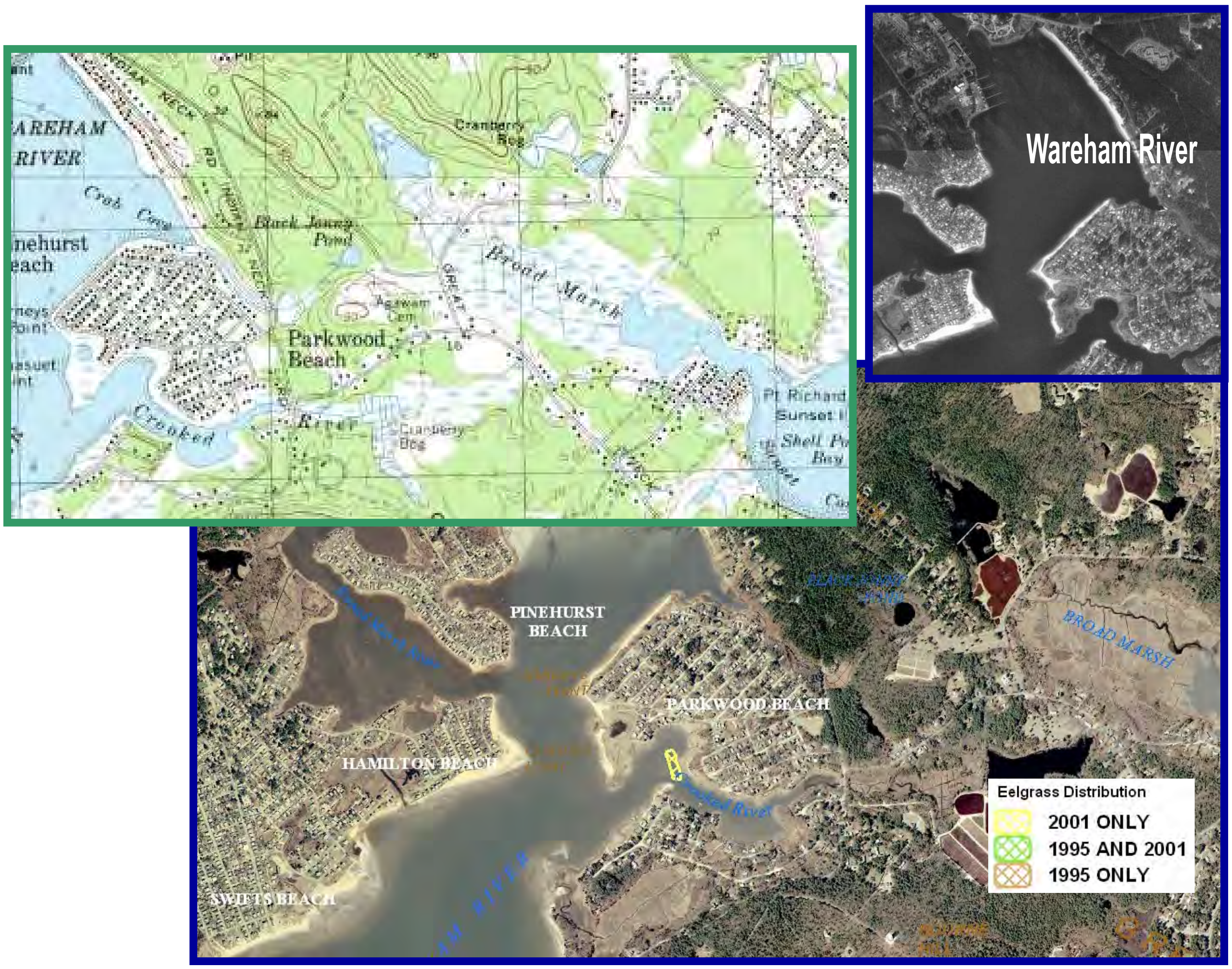
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Wareham River, Broad Marsh and Mark's Cove Embayment System, Wareham, Massachusetts



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Massachusetts Department of
Environmental Protection

FINAL UPDATED REPORT – MAY 2014

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Executive Summary

1. Background

This updated report builds on the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach which was applied to the Wareham River / Marks Cove / Broad Marsh Embayment System and first completed in 2007. The 2007 draft report was refined and submitted to the MassDEP on June 30, 2009 subsequent to an update of the watershed delineations completed by the US Geological Survey during the USGS upgrade of the Plymouth-Carver Aquifer Model. The overall embayment system is situated primarily within the Town of Wareham, Massachusetts, the major steward of the water and resource quality. However, portions of the overall watershed does extend up into the Towns of Plymouth and Carver (more so Plymouth than Carver). The present update incorporates information obtained subsequent to the completion of the original analysis (2009) and addresses clarifications requested by the Buzzards Bay Project (September 29, 2009). Point by point responses to comments from the Buzzards Bay Project are also available in a MEP Technical Memorandum issued to the MassDEP on March 14, 2010. The key underlying refinement in the present report involves an update to the land-use database used by the Towns and provided to the MEP. The updating of the parcel database included reformatting GIS files and cross-checks as well as a re-evaluation of water use and sewershed linkages, updates related to developed versus undeveloped and developable parcels, in addition to new wetland survey information and the treatment of cranberry bogs, all of which has been conducted over the past several years by the Buzzards Bay Project, MassDEP and MEP/SMAST staff. The refinements to the land-use database have been used by the MEP to reconstruct the watershed nitrogen loading model, which then required a recalibration of the water quality model and associated assessments. In support of the revision of the loading models, additional data on nitrogen sources/strength were integrated into the update of the MEP threshold analysis. As a result of the refinements to the land-use database, the MEP/SMAST Technical Team completed a new build-out nitrogen loading projection for the present report update which will greatly enhance on-going nutrient management planning associated with these estuaries.

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Wareham River / Marks Cove / Broad Marsh embayment system, a coastal embayment within the Town of Wareham, Massachusetts. Updated analyses of the Wareham River embayment system were performed to assist the Town with on-going nitrogen management decisions associated with the Towns' current and future wastewater planning efforts, as well as wetland restoration, cranberry bog management, anadromous fish runs, shell fishery, open-space, and watershed development issues. As part of the MEP approach, habitat assessment was conducted on the embayment based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Town of Wareham 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 Wareham River embayment system (inclusive of Marks Cove and Broad Marsh), (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 Wareham River 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 Wareham River embayment system within the Town of Wareham and parts of Carver and Plymouth is at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater and surface water from the increasingly developed watershed to this coastal system. Eutrophication is a process that occurs naturally and gradually over a period of tens or hundreds of years. However, human-related (anthropogenic) sources of nitrogen may be introduced into ecosystems at an accelerated rate that cannot be easily absorbed, resulting in a phenomenon known as cultural eutrophication. In both marine and freshwater systems, cultural eutrophication results in degraded water quality, adverse impacts to ecosystems, and limits on the use of water resources.

The Town of Wareham has recognized the severity of the problem of eutrophication and the need for watershed nutrient management and while engaging in the MEP assessment of the Wareham River system, in 2007 the Town invested significant resources to upgrade its municipal wastewater treatment facility. However, the need for continued nitrogen management remains as large development projects are proposed within the coastal watershed of the Wareham River system. The Town of Wareham recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making and alternatives analysis relative to the upgrade of the Town of Wareham Wastewater Treatment Plant that operates within the Agawam River sub-watershed as well as current nitrogen management issues related to proposed development projects in the Wareham River watershed. The completion of this multi-step process has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, which is a partnership effort between all MEP collaborators and the Town. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns' nutrient management groups to predict the impacts on water quality from a variety of proposed management scenarios.

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

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

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

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

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

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

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

Application of MEP Approach: The Linked Model was applied to the Wareham River embayment system by using site-specific data collected by the MEP and water quality data from the Buzzards Bay Coalition BayWatcher Program (see Chapter 2). Evaluation of upland nitrogen loading was conducted by the MEP with land use and water use data provided by the Town of Wareham Planning Department as well as the Southeastern Regional Planning and Economic Development District (SRPEDD) and the Buzzards Bay Project. Watershed boundaries were re-delineated by the USGS during its 2009 update of the Plymouth-Carver Aquifer Model. This land-use data was used to determine watershed nitrogen loads within the Wareham River embayment system and the systems sub-embayments (Mark's Cove and Broad

Marsh) as appropriate (current and build-out loads are summarized in Table IV-3). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Wareham River – Mark's Cove – Broad Marsh embayment system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates. Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic model was then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis while nitrogen entering Wareham's 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 Buzzards Bay source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Wareham River embayment system were 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 system in this study were developed to restore or maintain SA waters or high habitat quality. High habitat quality was defined as supportive of eelgrass and infaunal communities. Dissolved oxygen and chlorophyll a were also considered in the assessment.

The nitrogen thresholds developed in Section VIII-2 of this report were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Wareham River system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel station (WR-6) chosen for the Wareham River system, being mindful of target concentrations for secondary check stations WR-5, WR-2 and BMR-4 (Broad Marsh). It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented in the report represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation in this report of load reductions aims to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Wareham River embayment system in the Town of Wareham. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. The MEP analysis has initially focused upon nitrogen loads from on-site septic systems as a test of the potential for achieving the level of total nitrogen reduction for restoration of each embayment system. It should be noted that nutrient load reductions resulting from the recent upgrade to the Wareham WWTF was incorporated into this analysis thus further refining the target nitrogen loads to the overall Wareham River system as this upgrade significantly reduced the total nitrogen load entering this system.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout the Wareham River system based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. The Wareham River Embayment System is a complex estuary composed of 3 functional types of component basins: an embayment (Wareham River-Marks Cove), a salt marsh pond/embayment (Broad Marsh River) and a tidal river with significant marginal wetlands (Agawam-Wankinco estuarine reaches). Each of these 3 functional components has different natural sensitivities to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of each system and their respective ability to support eelgrass beds and the types of infaunal communities that they support. At present, the Wareham River Embayment System is showing variations in nitrogen enrichment and habitat quality among its various component basins. In general the system is showing healthy to moderately impaired benthic habitat. However, the lower basins (e.g. lower Wareham River, Marks Cove) are clearly significantly impaired based on eelgrass criteria, as historical eelgrass beds have been lost and eelgrass is no longer present within these areas of the System. The upper Wareham River basin is moderately impaired based upon eelgrass criteria, as it still supports some eelgrass, but the prior beds have been reduced to sparse coverage at the basin's northeast margin. All of the habitat indicators show consistent patterns of habitat quality in each of the major subembayments and those habitat impairments are consistent with nitrogen enrichment (Chapter VII).

Overall, the oxygen levels within the major sub-basins to the Wareham River System are indicative of relatively healthy or only moderately impaired conditions, since the upper reaches are defined as infaunal habitats (e.g. historically have not supported eelgrass) and considering their physical structure and natural biogeochemical cycling. The dissolved oxygen throughout the Wareham River Embayment System generally showed moderate depletions during the critical summer period. Oxygen depletions were generally associated with the wetland dominated tributary basins, with higher oxygen levels maintained in the main embayment basin. The continuous D.O. records indicate that the upper region of Wareham River Embayment System, defined by the Agawam River estuarine reach, shows periodic oxygen depletion during summer given its nitrogen and organic matter enrichment. It appears that the organic matter enrichment results in part from the system's role as a tidal river bordered by extensive wetlands and from in situ phytoplankton production supported by nitrogen inputs. Oxygen conditions and chlorophyll a levels tend to improve with decreasing distance to the tidal inlet. Oxygen levels in the region of The Narrows are influenced by outflows from the estuarine reaches of the Agawam and Wankinco Rivers, but only rarely showed oxygen depletions to <5 mg L^{-1}, while the lower Wareham River consistently maintained oxygen levels of >5 mg L^{-1}. The lower basin of the

Broad Marsh River also supported oxygen levels >5 mg L^{-1}, except for brief excursions slightly below 5 mg L^{-1}.

The infaunal study indicated an overall system generally supportive of healthy to moderately impaired infaunal habitat relative to the ecosystem types represented (i.e. embayment versus salt marsh creek/pond). The Infauna Study indicated that most areas, with the exception of the uppermost stations in the Agawam River estuarine reach are presently supporting healthy to moderately impaired habitat for infaunal animal communities. The habitat quality of the uppermost reach of the Agawam River Estuary is uncertain, as it contains fresh/brackish water invertebrates and appears to be transitional between fresh and estuarine habitat. The low species numbers and moderate density of individuals with low diversity and evenness indicated a stressful environment, but the cause, nutrient enrichment versus salinity versus wetland influences, could not be differentiated.

Of the remaining clearly estuarine basins, the lower Agawam River estuary supported infaunal communities consistent with a wetland dominated, organic matter enriched estuarine sediment, with moderate to high numbers of individuals and a moderate number of species, hence moderate diversity and evenness. These characteristics are typical of a healthy to moderately impaired condition. In contrast, the Wankinco/Agawam basin and the down-gradient region of the upper Wareham River (basin south of The Narrows) show clear impairment of their communities as assessed by numbers, diversity and evenness and as such are classified as significantly to moderately impaired. The upper basin of the Wareham River showed a clear difference from the entrance to The Narrows (Significantly Impaired) compared to its lower portion (Moderately Impaired). This gradient is consistent with the observed oxygen gradient and the likely transport of low quality water from the Agawam/Wankinco basin on the ebbing tides. The overall results indicate a system generally supportive of high quality to moderately impaired infaunal community habitat, relative to each of the 3 component functional basin types comprising the Wareham River Embayment System, each with its different sensitivity to nitrogen enrichment and organic matter loading.

The present virtual absence of eelgrass throughout the Wareham River Embayment System is consistent with the observed nitrogen and the chlorophyll levels and functional basin types comprising this estuary. The upper estuarine reaches and most of the Broad Marsh River are strongly influenced by surrounding wetlands and do not typically support eelgrass habitat, due to their naturally nutrient enriched shallow waters and salt marsh function. However, basins like the Wareham River and Marks Cove (from The Narrows to Cromset Point and especially the lower basin of the Wareham River) typically do support eelgrass habitat under low to moderate nitrogen loading conditions. The distribution of eelgrass in 1985 is fully consistent with this functional analysis and the conclusion that the lower region of this Estuary (e.g. Barneys Point to Cromset Point), as well as the upper basin (The Narrows to Barneys Point) are currently over their nitrogen threshold level that supports healthy eelgrass habitat

Analysis of the MassDEP mapped eelgrass beds which have persisted just outside of the tidal inlet in the large boundary basin between Cromset Point and Buzzards Bay (e.g. Bourne Point), supports the contention that the recent loss of eelgrass within the Wareham River is the result of nitrogen enrichment, as the well flushed outermost beds have been extremely stable over the past decades. These beds are at similar water depths and have the same tidal excursion as the historical bed areas within the lower estuary, so the major environmental differences between the sites appear to be directly related to nitrogen enrichment. It appears from the eelgrass and water quality information that eelgrass beds within the lower basin of the Wareham River (inclusive of Marks Cove) and in the shallow margins of the upper basin should be the target for restoration and that this habitat should be recovered with appropriate nitrogen management.

3. Conclusions of the Analysis

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

Threshold nitrogen levels for each of the sub-embayment systems in this study were developed to restore or maintain SA waters or high habitat quality. In these systems, high habitat quality was defined as supportive of eelgrass and 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 Wareham River embayment system were comprised primarily of wastewater nitrogen. The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and cranberry bogs, with lawns usually being the predominant source within this category. In order to add these sources to the nitrogen loading model for the Wareham River estuary system, MEP staff reviewed available information about residential lawn fertilizing practices and incorporated site-specific information to determine nitrogen loading from other fertilization applications in the watershed. Cranberry bog nitrogen loading was determined based on previous studies conducted in southeastern Massachusetts

A major finding of the MEP clearly indicates that a single total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of the Great, Green and Bournes Pond Systems, Popponesset Bay System, the Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay and the Pleasant Bay and Nantucket Sound embayments associated with the Town of Chatham, to name a few. This is almost certainly going to be true for the other embayments within the MEP area as well, including the systems in the Town of Wareham such as the Weweantic River (MEP threshold analysis to be completed).

The threshold nitrogen levels for the Wareham River embayment system were determined as follows:

Wareham River Embayment System Threshold Nitrogen Concentrations

- The sentinel station (WR-6) for the Wareham River Embayment System was selected based upon its location within the uppermost reach of documented established eelgrass coverage in this estuary, with only fringing beds in shallow waters north of this point. The sentinel station is within the Wareham River lower basin, near the mouth of Broad Marsh River and is a long-term BayWatcher Water Quality Monitoring station. The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location within the lower reach of the Wareham River was determined to be 0.40 mg TN L^{-1} at the sentinel station (WR-6) and 0.42 mg TN L^{-1} within the marginal regions (shallows) north of this region (adjacent to WR-5).

