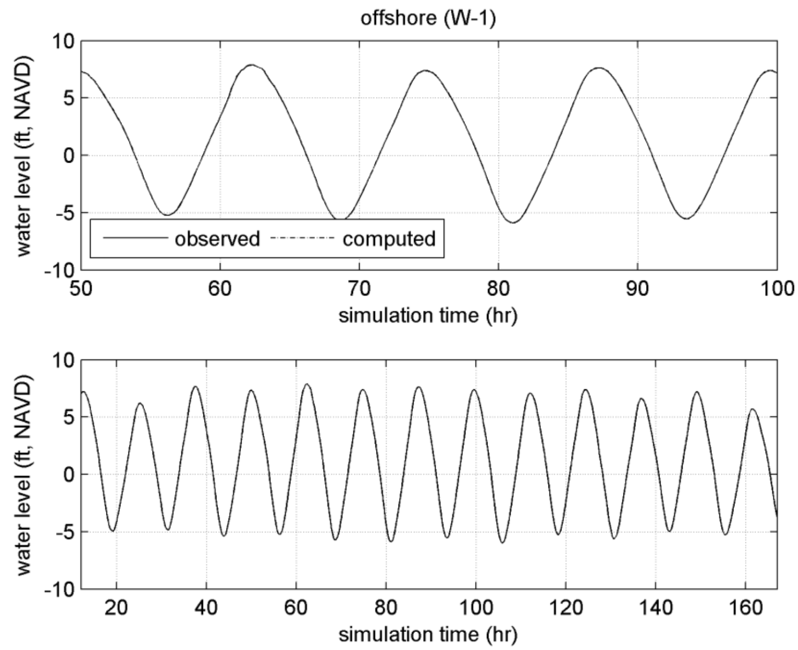


Figure V-11. Comparison of model output and measured tides for the offshore TDR station for the final calibration model run (September 15, 2005 at 0910 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

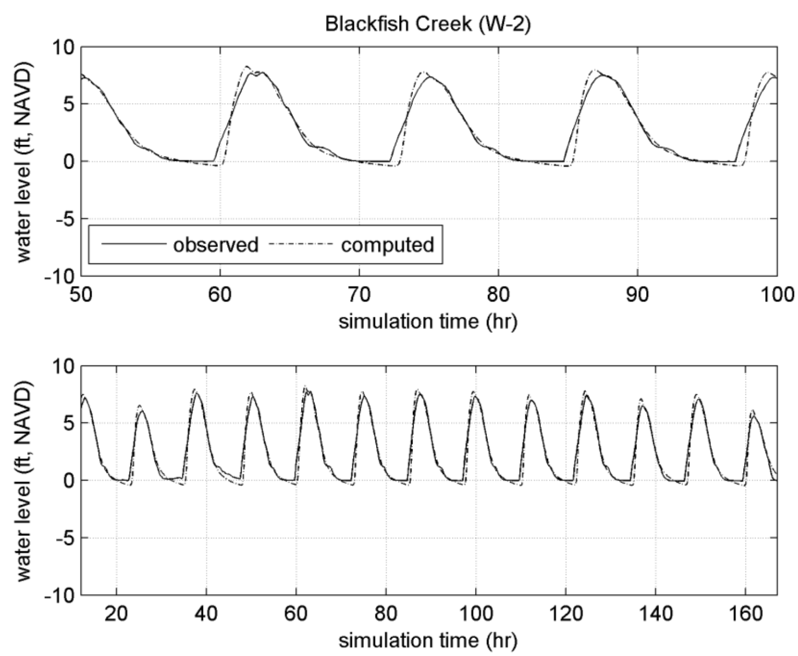


Figure V-12. Comparison of model output and measured tides for the TDR at Blackfish Creek (W-2) for the final calibration model run (September 15, 2005 at 0910 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

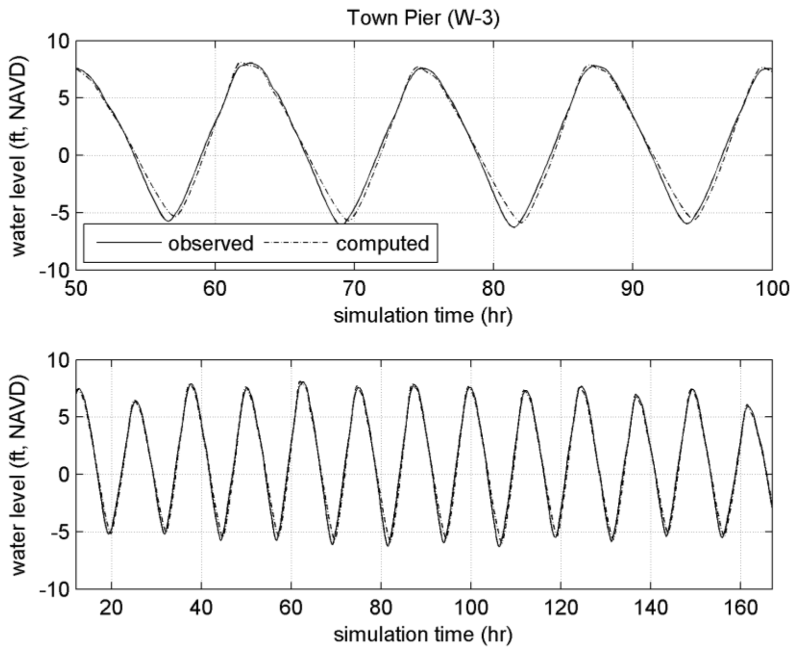


Figure V-13. Comparison of model output and measured tides for the TDR location at the town pier (W-3) for the final calibration model run (September 15, 2005 at 0910 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

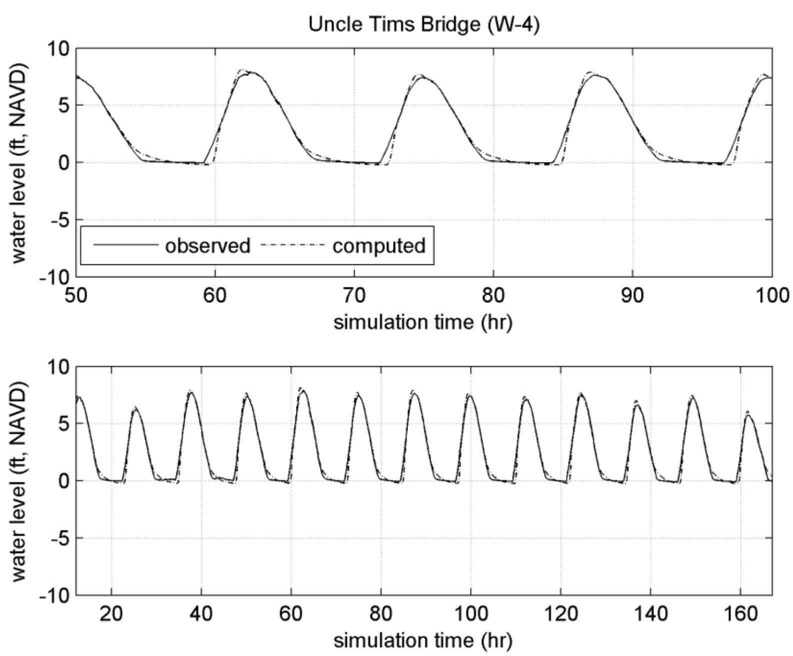


Figure V-14. Comparison of model output and measured tides for the TDR location at Duck Creek (W-4) for the final calibration model run (September 15, 2005 at 0910 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

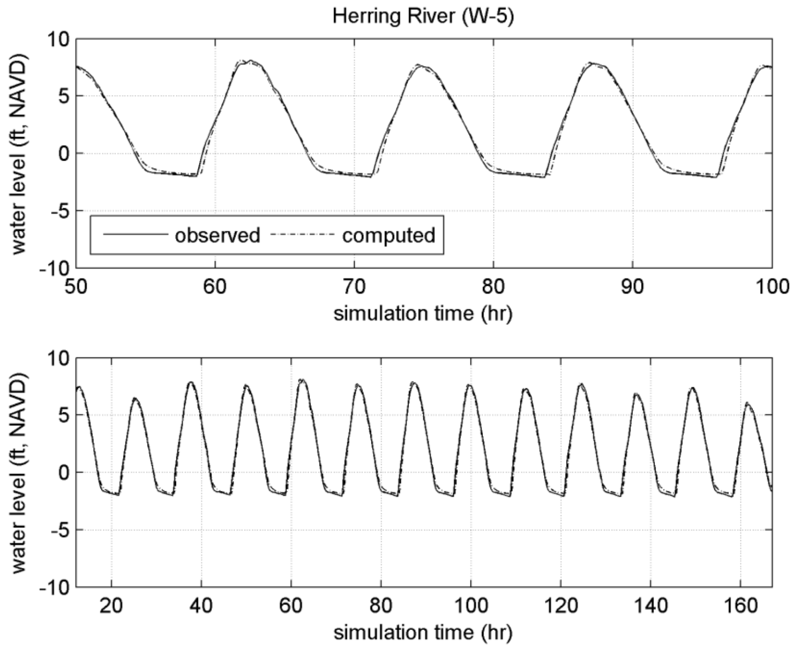


Figure V-15. Comparison of model output and measured tides for the TDR location at the lower Herring River (W-5) for the final calibration model run (September 15, 2005 at 0910 EDT). The top plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the bottom plot.

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-8 for all stations.

V.3.2.4 ADCP verification of the Hydrodynamic Model

An additional model verification check was possible by using collected ADCP velocity data to verify the performance of the Wellfleet system model. Computed flow rates from the model were compared to flow rates determined using the measured velocity data. The ADCP data survey efforts are described in Section V.2. For the model ADCP verification, the Harbor model was run for the period covered during the ADCP survey on October 6, 2005. Model flow rates were computed in RMA-2 at a continuity line (channel cross-section) that correspond to the actual ADCP transect followed during survey (i.e., between the town pier and the inner harbor jetty).

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

Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕK_1
Model calibration run						
Cape Cod Bay	5.99	0.22	0.32	0.11	23.0	-89.3
Blackfish Creek	3.50	1.49	0.64	0.14	44.6	-47.6
Town Pier	5.92	0.70	0.21	0.12	33.6	-81.5
Duck Creek	3.59	1.35	0.45	0.14	38.5	-48.5
Herring River	4.62	1.03	0.42	0.14	33.4	-55.6
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕK_1
Cape Cod Bay	5.99	0.22	0.32	0.11	23.4	-90.4
Blackfish Creek	3.37	1.18	0.23	0.13	40.6	-36.8
Town Pier	6.10	0.37	0.36	0.12	31.3	-77.1
Duck Creek	3.58	1.16	0.27	0.14	34.6	-43.6
Herring River	4.79	0.81	0.31	0.14	32.4	-53.5
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕK_1
Cape Cod Bay	0.00	0.00	0.00	0.00	-0.8	1.1
Blackfish Creek	0.13	0.31	0.41	0.01	8.3	-11.2
Town Pier	-0.18	0.33	-0.15	0.00	4.8	-4.6
Duck Creek	0.01	0.19	0.18	0.00	8.1	-5.1
Herring River	-0.17	0.22	0.11	0.00	2.1	-2.2

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

	R^2	RMS error (feet)
Cape Cod Bay	1.00	0.04
Blackfish Creek	0.94	0.62
Town Pier	0.99	0.46
Duck Creek	0.98	0.38
Herring River	0.99	0.32

Comparisons of the measured and modeled volume flow rates in the Bass River system are shown in Figure V-16. Each ADCP data point (circle markers shown on the plots) is a summation of flow measured along the ADCP transect. The ‘bumps’ and ‘skips’ of the flow rate curve (more evident in the model output) can be attributed to the effects of winds (i.e., atmospheric effects) on the water surface and friction across the seabed periodically retarding or accelerating the flow through the inlets, and inside the system channels. If water surface elevations changed smoothly as a sinusoid, the volume flow rate would also appear as a smooth curve. However, since the rate at which water surface elevations change does not vary smoothly, the flow rate curve is expected to show short-period fluctuations.

Data comparisons at the ADCP transect shows exceptionally good agreement with the model predictions. The calibrated model accurately describes the discharge magnitude. The R^2 correlation coefficients between data and model results 0.94. The RMS error computed from each transect is 901 ft3/sec, which is 5.1% of the maximum measured discharge rate. Correlation statistics between the modeled and measured flows for each ADCP transect are presented in Table V-9.

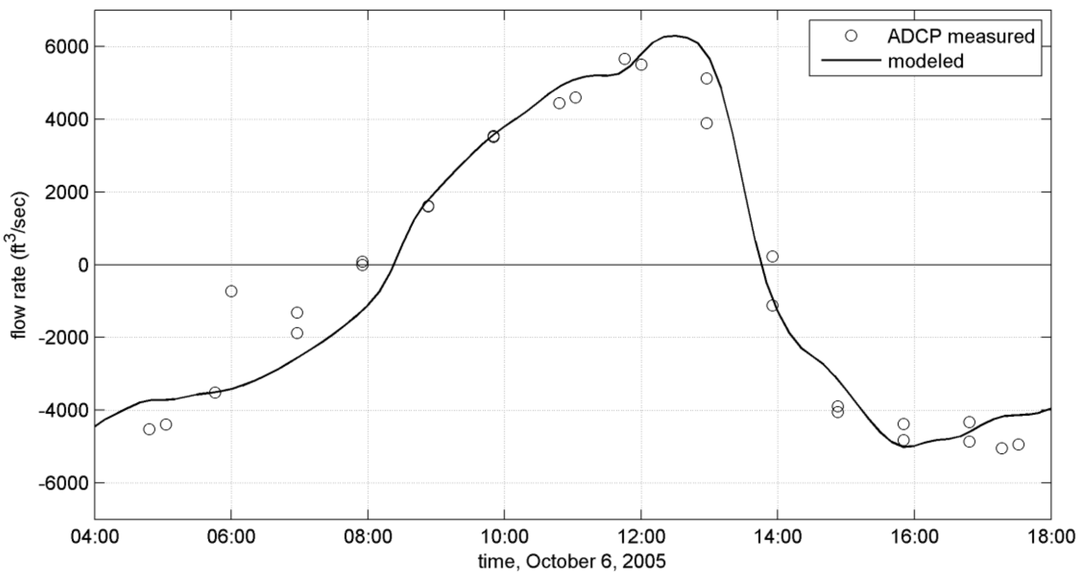


Figure V-16. Comparison of measured volume flow rates versus modeled flow rates at the surveyed ADCP transect (between the town pier and jetty), over a tidal cycle on October 6, 2005. Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). R2=0.94, ERMS=901 ft^3/sec.

Table V-9. Correlation statistics between modeled and measured total flow rates at the ADCP transects used in the model verification of the Wellfleet Harbor model.

Transect	R^2 correlation	RMS error (ft^3/sec)	Max Error (ft^3/sec)	Min Error (ft^3/sec)
Town Pier to Jetty	0.94	901	2,684	13

V.3.3 Model Circulation Characteristics

The final calibrated model serves as a useful tool in investigating circulation characteristics of the whole Wellfleet Harbor system. Inputs of bathymetry and tide data can be leveraged to develop further insight into tidal velocities and flow rates 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-17 shows color contours and vectors that indicate velocity during a single model time step, during a period of maximum flood currents at the inlet.

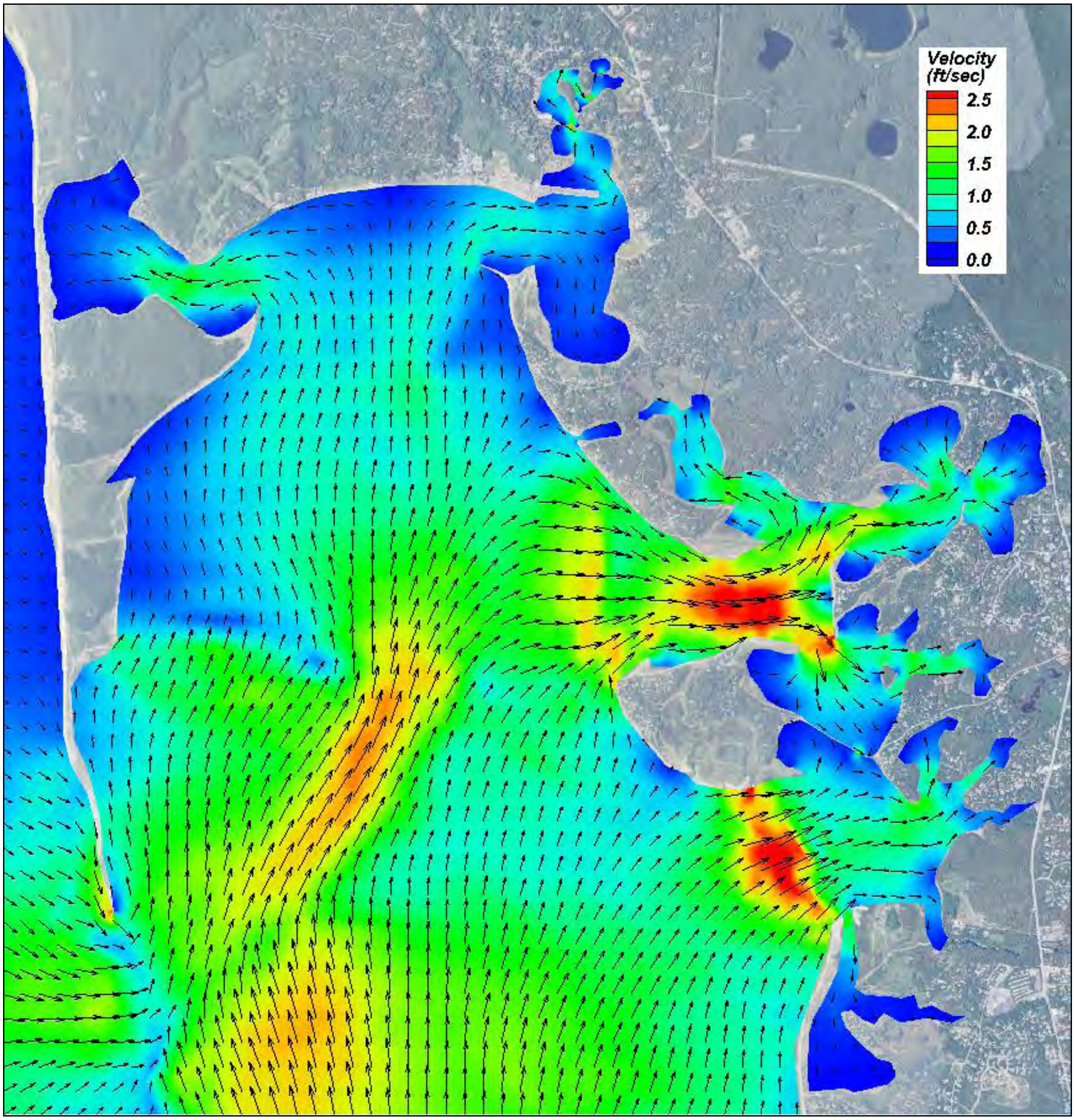


Figure V-17. Example of Wellfleet Harbor hydrodynamic model output for a single time step during a flooding tide. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

As another example, from the calibration model run of the Wellfleet 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-18. During spring tides, the maximum flood flow rates into the harbor reach 177,000,000 ft^3/. Maximum ebb flow rates during spring tides are slightly smaller (116,000,000 ft^3/sec).