- The secondary level to check restoration of marginal beds in lower reach of Wareham River (0.42 mg TN L^{-1}) is consistent with the analysis of restoration of fringing eelgrass beds in Great Pond (Falmouth), and analysis where eelgrass beds in deep waters could not be supported at a tidally averaged TN of 0.412 mg TN L^{-1} at depths of 2 m. Similarly prior MEP analysis in Bournes Pond indicated that tidally averaged TN levels of 0.42 mg TN L^{-1} excluded beds from all but the shallowest water. The MEP Technical Team cannot specify the exact extent of marginal beds to be restored in the upper deep basins. At tidally averaged TN levels of 0.42 mg TN L^{-1} the eelgrass habitat would be restricted to very shallow waters, while at 0.40 mg TN L^{-1} the eelgrass habitat should reach to 1-2 meters depth, based upon the data from regional systems.

- In addition to the primary nitrogen threshold at the sentinel station and secondary check associated with restoration of marginal eelgrass beds, the MEP establishes additional criteria, to ensure that all impaired regions are restored if the threshold at the sentinel station is achieved. These values merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station. Secondary criteria were established at two locations within the Wareham River System: a TN level of 0.5 mg N L^{-1} within the Agawam/Wankinco basin (measured at WR-2) and within Broad Marsh River (BMR-4) to ensure restoration of infaunal habitat throughout these sub-embayments. In tributary systems to Buzzards Bay, where certain basins are characterized as deep, enclosed, depositional environments, TN levels <0.5 mg N L^{-1} were found to be supportive of healthy infaunal habitat (e.g. Eel Pond in Bourne).

It is important to note that the analysis of future nitrogen loading to the Wareham River estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that significant increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers. Therefore, watershed-estuarine nitrogen management must include management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Wareham River estuarine system is that restoration will necessitate a reduction in the present (Wareham 2009, Plymouth and Carver 2006) nitrogen inputs and management options to negate additional future nitrogen inputs.

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

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. [8] (mg/L)
WAREHAM RIVER SYSTEM										
groundwater sources										
Broad Marsh	0.627	3.674	4.271	-	7.945	1.681	15.656	25.282	0.54-0.65	0.50
Marks Cove	0.411	3.271	1.603	-	4.874	0.959	2.987	8.820	0.42-0.46	-
Crab Cove	0.156	1.049	2.499	-	3.548	1.614	-0.125	5.037	0.46-0.49	0.42
Crooked River	0.296	1.351	4.000	-	5.351	0.333	-0.745	4.938	-	-
Wareham River - lower	0.123	0.219	0.499	-	0.718	5.180	73.028	78.926	0.41-0.45	0.40
Wareham River - upper	1.332	5.526	18.140	18.523	42.189	1.803	-1.431	42.561	0.53-0.55	-
surface water sources										
Agawam River	8.584	22.112	12.156	-	34.268	-		34.268	-	-
Wankinco River	8.110	25.909	4.677	-	30.586	-		30.586	-	-
Wareham River System Total	19.638	63.111	47.845	18.523	129.479	11.570	89.369	230.419	**0.41-0.65**	**0.40**

[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 attenuated wastewater treatment facility discharges to groundwater
[4] composed of combined natural background, fertilizer, runoff, and septic system loadings (the sum of land use, septic, and WWTF loading)
[5] atmospheric deposition to embayment surface only. Atmospheric loads to surface water inputs are included with their respective watershed load.
[6] composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
[7] average of 2001 – 2006 data, ranges show the upper to lower regions (highest-lowest) of a sub-embayment.
[8] Main eel grass threshold for sentinel site located in Wareham River (0.40 mg/L), and infaunal target in Broad Marsh River (0.50 mg/L).

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

Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
WAREHAM RIVER SYSTEM						
groundwater sources						
Broad Marsh	7.945	4.101	1.681	12.168	17.950	-48.4%
Marks Cove	4.874	4.073	0.959	2.407	7.438	-16.4%
Crab Cove	3.548	2.299	1.614	-0.097	3.815	-35.2%
Crooked River	5.351	2.551	0.333	-0.594	2.290	-52.3%
Wareham River - lower	0.718	0.468	5.180	58.800	64.449	-34.7%
Wareham River - upper	42.189	19.121	1.803	-1.133	19.791	-54.7%
surface water sources						
Agawam River	34.268	22.112	-	-	22.112	-35.4%
Wankinco River	30.586	25.851	-	-	25.851	-15.5%
Wareham River System Total	129.479	80.634	11.570	71.551	163.694	-37.7%

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

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The Massachusetts Estuaries Project Technical Team would like to acknowledge the contributions of the many individuals who have worked tirelessly for the restoration and protection of the critical coastal resources of the Wareham River, Broad Marsh and Mark's Cove Embayment System and supported the application of the Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for this system. Without these stewards and their efforts, this project would not have been possible.

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I. INTRODUCTION

The Wareham River Estuarine System (inclusive of Wankinco River, Agawam River, Broad Marsh Rivers and Marks Cove) and its associated watershed is located primarily within the Town of Wareham, in southeastern Massachusetts. A smaller fraction of the overall watershed to the estuarine system extends into the Towns of Plymouth and Carver. This complex estuary is a tributary embayment to Buzzards Bay, with which it exchanges tidal water twice daily. The watershed contributing freshwater and nutrients to this embayment system is comprised mostly of forestlands and is the third largest drainage basin within the greater Buzzard's Bay watershed. Land use in the lower watershed includes dense residential and commercial areas, while the upper watershed is lightly developed with significant cranberry growing operations. The Wareham River System is one of the Town of Wareham's significant marine resources. Despite the high acreage of undeveloped land in the Wareham watershed, the Wareham River System has been degraded through nitrogen enrichment. The historical major point source of nitrogen to the system has been the Wareham Wastewater Treatment Facility which has been recently upgraded to discharge 1 MGD (million gal/day) of tertiary treated effluent to the headwaters of the estuarine reach of the Agawam River. While the upgrade to the WWTF has reduced the nitrogen loading to this system in the short-term, development of the watershed is continuing. Also, significant in maintaining the water quality within this system is the flushing rate and tidal exchange with the high quality waters of Buzzards Bay.

The Wareham River System is a drowned river estuary receiving freshwater inflows from 2 of the major rivers to Buzzards Bay, the Wankinco River to the west and the Agawam River to the east. These 2 rivers discharge to the upper reaches of the estuarine system. The merging of these 2 rivers forms the Wareham River, which is fully tidal throughout its length (Figure I-1). The Wankinco and Agawam rivers together contribute almost 10% of the total freshwater inflow to Buzzards Bay. The Wareham River Embayment System, is a complex estuary with several tributary sub-basins including Broad Marsh River, Crab Cove, Crooked River and Marks Cove. The mouth of the Estuary occurs at Long Beach Point and Cromset Point at the tip of Cromset Neck. Cromset Neck separates the Wareham River Estuarine System from the adjacent Weweantic River System. Since the Wareham River and the Weweantic River discharge to and receive tidal inflows through a common basin it can be ascertained that nitrogen outflows from the two systems mix and portions of this nitrogen load re-enters both systems on flooding tides. Nutrient management of the Wareham River System is linked in part to the Weweantic River, although the dominant source of its nutrients is its own watershed.

The Wareham River Estuary is a tidal embayment with two large groundwater fed rivers, the Wankinco and Agawam, originating in shallow Parkers Mill Pond (up gradient of Main Street) and Mill Pond (up gradient of Route 6), respectively. Both the estuarine reaches of the Wankinco and Agawam Rivers come together and discharge to the headwaters of the Wareham River estuary through Wareham Narrows. Also included in the Wareham River Estuary are 291 acres of salt marsh bordering the Agawam and Broad Marsh Rivers and Marks Cove. Almost all of the of salt marsh in the Wareham River System is held within the Agawam River estuarine reach with a smaller portion of salt marsh present in the Broad Marsh sub-embayment. The Wareham River acts as a mixing zone for terrestrial freshwater and groundwater inflows and saline tidal flow from Buzzards Bay. The salinity characteristics of the system vary with the volume of freshwater inflow, as well as the effectiveness of tidal exchange and possibly interactions with the outflow from the Weweantic River, south of Cromset Point. Overall, the large freshwater contributing area and moderate tide range results in a relatively well-defined horizontal salinity gradient throughout much of the upper portions of the estuarine system.

Figure I-1. Wareham River study region for the Massachusetts Estuaries Project nutrient analysis. Tidal waters enter the estuarine system through one inlet to Buzzards Bay. Freshwaters enter from the watershed primarily through the Wankinco and Agawam Rivers.

The Wareham River Estuarine System has historically supported high quality habitats associated with high nutrient related water quality, such as eelgrass beds throughout the Wareham River Basin from The Narrows to south of Long Beach Point. But as in many other embayments in southeastern Massachusetts, the Wareham River System is presently a nitrogen enriched shallow water estuarine system. Current eelgrass surveys and mapping by the Massachusetts DEP Wetland Conservancy Program in 1996 show that eelgrass communities had all but disappeared by 1995. The presence of eelgrass is particularly important to the use of Wareham River as fish and shellfish habitat. The Wareham River System represents an important shellfish resource to the Town of Wareham that is primarily off-limits based on year round prohibition by the Division of Marine Fisheries (Wareham Narrows up gradient of Pinehurst Beach). In a few areas, however, shellfishing activities are only seasonally suspended by the Massachusetts Division of Marine Fisheries as a result of bacterial contamination from watershed run-off and other potential sources. Selectively open DMF segments located in the Wareham River system include BB:36.8 (Broad Marsh middle region and lower region by the mouth), BB:36.21 (portion of Marks Cove), and BB:36.20 (Cromset Neck north of Nobska Point). The DMF designated shellfish growing area BB:36.0 (main open water portion of Wareham River) is approved for shellfishing year round. The shellfish closures and documented eelgrass loss has raised public concern over the estuarine resources within this system in recent years.

The Wareham River Estuary is important for recreational boating and swimming and supports boat slips for approximately 486 boats and 4 public beaches. The Warr's Marina facility, on lower Main Street, includes facilities for off-loading boat waste including a pump-out boat, dockside facility and waste dump facility.

The nature of enclosed embayments in populous regions brings two opposing elements to bear: as protected marine shoreline they are popular regions for boating, recreation, and land development; as enclosed bodies of water, they may not be readily flushed of the pollutants that they receive due to the proximity and density of development near and along their shores. In particular, the Wareham River System, like many other embayment systems in the region, is at risk of eutrophication from high nitrogen loads in the groundwater and runoff from their watersheds.

The primary ecological threat to Wareham River Estuary resources is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters has declined slightly as a result of the upgrade of the Wareham WWTF to tertiary treatment. However, new nitrogen sources are added to the watershed as development continues. At present, nitrogen loading to the estuary is not supportive of healthy estuarine habitats and impairment is likely to increase over what has been observed over the past few decades unless nitrogen management is implemented. The nitrogen loading to Wareham River and other Wareham embayments (e.g. the Weweantic River), like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. Unlike other towns in the MEP study region, the Town of Wareham does have centralized wastewater treatment. The Wareham Wastewater Treatment Facility currently discharges 1 MGD (million gal./day) of high quality effluent, which enters the estuary near the upper estuarine reach of the Agawam River. This facility services areas outside of the Wareham River Watershed including the Town of Bourne. These sewered areas contribute significantly to the nitrogen loading of the Wareham River System. In addition, the Wareham River watershed includes a variety of nutrient sources, among them the runoff from roads and lawns, as well as effluent from a growing number of residential septic systems. One of the potential sources of nitrogen of public concern has been cranberry agriculture which has been carefully considered in the MEP loading analysis and has been the subject of numerous scientific studies, the results of which have been incorporated into the MEP analysis.

The greatest level of development and residential load is situated in the nearshore regions of the system. Estimates of nitrogen loading to the Wareham River from the watershed have been previously conducted by Camp Dresser and McKee for the Town of Wareham and

SMAST scientists, the Cape Cod Commission and the Buzzards Bay Project. The bulk of the present nitrogen loading is from unsewered residential housing and light commercial areas, associated impervious sources (roads, driveways, etc.), and the Wastewater Treatment Facility within the system watershed. At present, Wareham River appears to be beyond its ability to tolerate additional nitrogen inputs.

The Town of Wareham and its citizens, as the primary stakeholders to the Wareham River embayment system, have been concerned over the resource quality of this significant coastal system. The community has gradually worked to implement controls on direct stormwater discharges, while also undertaking significant improvement of the treatment train at the Wastewater Treatment Facility. In addition, the Town of Wareham has supported the Coalition for Buzzards Bay's Water Quality Monitoring Program, which has been collecting data on nitrogen related water quality within the Wareham River System since 1992. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of Wareham's embayments and harbors. The BayWatchers is a citizen-based water quality monitoring program run by the Coalition for Buzzards Bay (T. Williams, Project Coordination) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD. The common focus of the Coalition for Buzzards Bay BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay and determine the relationship between observed water quality and habitat health. The present MEP effort builds upon the Coalition for Buzzards Bay water quality monitoring program and previous analyses conducted by the Town of Wareham and its wastewater consultants (CDM Inc), while also including high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Wareham River embayment system. The present MEP effort is the necessary "next step" in the restoration of the Wareham River System, by providing quantitative restoration targets for nitrogen throughout this complex estuary.

In conjunction with other Town efforts, the Town of Wareham's Planning Office continues to enhance its tools for gauging future nutrient effects from changing land-uses. The GIS database used in the present MEP evaluation is part of that continuing effort. Based on the wealth of information obtained over the many years of study of the Wareham River System, particularly as relates to 1) the Wareham Wastewater Treatment Facility, 2) the Coalition for Buzzard Bay's Water Quality Monitoring Program and 3) the eelgrass mapping (Costa 1988, MassDEP), the Wareham River Embayment System (inclusive of Broad Marsh River, Crooked River and Marks Cove) was included in the first round prioritization of the Massachusetts Estuaries Project to receive state-of-the-art analysis and modeling.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning and nitrogen management alternatives development needed by the Town of Wareham. 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 Wareham to develop and evaluate the most cost effective nitrogen management alternatives to restore the Town's valuable coastal resources currently being degraded by nitrogen overloading.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

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

The primary nutrient causing the increasing impairment of the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within Southeastern Massachusetts alone, almost all of the municipalities (as is the case with the Town of Wareham) 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 newest generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (MassDEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts.

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region's coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the MASSDEP with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads

(TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

In appropriate estuaries, TMDLs for bacterial contamination will also be conducted in concert with the nutrient effort (particularly if there is a 303d listing). However, the goal of the bacterial program is to provide information to guide targeted sampling for specific source identification and remediation. As part of the overall effort, the evaluation and modeling approach will be used to assess available options for meeting selected nitrogen goals, protective of embayment health.

The major Project goals are to:

- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of 70 of 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment model available to address future regulatory needs.

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

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

The Linked Model has been applied for watershed nitrogen management in ca. 59 embayments throughout Southeastern Massachusetts. In these applications it has become clear that the Linked Model Approach’s greatest assets are its ability to be clearly calibrated and validated, and its utility as a management tool for testing “what if” scenarios for evaluating watershed nitrogen management options.

The Linked Watershed-Embayment Model when properly parameterized, calibrated and validated for a given embayment becomes a nitrogen management planning tool, which fully supports TMDL analysis. The Model suggests "solutions" for the protection or restoration of nutrient related water quality and allows testing of "what if" management scenarios to support evaluation of resulting water quality impact versus cost (i.e., "biggest ecological bang for the buck"). In addition, once a model is fully functional it can be "kept alive" and corrected for continuing changes in land-use or embayment characteristics (at minimal cost). In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries.

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

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

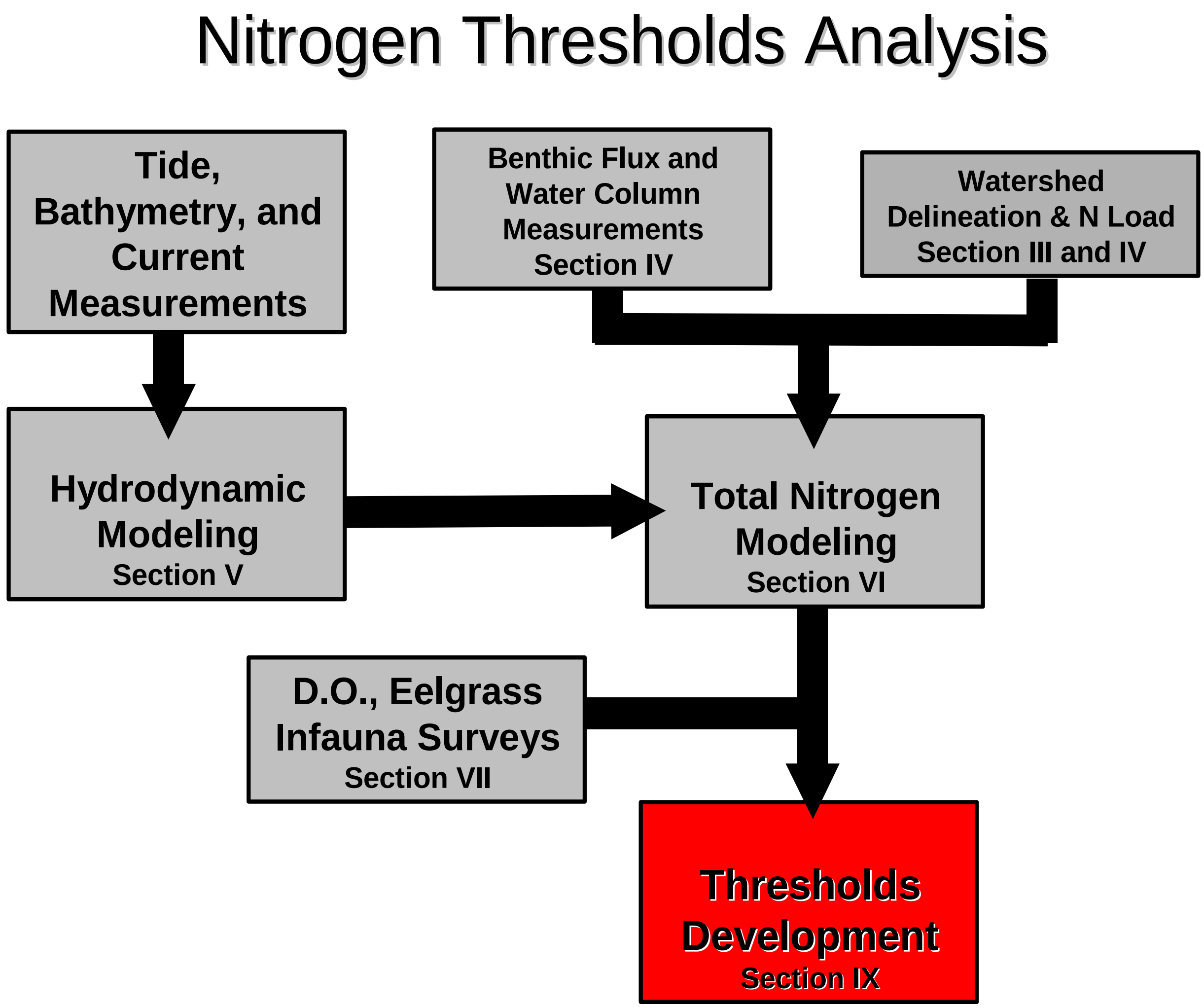


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

I.2 SITE DESCRIPTION

The Wareham River Embayment System is a complex estuarine system tributary to Buzzards Bay on its northwestern shore. The large upper watershed is drained by 2 large river systems, the Wankinco River and Agawam River, which run in a north – south manner. Both the Agawam River and Wankinco River are among the largest rivers discharging to Buzzards Bay. These rivers discharge to the head of the estuary. The central estuary from the discharge of these rivers to the systems mouth at Cromset Point is a drown river valley estuary, with smaller tributary basins, Broad Marsh Cove, Crooked River and Marks Cove.

The watershed to the Wareham River embayment system is geologically complex and resides within the Buzzards Bay Basin. The Buzzards Bay Basin is characterized by glacial processes that defined the surficial geology of the region during the retreat of the Cape Cod Lobe of the Laurentide Ice sheet ~18,000 years ago. The Buzzards Bay Basin is underlain primarily by granitic and metamorphic bedrock at depths ranging from outcrops at the land surface to approximately 100 to 200 feet below land surface depending on the location in the basin (Bent, 1995). Most of the surficial deposits in the Buzzards Bay Basin were deposited during the retreat of the glaciers during the last glacial period and are primarily composed of till and stratified drift deposits. Till was deposited over bedrock during the retreat of the glaciers and characterizes much of the Buzzards Bay Basin. The till is generally overlain by stratified drift deposits. As described by Melvin and others (Melvin, 1992) the till deposits in southern New England are relatively sandy and in areas overlain by stratified drift deposits the thickness of till layers can be less than 10 feet. In areas not overlain by stratified drift deposits the thickness of the till layer can be as much as 30 feet. Unlike till, stratified drift deposits are composed of glaciofluvial and glacial lacustrine deposits of all grain sizes ranging from cobbles to clay (inclusive of silts, sands and gravels). The glaciofluvial deposits were generated mainly by glacial meltwater streams in outwash plains and river valleys (Stone and Peper, 1982). Glaciolacustrine deposits were generated during the presence of glacial lakes formed during the retreat of the ice sheet in southern New England and are comprised mainly of silts and clays as well as fine sands (Hansen and Lapham, 1992).

In the watershed of the Wareham River System, stratified-drift deposits are common (Williams and Tasker, 1994). Additionally, the watershed to the Wareham River system can be further characterized as an outwash plain termed the Wareham Pitted Plain that slopes to the south – southwest. This outwash plain is composed mostly of flat-lying to gently dipping beds of sand and gravel deposited by glacial meltwater streams (Hansen and Lapham, 1992). The vast majority of the depositional and structural characteristics of the watershed to the Wareham River System were defined by a complicated sequence of advances and retreats of the ice sheet in this region. As such, the predominant features in the watershed are moraines and outwash plains interspersed with glaciofluvial and glaciolacustrine deposits. Two southwest trending moraines, the Hog Rock and the Snipatuit moraines are present in the upper portions of the Wareham River watershed and demarcate the various outwash plains extant in the watershed (the Wareham pitted Plain, the Kings Pond plain and the Carver pitted plain). However, the majority of the Wareham River System's watershed is within the Wareham Pitted Plain which is sand and gravel deposited by glacial meltwater streams (Hansen and Lapham, 1992).

The habitat quality of the Wareham River System is linked to the level of tidal flushing through its inlet to Buzzards Bay, which has a moderate tide range, ca. 5 ft. Since the water elevation difference between the Bay and River is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle (note the tide range off Stage Harbor Chatham is ~4.5 ft, Wellfleet Harbor is ~10 ft). The inlet to the Wareham River system is not presently armored with jetties, although there is a large spit at Long Beach. The inlet configuration does not appear to impede the propagation of the tide in Marks Cove or the Narrows. However, the inlet to Broad Marsh, not being stabilized, could over time become occluded, thereby affecting tidal forcing in that portion of the overall system. The MEP hydrodynamic analysis investigated the system for tidal attenuation (Chapter V).

Unlike the Estuary itself, which is fully within the Town of Wareham, the watershed areas contributing nitrogen to the Wareham River system are distributed amongst three Towns, Wareham, Carver and Plymouth, although the majority of the land area constituting the Wareham River watershed is in the Town of Wareham. A small portion of the upper watershed in the Towns of Plymouth and Carver is forested watershed associated with the Myles Standish State Park, which contributes negligible nitrogen load. The Wareham River is one of the Town of Wareham’s significant marine resources.

The Wareham River System has been undergoing degradation of its resources over the past decades as a result of nutrient overloading from its watershed, primarily resulting from residential development. Recent significant effort by the Town of Wareham to significantly reduce nitrogen loading to the estuary from its WWTF, has resulted in an important shift in the continuously increasing nitrogen loading to this system over the past several decades. However, as new development is continuing, watershed nitrogen management will be required to restore this significant coastal resource. At present, the Wareham River is a nutrient enriched shallow embayment system. For the MEP analysis, the Wareham River System was analyzed individually as a stand-alone system. Similar to other embayments in southeastern Massachusetts and Cape Cod (e.g. Westport River, Phinneys Harbor, West Falmouth Harbor, Popponesset Bay, Nantucket Harbor). The Wareham River estuarine system was partitioned into several basins: (1) the upper estuary of the estuarine reaches of the Agawam and Wankinco River, (2) the main basin or the Wareham River Estuary from The Narrows to Long Beach Point, (3) Broad Marsh River, (4) Crooked River, and (5) Marks Cove (see Figure I-1). Wareham River Estuary is a true estuary, acting as the mixing zone of terrestrial freshwater inflow and saline tidal waters from Buzzards Bay. Salinity ranges from approximately 28 ppt at the Buzzards Bay inlet in the vicinity of outer Marks Cove to less than 4 ppt at the uppermost end of the estuarine reach of the Agawam River. However, salinities throughout the basins comprising the upper Wareham River at the Narrows to the mouth range from 23 ppt. in the upper Wareham River to 25 ppt. in the Lower Wareham River.

Given the present hydrodynamic characteristics of the Wareham River embayment system, it appears that estuarine habitat quality is primarily dependent on the level of nutrient loading to embayment waters as opposed to tidal characteristics. In the Wareham River embayment system, minimal enhancements to tidal flushing may be achieved via inlet or channel modification thereby resulting in some mediation of the nutrient loading impacts from the watershed. The details of such are a part of the MEP analysis described later in this report.

Nitrogen loading to the Wareham River Embayment System was determined relative to the 5 basins comprising the estuary as depicted in Figure I-1. Based upon land-use and the watershed being primarily within Wareham, it appears that nitrogen management for overall system restoration may likely be more rapidly developed and implemented than otherwise. As management alternatives are being developed and evaluated, it is important to note the ecological differences of the 5 major basins comprising the Estuary. The Agawam River and Broad Marsh sub-estuaries currently function primarily as tidal salt marsh systems, which have a relatively higher tolerance for nitrogen inputs. In contrast, the Marks Cove and Wareham River portions of the system are deep and generally well flushed sub-embayments, functioning as open water basins. These physical and ecological characteristics interact with tidal flushing and watershed nitrogen loading in varying ways to define the nutrient characteristics of the River and the associated habitat impacts. There is a gradient in nitrogen level and health moving from the Agawam River through the Wareham Narrows basin to the outer portion of the Wareham River near the mouth of the system, with highest nitrogen and lowest environmental health being found in the upper estuary and lowest nitrogen and greatest health near the inlet to Buzzards Bay. Eelgrass is currently mostly absent from the whole of the Wareham River system except for a few small beds fringing a small area south east of The Narrows. A relatively high level of water clarity will be needed to restore eelgrass to the Wareham River basin due to its moderate water depth.

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 glacially dominated aquifers with a mix of sandy outwash, till and stratified drift, such as in the watershed to the Wareham River embayment system and others in the region, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer mineral (Weiskel and Howes 1992). Since rivers in the region 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, especially the case on Cape Cod (DeSimone and Howes 1998, Weiskel and Howes 1992, Smith *et al.* 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). Tidal reaches within the Wareham River 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 the nearshore coastal waters. Coastal embayments, because of their enclosed basins, shallow waters and large shoreline area, are generally the first indicators of nutrient pollution from terrestrial sources. By nature, these systems are highly productive environments, but nutrient over-enrichment of these systems worldwide is resulting in the loss of their aesthetic, economic and commercially valuable attributes.

Each embayment system maintains a capacity to assimilate watershed nitrogen inputs without degradation. However, as loading increases a point is reached at which the capacity (termed assimilative capacity) is exceeded and nutrient related water quality degradation occurs. 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, and the Falmouth Coastal Overlay Bylaw). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the “allowable N concentration increase” or “threshold nitrogen concentration” used in previous studies had a significant uncertainty due to the need for direct linkage of watershed and embayment models and site-specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout the Wareham River system monitored by the Coalition for Buzzards Bay BayWatchers Monitoring Program, with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) to "tune" general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, the Wareham River Embayment System appears to be beyond its ability to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated throughout the system and eelgrass beds are almost non-existent in the Wareham River Estuary. The result is that nitrogen management of the primary sub-embayments is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed "eutrophication" and when the nutrient loading is primarily from human activities, it is considered "cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to the system and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within a given embayment system could potentially occur without human 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 Wareham River 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 the Wareham River System. 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 were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations by the USGS using a modification of the West Cape model, to enhance an earlier hydrologic model of the Plymouth Carver Aquifer. Virtually all nitrogen entering Wareham's embayment systems is transported by freshwater, predominantly groundwater, either through direct discharge or after discharging to a stream flowing to estuarine waters. Concentrations of total nitrogen and salinity of Buzzards Bay source waters and throughout the Wareham River system were taken from the Coalition for Buzzards Bay BayWatchers Monitoring Program (associated with the Coastal Systems Program at SMAST) and from previous sampling of Buzzards Bay nearshore waters by MEP staff. Measurements of 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 Wareham River Embayment System for the Town of Wareham. A review of existing water quality studies is provided (Section II). The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Sections III and IV. In addition, nitrogen input parameters to the water quality model are described. Since benthic flux of nitrogen from bottom sediments is a critical (but often overlooked) component of nitrogen loading to shallow estuarine systems, determination of the site-specific magnitude of this component also was performed (Section IV). Nitrogen loads from the watershed and sub-watershed surrounding the estuary were derived from Cape Cod Commission data and offshore water column nitrogen values were derived from an analysis of monitoring stations in Buzzards Bay (Section IV). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Section IV. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of each embayment was performed that included a review of existing water quality information, temporal changes in eelgrass distribution, dissolved oxygen records and the results of a benthic infaunal animal analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration in a given estuarine basin. This latter assessment represents only one of many solutions and is produced to assist the Town in developing a variety of alternative nitrogen management options for the Wareham River System. Finally, analyses of the Wareham River System was relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of dredging options to improve nitrogen related water quality in the various sub-embayments.

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: 1) excessive plankton and macrophyte growth (which leads to reduced water clarity), 2) organic matter enrichment of waters and sediments, with the concomitant resulting increased rates of oxygen consumption and periodic depletion of dissolved oxygen, (especially in bottom waters), and 3) the limitation of the growth of desirable species such as eelgrass. Even without changes to water clarity and bottom water dissolved oxygen, the increased organic matter deposition to the sediments generally results in a decline in habitat quality for benthic infaunal communities (animals living in the sediments). This habitat change causes a shift in infaunal communities from high diversity deep burrowing forms (which include economically important species), to low diversity shallow dwelling organisms. This shift alone causes significant degradation of the aquatic resource and a loss of productivity to the local shellfisherman, the sport-fishery and the offshore fin fishery. All three components of the local economy are dependent upon these highly productive estuarine systems as a habitat and food resource during migration or during different life cycle phases. This process is generally termed "eutrophication" and in embayment systems, unlike in shallow lakes and pond, it is not necessarily a part of the natural evolution of a system.

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

These tools for predicting loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. The present Massachusetts Estuaries Project (MEP) study focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Wareham River System. As the MEP approach requires substantial amounts of site-specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of "data mining" and to gather additional information on an estuary's habitat quality or unique features.

Concern over the health of Buzzards Bay's tributary embayments have resulted in a number of studies relating to the nutrient related health of the Wareham River System over the past 2 decades. These investigations include both habitat assessments and studies relating to nitrogen loading, hydrodynamics and habitat health. While none of the previous studies was able to link watershed nitrogen loading and attenuation processes with quantitative hydrodynamics of the estuary, some did focus on developing nitrogen thresholds for the restoration of the Wareham River System or key component basins. These studies provide useful information to the present MEP effort. Other earlier efforts were generally survey studies to evaluate this estuary and its watershed within the larger regional system or to examine aquifer properties.

An initial watershed land-use and nitrogen loading analysis was conducted by the Buzzards Bay Project (BBP, 1996) as part of a survey of all of the tributary embayments to Buzzards Bay. This survey used Mass GIS 1984 coverages and approximate watershed delineations. The results indicated that the Wareham River system appeared to be receiving nitrogen inputs more than 2.5 times that for maintaining high quality waters (Massachusetts SA Classification). While the overall nitrogen load estimates developed by the BBP for the Wareham River watershed have basically held true, the analysis is insufficient to simulate changes in nitrogen within the estuary under different management alternatives. In addition, as the land use models did not account for nitrogen attenuation by the wetland and up gradient pond ecosystems (no data available), it over estimated the role of nitrogen sources in upper (inland most) sub-watersheds compared to the direct groundwater discharge watersheds to the estuary. While watershed delineation and nitrogen loading data from earlier efforts were considered by the MEP, direct use of the modeling results was problematic. Since the BBP land use model was based upon earlier watershed delineations rather than the most current delineations provided to the MEP by the USGS (with further refinement of the Plymouth-Carver Aquifer Model), the contributing areas are slightly different (Chapter III). Due to the difference in watershed areas and the MEP's update and refinements to the watershed nitrogen loading model (e.g. to incorporate attenuation and new nitrogen source information), the results generated by the MEP are a more quantitative approach and therefore supersede earlier studies.