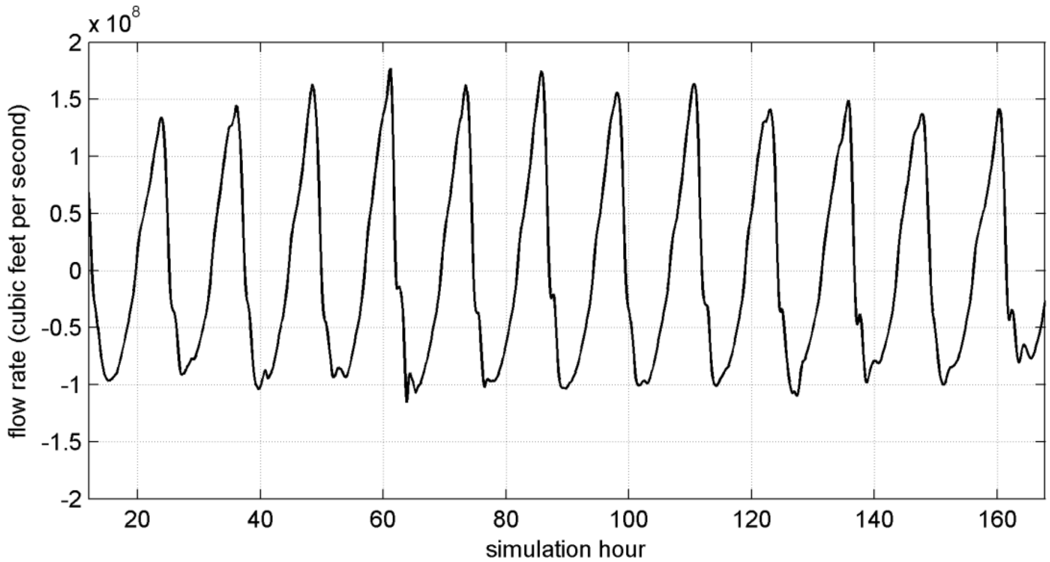


Figure V-18. Time variation of computed flow rates for the whole of the Wellfleet Harbor system. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flow indicated flooding tide flows, while negative flow indicates ebbing tide flows.

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 Wellfleet 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.

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 the inner harbor as an example, the system residence time is the average time required for water to migrate out of the inner harbor, then across the main basin of the Harbor, and finally out through the harbor inlet and into Cape Cod Bay. Alternatively, the local residence time is the average time required for water to migrate from the inner harbor and into the main basin of Wellfleet Harbor (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.

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 as two 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). The mean volumes and tide prisms of the three system divisions used in this analysis are presented in Table V-10.

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

Embayment	Mean Volume	Tide Prism Volume

	(ft^3)	(ft^3)
Wellfleet Harbor	2,005,202,000	2,772,181,600
The Cove - Inner Harbor	53,818,200	94,403,700
Blackfish Creek	39,520,800	70,955,200

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 correspond to the model calibration period, and included the transition from neap to spring tide conditions. The RMA-2 model calculated flow crossing specified grid continuity lines (similar to an ADCP transect) 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 Wellfleet Harbor system.

Embayment	System Residence Time (days)	Local Residence Time (days)
Wellfleet Harbor	0.4	0.4
The Cove - Inner Harbor	11.0	0.3
Blackfish Creek	14.6	0.3

The computed flushing rates for the entire system show that as a whole, the system flushes very well. A flushing time of 0.4 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 Wellfleet Harbor system show that water quality in the system is not impacted negatively by tidal flushing. This is a typical result for estuaries dominated by marsh resources or with extensive tidal flats, where the tide prism volume is of a magnitude comparable to the mean volume of the system.

For the smaller sub-embayments of the Harbor system, computed system residence times are typically two 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 Wellfleet 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 Wellfleet 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 Wellfleet 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 September 15, 2005 at 0910 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 Wellfleet 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 Wellfleet 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. Nine years of data (collected between 2003 and 2011) were available for stations in the harbor.

Table VI-1. Measured data and modeled nitrogen concentrations for the Wellfleet 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 between 2003 and 2011.

Location	Monitoring station	Data Mean	s.d. all data	N	model min	model max	model average
Lower Wellfleet Harbor	WH-1	0.485	0.170	102	0.42	0.50	0.45
Lower Wellfleet Harbor	WH-2	0.511	0.160	113	0.42	0.52	0.47
Wellfleet Harbor by Audubon	WH-3	0.542	0.158	213	0.46	0.49	0.48
Mid Wellfleet Harbor	WH-4	0.539	0.147	160	0.45	0.59	0.51
Upper Wellfleet Harbor	WH-5	0.547	0.152	84	0.49	0.64	0.55
Lower Blackfish Creek	WH-6	0.618	0.170	79	0.48	0.55	0.52
Upper Blackfish Creek	WH-7	0.638	0.126	20	0.50	0.56	0.53
The Gut	WH-8	0.722	0.168	32	0.53	0.71	0.60
Herring River the Gut	WH-9	0.741	0.214	74	0.61	0.90	0.73
Outer Cove	WH-10	0.762	0.213	116	0.55	0.80	0.64
The Cove	WH-11	0.849	0.231	122	0.59	1.05	0.76
Duck Creek	WH-12	0.908	0.234	78	0.64	1.89	0.93

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 Wellfleet 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 Wellfleet 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 Wellfleet Harbor system.

Figure VI-1. Estuarine water quality monitoring station locations in the Wellfleet 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 Wellfleet 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 Wellfleet 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 Wellfleet 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 Fresh Brook was input at the head of the creek. Benthic loads were distributed at a specific number of grid elements within the separate tidal creeks and the larger Harbor system. The atmospheric deposition onto Duck Creek has been incorporated into the atmospheric deposition specified for the Cove.

The loadings used to model present conditions in the Wellfleet Harbor system are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of benthic flux (regeneration) summarized in Section IV.3. 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 portion of Wellfleet harbor, net benthic fluxes that are negative indicates a net uptake of nitrogen in the bottom sediments, and positive values indicate contribution of nitrogen from 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 0.422 mg/L, based on data collected offshore of Wellfleet Harbor. The concentration of WH-1 is 0.485 mg/L. Based on the circulation of water in Cape Cod Bay which flows from Plymouth Harbor towards Provincetown Harbor and entrains nutrient rich discharges from estuaries discharging to Cape Cod Bay, the MEP Technical Team decided that the most representative boundary condition for Wellfleet Harbor would be an average of the TN concentration for the water quality monitoring station offshore from Rock Harbor (Orleans, 0.357 mg/L) and the TN concentration at station WH-1 (entrance to Wellfleet Harbor, 0.485 mg/L). Average of the two values = 0.422 mg/L.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Wellfleet 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)
Herring River/The Gut	27.72	2.81	20.65
Duck Creek	5.40	--	19.82
The Cove	9.82	2.22	148.71
Drummer/Blackfish	7.36	1.66	7.31
Hatches Creek	9.46	0.15	-8.58
Wellfleet Harbor	17.53	64.72	47.51
Loagy Bay	2.45	0.99	9.75

VI.2.4 Model Calibration

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

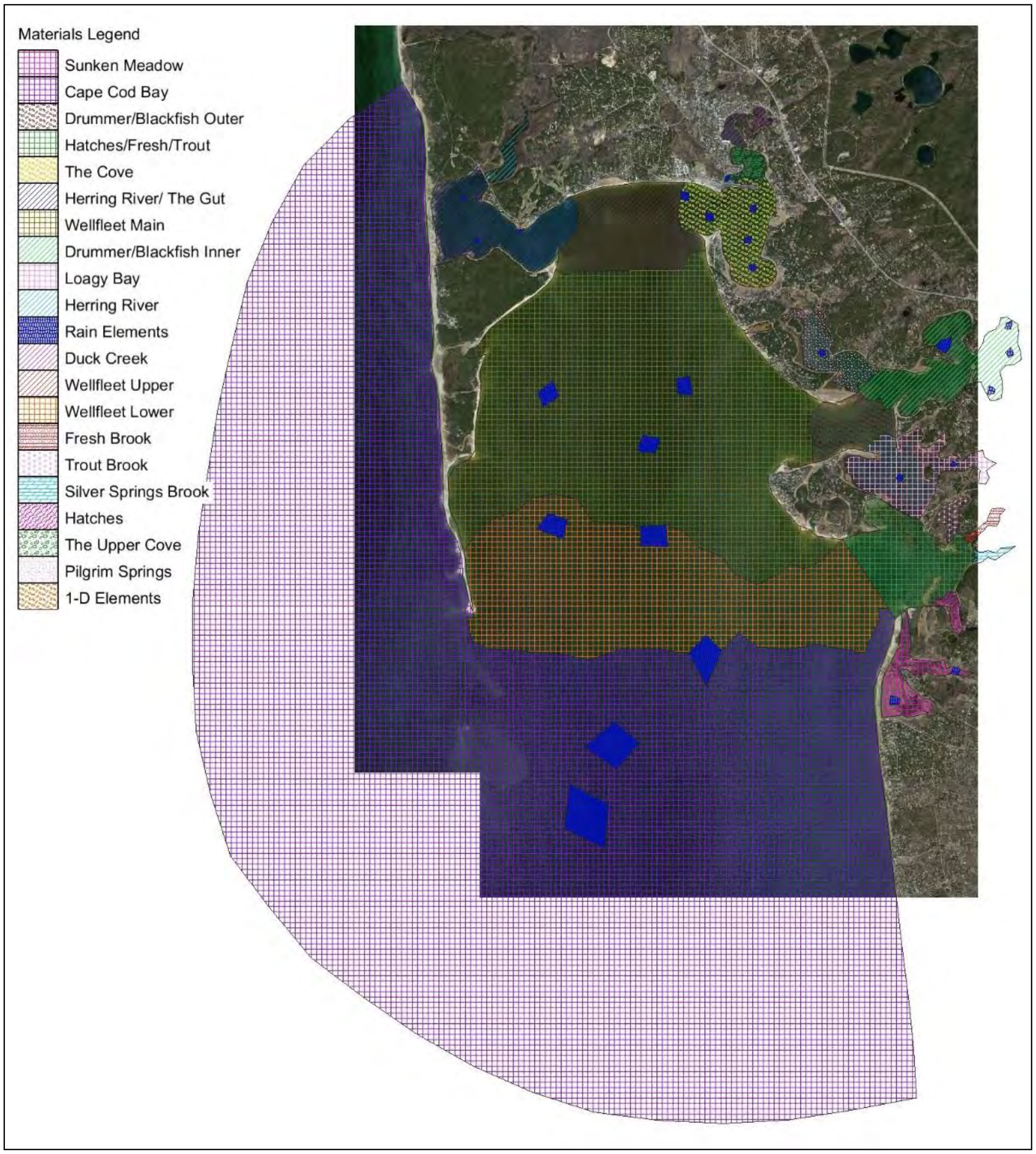


Figure VI-2. Map of Wellfleet Harbor system water quality model longitudinal dispersion coefficients. Color patterns designate the different areas used to vary model dispersion coefficient values.

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

Embayment Division	E m^2/sec
Sunken Meadow	3.0
Cape Cod Bay	5.0
Drummer/Blackfish Outer	1.0
Hatches / Fresh / Trout Brook	5.0
The Cove	4.0
Herring River / The Gut	5.0
Wellfleet Main	20.0
Drummer / Blackfish Inner	10.0
Loagy Bay	3.0
Wellfleet Harbor	20.0
W/S Inputs	20.0
Duck Creek	15.0
Wellfleet Upper	13.0
Wellfleet Lower	30.0
Fresh Brook	10.0
Trout Brook	10.0
Silver Springs Brook	10.0
Hatches	10.0
The upper Cove	10.0
Pilgrim Springs	8.0
1-D Elements	0.4

Comparisons between model output and measured nitrogen concentrations are shown in plots presented in Figures VI-3 and VI-4. In these plots, means of the water column data and a range of two standard deviations about the annual means at each individual station are plotted against the modeled maximum, mean, and minimum concentrations output from the model at locations which corresponds to the water quality monitoring stations. The emphasis during calibration was to concentrate on representing the conditions measured at the data collection stations.

For model calibration, the mid-point between maximum modeled TN and average modeled TN was compared to mean measured TN data values, at each water-quality monitoring station. The calibration target would fall between the modeled mean and maximum TN because the monitoring data are collected, as a rule, during mid ebb tide. Also presented in these figures are unity plot comparisons of measured data versus modeled target values for the system. The model provides a good representation for the Wellfleet Harbor system, with rms error of 0.04 mg/L and an R^2 correlation coefficient of 0.93 at the key stations.

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

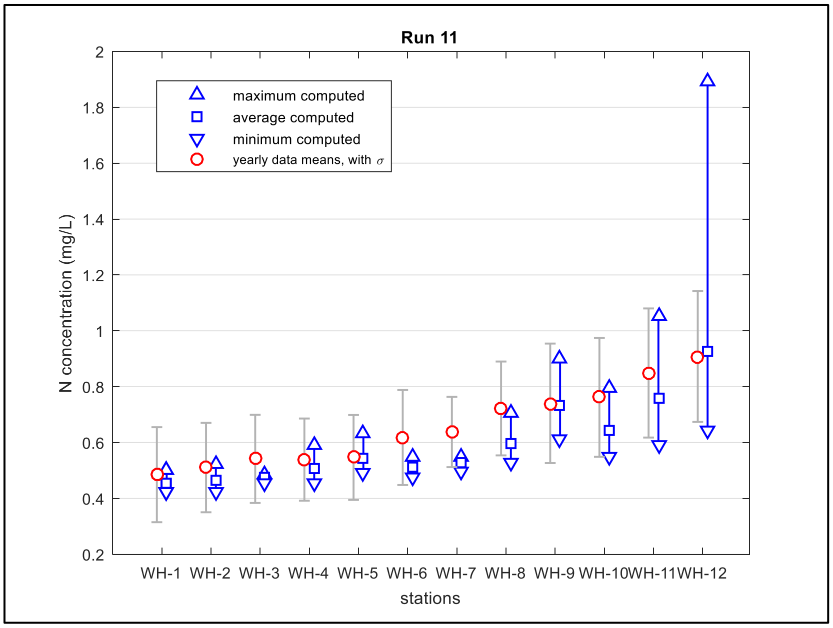


Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Wellfleet Harbor. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset.

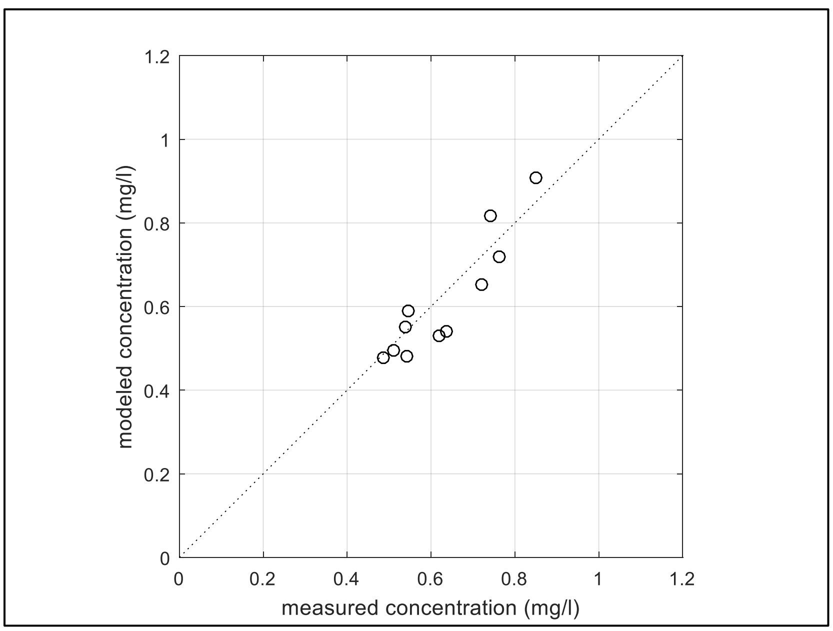


Figure VI-4. Model TN target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) is 0.93 and RMS error for this model verification run is 0.04 mg/L.

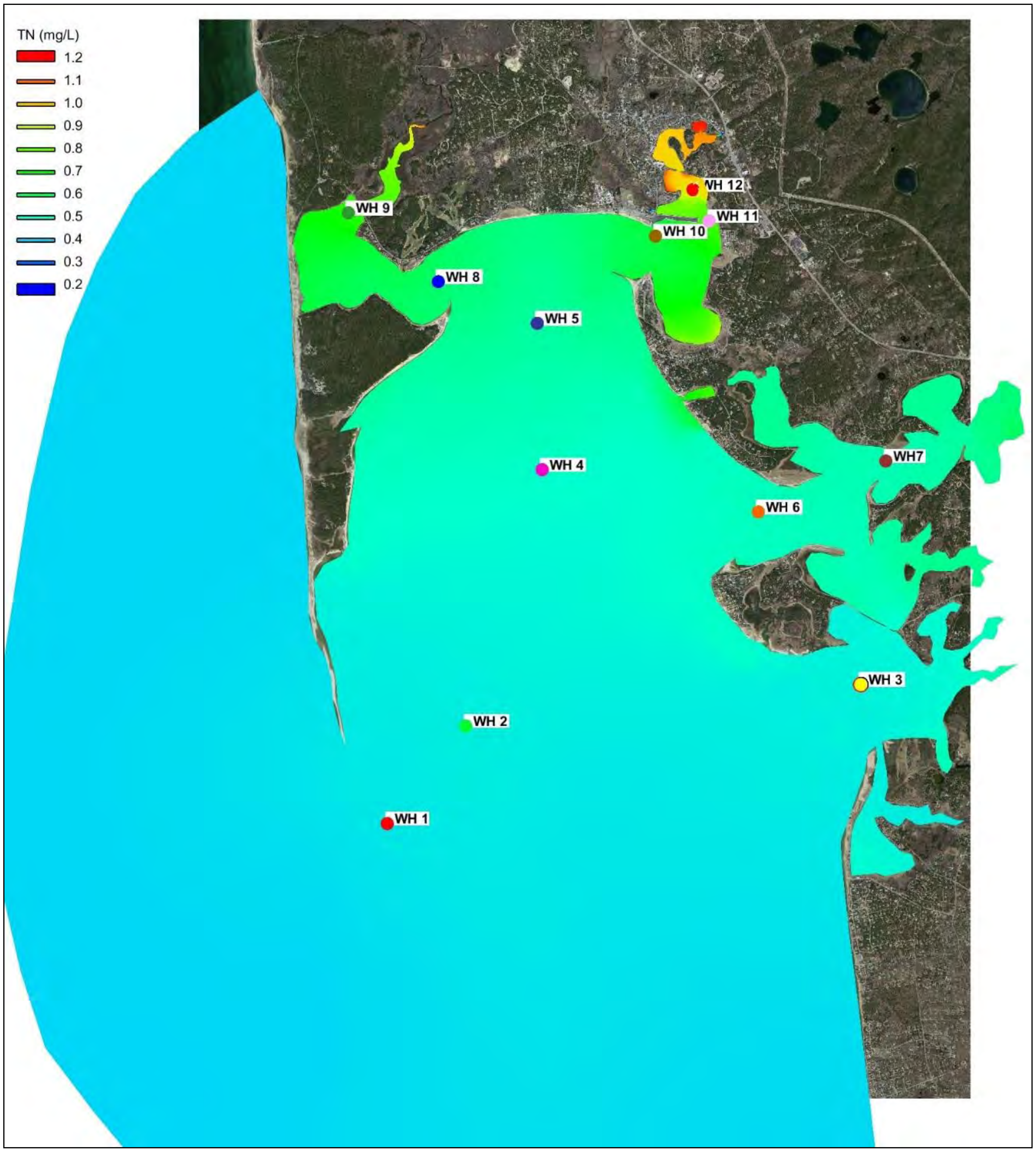


Figure VI-5. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for Wellfleet Harbor. The approximate location of the sentinel threshold station for Wellfleet Harbor is shown at Station WH5.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Wellfleet Harbor system using salinity data collected at the same stations as the nitrogen data. 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 and groundwater inputs. The open boundary salinity was set at 32.1 ppt. For groundwater inputs salinities were set at 0 ppt. Groundwater input used for the model was 27.6

ft^3/sec (67,525 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed on the border of individual watersheds in the model domain through the use of element input points positioned along the model's land boundary and flow boundary conditions.