The Town of Wareham, as the primary stakeholder to the Wareham River System, has been concerned over the declining quality of this significant coastal resource. The community has worked to implement controls on direct stormwater discharges and has recently completed an upgrade to its WWTF that discharges to the headwaters of the Agawam Estuary within the Wareham River System. This facility upgrade reduced the nitrogen loading to the estuary by ca. 70%. The Town of Wareham, with its wastewater consultant (Camp Dresser and McKee Inc.), conducted a detailed investigation of the upper Wareham River System in order to determine the amount of watershed nitrogen entering the estuary and to determine the need for tertiary versus secondary treatment at the Town's WWTF (CDM, 2000). The study provided significant data to the present effort, specifically relating to watershed land-uses and the amount of nitrogen discharging to the estuary through the Agawam and Wankinco Rivers. This investigation indicated significant nitrogen removal during transport, which has been confirmed by the MEP. In addition, this Town study confirmed the importance of nitrogen to the health of this embayment system. The MEP watershed analysis builds on these earlier efforts in addition to another historical study by the USGS in the 1990's detailing the hydrogeologic characteristics of the Plymouth/Carver Aquifer. The aquifer investigation supported a refined watershed delineation based upon both updated water table data and updating of the pre-existing USGS Plymouth-Carver Aquifer Model (Chapters III & IV). The refined watershed delineations included each sub-embayment to the Wareham River Embayment System, and the major rivers, ponds and lakes within the upper watershed .

The MEP analysis of the Wareham River Embayment System also benefited from another independent research effort. A key historical study related to eelgrass coverage within this estuary was conducted in the mid 1980's (Costa 1988). This investigation provided field verified maps of eelgrass for comparison with more recent surveys by the MassDEP in 1995 and 2001, information critical to determining the decline in eelgrass in this system and for setting site-specific nitrogen thresholds for recovery.

The updated MEP analysis of the Wareham River Embayment System also benefited from an independent research effort undertaken for the MassDEP and the Cape Cod Cranberry Growers Association and related to the nutrient (phosphorous and nitrogen) dynamics of White Island Pond (Eichner et al., 2012). White Island Pond is a 111 ha (291 acre) freshwater pond located mostly within the Town of Plymouth, but with a small southern portion in the Town of Wareham. The pond has two major basins and supports two active cranberry bogs located along its northern shoreline. Some early watershed delineations of the Wareham River Estuary suggested that White Island Pond could be supplying freshwater and associated nitrogen to the downgradient estuarine waters. Part of the research effort was to conduct a hydrologic balance of the pond, including measuring the volume and fate of its surface water outflow. The hydrologic balance indicated that (1) freshwater leaving the pond was predominantly through the surface water stream on the pond's southern shore and that the measured outflow was equivalent to the watershed freshwater inflow plus net input from rainfall. The surface water stream is part of the Red Brook stream system that discharges outside of the Wareham River Estuary, i.e. the White Island Pond watershed does not supply nitrogen to Wareham River Estuary.

To more clearly understand the water balance of White Island, MEP-SMAST technical team leaders also developed a subwatershed for both the eastern and western basins to White Island Pond. Based on a review of water quality data collected from White Island Pond, it was determined that the western basin of the pond generally has significantly different water quality characteristics than the larger eastern basin of the pond. Because both basins of White Island Pond are oriented perpendicular to the primary regional groundwater flow path, the western basin functions somewhat separately from the main portion of the pond, although outlet flow measurements suggest internal flow from the western to the eastern basin. The western basin watershed delineation is based on consideration of the flow paths shown on the outer boundaries of the White Island Pond watershed, a review of the shoreline, the shallow area between the two basins shown in a detailed bathymetry survey and analysis of other ponds in the region.

Confirmation of the White Island Pond delineation was achieved through stream gauging at critical locations in the White Island Pond system (most importantly down gradient of both the eastern and western basins). Annual flow was determined based on flow and stage measurements and the development of a stage-discharge relationship (rating curve) for the main stream outlet from the cranberry bog immediately south of the eastern and western basins of White Island Pond. The stream outlet focuses pond outflow and functions as a “path of least resistance” where pond water can more easily discharge down gradient rather than flowing back into the aquifer among the sand pore spaces along the down gradient shoreline of the pond. For this reason, streams frequently dominate total pond outflow and are critical places for determining flow out of a system.

Stream outflow from White Island Pond was measured weekly between October 30, 2009 and November 30, 2010 along with stage measurements collected every 10 minutes over the same period of time. For confirmation of the White Island Pond watershed delineation, stream gauging and flow measurements were collected at the most downstream location (WIP Outlet2) where the outlet flow would be representative of both of the basins of the pond as well as associated cranberry bogs. The down gradient most stream gauge (WIP Outlet2) was placed approximately 1.8 km downstream of the main outlet from the pond (as the southern end of the east basin) within an adjacent cranberry bog. This gauge was placed to assess whether all pond outflow might be captured by this down gradient bog system.

Stream flow at the WIP Outlet 2 gauging location was continuous and produced a reliable rating curve (R^2 = 0.95 between stage and discharge). The average flow at the stream gauging location WIP Outlet2 between October 30, 2009 and November 30, 2010 was 16,695 m^3/d. Watershed flow to the whole White Island Pond system based on recharge rates and watershed delineation was calculated to be 16,893 m^3/d. The comparison of the measured flow at the WIP Outlet 2 gauging location and the flow generated by the entire White Island Pond watershed results in only a 1% difference between the two flow values indicating that all the water from the White Island Pond watershed is entering Red Brook and flowing to Buttermilk Bay rather than the Wareham River Estuary. Review of the USGS modeled water table contours and flow paths suggest that the cranberry bog upstream of WIP Outlet 2 should capture most of the discharge from White Island Pond. These measurements provide an independent confirmation that the watershed delineation is reasonable and White Island Pond should be excluded from the broader Wareham River Estuary system.

The update to the Wareham MEP analysis also benefitted from research on cranberry bog nitrogen losses. The study focused on developing nitrogen balances for six (6)non-flow through bogs (bogs without a stream flowing through). The bogs were sited in both inorganic and organic soils. N balance was based upon determinations for each bog of inputs from irrigation, fertilizer, groundwater inflow, flooding (frost protection, harvest, winter protection) and outputs through drainage/infiltration and release of flood waters. Determinations were made from TN measurements and water volumes (Demoranville et al., 2009). Re-analysis of the results indicated that a more accurate estimate of losses through Drainage/Infiltration could be made than in the original report and this refinement with the original datasets was conducted to provide more accurate estimates of nitrogen loss per hectare of bog surface. The refinement of the cranberry bog nutrient flux rates was undertaken by scientists from the SMAST Coastal Systems program and the UMASS Cranberry Experiment Station. The results generated by direct measurements of nitrogen levels and determinations of water volumes yielded a relatively low rate of total nitrogen loss for the non-flow through bogs compared to flow though bogs, 6.9 kg ha^{-1} yr^{-1} versus 9.6 kg ha^{-1} yr^{-1}. These coefficients are directly applicable to cranberry bog agriculture occurring in the Wareham River watershed and were used in the present MEP analysis.

Finally, the MEP analysis requires high quality water quality data in order to complete its assessment and modeling approach. The Town of Wareham has supported the Coalition for Buzzards Bay's Water Quality Monitoring Program, which has been collecting data on nutrient related water quality throughout the Wareham River System for more than a decade. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of each of Wareham's embayments and harbors. The BayWatchers is a citizen-based water quality monitoring program that was run by the Coalition for Buzzards Bay (T. Williams, Project Coordination) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD.

The common focus of the Coalition for Buzzards Bay BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay. The program was tailored to the gathering of data specifically to support evaluations relating observed water quality to habitat health. The BayWatcher Water Quality Monitoring Program in the Wareham River Embayment System developed a data set that elucidated the long-term water quality of this system (Costa et al. 1996. Howes et al. 1999). The BayWatcher Program provided the quantitative watercolumn nitrogen data (1999-2011) required for the implementation of the MEP's Linked Watershed-Embayment Approach. The MEP effort also builds upon the previous watershed delineation and land-use analyses, river transport and attenuation data, and embayment water quality and eelgrass surveys. This information is integrated with MEP collected higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Wareham River System. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the Wareham River System and to reduce costs to the Town of Wareham.

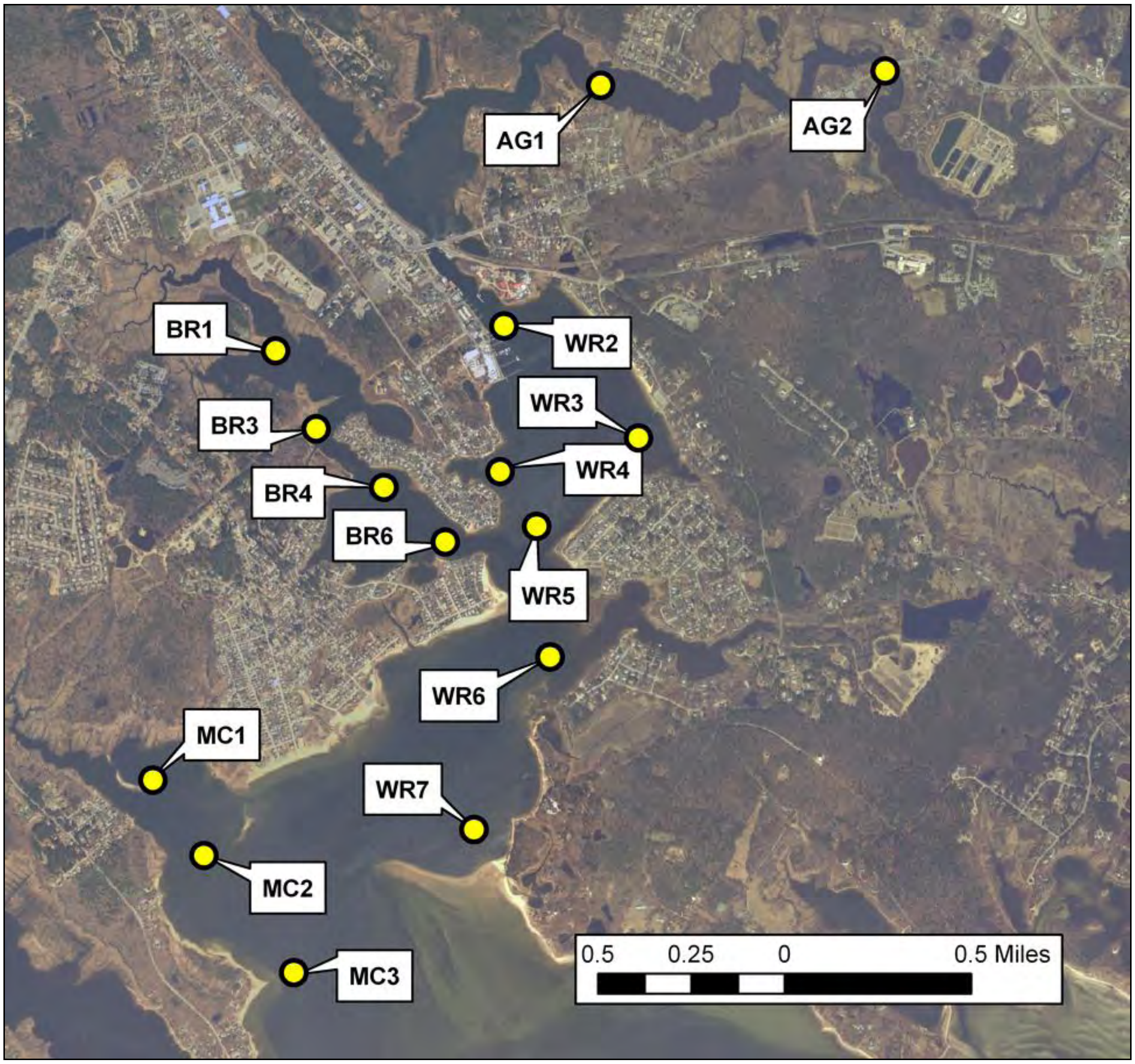


Figure II-1. Wareham River Water Quality Monitoring Program. Estuarine water quality monitoring stations sampled by the Coalition for Buzzards Bay. Stream water quality stations depicted in Section IV sampled weekly by the MEP.

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 groundwater models, including the Plymouth-Carver Aquifer groundwater model utilized for delineation of the watersheds to the Wareham River system. 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 these groundwater models. The USGS groundwater models organize and analyze available data utilizing up-to-date mathematical codes and create better tools to answer the wide variety of questions related to watershed delineation, surface water/groundwater interaction, groundwater travel time, and drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including the Wareham River estuary system. The Wareham River estuary system watershed, including the sub-watersheds to the Agawam River and the Wankinco River, is located within the Towns of Wareham, Plymouth and Carver and is situated between the Weweantic River estuarine system to the west and the Onset Bay and Buttermilk Bay estuarine systems to the east.

In the present MEP investigation, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the Wareham River system (Masterson, *et al*., 2009). The Wareham River estuarine system is a complex estuary, with one large main drown river valley channel, with a large tidal inlet at its terminus, multiple tributary coves acting as sub-embayments, two large freshwater rivers in the upper region which join to form the main basin of the Wareham River estuary. These large rivers reach far up into the upper watershed regions and form major conduits for draining the freshwaters of the groundwater system into the upper reaches of the estuarine system. The current USGS regional aquifer model is based on updated information added to previous efforts, including the Hansen and Lapham (1992) regional model. Using the updated model, watershed modeling was undertaken to sub-divide the overall watershed to the Wareham River system into functional sub-units based upon: (a) defining inputs from contributing areas to each major portion within the embayment system and (b) defining contributing areas to major freshwater aquatic systems which generally attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands). The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in the Wareham River watershed. Average stream gage data developed through the MEP (1999 to 2000) was available to the USGS for model evaluation and calibration.

The relatively transmissive sand and gravel deposits that comprise most of this portion of southeastern Massachusetts create a hydrologic environment where watershed boundaries are usually better defined by elevation of the groundwater and its direction of flow, rather than by the land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). The Wareham River watershed is part of the Plymouth Carver Aquifer. 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 sources of water inputs and tracking the nitrogen that they carry requires determination of the portion of the watershed that contributes to the rivers and, separately, the portion of the groundwater system that discharges directly into the estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Wareham River system and local freshwater bodies (*e.g*. ponds, cranberry bogs, rivers) were delineated using a regional model of southeastern Massachusetts known as the Plymouth-Carver-Kingston-Duxbury Aquifer Model (Masterson, *et al*., 2009). This version of the aquifer model builds on the original 1992 USGS model of the same area (Hansen and Lapham, 1992). The USGS used a combination of publicly available USGS modeling programs to complete the analysis necessary for the delineation of the MEP watershed and sub-watersheds. MODFLOW-2000 (Harbaugh and others, 2000) solves three-dimensional groundwater flow equations by finite-difference methods and these results are then used with MODPATH4 (Pollock, 2000) to track the simulated movement of water in the aquifer. The resulting particle-tracks are then used to delineate the areas at the water table that contribute water to wells, streams, ponds, and coastal water bodies. This approach was used to determine the contributing areas to the overall Wareham River system, as well as sub-watersheds to the Agawam and Wankinco Rivers.

The 2009 Plymouth-Carver-Kingston-Duxbury Aquifer Groundwater Model has a grid area of approximately 280 square miles. This model served as base for the refined watershed delineations utilized by the MEP. The model grid consists of 355 rows and 270 columns with each grid block measuring 400 ft. by 400 ft. square. The active area of the model grid includes physical boundaries of the modeled area as defined by the coast along Plymouth Harbor and Cape Cod Bay, the Cape Cod Canal, the coastline along Buzzards Bay, the surface water divide west of the Weweantic River in the Town of Rochester, the surface water divide between the Taunton River Basin and the Buzzards Bay Basin, tributaries to the Winnetuxet River in the Taunton River Basin, Jones Brook (tributary to the Jones River) and Jones River. In constructing the groundwater model, the aquifer was divided vertically into eight discrete layers in order to allow for the modeling of vertical flow in the aquifer, allow for vertical variations in horizontal hydraulic conductivities, accommodate local confining layers thereby allowing variations in vertical hydraulic conductivities, and factor in the effects of water withdrawals related to pumping of partially penetrating wells.

The structure and orientation of the glacial sediments that constitute the Plymouth-Carver-Kingston-Duxbury aquifer are geologically complex, being composed primarily of three glacial outwash plains associated with the Buzzards Bay lobe and the Cape Cod Bay Lobe. Both lobes were part of the Laurentide ice sheet that extended to this region during the Late Wisconsinan glacial period approximately 15,000 to 18,000 years before present. The vast majority of the depositional and structural characteristics of the watershed to the Wareham River estuarine system were defined by a complicated sequence of advances and retreats of the ice sheet in this region. As such, the predominant features in the watershed are moraines and outwash plains interspersed with glaciofluvial and glaciolacustrine deposits. Two southwest trending moraines, the Hog Rock and the Snipatuit moraines are present in the upper portions of the Wareham River watershed and demarcate the various outwash plains extant in the watershed (the Wareham Pitted Plain, the Kings Pond Plain and the Carver Pitted Plain). Each moraine serves to distinguish the various recessional positions of the ice sheet. The majority of the Wareham River watershed is composed of the Wareham Pitted Plain, which is generally composed of sand and gravel deposited by glacial meltwater streams (Hansen and Lapham, 1992). Final aquifer parameters in the groundwater model were determined through calibration to observed water levels and stream flows (see Section IV.2). Hydrologic data used for model calibration included historic water-level data obtained from USGS records and stream flow data collected at the time the model was originally constructed as well as more recent stream flows collected in 1999 and 2000.

The 2009 Plymouth-Carver-Kingston-Duxbury Aquifer Groundwater Model simulates steady state, or long-term average, hydrologic conditions including a long-term average recharge rate of 27 inches/year for most of the aquifer and the pumping of public drinking water supply wells at average annual withdrawal rates. In the model, water pumped by public water supply wells is returned to the aquifer system either at wastewater treatment facilities or in residential areas. Residential areas that are not connected by sewers to the wastewater treatment facilities are assumed to utilize septic systems. The model assumes a 15% consumptive loss of pumped water prior to recharge back to the aquifer system (Masterson e*t al*., 2009).

III.3 WAREHAM RIVER SYSTEM CONTRIBUTORY AREA

Newly revised watershed and sub-watershed boundaries for the Wareham River Estuary were determined by the United States Geological Survey (USGS) with the assistance of the rest of the MEP Technical Team. Model outputs from the USGS Plymouth Carver Aquifer model were “smoothed” by the MEP Technical Team to: (a) correct for the grid spacing, (b) to enhance the accuracy of the characterization of the pond and coastal shorelines, (c) to include water table data in the lower regions of the watersheds near the coast (as available), and (d) to more closely match the sub-embayment segmentation of the tidal hydrodynamic model. The smoothing refinement was a collaborative effort between the USGS and the rest of the MEP Technical Team and resulted in the watershed delineations shown in Figure III-1. Overall, forty-five (45) sub-watershed areas, including watersheds to 20 freshwater ponds, were delineated within the watershed to the Wareham River embayment system.

Table III-1 provides the daily freshwater discharge volumes for each of the sub-watersheds as calculated by the groundwater model. The modeling results were compared to measured flow readings at the long-term MEP monitoring locations on the Agawam and Wankinko Rivers, as well as subsequent data collected by SMAST staff for a study of White Island Pond (Eichner, *et al*., 2012). These volumes were used to assist in the salinity calibration of the tidal hydrodynamic models. The total system flows were also adjusted to account for ponds that are located on groundwater divides between larger watershed systems; only a portion of the recharge from these pond watersheds discharges into the Wareham River watershed, the remainder discharges outside of the watershed. In the case of White Island Pond, down gradient stream flow measurements collected over a year indicate that the watershed flow to this pond discharges outside of the Wareham River watershed. The overall estimated freshwater inflow to the estuarine waters of the Wareham River system from the MEP watershed is 184,094 m3/d.

These newest delineations completed for the MEP project are at least the third watershed delineation completed in recent years for the Wareham River system. During the preparation of the Comprehensive Conservation and Management Plan (CCMP) for Buzzards Bay by the Buzzards Bay Project (1991), watershed delineations for each of the sub-basins to the bay, including the Wareham River estuary, were completed with the assistance of the USGS. Another interim MEP version of the watershed was also completed in 2008 using a prior update of the original USGS Plymouth-Carver-Kingston-Duxbury regional groundwater aquifer model. Figure III-2 compares the two previous watershed delineations with the refined delineation completed under the current MEP effort.

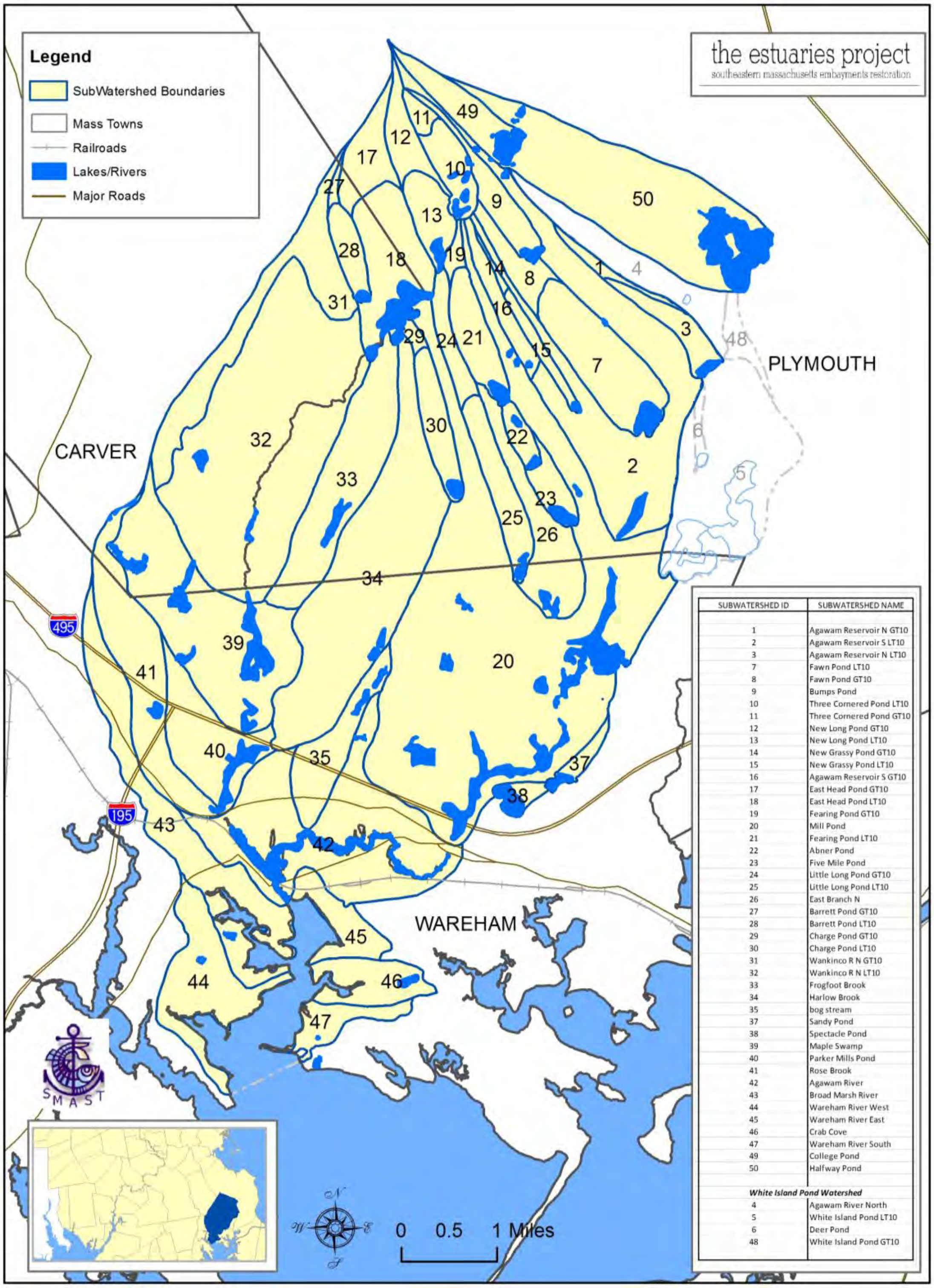


Figure III-1. Watershed (outer boundary) and sub-watershed delineations for the Wareham River estuary system. Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI). Sub-watersheds to White Island Pond are lightly shaded; recent studies indicate that White Island Pond does not provide discharge to the Wareham River Estuary. There is no shed #36.

Table III-1 (a). Daily groundwater discharge to each of the sub-watersheds in the watershed to the Wareham River system estuary, as determined from the USGS groundwater model.

Watershed	#	Watershed Area (acres)	Discharge	
			ft^3/day	m^3/day
Agawam Reservoir N GT10	1	71	19,111	541
Agawam Reservoir S LT10	2	1,588	426,417	12,075
Agawam Reservoir N LT10	3	191	51,238	1,451
Fawn Pond LT10	7	636	170,908	4,840
Fawn Pond GT10	8	176	47,356	1,341
Bumps Pond	9	244	65,488	1,854
Three Cornered Pond LT10	10	213	57,253	1,621
Three Cornered Pond GT10	11	59	15,907	450
New Long Pond GT10	12	197	52,893	1,498
New Long Pond LT10	13	221	59,299	1,679
New Grassy Pond GT10	14	19	5,035	143
New Grassy Pond LT10	15	97	26,022	737
Agawam Reservoir S GT10	16	169	45,279	1,282
East Head Pond GT10	17	267	71,678	2,030
East Head Pond LT10	18	605	162,514	4,602
Fearing Pond GT10	19	49	13,065	370
Mill Pond	20	4,762	1,278,765	36,211
Fearing Pond LT10	21	284	76,166	2,157
Abner Pond	22	94	25,368	718
Five Mile Pond	23	147	39,369	1,115
Little Long Pond GT10	24	159	42,777	1,211
Little Long Pond LT10	25	312	83,854	2,374
East Branch N	26	480	128,903	3,650
Barrett Pond GT10	27	24	6,408	181
Barrett Pond LT10	28	161	43,198	1,223
Charge Pond GT10	29	32	8,587	243
Charge Pond LT10	30	247	66,425	1,881
Wankinco R N GT10	31	711	190,841	5,404
Wankinco R N LT10	32	2,647	710,734	20,126
Frogfoot Brook	33	869	233,443	6,610
Harlow Brook	34	1,866	501,078	14,189
bog stream	35	384	103,164	2,921
Sandy Pond	37	80	21,490	609
Spectacle Pond	38	82	22,077	625
Maple Swamp	39	1,444	387,685	10,978
Parker Mills Pond	40	559	150,129	4,251
Rose Brook	41	792	212,785	6,025

Table III-1 (b). Daily groundwater discharge to each of the sub-watersheds in the watershed to the Wareham River system estuary, as determined from the USGS groundwater model.

Watershed	#	Watershed Area (acres)	Discharge	
			ft³/day	m³/day
Agawam River	42	1,575	422,986	11,978
Broad Marsh River	43	994	266,927	7,559
Wareham River West	44	640	171,838	4,866
Wareham River East	45	263	70,730	2,003
Crab Cove	46	308	82,646	2,340
Wareham River South	47	207	55,545	1,573
College Pond	49	294	78,941	2,235
Halfway Pond	50	1,634	438,641	12,421
TOTAL WAREHAM RIVER SYSTEM			6,501,231	184,094

Notes: 1) total system discharge is not equal to sum of columns; numerous ponds along the watershed boundaries discharge out of the system; the listed sub-watershed flows are not corrected for these discharges (details are contained in the MEP data disk that accompanies this report)

2) sub-watersheds that discharge to White Island Pond (#4,5,6,48) are not listed because they discharge outside of the Wareham River watershed; there is no sub-watershed #36

3) discharge volumes are based on annual recharge over the watershed area; up-gradient ponds often discharge to numerous down gradient sub-watersheds, including out of the watershed system, percentage of outflow is determined by length of down gradient shoreline going to each subwatershed

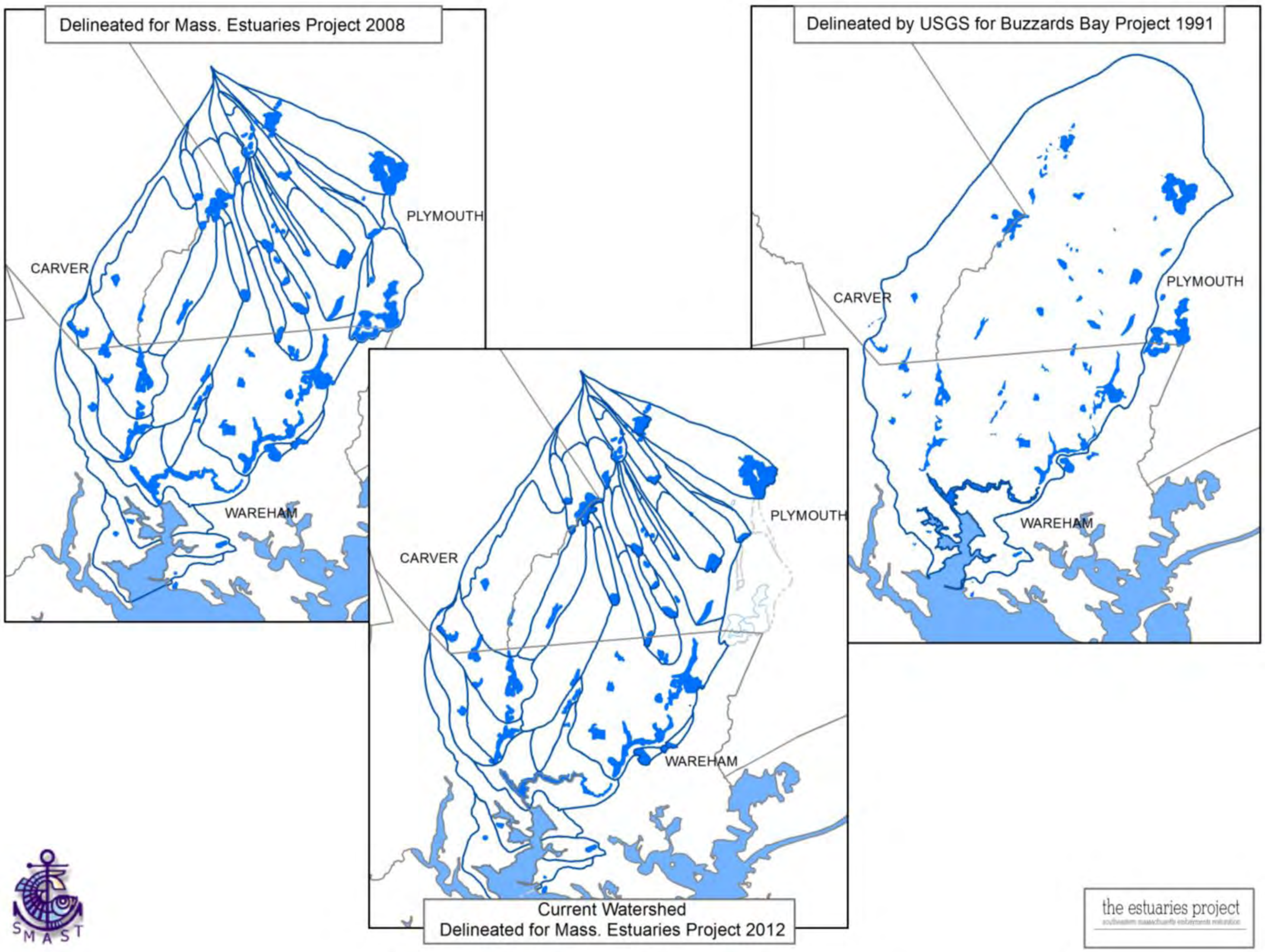


Figure III-2. Comparison of watershed and sub-watershed delineations used in the current MEP analysis, the Buzzards Bay Project delineation completed for the Comprehensive Conservation and Management Plan (BBP, 1991), and a previous MEP version completed in 2008. The current MEP watershed includes 45 separate sub-watersheds.

The evolution of the watershed delineations for the Wareham River system has allowed increasing accuracy as each new version adds new hydrologic data to those data previously collected. The latest groundwater model allows all the previous data to be organized and to be brought into congruence with data from adjacent watersheds and new data collected since the last model was developed. In addition, stream flow measurements collected through the MEP analysis and after the initial data collection effort allow additional validation data for the performance of the groundwater model. The evaluation of older data and incorporation of new data during the development of the model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model used for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon location of 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.

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

In order to determine watershed nitrogen loading inputs to the Wareham River estuary system, the MEP Technical Team developed nitrogen-loading rates (Section IV.1) to each component of the estuary (Section III). This effort was coordinated with staff from the Buzzards Bay National Estuary Program (BBNEP), the Southeastern Regional Planning & Economic Development District (SRPEDD), and the Town of Wareham. The Wareham River watershed was sub-divided to define contributing areas to each of the major inland freshwater systems and to each major sub-estuary. Further sub-divisions were made to identify watershed areas where a nitrogen discharge reaches embayment waters in less than 10 years or greater than 10 years. A total of 45 sub-watersheds were delineated for the Wareham estuary watershed (Figure IV-1). The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and each embayment/estuary (see Chapter III).