Comparisons of modeled and measured salinities are presented in Figures VI-6 and VI-7, with contour plots of model output shown in Figure VI-8. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in the Wellfleet Harbor system. The rms error of the models was 0.58 ppt, and correlation coefficient was 0.89. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical system.

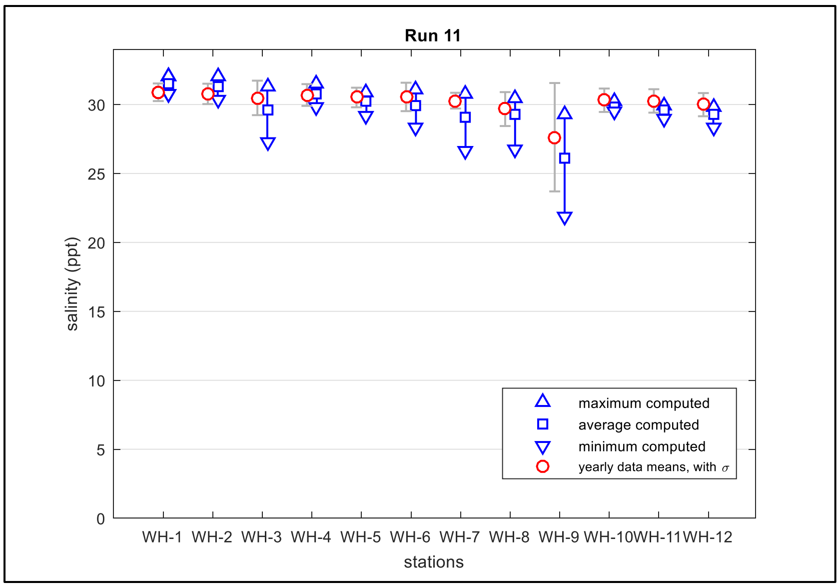


Figure VI-6. Comparison of measured and calibrated model output at stations in Wellfleet Harbor. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset.

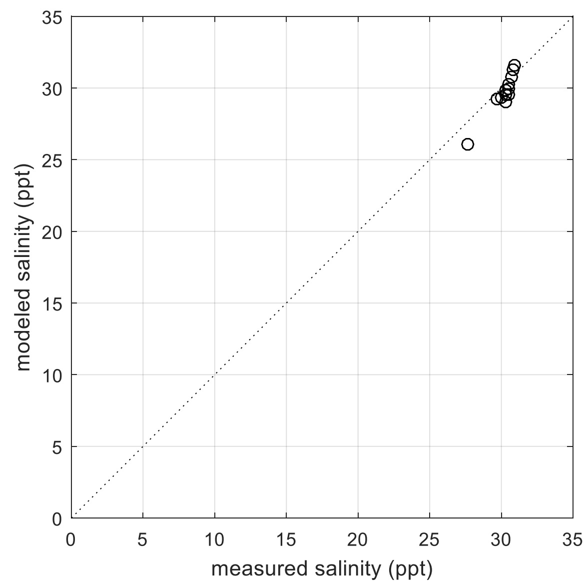


Figure VI-7. Model salinity target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) is 0.89 and RMS error for this model verification run is 0.58 mg/L.

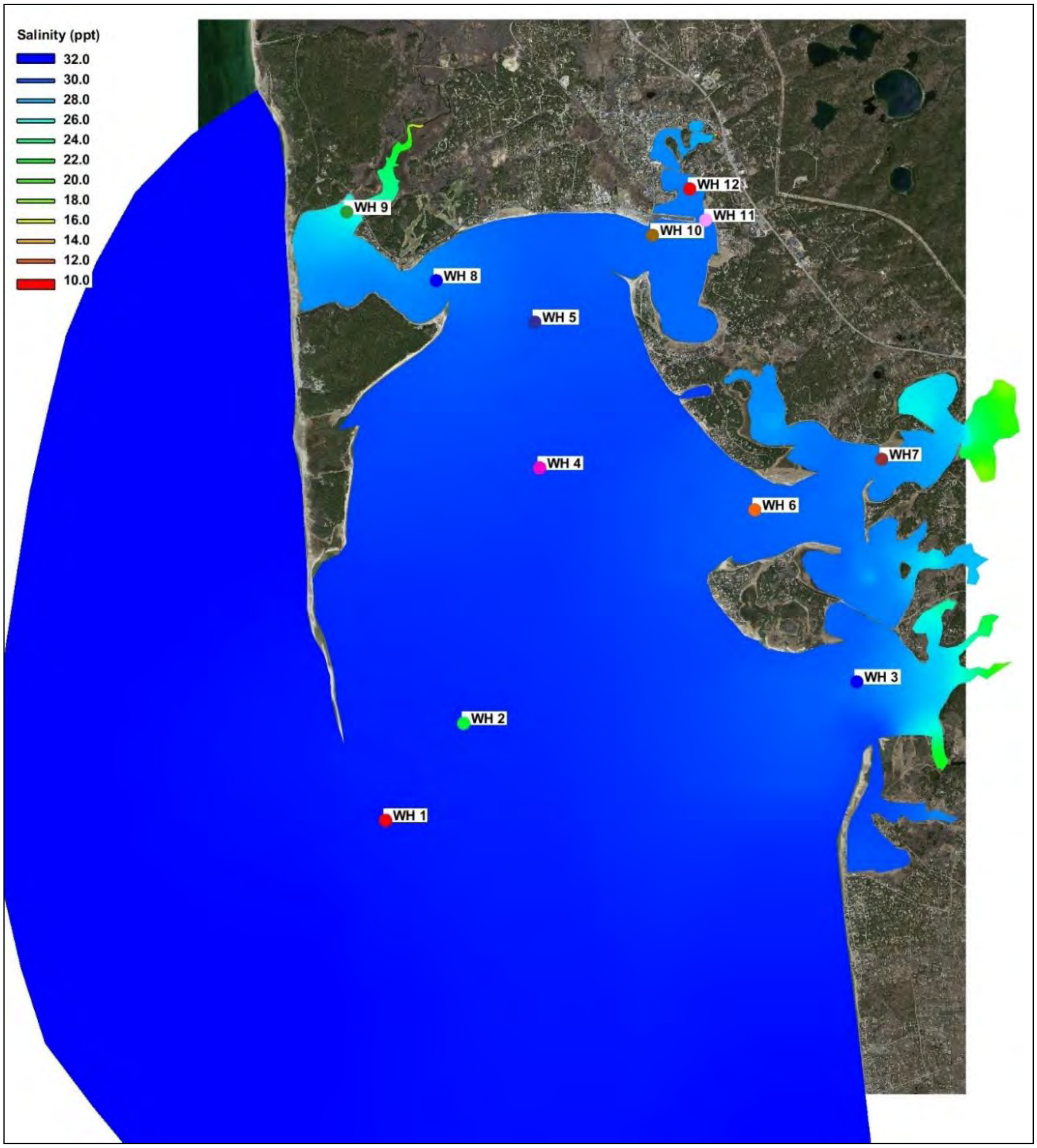


Figure VI-8. Contour plot of modeled salinity (ppt) in Wellfleet Harbor.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the Wellfleet Harbor system, 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.

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 Wellfleet 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
Herring River/The Gut	27.72	36.12	+30.3%	13.68	-50.6%
Duck Creek	5.40	7.35	+36.1%	0.35	-93.5%
The Cove	9.82	14.81	+50.8%	0.46	-95.3%
Drummer/Blackfish	7.36	10.93	+48.4%	0.43	-94.2%
Hatches Creek	9.46	14.82	+56.7%	0.73	-92.3%
Wellfleet Harbor	17.53	23.12	+31.9%	0.99	-94.3%
Loagy Bay	2.45	4.19	+70.9%	0.19	-92.2%

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:

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

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 just below the Herring River Dike in the Gut monitoring station (WH-9), where concentrations increase more than 32% above background. A contour plot showing average TN concentrations throughout the harbor system is presented in Figure VI-9 for the model of build-out loading.

Table VI-5. **Build-out** scenario sub-embayment and surface water loads used for total nitrogen modeling of the Wellfleet 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)
Herring River/The Gut	36.12	2.81	23.18
Duck Creek	7.35	--	22.28
The Cove	14.81	2.22	168.00
Drummer/Blackfish	10.93	1.66	5.22
Hatches Creek	14.82	0.15	-9.56
Wellfleet Harbor	23.12	64.72	52.15
Loagy Bay	4.19	0.99	11.02

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 (0.422 mg/L), for the Wellfleet Harbor system.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Lower Wellfleet Harbor	WH-1	0.452	0.458	+19.2%
Mid Wellfleet Harbor	WH-2	0.466	0.475	+19.2%
Mid Wellfleet Harbor	WH-3	0.476	0.488	+23.4%
Mid Wellfleet Harbor	WH-4	0.507	0.523	+19.2%
Upper Wellfleet Harbor	WH-5	0.546	0.571	+20.1%
Blackfish Creek	WH-6	0.516	0.534	+18.4%
Blackfish Creek	WH-7	0.531	0.551	+18.1%
Wellfleet Harbor	WH-8	0.599	0.642	+24.3%
Herring River / Gut	WH-9	0.732	0.833	+32.5%
The Cove Outer	WH-10	0.645	0.686	+18.5%
The Cove	WH-11	0.762	0.823	+17.7%
Duck Creek	WH-12	0.930	1.015	+16.8%

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 considerable, with all areas of the system experiencing reductions greater than 30%, compared to the background concentration of 0.422 mg/L in Cape Cod Bay (Table VI-8). A contour plot showing TN concentrations throughout the system is presented in Figure VI-10.

Table VI-7. "**No anthropogenic loading**" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of the Wellfleet 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)
Herring River/The Gut	13.68	2.81	15.72
Duck Creek	0.35	--	14.92
The Cove	0.46	2.22	110.23
Drummer/Blackfish	0.43	1.66	5.22
Hatches Creek	0.73	0.15	-6.62
Wellfleet Harbor	0.99	64.72	39.00
Loagy Bay	0.19	0.99	7.04

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 (0.422 mg/L), for the Wellfleet Harbor system.

Station Location	monitoring station	present (mg/L)	"no load" (mg/L)	% change
Lower Wellfleet Harbor	WH-1	0.452	0.441	-38.1%
Mid Wellfleet Harbor	WH-2	0.466	0.449	-38.0%
Mid Wellfleet Harbor	WH-3	0.476	0.451	-45.0%
Mid Wellfleet Harbor	WH-4	0.507	0.475	-38.1%
Upper Wellfleet Harbor	WH-5	0.546	0.497	-39.2%
Blackfish Creek	WH-6	0.516	0.480	-38.4%
Blackfish Creek	WH-7	0.531	0.488	-39.2%
Wellfleet Harbor	WH-8	0.599	0.519	-45.1%
Herring River / Gut	WH-9	0.732	0.556	-56.6%
The Cove Outer	WH-10	0.645	0.563	-36.6%
The Cove	WH-11	0.762	0.642	-35.4%
Duck Creek	WH-12	0.930	0.757	-34.0%

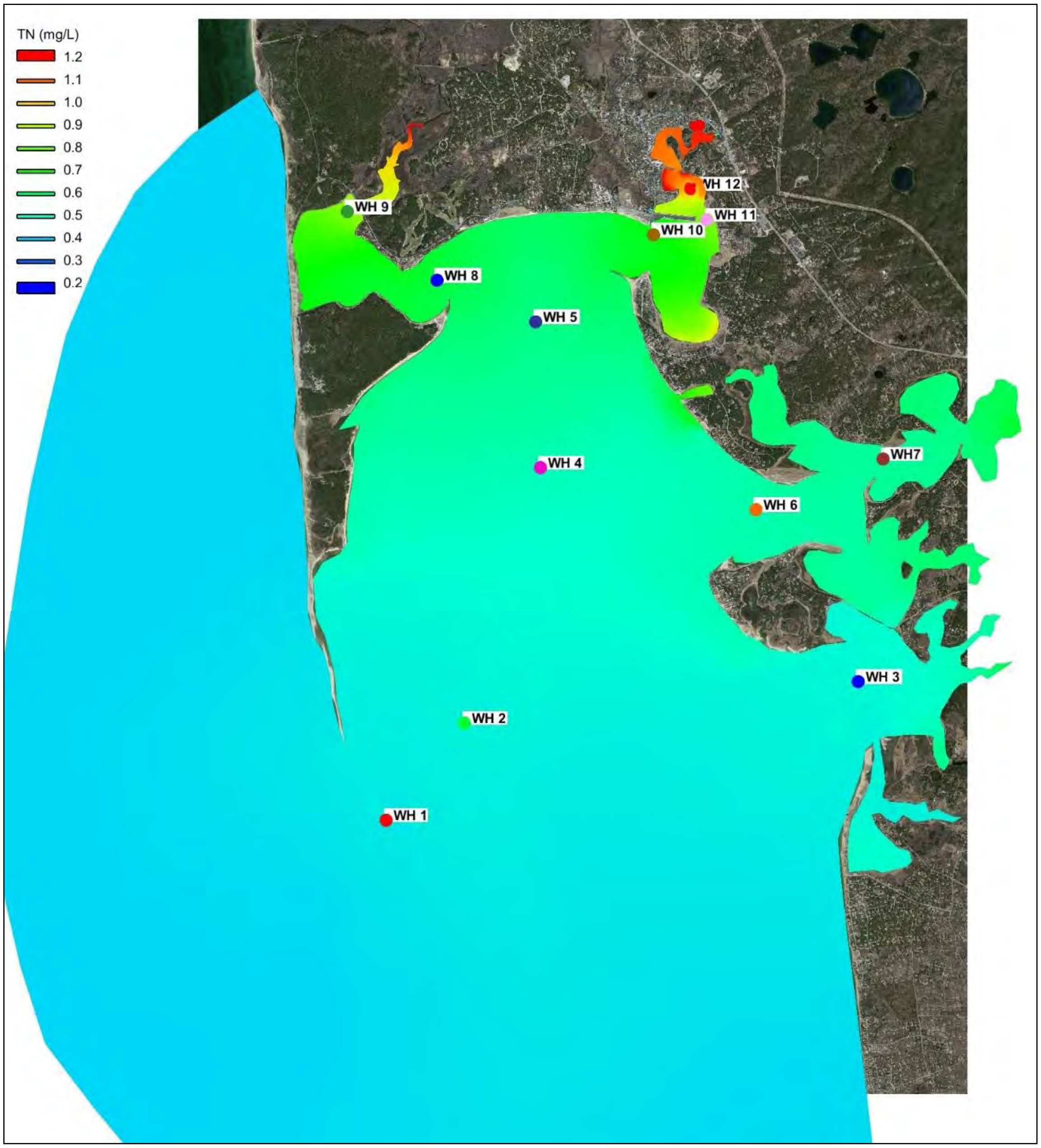


Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in the Wellfleet Harbor system, for projected build-out scenario loading conditions.

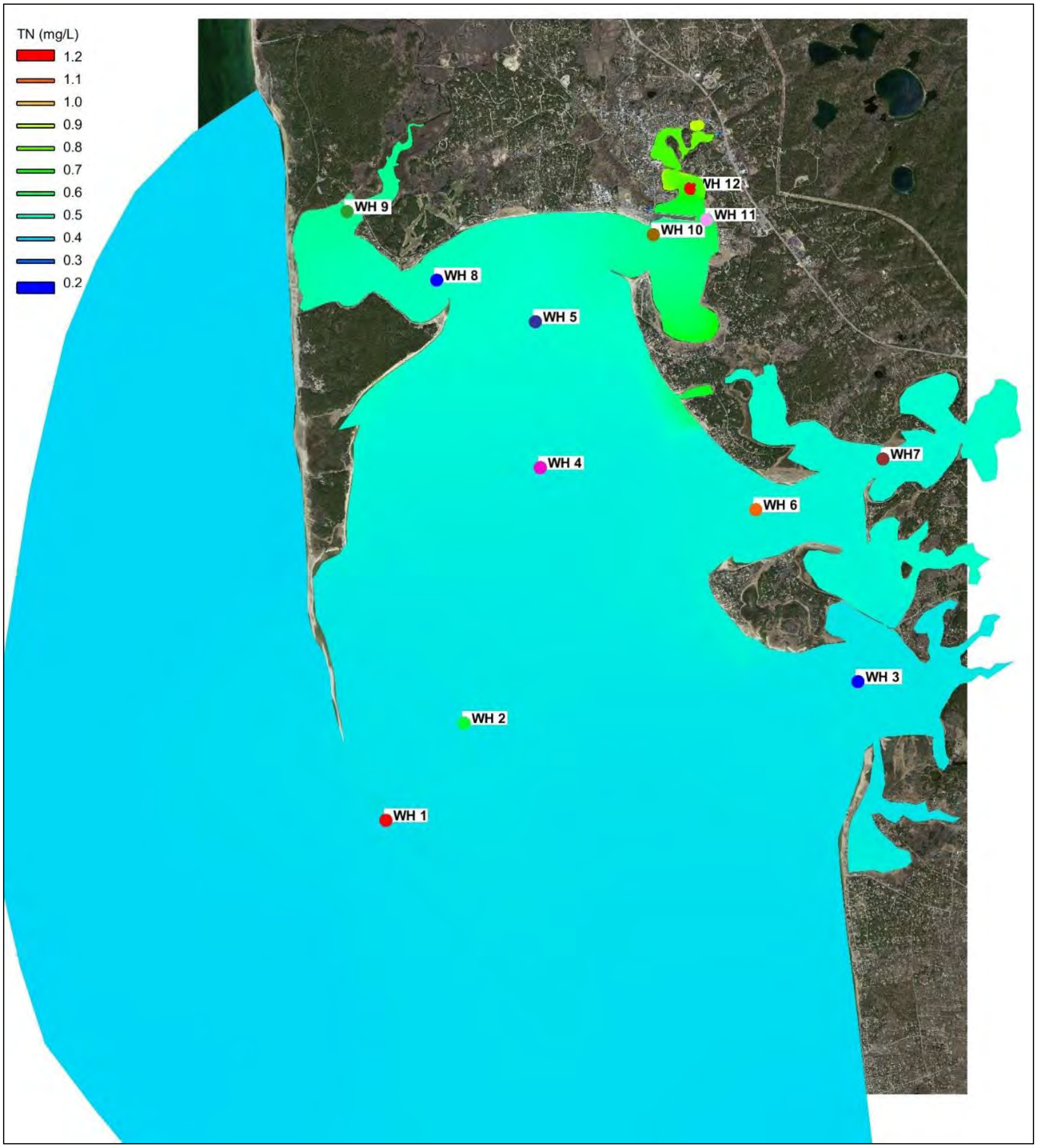


Figure VI-10. Contour plot of modeled total nitrogen concentrations (mg/L) in Wellfleet Harbor, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll-*a*, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Wellfleet Harbor embayment system in the Town of Wellfleet, MA, our assessment is based upon data from the water quality monitoring database developed by the Town of Wellfleet and its partners and surveys of eelgrass distribution, benthic animal communities and sediment characteristics, and dissolved oxygen records conducted during the summer and fall of 2004. These data form the basis of an assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for this system (Chapter VIII). It should be noted that nitrogen enrichment occurs through two primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with the low nitrogen waters of Cape Cod Bay. While Wellfleet Harbor does have increasing nitrogen loading from its watershed from shifting land-uses, generally the overall embayment system has good tidal exchange. It should be noted, however, that specific components of the system, such as Herring River and Duck Creek, may have restricted tidal exchange. Fundamentally, restriction of tidal exchange increases the sensitivity of an estuary and its tributary basins to nitrogen inputs.