The initial task in the MEP land use analysis is to gage whether or not nitrogen discharges to the watershed have reached the estuary. This generally involves a temporal review of land use changes, review of data at natural collections points, such as streams and ponds, and the time of groundwater travel provided by the USGS watershed model. Evaluation and delineation of ten-year time of travel zones are a regular part of the watershed analysis; 12 subwatersheds are divided by time of travel lines in the Wareham River watershed and six others directly discharge to the estuary without passing through a pond or river. Among the 12 subwatersheds with ten-year time of travel zones, an average of 87% of the subwatershed unattenuated load is within 10 years time of travel; overall range is 69% to 97%.

In addition, review of data from the stream gages and a review of the watershed configuration, especially the streams running almost to the upper watershed divide suggest that groundwater lags are not playing a significant role in the balance between estuarine nitrogen levels and watershed nitrogen loading. Review of stream flows at gages on the Agawam and Wankinco Rivers also match estimated flows from the watershed further confirming not only the watershed delineation, but also supporting the concept that the watershed system is in balance. This finding is consistent with other MEP analysis where a larger proportion of the watershed load is more than ten years groundwater travel time from the associated estuary. The overall result of the timing of development relative to groundwater travel times is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuary after accounting for natural attenuation (see below).

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other detailed studies is applied to other portions. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon sub-watershed-specific land uses and pre-determined nitrogen loading rates. For the Wareham River estuarine system, the model used Town of Wareham, Carver, and Plymouth land-use data transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as parcel-specific water use and sewer connections from the Town of Wareham). Determination of the nitrogen loads required obtaining watershed-specific information regarding wastewater (including municipal sewer connections), fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the “potential” or unattenuated nitrogen load to each receiving embayment, since attenuation during transport has not yet been included.

Natural attenuation of nitrogen during transport from land-to-sea (Section IV.2) within the Wareham River watershed was determined based upon a site-specific study of stream flow from the Agawam and Wankinco Rivers. MEP assessments generally assume attenuation through freshwater ponds, but in this watershed there was no data available on the ponds and the measured loads in the rivers suggested less than the standard 50% pond attenuation. In order to address this uncertainty, the MEP Technical Team decided to assign attenuation at the gage locations of the rivers and did not assign attenuation to any of the upgradient ponds. This is a conservative approach, keeping with MassDEP guidance to be conservative in uncertain characterizations, but was warranted based on the measured, known readings at the gages and the uncertainty above the gages. Sub-watersheds to these various waters allowed comparisons between field collected data from the streams and estimates from the nitrogen-loading sub-model. Stream flow and associated surface water nitrogen attenuation is included in the MEP’s watershed-specific investigation presented in Section IV.2.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. Watershed delineations were completed for the following 20 ponds: Halfway, College, Bumps, Fawn, New Long, Fearing, Abner, Five Mile, East Head, Barrett, Charge, Mill, Agawam Reservoir North and South, Three Cornered, New Grassy, Little Long, Sandy, Spectacle, and Parkers Mills. In the present effort, none of the ponds in the Wareham River System with sub-watershed delineations have recent water quality measurements that were available for review. As discussed in Section III, White Island Pond was originally included in the Wareham River watershed, but site-specific outlet monitoring shows that its watershed flow discharges outside of the watershed (Eichner, *et al.*, 2012). In the watershed nitrogen-loading model, none of the ponds were assigned an attenuation rate based on the lack of monitoring data and basic physical characterization necessary for a site-specific determination in MEP watershed analyses. In addition, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the seven sub-watersheds that directly discharge groundwater to the estuary without flowing through one of the interim measuring points. Internal nitrogen recycling was also determined throughout the tidal reaches of the Wareham River 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 the Wareham River includes portions of the Towns of Wareham, Plymouth, and Carver, Estuaries Project staff obtained digital parcel and tax assessor's data from these municipalities to serve as a base for the watershed nitrogen loading model. Digital parcels and land use/assessors data are from 2009, 2006, and 2006 for Wareham, Plymouth, and Carver, respectively. These land use databases contain traditional information regarding land use classification based on MassDOR (2012) land use codes. With the assistance of the BBNEP, Wareham 2009 water use and sewer databases were joined to the town parcels to provide additional clarification regarding parcel counts and wastewater nitrogen loads. Significant effort was made to reconcile and link all of the databases, including QA/QC by MEP staff to review incomplete entries in the datasets. During the course of the MEP analysis, Level III parcel data was made available by MassGIS for all three towns. MEP staff discussed updating the nitrogen loading model to the new parcels with MassDEP, BBNEP, and the Coalition for Buzzards Bay and the consensus was that the MEP analysis would not be substantively affected and analysis should proceed with the existing linked databases.

Figure IV-1 shows the land uses within the Wareham River estuary watershed areas. Land uses in the study area are grouped into nine land use categories: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) undeveloped, 6) residential/recreational open space, 7) agricultural, 8) forest lands, and 9) public service/government, including road rights-of-way. These land use categories are aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2012). These categories are common to each town in the watershed. "Public service" in the MADOR system is tax-exempt properties, including lands owned by town, state, and federal government (e.g., wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges.

In the overall Wareham River System watershed, the predominant land use based on area is public service/government, which accounts for 44% of the overall watershed area (Figure IV-2). Much of the area of this land use is due to the Myles Standish State Forest, which occupies most of the upper watershed, but Public Service land is also the dominant land use in the lower portion of the watershed, as well. In the lower portions of the watershed, the Inner Wareham River and the areas that contribute directly to the estuary, public service/government is the highest percentage land use (34%), but residential land use is only slightly lower (32%). In contrast, the westernmost portion of the watershed, the Wankinco River/Parker Mills Pond sub-watershed, agricultural land uses, which are mostly cranberry bogs, are the dominant land use with 54% of the sub-watershed area. Land classified by the town assessors as undeveloped is 8% of the overall system watershed area with most of this land within the portion the watershed that contributes directly to the estuary.

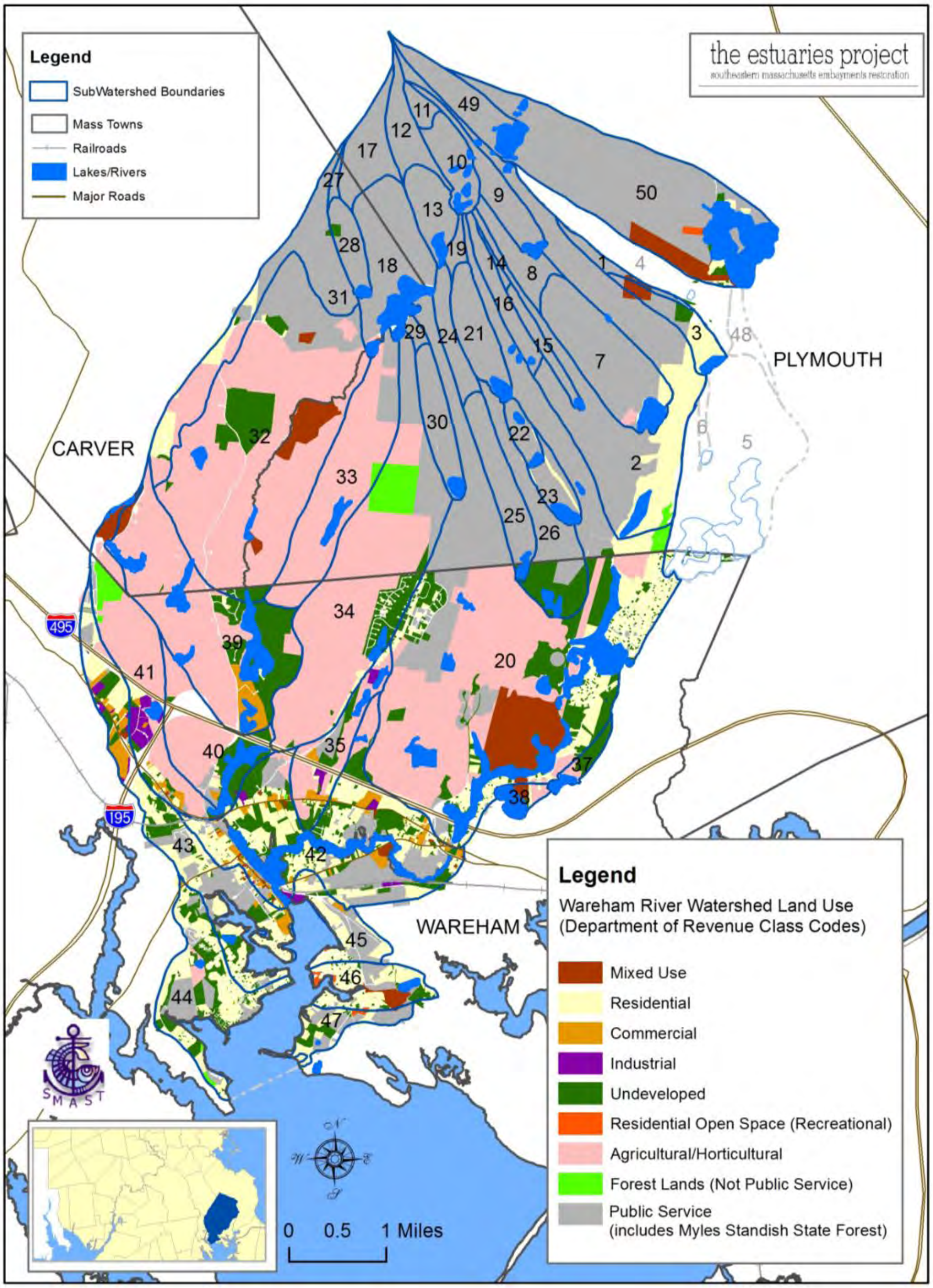


Figure IV-1. Land-use in the Wareham River watershed. The watershed is split among the Towns of Wareham, Carver, and Plymouth. Land use classifications are based on group classifications in MassDOR (2009), as assigned by individual town assessors.

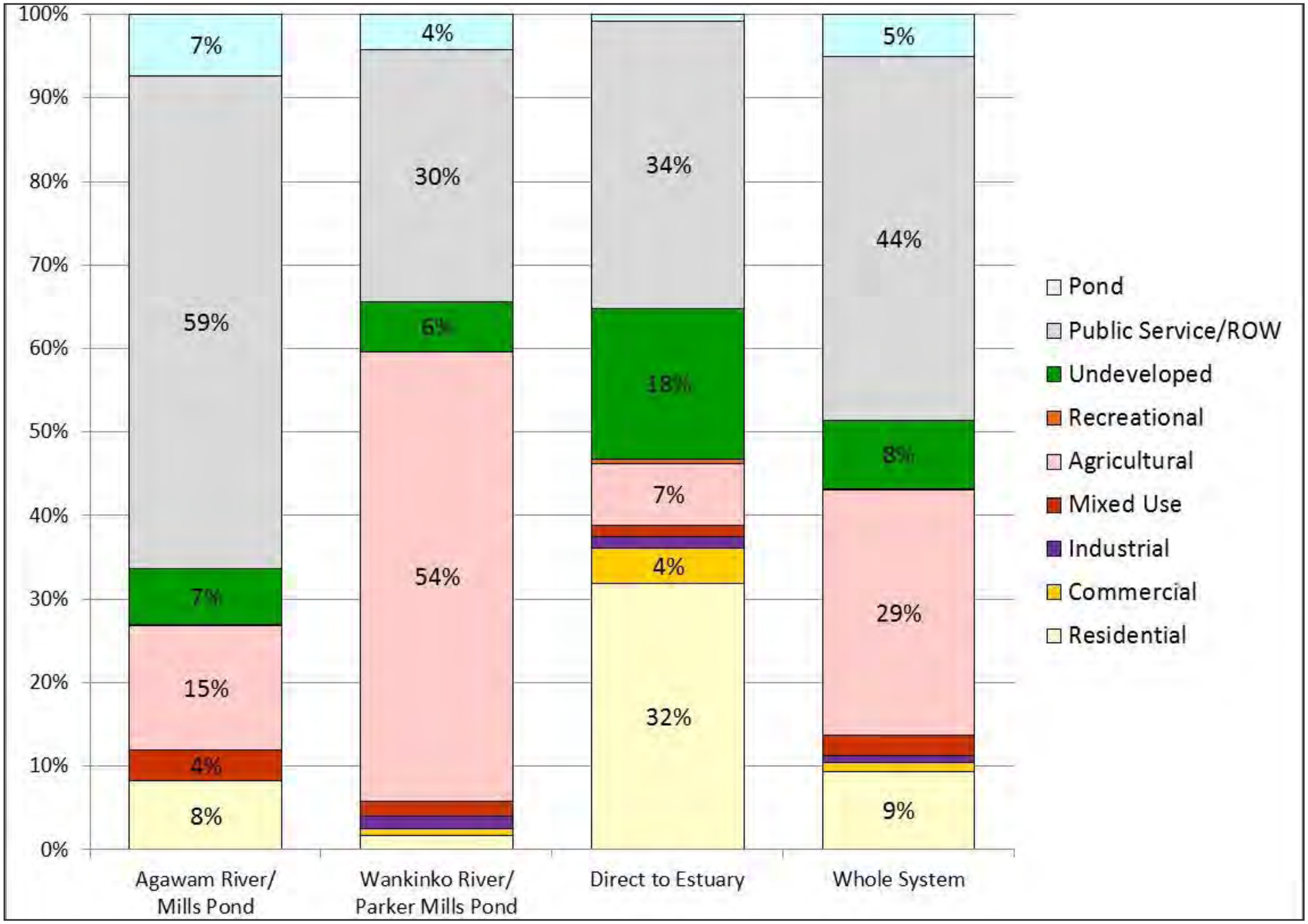


Figure IV-2. Distribution of land-uses within the major sub-watersheds and whole watershed to the Wareham River estuary system. Only percentages greater than or equal to 4% are shown. Note that "Direct to Estuary" represents the groundwater watershed discharging directly to the estuarine basins.

Parcel counts (rather than acreages) present a different perspective; residential parcels are the majority of parcels in all sub-watershed groups except for the Wankinco River/Parker Mills Pond sub-watershed. In the Wareham River Fresh and Direct to the Estuary subwatersheds, as well as for the whole system, residential parcels are over 70% of the total number of parcels in each subwatershed. In the Wankinco River/Parker Mills Pond sub-watershed, undeveloped parcels are the dominant type of parcel (42%) with 23% classified as residential parcels and 14% classified as agricultural parcels. Comparison of parcel counts with land use areas indicates that the cranberry bog/agricultural parcels in the Wankinco River/Parkers Mills Pond subwatershed are relatively large. Overall, undeveloped parcels are 18% of the parcel count in the entire Wareham River watershed. This type of information provides a sense of how many potential land owners exist in each subwatershed portion and how information on watershed management strategies might be tailored to address predominant land uses and concerns.

MEP analyses generally use water use as a proxy for wastewater flows and these loads are adjusted for any sewer collection systems. In the Wareham River watershed, the Town of Wareham provided water use and sewer connection databases for individual parcels. With the help of the BBNEP, these databases were linked to the town parcel GIS coverages and used in the watershed nitrogen loading model to provide subwatershed-specific wastewater nitrogen loads. Project staff also obtained performance data for the Town of Wareham Wastewater Treatment Facility from MassDEP; the WWTF discharges within a section of the upper estuarine reach of the Agawam River. MassDEP indicated that there are no other treatment facilities, public or private, have a state discharge permit within the Wareham River watershed.

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 avoid the uncertainty in the use of census data in seasonal communities and to more accurately assess current nitrogen loads, the MEP Technical Team 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, which reaches the aquatic receptors downgradient in the aquifer.

All nitrogen losses within a septic system are incorporated into the MEP analysis. For example, information developed on Title 5 septic systems at the Massachusetts Alternative

Septic System Test Center at the Massachusetts Military Reservation has shown nitrogen removals between 21% and 25%. Multi-year monitoring from the Test Center has revealed that nitrogen removal within the septic tank was small (1% to 3%), with most (20 to 22%) of the removal occurring within five feet of the soil adsorption system (Costa *et al.* 2001). Downgradient studies of septic system plumes indicate that further nitrogen loss during aquifer transport is negligible (Robertson *et al.* 1991, DeSimone and Howes 1996).