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 habitat health. To capture this variation, the MEP Technical Team deployed five (5) autonomous dissolved oxygen sensor in the Wellfleet Harbor system at locations that would be representative of the dissolved oxygen condition at critical points in the system from a habitat assessment point of view. Moorings were deployed specifically in the outer portion of Wellfleet Harbor, the Cove, Duck Creek, Herring River (mouth) and the upper main basin of Wellfleet Harbor. 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 overloading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Wellfleet Harbor system was conducted for comparison to historic records (MassDEP Eelgrass Mapping Program, C. Costello). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels and associated reductions in light penetration and oxygen levels. Analysis of inorganic N/P molar ratios within the water column of Wellfleet Harbor supports the contention that nitrogen is the nutrient to be managed, as the ratio measured throughout the Harbor is only 6 with the maximum and minimum at individual stations of 8 and 4, respectively. These ratios are far below the Redfield Ratio value of 16, indicating that nitrogen additions will increase phytoplankton production in this system. Within the Wellfleet Harbor Estuary, temporal changes in eelgrass distribution supported recent increases (nitrogen loading) or decreases (increased flushing-new inlet) in nutrient enrichment, although only spatial coverage of eelgrass from 1995 - 2005 was limited.

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

VII.2 BOTTOM WATER DISSOLVED OXYGEN

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

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column and sediment 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, five (5) autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Wellfleet Harbor system (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 deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the Wellfleet Harbor system was collected during the summer of 2004.

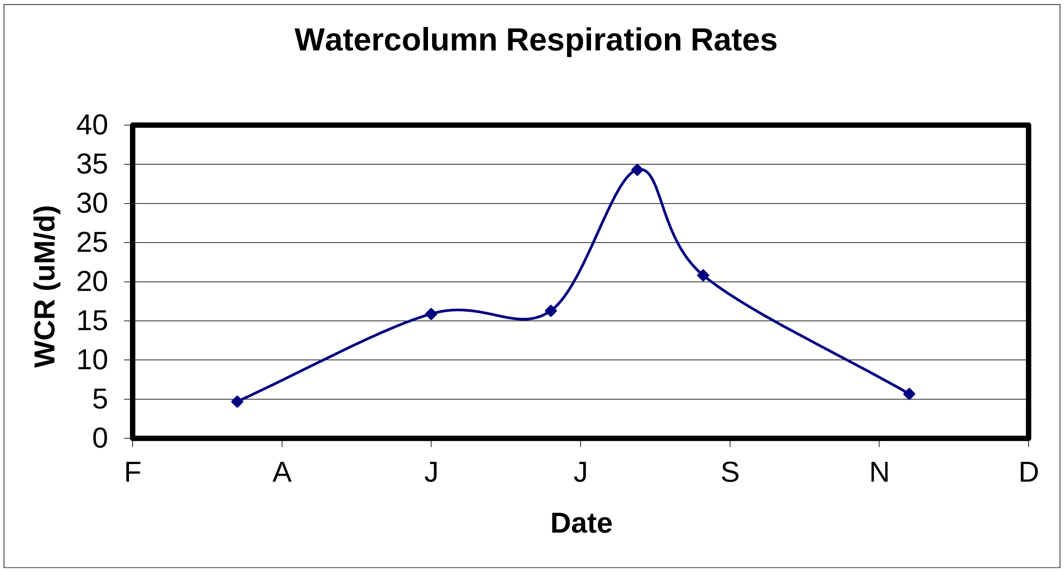


Figure VII-1. Example of typical average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System, Cape Cod (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter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

Similar to other embayments in southeastern Massachusetts, the Wellfleet Harbor system evaluated in this assessment showed high frequency variation in the dissolved oxygen records, apparently related to diurnal and sometimes tidal influences. Moreover, the variation changed depending on the location of a given mooring (outer harbor as opposed to more inner portions of the system). Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration at each mooring site, underscores the need for continuous monitoring within these systems.

Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 25 to 28 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.

Figure VII-2. Aerial Photograph of the Wellfleet Harbor Estuary in the Town of Wellfleet showing the location of the continuously recording Dissolved Oxygen / Chlorophyll-*a* sensors deployed during the Summer of 2004.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels indicate significantly nutrient enriched waters within the innermost basins of the Wellfleet Harbor system (Figures VII-3,5,7,9,11). The oxygen data are consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-*a*. The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follows the spatial pattern of total nitrogen levels in this system (Chapter VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

The oxygen records (both moorings and grab samples) collected from the Wellfleet Harbor system show that the inner most basins within the system (e.g. Wellfleet-inner, The Cove, Duck

Creek, Herring River) have large daily oxygen excursions, indicative of nitrogen enrichment. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally ~7-8 mg L^{-1} at the mooring sites). The clear evidence of oxygen levels above atmospheric equilibration indicates that the inner-most portions of the system are showing signs of nitrogen enrichment. Measured dissolved oxygen depletion from moored sensors and grab samples indicate that the much of the Wellfleet Harbor Estuary (e.g. Wellfleet-inner, The Cove, Duck Creek, Herring River, Drummers Cove/Loagy Bay and basin south of Lt. Island) with the exception of the lower main basin of Wellfleet Harbor, are exhibiting moderate to significant oxygen stress. The embayment specific results are as follows:

Wellfleet Harbor – Outer DO/CHLA Mooring (Figures VII-3 and VII-4):

The Wellfleet Harbor-outer main basin instrument mooring was centrally located in the main harbor basin and deployed north of Lieutenant's Island. This would represent oxygen and chlorophyll conditions in the southern end of the system nearest to the open low nutrient waters of Cape Cod Bay. Daily excursions in oxygen levels were observed at this location, however the range of the excursions was relatively narrow, ranging from levels at or only slightly above air equilibration to conditions where levels rarely decreased to 6 mg L^{-1} (Figure VII-3, Table VII-1). However, grab sampling data from the Water Quality Monitoring Program indicates that oxygen in this region is above 5mg/L in 97% of samples collected. Oxygen levels in the outer portion of Wellfleet Harbor are clearly indicative of healthy habitat and this is further demonstrated by the low chlorophyll levels averaging 3.5 ug L^{-1} over the mooring record..

Oxygen levels rarely exceeded 8 mg L^{-1} and only twice reached an instantaneous level of 9 mg L^{-1}. Generally, oxygen levels remained between 6.5 and 8 mg L^{-1} for the duration of the deployment period. 6 mg L^{-1} is the threshold for healthy DO levels in Class SA waters. Over the 27 day deployment there does not appear to be noticeable phytoplankton blooms and chlorophyll-*a* levels generally remain low, between 2-6 ug L^{-1}. Oxygen and chlorophyll levels are clearly indicative of healthy conditions in the outer harbor and low nitrogen enrichment (mooring chlorophyll average 3.5 ug L^{-1}). Chlorophyll-*a* levels never exceeded the 10 ug L^{-1} benchmark and exceed the 5 ug L^{-1} benchmark only 13% of the time (Table VII-2, Figure VII-4). Average chlorophyll-*a* levels over 10 ug L^{-1} have been used to indicate eutrophic conditions in embayments.

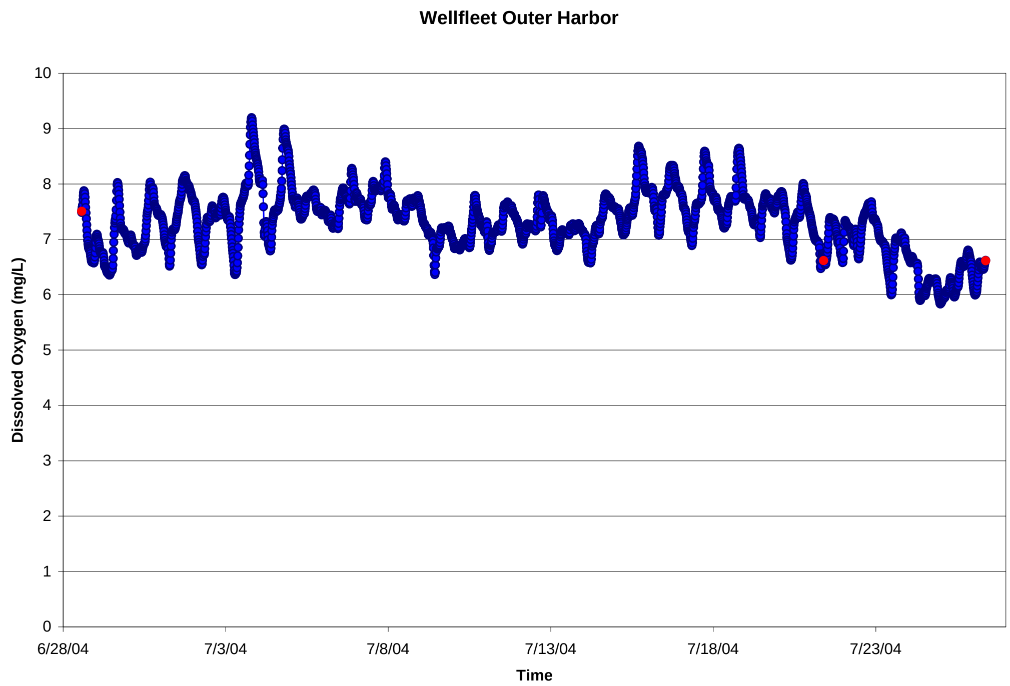


Figure VII-3. Bottom water record of dissolved oxygen at the Wellfleet Harbor - Outer station, Summer 2004. Calibration samples represented as red dots.

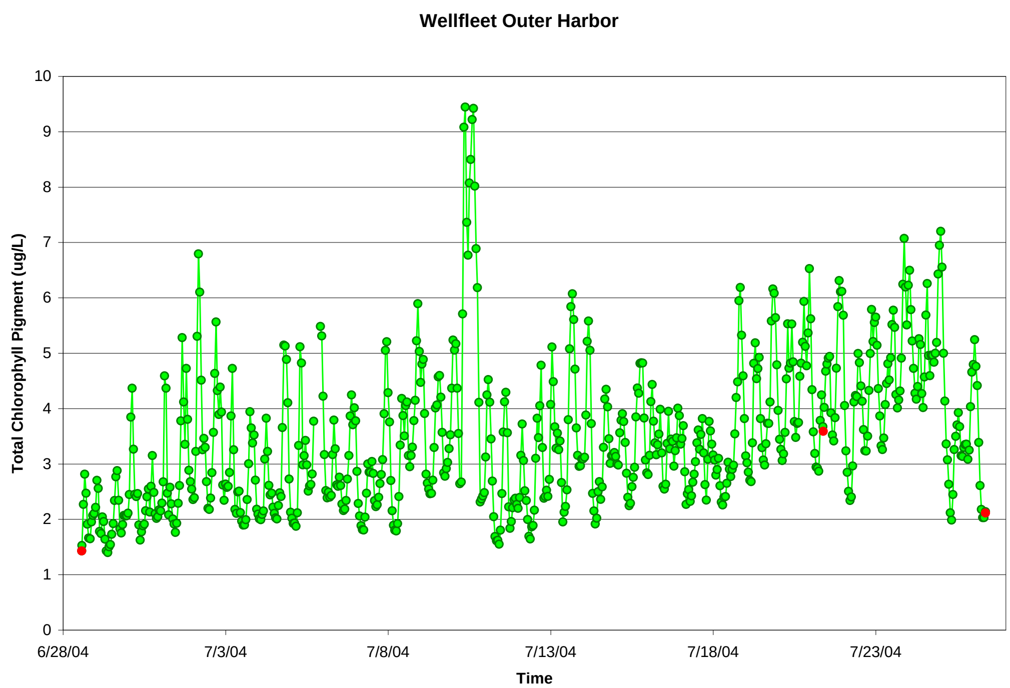


Figure VII-4. Bottom water record of Chlorophyll-*a* in the Wellfleet Harbor - Outer station, Summer 2004. Calibration samples represented as red dots.

Wellfleet Harbor – Inner DO/CHLA Mooring (Figures VII-5 and VII-6):

The Wellfleet Harbor-inner instrument mooring was centrally located in the upper-most reach of the main harbor basin and deployed almost equidistant between the northern tip of Indian Neck (which separates The Cove from the Harbor) and the eastern point of Great Island. This mooring location was established to capture oxygen and chlorophyll conditions in the northern end of the system as may be influenced by discharges from Herring River and Duck Creek. Daily excursions in oxygen levels were observed at this location and as expected, the range of the excursions was larger than observed at the Wellfleet Harbor-outer mooring location. The oxygen excursions ranged from levels at or above air equilibration to very close to 4 mg L^{-1} on a few occasions (Figure VII-5, Table VII-1). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The increased organic enrichment in this portion of the system is demonstrated by the relatively small algal bloom that was observed during the first week of the sensor deployment period, but barely peaked at the 10 ug L^{-1} benchmark. Oxygen levels in the upper main basin of Wellfleet Harbor are indicative of habitat that is experiencing only periodic slight oxygen depletions, typical of a relatively healthy habitat, which is further demonstrated by the low-moderate chlorophyll levels. It should be noted that the more northerly mooring (inner) does show more nitrogen enrichment with greater oxygen depletion and higher chlorophyll a levels than the more southern mooring within the central main basins.

Oxygen levels occasionally exceeded 8 mg L^{-1} and rarely exceeded an instantaneous level of 10 mg L^{-1}. Generally, oxygen levels remained between 5 and 8 mg L^{-1} for the duration of the deployment period. At this more inner location oxygen levels drop lower than at the Wellfleet outer location, an indication that discharges from the innermost basins of the system are affecting water quality conditions at this location. 6 mg L^{-1} is the threshold for healthy DO levels in Class SA waters. Over the 28 day deployment there does appear to be a slight phytoplankton bloom and chlorophyll-*a* levels generally appear elevated compared to the end of the deployment period, between 3-10 ug L^{-1}. Chlorophyll-*a* levels during the later part of the deployment drop noticeably, staying between 2-6 ug L^{-1}. Oxygen and chlorophyll levels, while indicative of healthy conditions in the inner harbor (mooring chlorophyll average 5.0 ug L^{-1}), do show a change in habitat conditions. Chlorophyll-*a* levels exceeded the 10 ug L^{-1} benchmark 1% of the time and exceed the 5 ug L^{-1} benchmark 42% of the time (Table VII-2, Figure VII-6). Average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

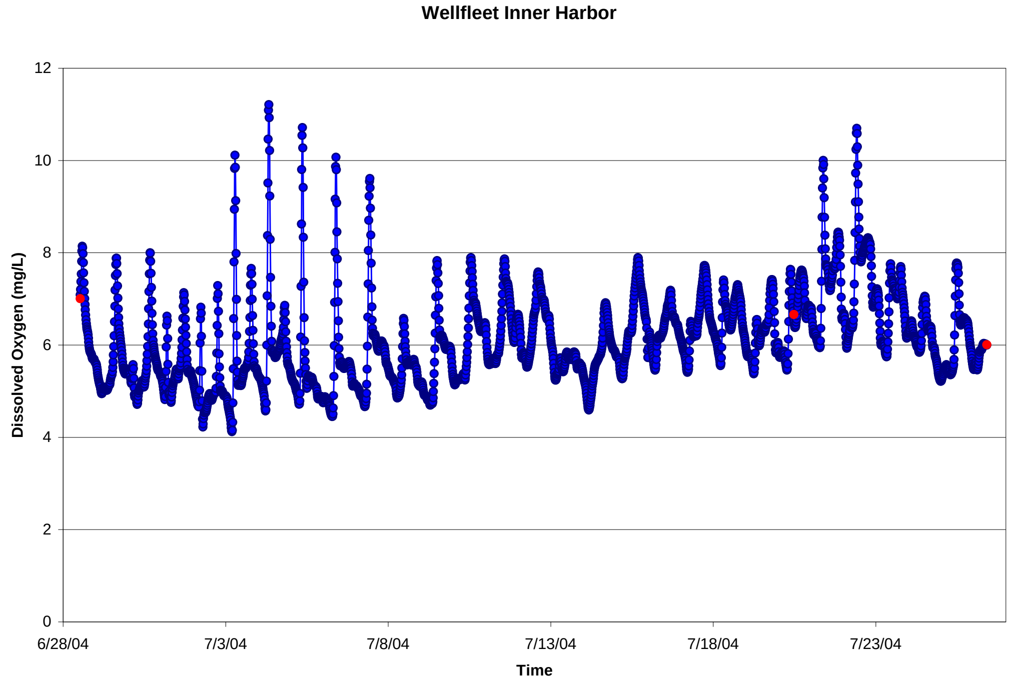


Figure VII-5. Bottom water record of dissolved oxygen at the Wellfleet Harbor - Inner station, Summer 2004. Calibration samples represented as red dots.

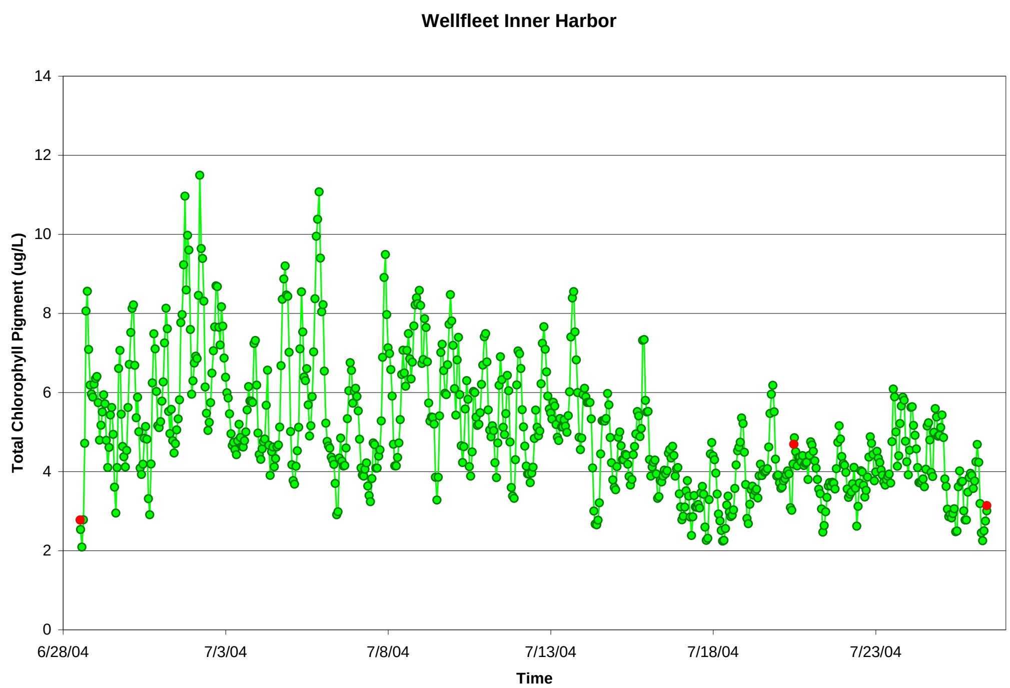


Figure VII-6. Bottom water record of Chlorophyll-*a* in the Wellfleet Harbor - Inner station, Summer 2004. Calibration samples represented as red dots.

Wellfleet Harbor - Cove DO/CHLA Mooring (Figures VII-7 and VII-8):

The Wellfleet Harbor-Duck Creek instrument mooring was centrally located in a small tributary basin of Wellfleet Harbor below Shirttail Point. This basin is part of a marina and is periodically dredged, and is a depositional area as seen in the sediment constituents. This mooring location was established to capture oxygen and chlorophyll conditions in the shallow northern end of the system as it may be influenced by discharges from Duck Creek. Daily excursions in oxygen levels were observed at this location and as expected, the range of the excursions was greater than observed at the Wellfleet Harbor-inner mooring location. The oxygen excursions ranged from levels at or above air equilibration to levels that periodically decline below 4 mg L^{-1} (Figure VII-7, Table VII-1). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The increased organic enrichment in this sub-basin is demonstrated by the steadily growing algal bloom that was observed to peak during the last week of the meter deployment period, reaching levels of ~25 ug L^{-1}. Oxygen levels in the Cove portion of Wellfleet Harbor are indicative of habitat that is experiencing oxygen stress and this is further demonstrated by the higher chlorophyll levels when compared to the Wellfleet Harbor-outer and inner mooring location.

Oxygen levels regularly exceeded 8 mg L^{-1} and approached 10 mg L^{-1} coincident with the period of greatest phytoplankton production. Generally, oxygen levels remained between 4 and 8 mg L^{-1} for the duration of the deployment period. At this more isolated location oxygen levels drop lower than at the main basin sites, suggesting the potential influence of low oxygen discharges from Duck Creek. 6 mg L^{-1} is the threshold for healthy DO levels in Class SA waters. Over the 28 day deployment there does appear to be a steady increase in phytoplankton biomass as represented by the chlorophyll-a record. The phytoplankton bloom and chlorophyll-*a* levels generally appear most elevated towards the end of the deployment and reach levels between 15-20 ug L^{-1}. Chlorophyll-*a* levels during the very last few days of the deployment drop noticeably, staying between 5-10 ug L^{-1}.indicating the die off of the bloom. Not surprisingly, oxygen excursions decrease significantly as do instantaneous dissolved oxygen levels. Oxygen and chlorophyll levels in the Cove indicate impaired conditions in this tributary basin (mooring chlorophyll average 11.2 ug L^{-1}) and do show a change in habitat conditions. Chlorophyll-*a* levels exceeded the 15 ug L^{-1} benchmark 21% of the time and exceed the 10 ug L^{-1} benchmark 57% of the time (Table VII-2, Figure VII-8). Average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

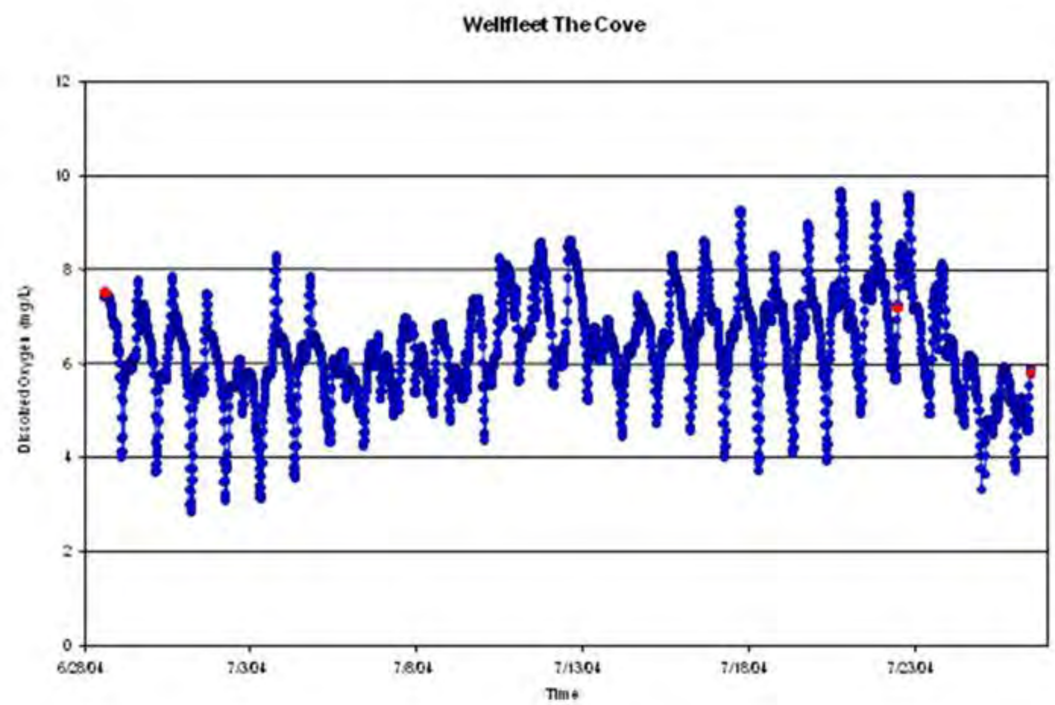


Figure VII-7. Bottom water record of dissolved oxygen at the Wellfleet Harbor – the Cove station, Summer 2004. Calibration samples represented as red dots.

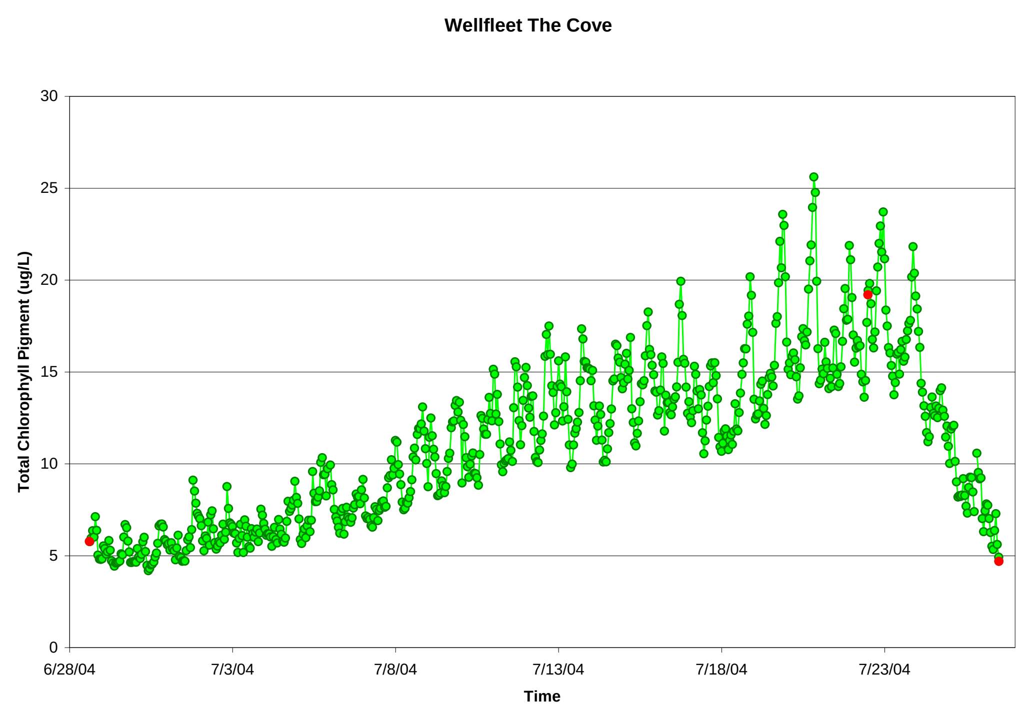


Figure VII-8. Bottom water record of Chlorophyll-*a* in the Wellfleet Harbor – the Cove station, Summer 2004. Calibration samples represented as red dots.

Wellfleet Harbor - Duck Creek DO/CHLA Mooring (Figures VII-9 and VII-10):

The Wellfleet Harbor-Duck Creek instrument mooring was placed on the floating dock that runs along the Wellfleet Town Pier at approximately the level of the boat ramp on the southern side of the pier. The meter was located in the boat basin that is fed by the tidal creek that nearly goes dry at low tide. Duck Creek and the basin in which the mooring was positioned are separated from The Cove by the Wellfleet Town Pier (Shirttail Point). This mooring location was established to capture oxygen and chlorophyll conditions in the shallow northernmost end of the system as it may be directly influenced by discharges from the watershed. Daily excursions in oxygen levels were observed at this location and as expected, the range of the excursions was greater than observed within the main basin sites. The oxygen excursions ranged from levels at or above air equilibration to conditions where levels declined below 3 mg L^{-1} (Figure VII-9, Table VII-1). At this mooring location in Duck Creek, oxygen levels periodically dropped to hypoxic conditions. Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress to animal communities. The increased organic enrichment in this portion of the system is demonstrated by the level of phytoplankton production, generally in the range of 8-14 ug L^{-1} for the duration of the mooring deployment.

Oxygen levels did occasionally exceed 8 mg L^{-1},however, oxygen levels generally remained between 4 and 8 mg L^{-1} for the majority of the deployment period. At this most isolated location, oxygen levels drop lower than at the mooring location in the Cove, with oxygen levels declining to between 2-3 mg L^{-1} and even reaching 1 mg L^{-1}. 6 mg L^{-1} is the threshold for healthy DO levels in Class SA waters, however it should be noted that Duck Creek is surrounded by salt marsh and as such oxygen levels may naturally dip lower than what would be observed in a classic embayment environment. The chlorophyll-*a* levels generally appear consistent through the majority of the deployment period with the exception of noticeably lower chlorophyll-a levels early in the deployment. Overall, chlorophyll-*a* levels remain between 8-14 ug L^{-1} for most of the deployment and rarely exceeded 16 ug L^{-1} exhibiting slightly lower chlorophyll-a levels then in the Cove. The Duck Creek mooring average chlorophyll was 9.0 ug L^{-1} whereas average chlorophyll recorded by the mooring in the Cove was 11.2 ug L^{-1}. Chlorophyll-*a* levels exceeded the 15 ug L^{-1} benchmark 1% of the time and exceed the 10 ug L^{-1} benchmark 33% of the time (Table VII-2, Figure VII-10). Average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

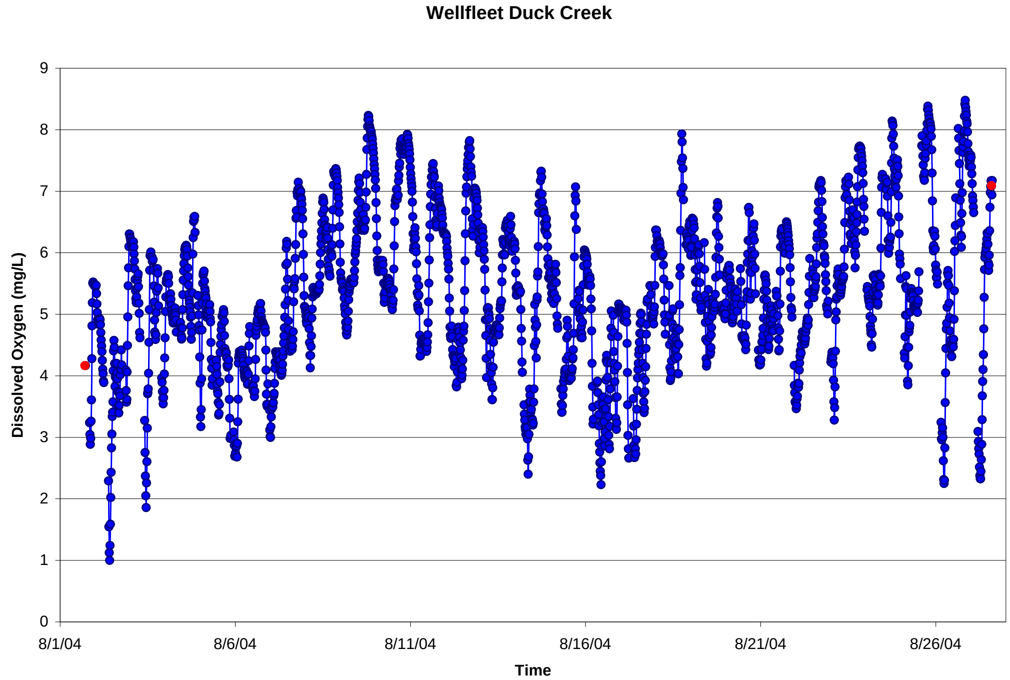


Figure VII-9. Bottom water record of dissolved oxygen at the Wellfleet Harbor – Duck Creek station, Summer 2004. Calibration samples represented as red dots.

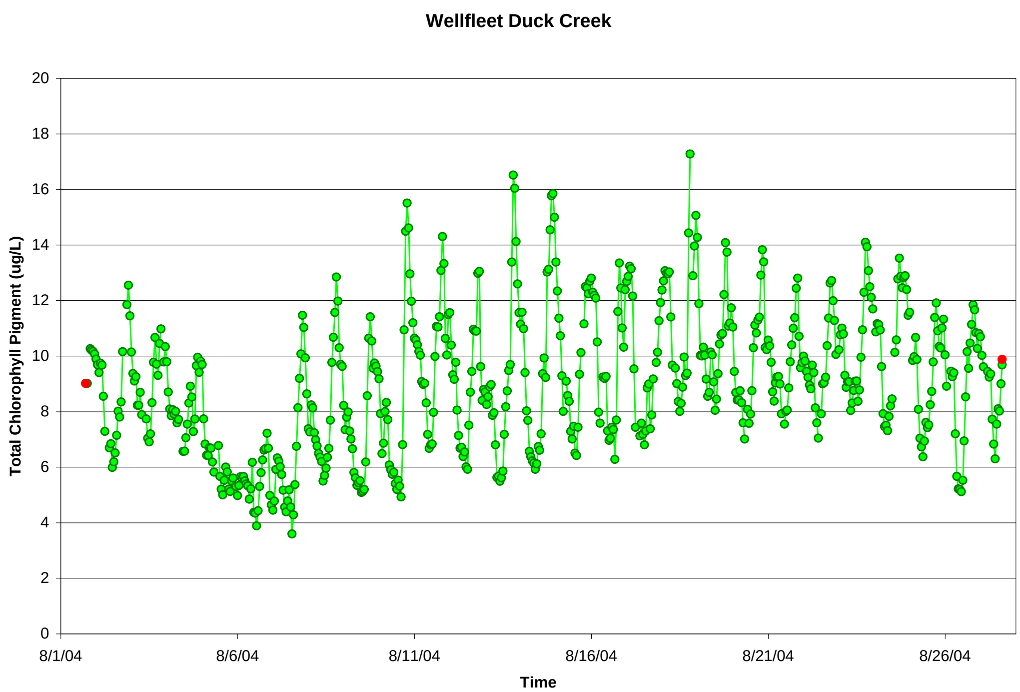


Figure VII-10. Bottom water record of Chlorophyll-*a* in the Wellfleet Harbor – Duck Creek station, Summer 2004. Calibration samples represented as red dots.

Wellfleet Harbor – Herring River DO/CHLA Mooring (Figures VII-11 and VII-12):

The Wellfleet Harbor-Herring River instrument mooring was located on the down gradient side of the dike that separates the lower most portion of the Herring River from the Herring River salt marsh. The mooring could not be positioned lower in the Herring River closer to where it joins Wellfleet Harbor because there was not enough water at low tide to keep the mooring from being exposed to the atmosphere. This mooring location was established to capture oxygen and chlorophyll conditions within the estuarine portion of the Herring River just prior to entry to the main basin of Wellfleet Harbor. Daily excursions in oxygen levels were observed at this location that were greater than observed at the main basin moorings and about the same as within the Cove. The oxygen excursions ranged from levels at or above air equilibration to slightly below 4 mg L^{-1} (Figure VII-11, Table VII-1). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The increased organic enrichment in this portion of the system is demonstrated by the relatively high (>10 ug L^{-1} benchmark) chlorophyll levels measured during the first part of the deployment period up until the chlorophyll probe became fouled.

Oxygen levels regularly exceeded 8 mg L^{-1} and occasionally exceeded an instantaneous level of 10 mg L^{-1}. Generally, oxygen levels remained between 5 and 9 mg L^{-1} for the duration of the deployment period. Within this shallow tributary basin oxygen minima were similar to the Wellfleet inner and the Cove locations (4 mg L^{-1}). 6 mg L^{-1} is the threshold for healthy DO levels in Class SA waters. Due to the limited chlorophyll-a record (most likely fouled by drifting algae) it is difficult to relate changes in chlorophyll to the oxygen dynamics in this portion of the Herring River, however, based on the record that was obtained it is clear that chlorophyll- a levels were high for at least part of the deployment period. The Herring River mooring average chlorophyll was 12.1 ug L^{-1} whereas average chlorophyll recorded by the main basin moorings was much lower at 3.5-5.0 ug L^{-1}. Chlorophyll-*a* levels exceeded the 10 ug L^{-1} benchmark 44% of the time (Table VII-2, Figure VII-6). Average chlorophyll-*a* levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

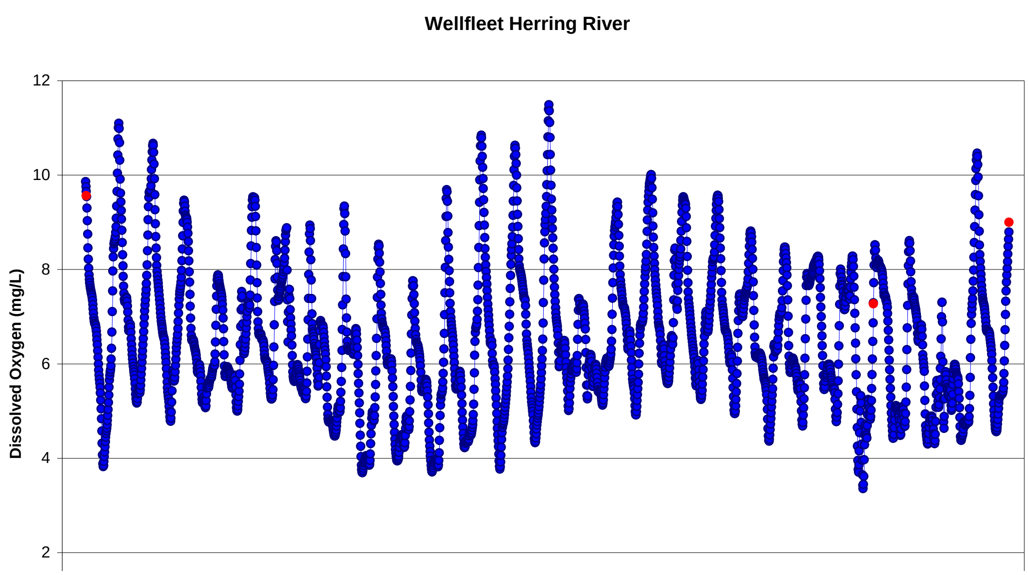


Figure VII-11. Bottom water record of dissolved oxygen at the Wellfleet Harbor – Herring River station, Summer 2004. Calibration samples represented as red dots.

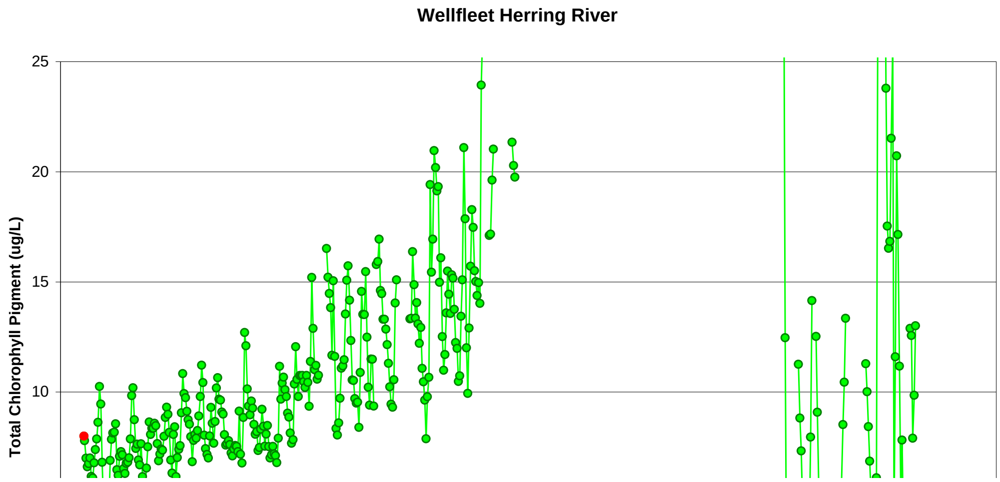


Figure VII-12. Bottom water record of Chlorophyll-*a* in the Wellfleet Harbor – Herring River station, Summer 2004. Calibration samples represented as red dots.