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

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

While census based population data has limitations in the highly seasonal MEP region, primarily due to seasonal occupancies, part of the regular MEP analysis is to compare expected water used based on average residential occupancy to measured average water uses. This use of census data is only performed as a approximation for quality assurance on the more accurate water-use derived loadings to increase certainty in the final results. In practice, this comparison has shown that the larger the watershed the better the match between average water use and occupancy. For example, in the cases of the combined Great Pond, Green Pond and Bournes Pond watershed in the Town of Falmouth and the Popponesset Bay/Eastern Waquoit Bay watershed, which covers large areas and have significant year-round populations, the septic nitrogen loading based upon the census data is within 5% of that from the water use approach. This comparison matches some of the variability seen in census data itself. Census blocks, which are generally smaller portions of any given town, have shown up to a $\pm$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.

For the Wareham River Watershed the MEP Technical Team reviewed US Census population and housing information for the Towns of Wareham, Carver, and Plymouth in order to provide a check on septic system nitrogen loads derived from measured residential water use. The state on-site wastewater design regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so for the purposes of Title 5 each person generates 55 gpd of wastewater. The number of persons per household derived from the 2000 and 2010 US Censuses for Wareham was 2.48 and 2.41 people per housing unit (average occupancy), respectively, while Carver was 2.80 and 2.68, and Plymouth was 2.81 and 2.65. Seasonal properties were 19% of housing units in Wareham during the 2010 Census, 2% in Carver, and 10% in Plymouth; 2000 Census percentages were approximately the same. Based on the Wareham 2009 water use data, the average single family residence water use in the watershed is 137 gpd. If this flow is then divided by 55 gpd, the average estimated occupancy based on the water use in the study area is 2.49 people per household. This water use derived estimate of occupancy is approximately the same as the Census occupancy in Wareham and provides a high degree of confidence that water use provides a solid basis for determining septic system wastewater nitrogen loads within Wareham River watershed.

The measured water uses are used for properties with water use accounts in Wareham. Not all developed properties have connections to the municipal water system, however, and these properties are assigned average water uses in the watershed nitrogen loading model depending on the type of land use assigned by the town assessor or a modified average based on individual site reviews completed by MEP staff. For example, there are 391 multi-family residential parcels within the Wareham River watershed and, of these, 241 have water use with an average per parcel flow of 630 gpd. This average flow is assigned to all other developed properties in this category. Other land use groups have the following average flows: 548 gpd for commercial properties and 911 gpd for industrial properties.

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

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

Wareham Wastewater Treatment Facility

The Wareham Wastewater Treatment Facility (WWTF) is located on Tony's Lane off Route 6 in Wareham. The WWTF has a National Pollutant Discharge Elimination System (NPDES) permit from US Environmental Protection Agency (USEPA) and MassDEP that allows direct discharge into the Agawam River and places limits on the total nitrogen load and concentration (www.epa.gov/region01/npdes/permits/warehampermit.pdf). The sewer collection system connected to the WWTF receives wastewater flow from the Towns of Wareham and Bourne.

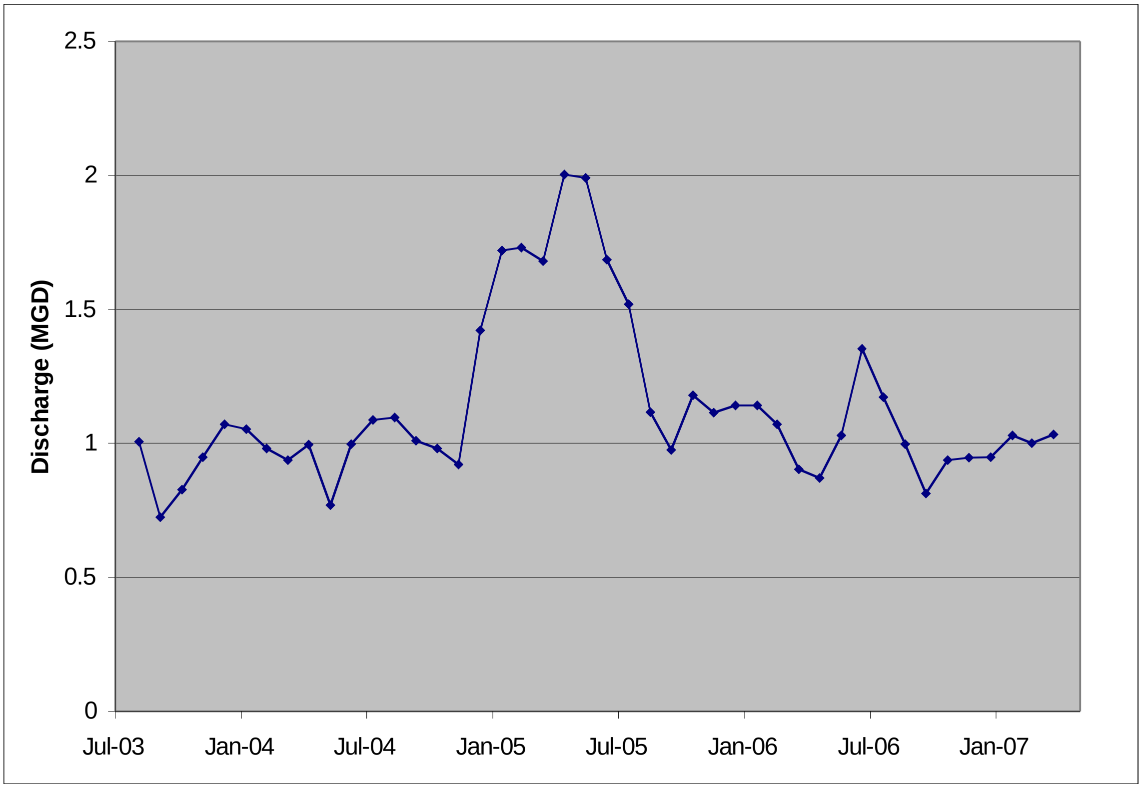
Monthly effluent flow and total nitrogen concentration data was provided to MEP staff by MassDEP staff for August 2003 through March 2007 (B. Dudley, MassDEP, personal communication). This period corresponds to the period when most of the estuarine water quality samples were collected. Total flow at the WWTF is generally around 1.0 million gallons per day (MGD) except for a period between December 2004 and July 2005 when flows spiked as high as 2.0 MGD (Figure IV-3). Total nitrogen loads averaged 47 kg/d from August 2003 to September 2005 and then averaged 18.5 kg/d between October 2005 and March 2007. An upgrade of the treatment system was implemented in September and October of 2005.

In order to determine the annual nitrogen load from the Wareham WWTF for existing conditions, MEP staff took the average monthly load from the 18 month post-upgrade period and converted it to an annual load of 6,761 kg. This period corresponds to the water quality monitoring in the estuary. Properties that were identified through town sewer account databases as having sewer connections were not assigned a wastewater nitrogen load. All other developed properties were assumed to utilize on-site septic systems and were assigned a wastewater load based on either the individual parcel's measured water use or assigned an average water use based on the land use category.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and cranberry bogs, with lawns usually being the predominant source within this category. In order to add this source to the nitrogen loading model for the Wareham River estuary system, MEP staff reviewed available information about residential lawn fertilizing practices and incorporated site-specific information to determine nitrogen loading from other fertilization applications in the watershed. The primary site-specific information in this watershed is for cranberry bog nitrogen loads, which were determined based on previous studies conducted in southeastern Massachusetts.

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



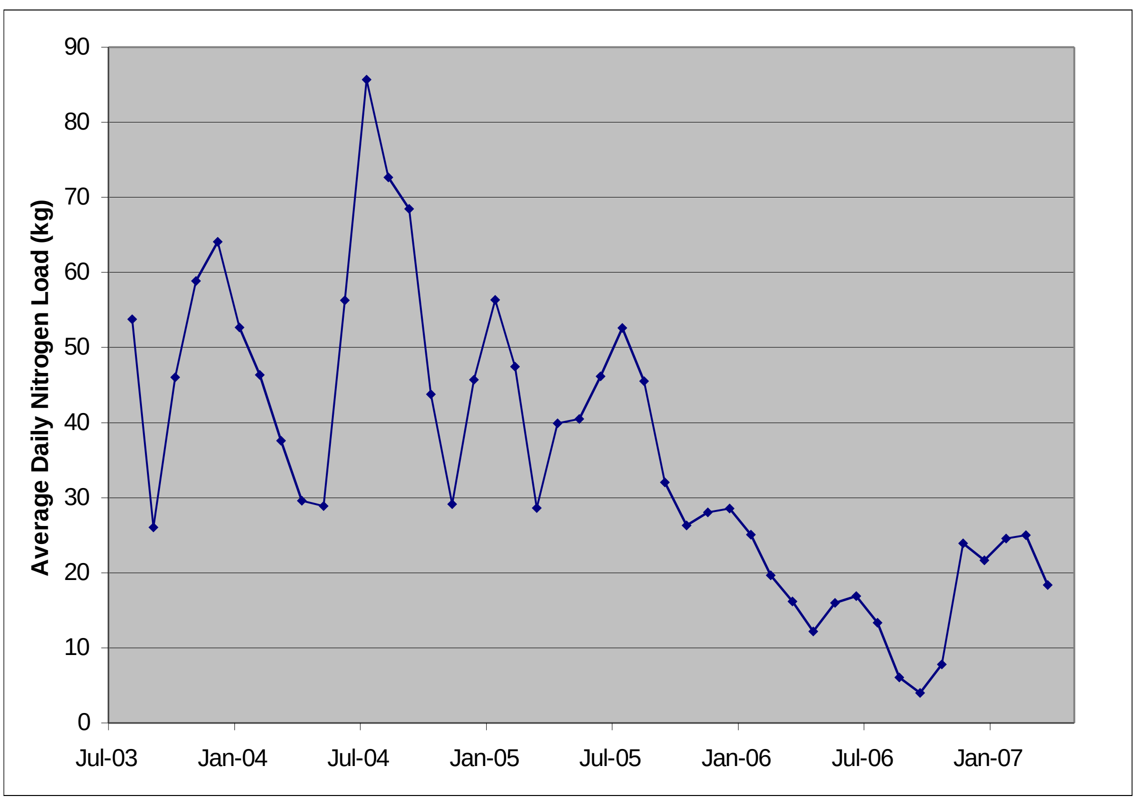


Figure IV-3. Average daily effluent flow and nitrogen load at the Wareham Wastewater Treatment Facility (August 2003 through March 2007). Data supplied by MassDEP.

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. The assessment accounted for proximity to fresh ponds and embayments. Based upon ~300 interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sq. ft., 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a leaching rate of 20% results in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors are used in the MEP nitrogen loading calculations. It should also be noted that a recent data review of lawn fertilizer leaching in settings similar to those on Cape Cod confirmed that the 20% leaching rate is appropriate (HWG, 2009). It is likely that these load rates still represents a conservative estimate of nitrogen load from residential lawns. It should also 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/lawn/yr.

Cranberry bogs are a significant land use within the Wareham River watershed. Bog areas in the MEP watershed nitrogen loading model are based on a GIS coverage maintained by MassDEP for Water Management Act purposes; this coverage identifies the surface areas of the bogs (personal communication, Jim McLaughlin, MassDEP). Cranberry bogs are located within 15 of the 45 sub-watersheds in the Wareham River MEP watershed. After reviewing previously existing and new studies of nitrogen export from regional cranberry bogs (*e.g.*, Howes and Teal, 1995; DeMoranville and Howes, 2009), MEP staff decided to refine the nitrogen loading factors assigned to cranberry bogs based on whether water continuously flowed through the bog or was pumped or diverted onto the bog (non-flow through bogs) from an outside source of water. The reason for the refinement was recent quantitative work on local bogs which indicated that non-flow through bogs lose less nitrogen to downgradient systems, since they only periodically have outflow. The recent study consisted of 6 non-flow through bogs including both those in inorganic and organic soils, measured over 3 years by researchers at the Cranberry Experiment Station and at SMAST-UMass Dartmouth. The finding of DeMoranville et al. (2009) were updated by the authors to better account for nitrogen losses through drainage and infiltration, with the result that each hectare on average loses 6.95 $\pm$ 1.14 kg/ha/yr (mean$\pm$S.E.; N=6) to downgradient waters. This is lower than the loss from continuously flowing or flow through bogs of 23.1 kg/ha/yr. The acreage and classification of bogs (flow through vs. non-flow through) was also refined from prior analyses. Review of bog construction in the watershed showed that many of the bogs have been altered during recent years to include stream bypasses and convert former flow-through bogs to non-flow through bogs. MEP consulted with USDA staff and BBNEP staff and reviewed available historic aerial photographs on Google Earth to classify the likely type of bog at the time of the stream water quality data used for the MEP modeling. Nitrogen loads from the cranberry bogs in the watershed nitrogen loading model are based on these classifications and loads; details are contained in the MEP Data Disk that accompanies this report.

Nitrogen Loading Input Factors: Solid Waste Sites

MEP staff reviewed MassDEP's solid waste database and identified one landfill site within the Wareham River watershed: the Carver-Marion-Wareham (CMW) Landfill. Project staff contacted MassDEP staff to obtain any available nitrogen monitoring data for this site (personal communication, Mark Dakers, MassDEP, 6/10). Using the available monitoring information, MEP staff developed a nitrogen load for the landfill site.

Figure IV-4. Carver-Marion-Wareham (CMW) Landfill, Carver, MA. CWM Landfill is located in Wankinco R N LT10 subwatershed (subwatershed #32). Image from Google Earth (dated 3/11/12). Over 41 monitoring well are located around the landfill. MEP staff review of monitoring data shows that groundwater flows toward the southeast, toward the Wankinco River. Based on monitoring data from the period when MEP streamflow data was collected (1999/2000), the landfill was estimated to be contributing 1,481 kg/yr of nitrogen to the subwatershed.

The CMW Landfill is located between Federal Road in Carver and the Wankinco River (Figure IV-4). The landfill is located within the Wankinco R N LT10 subwatershed (subwatershed #32). According to MassDEP records, the site was originally operated as a municipal solid waste landfill and has been reworked over the past decade to include lining and capping of portions, as well as disposal of municipal waste combustor ash and bypass municipal solid waste generated by the SEMASS Resource Recovery Facility in Rochester MA. MassDEP records show that 41 monitoring wells have been installed at the site and most have been sampled 21 times between April 1998 and January 2010. MEP staff focused on the 1999 to 2000 sampling runs and reviewed groundwater concentrations of nitrate-nitrogen (NO3-N), ammonia-nitrogen (NH4-N), alkalinity, specific conductivity, and dissolved oxygen in the monitoring wells, as well as water table elevation data.

Monitoring data generally shows groundwater flows toward the southeastern portion of the landfill, toward the Wankinco River. MEP staff review of water quality data shows that nine downgradient wells measured during the 1999/2000 period had consistent signs of groundwater contaminant concentrations generally associated solid waste sites. Nitrate-nitrogen (NO_3-N) plus ammonia-nitrogen (NH_4-N) concentrations in these wells averaged 8.7 mg/L with a range of 0.82 to 23.75 mg/L. Concentrations in a well on the other side of the river average 0.09 mg/L. 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). Using an estimate of 61 acres of solid waste based on the review of MassDEP files, available aerial photographs and the Wareham River recharge rate, MEP staff developed an estimated annual total nitrogen load of 1,481 kg from the CMW Landfill. Comparable review of 2008 to 2010 monitoring data shows that the estimated annual nitrogen load from the site has declined to 685 kg; the buildout estimate assumes that the site does not contribute a nitrogen load based on flushing out of the aquifer and the installation of a cap and liners on the site.

It is acknowledged that this approach for estimating a nitrogen load from the CMW Landfill includes a number of assumptions, but these are 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 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 are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the Cape Cod Commission's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and Massachusetts DEP's Nitrogen Loading Computer Model Guidance (1999). The recharge rate for natural areas and lawn areas is the same as utilized in the MEP-USGS groundwater modeling effort (Section III). Factors used in the MEP nitrogen loading analysis for the Wareham River watershed are summarized in Table IV-1.

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

Table IV-1. Primary Nitrogen Loading Factors used in the Wareham River MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Wareham, Carver, and Plymouth data.