Table VII-1. Days and percent of time during deployment of *in situ* sensors that bottom water oxygen levels were below various benchmark oxygen levels within the Wellfleet Harbor embayment system.

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Wellfleet Outer Harbor	**6/28/2004**	**7/26/2004**	**27.88**	**1%**	**0%**	**0%**	**0%**
			Mean	0.07	N/A	N/A	N/A
			Min	0.01	0.00	0.00	0.00
			Max	0.22	0.00	0.00	0.00
			S.D.	0.08	N/A	N/A	N/A
Wellfleet Inner Harbor	**6/28/2004**	**7/26/2004**	**28.31**	**53%**	**10%**	**0%**	**0%**
			Mean	0.40	0.17	N/A	N/A
			Min	0.02	0.02	0.00	0.00
			Max	1.56	0.52	0.00	0.00
			S.D.	0.33	0.15	N/A	N/A
The Cove, Wellfleet	**6/28/2004**	**7/26/2004**	**27.90**	**38%**	**10%**	**2%**	**0%**
			Mean	0.30	0.09	0.06	0.03
			Min	0.03	0.02	0.02	0.03
			Max	1.63	0.36	0.11	0.03
			S.D.	0.31	0.08	0.04	N/A
Duck Creek, Wellfleet	**7/1/2005**	**7/27/2005**	**25.80**	**62%**	**35%**	**12%**	**3%**
			Mean	0.40	0.17	0.09	0.05
			Min	0.01	0.01	0.01	0.01
			Max	2.26	0.81	0.30	0.10
			S.D.	0.45	0.18	0.08	0.03
Wellfleet Herring River	**6/28/2004**	**7/26/2004**	**28.14**	**42%**	**16%**	**3%**	**0%**
			Mean	0.32	0.17	0.09	N/A
			Min	0.01	0.01	0.04	0.00
			Max	0.82	0.49	0.25	0.00
			S.D.	0.22	0.14	0.07	N/A

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

Mooring Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Wellfleet Outer Harbor	**6/28/2004**	**7/26/2004**	**27.70**	**13%**	**0%**	**0%**	**0%**	**0%**
Mean Chl Value = 3.5 ug/L			**Mean**	0.13	N/A	N/A	N/A	N/A
			Min	0.04	0.00	0.00	0.00	0.00
			Max	0.50	0.00	0.00	0.00	0.00
			S.D.	0.10	N/A	N/A	N/A	N/A
Wellfleet Inner Harbor	**6/28/2004**	**7/26/2004**	**28.00**	**42%**	**1%**	**0%**	**0%**	**0%**
Mean Chl Value = 5.0 ug/L			**Mean**	0.28	0.06	N/A	N/A	N/A
			Min	0.04	0.04	0.00	0.00	0.00
			Max	1.67	0.08	0.00	0.00	0.00
			S.D.	0.30	0.02	N/A	N/A	N/A
The Cove, Wellfleet	**6/28/2004**	**7/26/2004**	**28.00**	**95%**	**57%**	**21%**	**3%**	**0%**
Mean Chl Value = 11.2 ug/L			**Mean**	3.33	1.34	0.21	0.15	0.04
			Min	0.04	0.04	0.04	0.04	0.04
			Max	24.88	11.79	0.83	0.25	0.04
			S.D.	8.71	3.34	0.22	0.08	N/A
Duck Creek, Wellfleet	**7/1/2005**	**7/27/2005**	**24.60**	**97%**	**33%**	**1%**	**0%**	**0%**
Mean Chl Value = 9.0 ug/L			**Mean**	2.38	0.29	0.06	N/A	N/A
			Min	0.04	0.04	0.04	0.00	0.00
			Max	16.21	0.50	0.08	0.00	0.00
			S.D.	5.01	0.17	0.02	N/A	N/A
Wellfleet Herring River	**6/28/2004**	**7/26/2004**	**17.30**	**86%**	**44%**	**20%**	**11%**	**9%**
Mean Chl Value = 12.1 ug/L			**Mean**	1.49	0.29	0.20	0.24	0.38
			Min	0.04	0.04	0.04	0.04	0.04
			Max	12.46	1.96	1.54	1.17	1.17
			S.D.	3.86	0.43	0.37	0.38	0.54

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data are a key part of the MEP Approach. Surveys of submerged aquatic vegetation were conducted in the Wellfleet Harbor Estuary, particularly within the shallow waters in the uppermost reaches of the system (mouth of Herring River, the Cove, Duck Creek) as well as the tidal flats around Lieutenants Island. Eelgrass surveying was also undertaken in the nearshore waters immediately east and west of the Great Island, Great Beach and the narrow barrier beach/sand spit that separates Wellfleet Harbor from Cape Cod Bay. The eelgrass surveying was undertaken primarily by the MassDEP Eelgrass Mapping Program (C. Costello). The most recent survey was conducted in 2001, as part of the MEP program with an earlier survey conducted in 1995. Additional analysis of available aerial photographs from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. Both the 1995 and 2001 mapping was field validated by the MassDEP Eelgrass Mapping Program. The primary use of the data is to indicate (a) estuarine regions that have historically or presently support eelgrass habitat, and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 (Figure VII-13); the period in which watershed nitrogen loading significantly increased to its present level. This temporal information can be used to determine the stability of the eelgrass community.

While there were no eelgrass beds within the Wellfleet Harbor Estuary in the MassDEP conducted 1995 and 2001 surveys (with the exception of the nearshore waters on the Cape Cod Bay side of the barrier beach spit extending southward from Great Island and Great Beach) and the recently lost small patch near the inlet, the MEP Technical Team also confirmed both the lack of eelgrass in the tidal flats areas around Lieutenants Island, as well as the shallow waters leading into the Herring River. The MEP Technical Team confirmed the lack of eelgrass throughout the Wellfleet Harbor system in 2004. The eelgrass surveying conducted by the MEP Technical Team was undertaken as part of the benthic regeneration and benthic animal surveys as well as during the deployment and recovery of the instrument moorings. The 1951 analysis was based upon high quality aerial photos. The 1951 assessment only indicated beds within the shallow waters at the mouth of the Herring River, also commonly referred to as The Gut, as well as the nearshore waters west of Great Island and Great Beach. While those extensive eelgrass beds still exist, the subsequent MassDEP surveying in 1995 and 2001 indicated that the eelgrass that previously existed in 1951 at the mouth of the Herring River was no longer present.

Overall, the historical distribution of eelgrass within the Wellfleet Harbor Estuary is consistent with both the natural history of eelgrass and the present nitrogen, oxygen and chlorophyll levels within the different component basins of the system (Herring River, Duck Creek, The Cove, tidal flats and creeks around Lieutenants Island and Drummers Cove). Very shallow tidal flats and shallow salt marsh basins that have no water for significant portions of the tidal cycle, like Drummers Cove and Loagy Bay, typically do not support eelgrass beds. In contrast, at lower overall nitrogen loading, it would be expected that the shallow lower portion of the Herring River (down gradient of the dike separating the more estuarine waters from what would more generally be considered “river”) would have sufficient water clarity and oxygen levels to support eelgrass beds. However, the current absence of eelgrass within this specific area within the Herring River system is expected given the nitrogen levels and chlorophyll levels in this tidal reach of the Herring River. Typically eelgrass beds exist at much lower nitrogen levels (0.35 - 0.45 mg N L^{-1}) than presently found in this system (0.45 - 0.93 mg N L^{-1}). It is interesting to note that the small patch of eelgrass recently lost in the region of the inlet has a tidally averaged nitrogen level of 0.45-0.47, just above the uppermost TN level typical of eelgrass in this region. This observation is also consistent with the absence of eelgrass from the basins of Wellfleet Harbor.

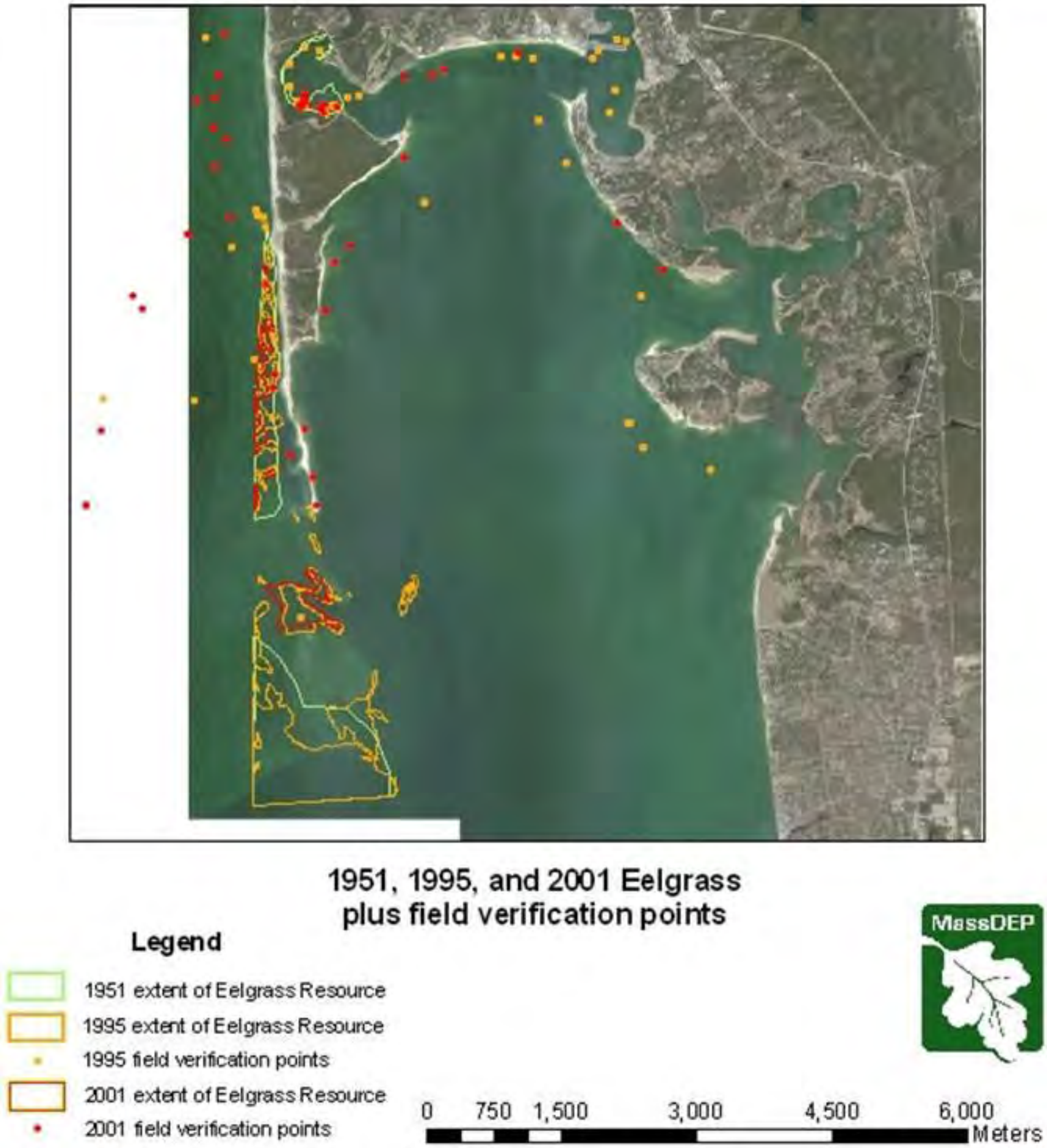


Figure VII-13. Eelgrass bed distribution associated with the Wellfleet Harbor Embayment System in 1951, 1995, 2001, as determined by the MassDEP Eelgrass Mapping Program (map courtesy of C. Costello). The light orange and red outlines circumscribe eelgrass beds as mapped in 1995 and 2001, respectively. The 1951 distribution (light green) was determined from aerial photography. Presently, there are no eelgrass beds within this system.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 21 locations within the Wellfleet Harbor Embayment System (Figure VII-14), with replicate assays at 9 of the 21 sites. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the presence of macroalgae and the recent loss of eelgrass from near the inlet and periodic oxygen declines in some sub-basins to <4 mg L^{-1}, it appears that portions of Wellfleet Harbor Estuary are impaired by nutrient enrichment, such as Duck Creek, the Cove and the mouth of the Herring River where it joins the upper portion of Wellfleet Harbor. To the extent that these areas can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

Analysis of the evenness and diversity of the benthic animal communities was also used to support the density data and the natural history information. The evenness statistic can range from 0-1 (one being most even), while the diversity index does not have a theoretical upper limit. In southeastern Massachusetts estuaries, the highest quality habitat areas, as determined from oxygen and chlorophyll-*a* records and eelgrass coverage, have the highest diversity (generally >3) and evenness (~0.7). The converse is also true, with poorest habitat quality found where diversity is <1 and evenness is <0.5. Highest quality benthic habitat on Cape Cod will generally support 20-25 species and >250 individuals per grab.

Overall, the Infauna Survey indicated that certain basins comprising Wellfleet Harbor Estuary are presently supporting impaired benthic infaunal habitat (Table VII-4). However, none of the basins had benthic communities with significant numbers of stress indicator species (e.g. *tubificids, capitellids*), which are typically found in highly nutrient and organic matter enriched estuarine basins. These species, where they did occur, generally comprised <5% of the community and were always less than 12% of the individuals present. Generally the communities throughout the system were comprised of crustaceans, mollusks, and polychaetes, with some deep burrowers, indicative of a system supporting moderate to high quality benthic habitat.

Infaunal habitat within the low velocity areas associated with the upper and lower main basin showed the highest quality habitat (including Lt. Island South) with moderate numbers of species (15-20) and moderate to high numbers of individuals (123-1079 individuals/grab). The main basin sites showed the highest diversity (2.7) and evenness (0.7-0.8). However, while similar communities were seen in the lower basin near the inlet, the area appears to be unstable with swept medium-coarse sands, which have been observed to negatively impact benthic communities, consistent with the observed low-moderate numbers of individuals (83) and species (9), but with and still high diversity (2.7) and evenness (0.8). A similar condition was found in Chatham Harbor (Pleasant Bay Estuary) near the inlet where high velocities created areas with shifting sands and low benthic animal production. In both cases, the benthic animal community results from natural conditions and is unrelated to nitrogen enrichment.

Figure VII-14. Aerial photograph of the Wellfleet Harbor system showing locations of benthic infaunal sampling stations (yellow symbol).

The Drummer Cove/Loagy Bay/Blackfish Creek tributary is showing signs of nitrogen related impairment as seen in the moderate number of species (10), low to moderate number of individuals (180) and low diversity and evenness. While stress indicator species were also low, the community was dominated by small polychaetes (*Streblospio*), which comprised 60%-80% of the community as most sites. In contrast the sub-basin of Duck Creek, in the upper estuary, had a low number of species (5) and individuals (<100) with low diversity (1.3), with small polychaete dominating this basin (*Streblospio*) consistent with an impaired benthic habitat. Downgradient of Duck Creek is the mooring basin, the Cove, which is a depositional basin. The Cove is supporting a benthic community with a moderate number of species (9) and high number of individuals, with low diversity (1.1) and evenness (0.4). These metrics are consistent with the observed community dominated by amphipods (*Ampelisca abdita*), a transitional species, which comprised >80% of the community. Amphipods are frequently found in high numbers and can form mats in areas of moderate to high organic matter enrichment. Amphipods are an initial recovery species and dominated parts of Boston Harbor during the initial recovery upon cessation of WWTF sludge discharges.

The mouth of Herring River is the lower portion of the Herring River wetland system, as such is it is an integration of embayment and wetland creek habitat. This sub-basin is supporting low numbers of individuals (~100), moderate numbers of species (18), with high diversity (2.7) and Evenness (>0.7). Based upon these metrics and its function as the intermediate basin between the upper wetland and lower embayment, it appears to be supporting high-moderate quality benthic habitat.

Classification of benthic habitat quality necessarily included the structure of the estuarine basin, specifically that it is fully representative of a tidal embayment, as opposed to a tidal river or salt marsh dominated basin. The Wellfleet Harbor Estuary is a complex estuary composed of 3 types of basins: shallow open water basins with no eelgrass or surrounding wetland, shallow basins with significant associated wetland, and an large open lagoon with high tidal velocities near the inlet and areas of shifting sands (lower main basin). Each of these 3 basins has difference natural sensitivities to nitrogen enrichment and organic matter loading and each has its own benthic community indicative of an unimpaired or impaired habitat. Evaluation of infaunal habitat quality considered the natural structure of each system and the types of infaunal communities that they support. The benthic animal communities throughout most of the Wellfleet Harbor Estuary (except Duck Creek and the Cove) indicated generally healthy to slightly impaired infaunal habitat, consistent with the tidally averaged nitrogen levels and levels of oxygen depletion in line with the ecosystem types represented. The general absence of dense macroalgal accumulations and sediments of consolidated sands and mud, with a visible oxidized surface layer is also consistent with the community measurements. None of the basins comprising the Wellfleet Harbor Estuary showed severe degradation by nitrogen enrichment, unlike many other estuaries on Cape Cod. Since there is no eelgrass habitat within the Wellfleet Harbor Estuary, restoring impaired benthic animal habitat is primary management objective for this system. Since generally only a moderate level of impairment was found in benthic habitat within the shallow semi-enclosed basins on the eastern shore, it is likely that only a modest reduction in nitrogen levels will be needed to restore infaunal animal habitat in most basins, with the possible exception of Duck Creek.

Table VII-4. Benthic infaunal community data for the Wellfleet Harbor Estuarine System. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations. Samples represent surface area of 0.0625 m^2. Stations refer to map in figure VII-16, replicate samples were collected at each location. S.E. is the standard error of the mean; N is the number of samples.

Basins	Station [1]	Actual Total Species	Actual Total Individuals	#Species Calc @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Tributary Basins	**WHRB**					
Duck Creek	1,2	9	59	6	2.09	0.64
The Cove	3,5,6,9	9	164	6	1.43	0.45
Herring River Mouth	7,8	8	153	5	0.86	0.30
Drummer Cove[2]	19-22	9	174	7	1.59	0.51
Lt Island South	28	18	1079	6	1.18	0.28
Main Basin	**WHRB**					
Upper Basin	10,13,14,16-18	12	277	8	2.06	0.60
Lower Basin	26,27,29	9	83	5	2.66	0.87

1 - Station numbers refer to ID's on maps presented above.
2 - Drummer Cove and Loagy Bay Combined.

Other Benthic Natural Resources:

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas relative to harvest (permitted/not permitted) as well as the suitability of a system for the propagation of shellfish (Figure VII-15,16). Unlike most systems on Cape Cod, nearly the entire Wellfleet Harbor system is approved for shellfish harvest. Duck Creek, one of the innermost sub-basins of the system is classified as conditionally approved as is also the case with most of the area that constitutes the mouth of the Herring River. The only area that is classified as prohibited for the taking of shellfish year-round is the upper most portion of the mouth of the Herring River. That so much of Wellfleet Harbor is approved for shell fishing indicates that the overall system is relatively healthy with regard to pathogens and organic contaminants. The conditional approval of the small innermost enclosed basins of the system is due to bacterial concerns potentially the result of both human activity (septic systems in the watershed) as well as natural fauna. Moreover, Duck Creek is considered part of an active marina and as such not typically considered for shell fishing. In association with the DMF classification of “Approved” for shell fishing, the Wellfleet Harbor system has also been classified as supportive of specific shellfish communities (Figure VII-17). The major shellfish species with potential habitat within the Wellfleet Harbor Estuary are quahogs (*Mercenaria*), primarily in the deeper open water main basin, as well as the shallow waters around Lieutenants Island, the American Oyster located primarily in the shallow waters particularly in the main basin and Bay Scallops, in the more open water of the main basin. A few areas were also classified as suitable benthic habitat for soft shell clams (*Mya*), mainly along the shallow waters at the edge of the upper portions of the harbor and the tidal flats around Lieutenants Island. Improving benthic animal habitat quality should also expand the available habitat for shellfish within this system.

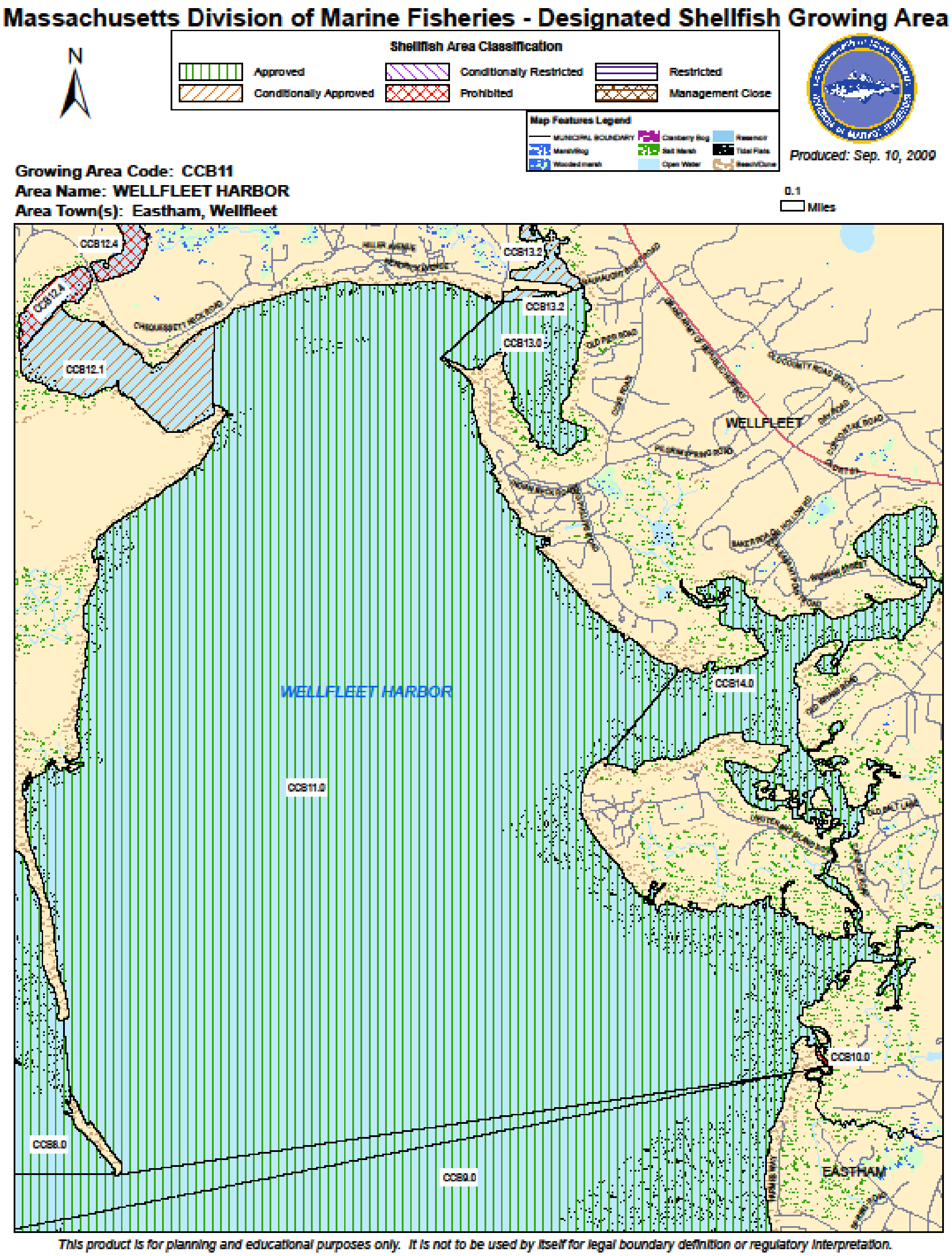


Figure VII-15. Location of shellfish growing areas and their status relative to permitted shellfish harvest as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

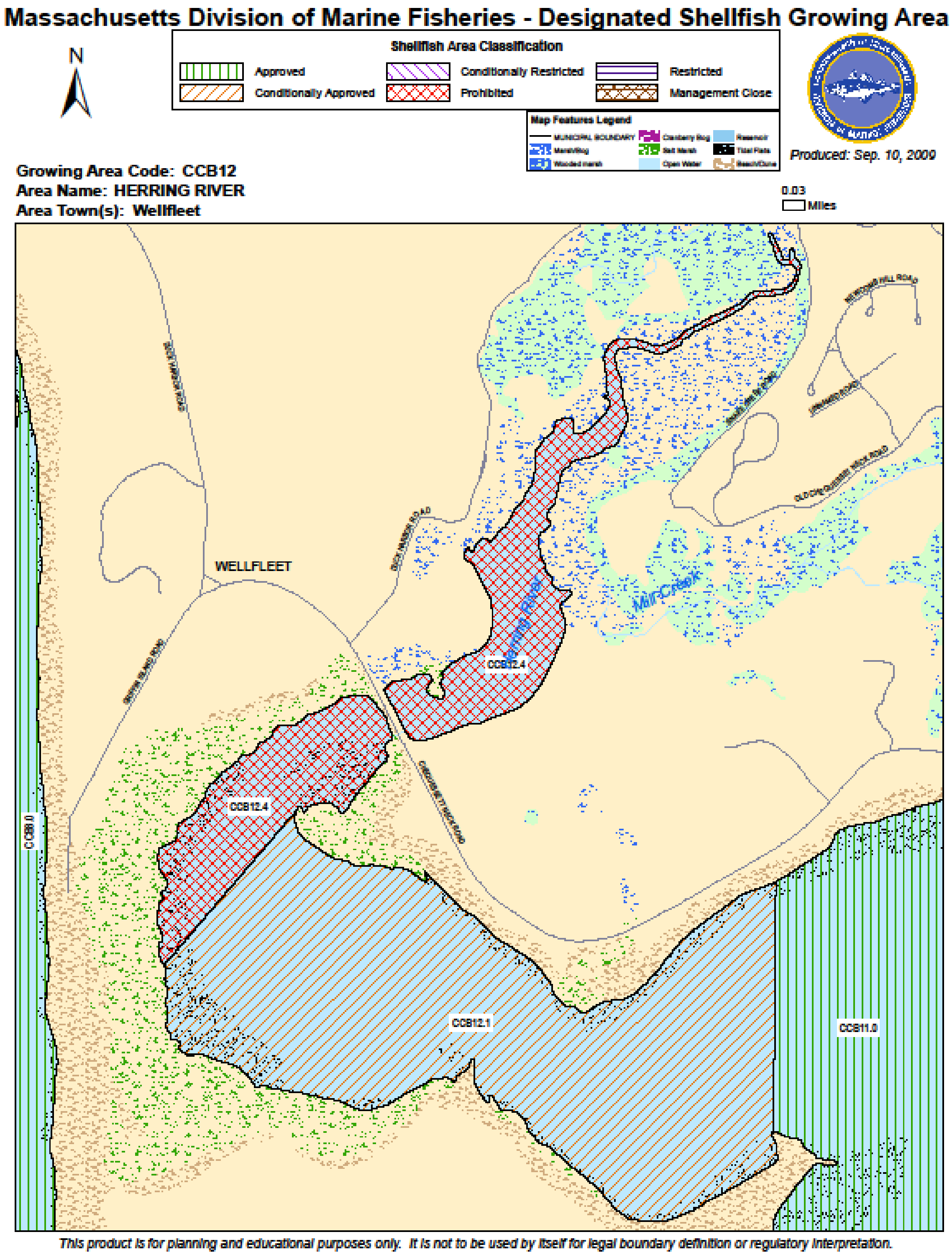


Figure VII-16. Location of shellfish growing areas and their status relative to permitted harvest of shellfish as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

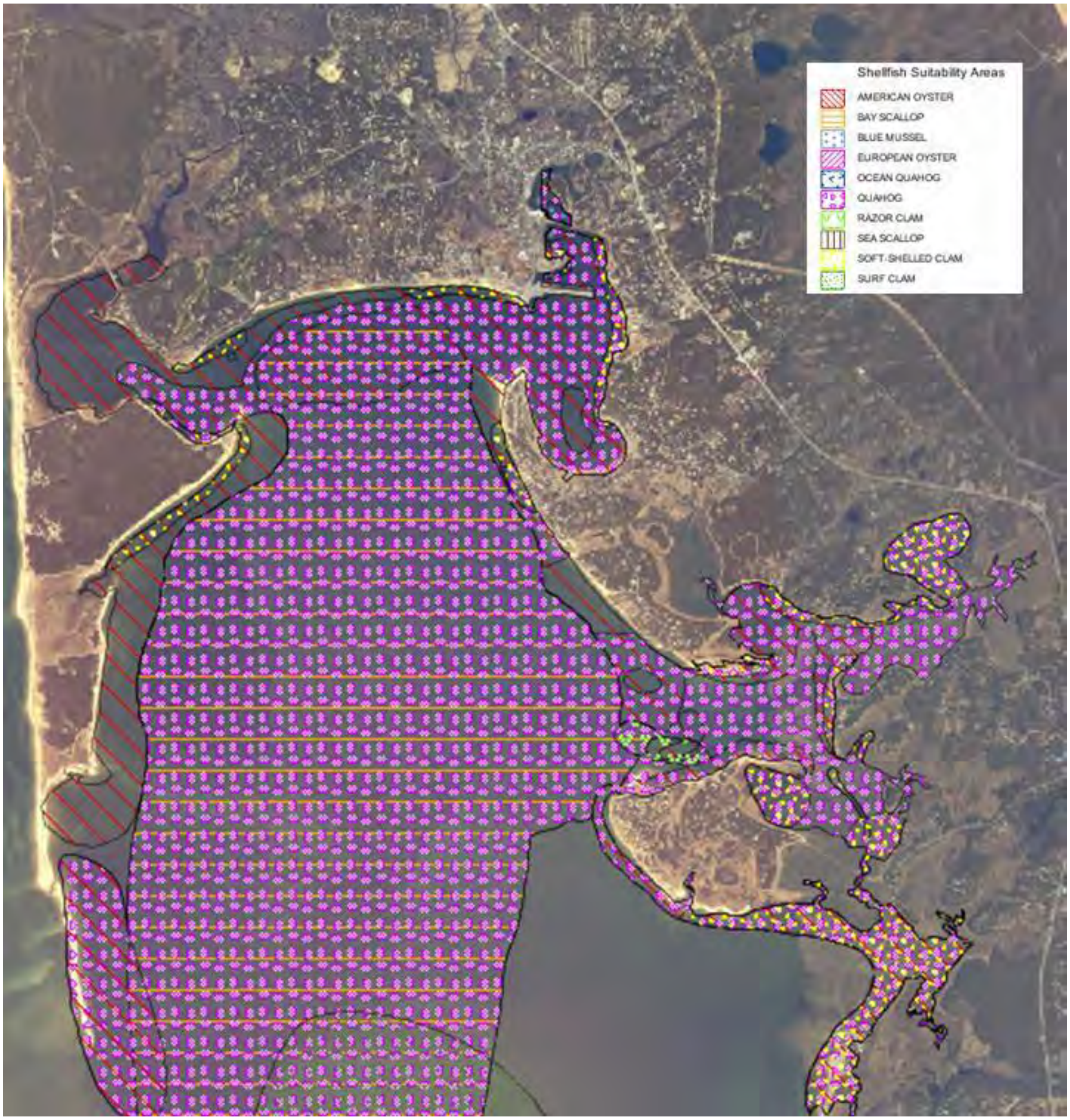


Figure VII-17. Location of shellfish suitability areas within the Wellfleet Harbor estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean that the shellfish are "present" or typically found in those areas.

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll). Additional information on temporal changes within each sub-embayment and its associated watershed nitrogen load further strengthen the analysis. These data were collected to support threshold development for the Wellfleet 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 baseline water quality monitoring program.

The Wellfleet Harbor Estuary is a complex estuary composed of 3 functional types of basins: shallow open water basins, shallow basins with significant associated salt marsh and a large estuarine lagoon (main basin) with high tidal velocities and areas of shifting sands (near inlet). Each of these 3 basin types have differences in their natural sensitivity to nitrogen enrichment and organic matter loading and each has its own benthic community indicative of unimpaired or impaired habitat. None of these basins have historically supported significant eelgrass beds. As a result, evaluation of habitat quality considered the natural structure of each system and the types of infaunal communities that they support. At present, the Wellfleet Harbor Estuary is showing differences in nitrogen enrichment and habitat quality among its various component basins (Table VIII-1).

Overall, the estuary is showing some nitrogen related habitat impairment within some of its component basins, however, most of the system is supporting high quality to moderately impaired habitat, with regions of moderate to significant impairment found only in Duck Creek, which was significantly nitrogen enriched (0.93 mg L^{-1} tidally averaged TN) and is furthest from the systems tidal inlet. As there is not a record of historical eelgrass coverage in this system, benthic animal habitat is the central focus for management. The benthic animal communities throughout most of the Wellfleet Harbor Estuary (except Duck Creek) indicate generally healthy infaunal habitat with only moderate impairment in some of the tributary basins, consistent with the tidally averaged nitrogen levels and levels of oxygen depletion and the ecosystem types represented. The general absence of macroalgal accumulations and sediments of consolidated sands and mud, with a visible oxidized surface layer is also consistent with the community measurements. Given the levels of nitrogen enrichment in the tributary basins, lowering the nitrogen levels provides a clear path to restoring infaunal animal habitat in those areas.

Oxygen and chlorophyll-*a* levels were generally consistent with the infaunal animal assessments and paralleled gradients in nitrogen enrichment. At all locations throughout the Wellfleet Harbor Estuary, tidally averaged nitrogen levels (Table VI-1) were higher than found by the MEP to be supportive of eelgrass in any Cape Cod estuary. The levels were from 0.45-0.93 mg TN L^{-1} (Lower Basin to Duck Creek), where other Cape Cod systems generally have healthy eelgrass at 0.35-0.42 mg L-1, with fringing shallow areas as high as 0.42 mg L^{-1}.

The levels of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels paralleled the level of nitrogen within the innermost basins of the Wellfleet Harbor system (Figures VII-3,5,7,9,11). The oxygen data are consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-*a*. The measured levels of oxygen depletion and enhanced chlorophyll-*a* levels follows the spatial pattern of total nitrogen levels in this system (Section VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of this estuarine system.

The main basin supports generally high-moderate quality habitat with generally high oxygen levels in the Mid/Upper Main Basin typically >6 mg L^{-1} and almost always >5 mg L^{-1} and low-moderate chlorophyll-*a* levels (WQMP=average 6-7 ug L^{-1}, mooring= 3.5-5 ug L^{-1}). Similarly the lower basin (closest to the tidal inlet showed slightly higher oxygen levels and lower chlorophyll-*a* levels than the upper main basin, consistent with the TN gradient from the tidal inlet to the upper basins. The low velocity areas associated with the upper and lower main basin (Lt. Island south) showed high-moderate quality habitat with moderate to high numbers of species (15-20) and moderate to high numbers of individuals (123-1079 individuals/grab). The main basin sites showed the highest diversity (2.7) and evenness (0.7-0.8). The lower main basin supported a similar benthic community as in the upper main basin, but areas in the lower basin appear to be physically disturbed with unstable swept medium-coarse sands, consistent with the observed low-moderate individuals (83) and species (9), but high diversity (2.7) and evenness (0.8). This is similar to MEP findings in Chatham Harbor (Pleasant Bay Estuary) and Westport Harbor near the inlet where high velocities created shifting sands and resulted in a benthic population with significantly reduced numbers. This latter finding is primarily due to physical disturbance, not nitrogen enrichment.

There was moderate impairment of benthic habitat in the shallow eastern sub-basins of Drummer Cove/Loagy Bay and the Cove. Both sub-basins had periodic oxygen depletions to <4 mg L^{-1}, which is stressful to benthic communities. Consistent with the moderate oxygen stress were the moderate chlorophyll-*a* levels in both basins averaging 10-11 ug/L, with blooms of 15-20 ug/L. These periodic moderate oxygen declines and moderate chlorophyll-*a* levels are consistent with the observed benthic communities in both basins. These communities were comprised of a moderate number of species (9-10), moderate-high number of individuals (180 and 428 individuals per grab, Bay and Cove, respectively) and low diversity (1.7-1.1) and evenness (0.5-0.4). Stress indicator species were in low numbers when they were present at all. The Drummer Cove/Loagy Bay community was dominated by small polychaetes (*Streblospio*), indicative of moderate organic enrichment and the Cove community was dominated by amphipods (*Ampelisca abdita*, a transitional species {>80% of the community}). Amphipods are an initial recovery species frequently found in high numbers and can form mats in areas of moderate to high organic matter enrichment.

The basin most impaired by nitrogen enrichment was Duck Creek which has tidally averaged Total Nitrogen (TN) levels of 0.93 mg L^{-1}, the highest observed in the Wellfleet Harbor Estuarine System and a concentration typically associated with significant habitat impairment in estuaries throughout southeastern Massachusetts. Consistent with this level of nitrogen enrichment, oxygen depletions to <5mg/L were typical with declines to <4 mg/L frequent and periodic declines to <3 mg/L. Chlorophyll-*a* levels were also elevated averaging 8-9 ug L^{-1} with periodic blooms to 14 ug L^{-1}. This basin also had moderate accumulations of drift algae (*Ulva*), generally in patches but with high coverage in some areas. Consistent with these nutrient related stresses, the benthic animal community was comprised of a low number of species (5) and low numbers of individuals (<100), with a poor diversity (1.3) and was dominated by *Streblospio* and organic enrichment tolerant polychaete, indicative of a moderately to significantly impaired basin.

In contrast, the lower reach of the Herring River, below the dike, is functioning as the lower reach of a wetland dominated tidal river. As such, the periodic oxygen depletions to <4 mg L^{-1} (but above 3 mg L^{-1}) and chlorophyll-*a* levels similar to the adjacent open waters are typical. The benthic communities in such basins are typically adapted to the conditions as can be seen in this case where there are a moderate to high number of species (18), low to moderate numbers of individuals in a community with high diversity (2.7) and evenness (>0.7). The benthic community is consistent with high quality habitat in a wetland type basin.

The above evaluation of infaunal habitat quality throughout the Wellfleet Harbor Estuary considered the natural structure of each system and the types of infaunal communities that they support. The benthic animal communities throughout most of the Wellfleet Harbor Estuary (except Duck Creek and the Cove) indicated generally healthy to slightly impaired infaunal habitat to moderately-significantly impaired habitat (Duck Creek), consistent with the tidally averaged nitrogen levels and levels of chlorophyll-*a* and oxygen depletion, all in line with the ecosystem types represented. The general absence of dense macroalgal accumulations and sediments of consolidated sands and mud, with a visible oxidized surface layer is also consistent with the community measurements. None of the basins comprising the Wellfleet Harbor Estuary showed severe degradation by nitrogen enrichment, unlike many other estuaries on Cape Cod. Since there is no eelgrass habitat within the Wellfleet Harbor Estuary, restoring impaired benthic animal habitat is the primary management objective for this system. Since generally only a moderate level of impairment was found in benthic habitat within the shallow semi-enclosed basins on the eastern shore, it is likely that only a modest reduction in nitrogen levels within the system will be needed to restore infaunal animal habitat in most basins, with the possible exception of Duck Creek.

Based upon the lack of historical eelgrass coverage and the above analysis, benthic animal habitat was selected as the primary nitrogen management goal for each of the sub-basins of the Wellfleet Harbor Estuary. Restoration of impaired benthic animal habitat within each sub-basin is the focus of the MEP threshold analysis presented in Section VIII.3.

VIII.2. THRESHOLD NITROGEN CONCENTRATIONS

Overall, the infauna survey indicated that certain basins comprising the overall Wellfleet Harbor Estuary are presently supporting impaired benthic infaunal habitat (Table VII-4). However, none of the basins had benthic communities with significant numbers of stress indicator species (e.g. *tubificids, capitellids*), which are typically found in highly nutrient and organic matter enriched estuarine basins. These species, where they did occur, generally comprised <5% of the community and were always less than 12% of the individuals present. Generally the communities throughout the system were comprised of crustaceans, mollusks, and polychaetes, with some deep burrowers, indicative of a system supporting moderate to high quality benthic habitat.

The approach for determining nitrogen loading rates that will support acceptable habitat quality throughout an embayment system is to first identify a sentinel location within the embayment and secondly, to determine the nitrogen concentration within the water column that will restore the location to the desired habitat quality. The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined (Section VIII.2), the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved (Section VIII.3).

Table VIII-1. Summary of Nutrient Related Habitat Health within the Wellfleet Harbor Estuarine System (Towns of Wellfleet and Truro), based upon assessment data presented in Chapter VII. The main basin of Wellfleet Harbor and its major tributary sub-embayments have open exchange with ocean waters of Cape Cod Bay. Some basins were approximated using water quality monitoring data coupled with instrument mooring data (D.O., chlorophyll a). WQMP refers to water quality monitoring program.

	Wellfleet Harbor Estuarine System						
	Main Basin		**Tributary Coves**				
Health Indicator	**Upper**	**Lower**	**Duck Creek**	**Cove**	**Herring River Mouth**	**Drummer[a] Cove**	**South of Lt. Island**
Dissolved Oxygen	H[1,2]	H[3]	MI/SI[1,4]	MI/SI[1,5]	H/MI[1,6]	H/MI[7]	H[8]
Chlorophyll	H[9]	H[10]	MI[11]	MI[12]	MI[13]	MI[14]	H[15]
Macroalgae	--[16]	--[16]	MI[17]	--[16]	--[16]	--[16]	--[16]
Eelgrass	--[18]	--[18]	--[18]	--[18]	--[18]	--[18]	--[18]
Infaunal Animals	H/MI[19]	H[20]	MI-SI[22]	MI[23]	H[24]	MI[21]	H/MI[19]
Overall:	**H/MI [18,25]**	**H [18,26]**	**MI-SI [18,27]**	**MI [18,28]**	**H [18,30]**	**MI [18,28]**	**H/MI [18,29]**

a -- Drummer Cove and Loagy Bay combined for assessment
1 -- integration of moored instrument results and WQMP data, as appropriate.
2 – oxygen levels in Mid/Upper Main Basin were generally >5mg/L 97% of WQMP samples and >6mg/L mooring (99% record); uppermost main basin >5mg/L 96% of WQMP and >5 mg/L (mooring 90% record), DO almost always > 5mg/L.
3 – oxygen levels in Lower Main Bain were >5mg/L 98% of WQMP samples, >6 mg/L (87% of samples).
4 – mooring <5mg/L 38% of record, frequently <4 mg/L, with periodic declines to <3 mg/L, WQMP <4 mg/L and <3 mg/L (12% and 1% of samples, respectively).
5 – mooring <5mg/L 10% of record, periodic declines to <4 mg/L, WQMP <4 mg/L, only >6 mg/L 47% of record and 26% of WQMP samples.
6 – oxygen frequently <5mg/L and <4 mg/L, 35% and 12% of record, respectively, similarly <5mg/L 34% of WQMP samples and <4 mg/L 10% of 78 samples, may be result of receiving outflow from a large wetland.
7 – oxygen levels were >4mg/L 16% (inner) and 5% (outer) of WQMP samples, <6 mg/L only 47% and 53% of outer and inner samples, with <5mg/L frequent in inner basin 37% of samples.
8 – oxygen levels, >5mg/L 96% of WQMP 212 samples, >6 mg/L (56% samples), only 2% of samples <4 mg/L.
9 – low-moderate chlorophyll a levels, WQMP average 6-7 ug/L, consistent with mooring record of <10ug/L 99% and >5 ug/L 13%-42% of record, averaging 3.5-5.0 ug/L over deployment.
10 – low-moderate chlorophyll a levels, WQMP average <6 ug/L,
11– moderate chlorophyll a , WQMP average 8 ug/L, mooring average, 9 ug/L with periodic blooms to 14 ug/L;
12 – moderate chlorophyll a levels, average 11 ug/L, with blooms typically 15-20 ug/L; WQMP average ~7 ug/L.
13 – moderate chlorophyll a levels, average 12 ug/L, with blooms typically 15-20 ug/L; WQMP average 6-8 ug/L.
14 – moderate chlorophyll a levels, WQMP average 10 ug/L, with blooms up to 18 ug/L.
15 – moderate chlorophyll a levels, WQMP average ~6 ug/L, with rare blooms to 22 ug/L.
16 – drift algae sparse or absent, little surface microphyte mat, no visible accumulations
17 – moderate accumulations of drift algae, *Ulva*, patchy with some areas with coverages of 75%.
18 – no evidence this basin is supportive of eelgrass within the main basin or tributary coves based on MassDEP Eelgrass Monitoring Program and MEP surveys.
19 – in the low velocity areas associated with the upper and lower main basin (Lt. Island South) showed high quality habitat with moderate to high numbers of species (15-20) and moderate to high numbers of individuals (123-1079 individuals/grab). The main basin sites showed the highest diversity (2.7) and evenness (0.7-0.8), Lt. Island South had high numbers but low diversity and evenness indicative of some impairment..
20 – similar communities were in lower basin near the inlet as in upper main basin, area appears to be unstable with swept medium-coarse sands, consistent with the low-moderate # individuals (83) and species (9), but high diversity (2.7) and evenness (0.8), similar to Chatham Harbor near inlet where high velocities created shifting sands & low benthic production.
21 –moderate number of species (10), low to moderate number of individuals (180), low diversity & evenness. Stress indicator species low, but community was dominated by small polychaetes (*Streblospio*), 60%-80% of the community at most sites.
22 –low number of species (5) and individuals (<100) and low diversity (1.3), dominated by *Streblospio*.
23 –moderate number of species (9), high number of individuals, with low diversity (1.1) and evenness (0.4), consistent with the observed community dominated by amphipods (*Ampelisca abdita*), a transitional species (>80% of the community). Amphipods are an initial recovery species frequently found in high numbers and can form mats in areas of moderate to high organic matter enrichment.
24 –low numbers of individuals (~100), moderate numbers of species (18), with high diversity (2.7) and Evenness (>0.7). Benthic community is consistent with high-moderate quality habitat in a wetland basin.

25 --assessment based on impairment of benthic communities showing low-moderate impairment: moderate-high number of species with low-moderate individuals, high diversity & Evenness, with high oxygen and low chlorophyll a levels.
26 -- assessment based on impairment of benthic communities in high oxygen/low chlorophyll a waters showing only natural impairment by high velocity flows.
27 --assessment based on moderate-significant impairment of benthic communities (low # species & individuals, with low diversity) with periodic hypoxia, macroalgal accumulations, high chlorophyll.
28 --assessment based on moderate impairment of benthic communities (moderate # species & individuals, with low diversity and evenness) with periodic hypoxia, high chlorophyll.
29 --assessment based on low-moderate impairment of benthic communities (moderate-high # species & individuals, with low diversity and evenness) with generally high oxygen and low chlorophyll.
30 --assessment based on low impairment of benthic communities (moderate-high # species & high # individuals, with high diversity & evenness) with generally moderate oxygen and chlorophyll levels. Habitat indicators consistent with a unimpaired wetland influenced basin.

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

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Wellfleet Harbor Estuary is based primarily upon the nutrient, chlorophyll-*a* and oxygen levels, basin characteristics and current benthic community indicators. Given the information on a variety of key habitat characteristics, it is possible to develop a site-specific threshold, which is a refinement upon more generalized threshold analyses frequently employed.

The upper main basin, the Drummer Cove/Loagy Bay sub-basin, the basin south of Lt. Island and the Cove are currently showing low to moderate impairment of benthic animal communities. The uppermost basin or Duck Creek has the greatest impairment and Lower main basin and the mouth of Herring River do not show symptoms of nitrogen related impairment to benthic habitat. Tidally averaged TN levels at WH-5 (0.55 mg TN L^{-1}) is slightly higher than typically found in open water systems supporting healthy benthic animal habitat (0.50 mg TN L^{-1}). As this basin is showing only a low level of impairment lowering the TN level to 0.53 mg TN L^{-1} should reverse its impairment. This slightly higher threshold is due in part to the well mixed, oxygenated nature of the main basin (resulting from its shallow depth and large fetch for wind driven mixing). In addition this lagoon does not support high rates of organic deposition, evidenced by the observed generally sandy sediments with oxidized surfaces. The semi-enclosed sub-basins on the eastern shore are less well mixed and allow more organic deposition, such that a level of 0.50 mg TN L^{-1} would be more conducive to high quality benthic habitat, which is typically a secondary threshold (check).

It should be noted that the Cove is highly depositional and supports a community adapted to those conditions. Lowering the nitrogen level within that basin will improve the community, but the high rates of deposition are due significantly to its geomorphology and this physical constraint will limit the amount of reduction in TN level possible at this location. Similarly, Duck Creek, behind Shirttail Point, has reduced mixing and is also depositional. This combined basin, with its fringing salt marsh, is structurally nitrogen enriched. None-the-less, these basins will be significantly restored if the threshold is met at the sentinel station, particularly if the function of Duck Creek as a salt marsh dominated tidal creek is considered.

It should also be noted that in numerous estuaries evaluated by the MEP, it has been previously determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat (e.g. Eel Pond {Waquoit Bay}, Parkers River, upper Bass River, upper Great Pond, Rands Harbor and Fiddlers Cove). Present TN levels within the upper reaches of the open water sub-basins of Wellfleet Harbor Estuary are $\geq$0.55 mg N L^{-1}, consistent with moderately impaired benthic animal habitat. Based upon comparisons to other systems and given the TN levels in the non-wetland influenced basins, the periodic oxygen depletions and the phytoplankton blooms, it appears that a water column nitrogen threshold for the main basin of 0.53 mg TN L^{-1} with 0.50 for the eastern sub-basins is required for restoration in this system. All habitat metrics indicate a moderate level of habitat impairment (Table VIII-1) in these basins. Based upon these results, a threshold for tidally averaged TN at long-term monitoring station WH-5 in the upper main basin was selected to restore benthic animal habitat. In this system meeting the 0.53 mg N L^{-1} (tidally averaged) at station WH-5 for benthic habitat restoration should ensure restoration of benthic animal habitat throughout the estuary. The nitrogen loads associated with the threshold concentration at the sentinel location are discussed in Section VIII.3, below.

As a point of comparison, presently, in other estuaries of Cape Cod that have regions with moderately impaired infaunal habitat, for example within the Hyannis Inner Harbor and the impaired habitat within Mill Creek, both sites have total nitrogen (TN) levels in the range of 0.518 - 0.574 mg N L^{-1}. Additionally, the observed moderate impairment at these sites is consistent with observations by the MEP Technical Team in other enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5-0.55 mg N L^{-1} were found to be supportive of healthy infaunal habitat with a lower threshold in deeper enclosed basins in Buzzards Bay (e.g. Eel Pond in Bourne) where healthy infaunal habitat had a slightly lower threshold level, 0.45 mg N L^{-1}. Similar to Wellfleet Harbor tributary basins, only low-moderate impairment was observed at TN levels (0.535-0.600 mg N L^{-1}) within the Wareham River. Based upon these observations, the MEP Technical Team concluded that an upper limit of 0.53 mg N L^{-1} tidally averaged TN would support healthy infaunal habitat in the main basin of Wellfleet Harbor with 0.5 mg N L^{-1} in the open water shallow eastern basins. A higher level of TN was found to support relatively unimpaired benthic habitat in more wetland dominated basins, as high as 0.6 mg N L-1 (Mashpee River) and salt marsh tidal creeks (1 mg N L^{-1}).

With the sentinel stations established and a threshold concentration selected (as described above), the Linked Watershed-Embayment Model was used to sequentially adjust nitrogen loads from the Wellfleet Harbor estuary watershed until the targeted nitrogen concentration is achieved. The modeling simulations in Section VIII-3 targeted the restoration of benthic animal habitat in the main basin, with secondary thresholds within the tributary Coves. The lowering of average TN levels within the upper main basin of the Wellfleet Harbor System will also simultaneously improve benthic animals throughout this estuarine system.

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 for infaunal habitats in the Wellfleet Harbor system. The threshold level, at the sentinel station WH-5, was set at 0.53 mg/L for the Wellfleet Harbor system. It is important to note that load decreases could be produced by decreasing any or all sources of nitrogen to the system.

The septic loading for the threshold condition is shown in Table VIII-2. The nitrogen septic loads have not changed from the Present Conditions loads developed in Section VI.

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the Wellfleet Harbor System. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.			
sub-embayment	Present septic load (kg/day)	Threshold septic load (kg/day)	Threshold % change
Herring River/The Gut	11.75	11.16	-5.0%
Duck Creek	4.24	0.64	-85.0%
The Cove	7.97	1.19	-85.0%
Drummer/Blackfish	5.80	2.03	-65.0%
Hatches Creek	7.30	7.30	+0.0%
Wellfleet Harbor	13.68	4.79	-65.0%
Loagy Bay	1.93	0.67	-65.1%

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the septic loads depicted in Table VIII-2. The total nitrogen loads for Wellfleet Harbor are presented in Table VIII-4. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent 'worst-case' summertime conditions. The benthic flux for this modeling effort is reduced from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Cape Cod Bay.

Table VIII-3. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of Wellfleet 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
Herring River/The Gut	27.72	27.13	-2.1%
Duck Creek	5.40	1.80	-66.7%
The Cove	9.82	3.04	-69.0%
Drummer/Blackfish	7.36	3.59	-51.2%
Hatches Creek	9.46	9.46	+0.0%
Wellfleet Harbor	17.53	8.64	-50.7%
Loagy Bay	2.45	1.19	-51.2%

Table VIII-4. Threshold sub-embayment loads and attenuated surface water loads used for total nitrogen modeling of the Wellfleet 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)
Herring River/The Gut	27.13	2.81	18.70
Duck Creek	1.80	--	17.88
The Cove	3.04	2.22	133.46
Drummer/Blackfish	3.59	1.66	6.47
Hatches Creek	9.46	0.15	-7.84
Wellfleet Harbor	8.64	64.72	44.61
Loagy Bay	1.19	0.99	8.65

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

Table VIII-5. Comparison of model average total N concentrations from present loading and the modeled threshold scenario, with percent change over background in Cape Cod Bay (0.422 mg/L), for the Wellfleet Harbor system.				
Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	Threshold % change
Lower Wellfleet Harbor	WH-1	0.452	0.449	-11.6%
Mid Wellfleet Harbor	WH-2	0.466	0.461	-11.8%
Mid Wellfleet Harbor	WH-3	0.476	0.470	-10.3%
Mid Wellfleet Harbor	WH-4	0.507	0.497	-11.8%
Upper Wellfleet Harbor	WH-5	0.546	0.532	-11.6%
Blackfish Creek	WH-6	0.516	0.504	-12.6%
Blackfish Creek	WH-7	0.531	0.517	-13.4%
Herring River-Mouth Lo	WH-8	0.599	0.581	-10.0%
Herring River-Mouth Up	WH-9	0.732	0.710	-7.1%
The Cove Outer	WH-10	0.645	0.616	-12.9%
The Cove	WH-11	0.762	0.716	-13.7%
Duck Creek	WH-12	0.930	0.859	-14.0%

IX. ALTERNATIVE WATER QUALITY MODEL SCENARIO

While discussing potential future water quality management strategies with Town of Wellfleet staff and committee member, the Town requested an alternative buildout scenario. This scenario is based on an interim 2030 development forecast and refinements coordinated with the Town to incorporate the forecast results into the MEP linked models. This scenario did not look at land classification, but rather evaluated housing and populations trends. Data reviewed included a) housing additions, including new residences and rebuilds, allowed through town permits between 2005 and 2010, b) town year-round population based on US Census counts between 1900 and 2010, and c) estimates of summer population based on an assumed ratio of ~5 between summer and winter populations (9/30/11 Memo from Wellfleet Comprehensive Wastewater Management Planning Committee). This analysis completed by the Town CWMP committee resulted in 131 new dwelling units in Wellfleet at 2030, as compared to MEP estimate of 1,517 new dwelling units based on development of all available properties according to current zoning. Under this scenario, Truro and Eastham buildout additions within the watershed remain the same as estimated under the MEP buildout. In addition, no future additional commercial or industrial development is included in this alternative buildout scenario. Dwelling unit additions for the alternative scenario were assigned on a subwatershed basis and the resulting watershed nitrogen loads are shown in Table IV-3. Based on the alternative buildout assessment, buildout additions within the Wellfleet Harbor watersheds will increase the unattenuated watershed nitrogen loading rate by 3%.

IX.1 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 alternative buildout 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 Hatches Creek watershed, where the N load increase is 3.7 kg/day, which is a 39% increase over existing loading conditions. Overall, the total watershed loading of the whole Wellfleet Harbor system increases 5.79 kg/day, which is a 7.3% increase compared to present loading.

Table IX-1. Alternative Buildout scenario sub-embayment and surface water loads used for total nitrogen modeling of the Wellfleet 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)
Herring River/The Gut	28.43	2.81	21.00
Duck Creek	5.51	--	20.13
The Cove	10.22	2.22	151.05
Drummer/Blackfish	7.61	1.66	7.31
Hatches Creek	13.16	0.15	-8.70
Wellfleet Harbor	18.04	64.72	48.62
Loagy Bay	2.55	0.99	9.83

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 Wellfleet 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)	alternative buildout scenario load (kg/day)	scenario % change
Herring River/The Gut	27.718	28.430	+2.6%
Duck Creek	5.403	5.507	+1.9%
The Cove	9.819	10.219	+4.1%
Drummer/Blackfish	7.362	7.614	+3.4%
Hatches Creek	9.458	13.156	+39.1%
Wellfleet Harbor	17.526	18.044	+3.0%
Loagy Bay	2.449	2.551	+4.1%

Table IX-3. Comparison of model average total N concentrations from present loading and the Alternative Buildout scenario, with percent change over background in Cape Cod Bay (0.422 mg/L), for the Wellfleet Harbor system.				
Station Location	monitoring station	present (mg/L)	alternative buildout (mg/L)	% change
Lower Wellfleet Harbor	WH-1	0.452	0.453	+2.6%
Mid Wellfleet Harbor	WH-2	0.466	0.467	+2.7%
Mid Wellfleet Harbor	WH-3	0.476	0.479	+7.3%
Mid Wellfleet Harbor	WH-4	0.507	0.509	+2.5%
Upper Wellfleet Harbor	WH-5	0.546	0.549	+2.5%
Blackfish Creek	WH-6	0.516	0.519	+2.7%
Blackfish Creek	WH-7	0.531	0.534	+2.6%
Wellfleet Harbor	WH-8	0.599	0.604	+2.7%
Herring River / Gut	WH-9	0.732	0.742	+3.1%
The Cove Outer	WH-10	0.645	0.650	+2.2%
The Cove	WH-11	0.762	0.769	+2.1%
Duck Creek	WH-12	0.930	0.940	+1.9%

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