Nitrogen Concentrations:	mg/l	Recharge Rates:[2]	in/yr
Road Run-off	1.5	Impervious Surfaces	40
Roof Run-off	0.75	Natural and Lawn Areas	27
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater (all in gpd): [3]	
Natural Area Recharge	0.072	Parcels wo/water use and buildout	
Wastewater Coefficient	23.63	All others based on town-reported flows	
Fertilizers:		Single-family residential parcels	137
Average Residential Lawn Size (sq ft)[1]	5,000	Multi-family residential parcels	630
Residential Watershed Nitrogen Rate (lbs/lawn) [1]	1.08	Commercial parcels	548
Cranberry Bogs export – flow through (kg/ha/yr)	23.1	Industrial parcels	911
Cranberry Bogs export – non-flow through(kg/ha/yr)	6.95	Wareham Wastewater Treatment Facility [4]	
Nitrogen Fertilizer Rate for golf courses, cemeteries, and public parks determined from site-specific information		Annual Total Nitrogen load (kg)	6,761
		Effluent Flow (million gallons per day)	1.04
		Effluent Total Nitrogen concentration (mg/l)	4.67

Notes:
1) Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.
2) Based on USGS recharge rates for Plymouth-Carver-Kingston-Duxbury Aquifer Model (Masterson, *et al.*, 2009)
3) Based on Town of Wareham 2009 water use billing records
4) Averages based on review of Town of Wareham WWTF reporting data to MassDEP (October 2005 to March 2007)

For impervious surfaces, MEP staff reviewed a number of different sources. MassGIS maintains a GIS coverage of impervious surfaces based on semi-automated interpretation of April 2005 aerial photography (MassGIS, 2007). MEP staff has reviewed this coverage in a number of watersheds, including the Wareham River watershed, and has generally found it to be inaccurate, often including extensive pervious areas adjacent to roads and excluding portions of roof areas. MEP staff also reviewed town assessors' data, which appears to include total living area, rather than just the building footprints; measured footprints from aerial photographs revealed smaller areas. When staff reviewed the 2011 Wareham assessor's database, the average area for single family residences was 2,540 square feet, which seems exceptionally high. Similarly classified buildings in other nearby watersheds are approximately 1,500 sq ft; single family residences in the Nasketucket Harbor, West Falmouth Harbor, and

Slocums River MEP watersheds average 1,504 sq ft, 1,500 sq ft, and 1,472 sq ft, respectively. However, average area of all buildings types is typically between 2,000 and 2,500 sq ft; the average of all building types within the Town of Falmouth and City of New Bedford averaged 1,973 sq ft and 2,437 sq ft, respectively. Using MassDEP guidance to assign conservative factors where uncertainty exists, MEP staff assigned the Town of Wareham assessor's average of 2,540 sq ft to all buildings within the Wareham River watershed. Changing this factor to 1,500 sq ft would alter the system nitrogen load by <1%. Impervious surfaces for roads are based on MassHighway road segments which include measurements of road, shoulder, and right-of-way (ROW) widths. MEP watershed assessments typically use MassHighway road widths for calculating road impervious surfaces. It should also be noted that in portions of the town parcel GIS coverages, road areas or ROWs are not delineated as separate parcels, so care was taken to avoid double counting of these areas in the nitrogen loading calculations.

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, parcels were assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel was located within a respective watershed. Following the initial assigning of boundary parcels, all large parcels were examined individually and split (as appropriate) in order to obtain less than a 2% difference between the total land area of each sub-watershed based on the watershed delineations and the sum of the area of the parcels within each sub-watershed.

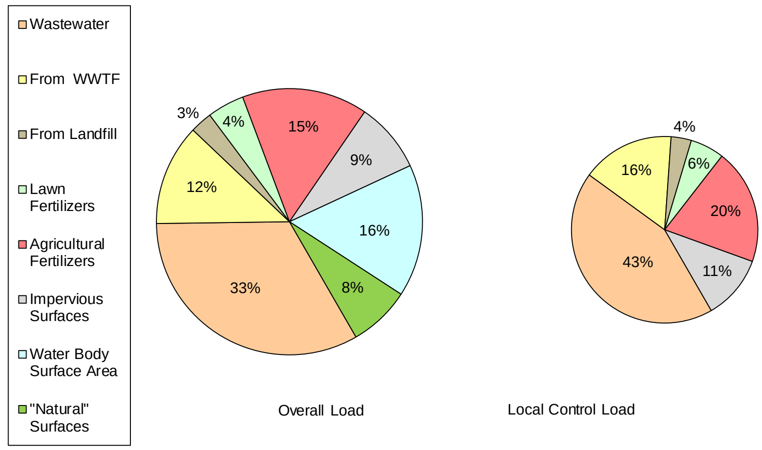
The review of individual parcels straddling watershed boundaries included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Individualized information for parcels with atypical nitrogen loading (condominiums, golf courses, etc.) was also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the Wareham River estuary. The assignment effort was undertaken to better define sub-estuary loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Following the assignment of all parcels, sub-watershed modules were generated for each of the 45 sub-watersheds summarizing water use, parcel area, frequency, sewer connections, private wells, and road area. The individual sub-watershed modules were then integrated to create a Wareham River Watershed Nitrogen Loading module with summaries for each of the individual sub-embayments and sub-estuaries. The sub-embayments represent the functional embayment units for the Linked Watershed-Embayment Model's estuary water quality component.

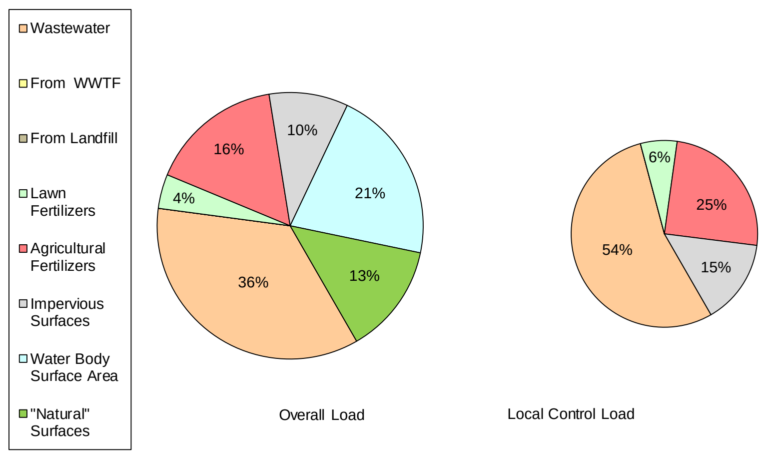
For management purposes, the aggregated watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Wareham River study area, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), the municipal wastewater treatment facility, fertilizer, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-2). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to each component sub-embayment, by each source category (Figure IV-5 a-c). The annual watershed nitrogen input is then reduced by natural nitrogen attenuation in the ponds and rivers during transport and the estuary receives this reduced load. The nitrogen loads used in the MEP embayment water quality sub-model are a combination of the estimated loads in Table IV-2 and the measured loads from the rivers discussed in Section IV.2.

Table IV-2. Wareham River Watershed Nitrogen Loads. Attenuation of Wareham River system nitrogen loads occurs as nitrogen moves through upgradient ponds and streams during transport to the estuary. Attenuation factors related to the freshwater inflows from the Agawam and Wankinco Rivers were based upon measurements. All values are kg N yr^{-1}.

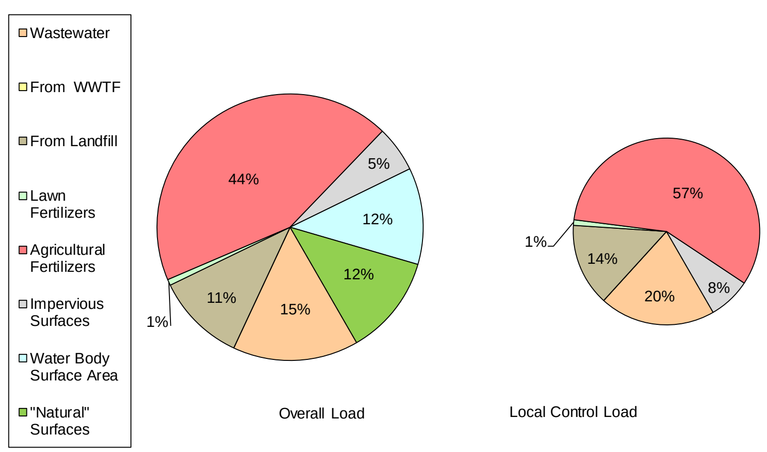
		Wareham River System N Loads by Input (kg/y):									% of Pond Outflow	***Present N Loads***			***Buildout N Loads***		
Name	Watershed ID#	Wastewater	From WWTF	From Landfill	Lawn Fertilizers	Agricultural Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout		UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
Wareham River System		18199	6761	1481	2473	8397	4683	8836	4125	21694		54954		51489	76648		70378
Broad Marsh River	43	1559	0	0	531	0	647	16	145	1625		2898		2898	4523		4523
Wareham River West	44	585	0	0	514	24	569	10	77	-149		1778		1778	1629		1629
Wareham River East	45	912	0	0	138	0	207	0	38	-707		1295		1295	588		588
Crooked River	46	1460	0	0	168	0	240	43	42	-605		1953		1953	1348		1348
Wareham River South	47	182	0	0	14	0	24	3	40	117		262		262	379		379
Wareham River Estuary surface deposition								3565				3565		3565	3565		3565
Inner Wareham River		13500	6761	1481	1109	8373	2996	5200	3783	21412		43204		39738	64615		58346
bog stream	35	340	0		20	172	100	68	57	48		757		757	805		805
Agawam River	42	6281	6761		428	69	835	9	256	5412		14639		14639	20051		20051
Inner Wareham River Estuary surface deposition								658				658		658	658		658
Agawam River/ Mill Pond	MP	4797	0	0	562	2194	1300	2870	1815	643		13537	7.5%	12522	14181	8%	13117
Mill Pond	20	4658	0		558	2059	905	1560	762	211	100%	10502		10502	10713		10713
East Branch N	EBN	8	0		0	0	120	435	374	0	100%	938		938	938		938
Agawam Reservoir S	ARS	69	0		4	135	198	417	511	424	88%	1333		1333	1758		1758
Five Mile Pond	FMP	1	0		0	0	6	50	17	0	31%	75		75	75		75
Spectacle Pond	SPP	5	0		0	0	0	67	3	2	34%	76		76	79		79
Sandy Pond	SP	0	0		0	0	0	28	5	6	37%	33		33	39		39
Fearing Pond	FP	0	0		0	0	7	23	16	0	23%	46		46	46		46
Three Cornered Pond	TCP	0	0		0	0	2	12	6	0	12%	20		20	20		20
East Head Pond	EHP	13	0	0	0	0	35	179	68	0	36%	295		295	295		295
Charge Pond	CP	43	0		0	0	26	99	53	0	66%	220		220	220		220
Wankinco River		2082	0	1481	99	5938	761	1595	1656	15309		13612	18%	11162	28921	18%	23715
Rose Brook	41	1127	0		18	718	184	74	121	435		2241		2241	2676		2676
Parker Mills Pond	PMP	954	0	1481	82	5221	577	1521	1535	14874		11371	0%	11371	26245	0%	26245
Parker Mills Pond	40	50	0		6	515	132	244	78	10692		1026		1026	11718		11718
Harlow Brook	34	124	0		9	756	49	60	339	27		1336		1336	1363		1363
East Head Pond	EHP	3	0	0	0	0	7	36	14	0	7%	59		59	59		59
Charge Pond	CP	22	0	0	0	0	13	51	27	0	34%	114		114	114		114
Maple Swamp		756	0	1481	67	3950	376	1130	1076	4155		8835		8835	12990		12990
Maple Swamp	39	147	0		6	755	65	708	221	1018		1902		1902	2919		2919
Frogfoot Brook	33	0	0		0	580	12	108	163	-151		863		863	712		712
East Head Pond	EHP	14	0	0	0	0	38	197	74	0	39%	324		324	324		324
Wankinco River N	WRN	595	0	1481	61	2615	261	117	618	3288		5747		5747	9035		9035
Wankinco R N GT10	31	547	0		59	54	88	0	132	479		880		880	1359		1359
Wankinco R N LT10	32	48	0	1481	1	2561	170	102	481	2809		4844		4844	7653		7653
East Head Pond	EHP	1	0		0	0	3	15	5	0	3%	24	0%	24	24	0%	24



a. Wareham River Estuary Watershed System Overall



b. Agawam River/Mill Pond Subwatershed Total



c. Wankinco River Subwatershed Total

Figure IV-5 (a-c). Unattenuated nitrogen load for various land use categories to the (a) overall Wareham River Estuary System watershed, (b) Agawam River sub-watershed, and (c) Wankinco River sub-watershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.

Freshwater Pond Nitrogen Loads

Freshwater ponds in aquifer systems like those in the Plymouth-Carver-Kingston-Duxbury Aquifer are generally kettle hole depressions that intercept the water table of surrounding groundwater. Groundwater typically flows into the pond along the upgradient shoreline, then lake water flows back into the groundwater system along the downgradient shoreline. Occasionally these ponds will also have a stream outlet or herring run that also acts as a discharge point; many of the ponds in the Wareham River watershed are connected to each other through streams and rivers, as well as connections that have been developed for cranberry bog operations. Since watershed nitrogen loads flow into the ponds along with the groundwater, the pond biomass (plants and animals) have the opportunity to incorporate some of the nitrogen, as well as transporting some of it to the pond sediments. As the nitrogen is captured and used in the pond ecosystem, it is also changed amongst its various oxidized and reduced forms. These interactions also allow for some chemical denitrification and release of some of the nitrogen to the atmosphere, as well as permanent burial in the pond sediments of some portion of the load that the pond receives. Through the cumulative effect of these interactions with the pond ecosystem, some of the nitrogen from the pond watershed is removed and is not transferred downgradient or downstream. If this reduced (or attenuated) load does not encounter any streams or other ponds, it will eventually discharge to the downgradient embayment. If it enters another pond or stream prior to discharge, this load can be further attenuated. In the nitrogen loading summary in Table IV-2 none of the ponds are assigned attenuation rates, so unattenuated (nitrogen load to each sub-watershed) and attenuated nitrogen loads are equal in all pond watersheds.

Pond nitrogen attenuation in freshwater ponds has generally been found to be at least 50% in MEP analyses, so this value, which has been shown to be conservative, is generally used as a standard MEP default attenuation rate when sufficient pond-specific data is not available. In order to estimate nitrogen attenuation in the ponds, available physical and water quality data for each pond is reviewed. Available bathymetric information is reviewed relative to measured pond temperature profiles to determine whether an epilimnion (*i.e.*, well mixed, uniform temperature, upper portion of the water column) exists in each pond. This step is completed to assess whether available data is influenced significantly by sediment regeneration of nitrogen. Bathymetric information is necessary to develop a residence or turnover time and complete an estimate of nitrogen attenuation.

In the Wareham River watershed, available data on the freshwater ponds is limited to selected bathymetric maps. No water quality data was discovered during reviews of available town and state databases. Bathymetric information is available for six of the 22 ponds with watersheds through the Massachusetts Division of Fisheries and Wildlife (www.mass.gov/dfwele/dfw/habitat/maps/ponds/pond_maps.htm). This bathymetric information was used to determine pond volumes. Residence times were determined based on these volumes and watershed recharge rates (Table IV-3).

In the Wareham River watershed, the MEP team had measured nitrogen loads at the Wankinco and Agawam stream gages. Assignment of the standard MEP 50% attenuation in all of the upstream/upgradient ponds with delineated subwatersheds resulted in attenuated nitrogen loads at the gages that were significantly less than the measured nitrogen loads. In order to be conservative and match the measured data, MEP staff assigned no attenuation to any of the pond nitrogen loads and assigned the stream gage attenuations based on the measured readings.

Table IV-3. Freshwater Ponds in the Wareham River watershed with delineated subwatersheds. Since limited bathymetric and no nitrogen sampling data were available, site-specific evaluation of nitrogen attenuation in these systems could not be completed. Because of uncertainty in the nitrogen loads, no attenuation is assigned to any of the ponds in the MEP Linked N Model for Wareham River; all attenuation is determined based on measured nitrogen loads at the gages for the Agawam and Wankinco Rivers.

Pond	Sub-watershed #	Area (acres)	Maximum Depth (feet)	Overall turnover time (years)	TN samples for Attenuation calculation	N Load Attenuation (%)
Agawam Reservoir S	2	27			None available	Not calculated due to lack of nitrogen data or bathymetry; no attenuation assigned to ponds
Agawam Reservoir N	3	14				
Fawn	7	40				
Bumps	9	15				
Three Cornered	10	9				
New Long	13	17				
New Grassy	15	4				
East Head	18	103				
Mill	20	121				
Fearing	21	19	20	0.23		
Abner	22	7				
Five Mile	23	21	21	No avg depth from MADFW		
Little Long	25	12				
Barrett	28	9	17	0.12		
Charge	30	15	17	0.09		
Sandy	37	18				
Spectacle	38	43				
Parker Mills	40	54				
College	49	50	24	0.24		
Halfway	50	228	13	0.47		
				Mean	**n/a**	

Data sources: all areas based on town parcels coverages; all depth information from MADFW bathymetric maps (www.mass.gov/dfwele/dfw/dfw_pond.htm); pond volume determined from average depth reported on MADFW bathymetric maps

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development within the study area watersheds and evaluate its water quality impacts on the estuary. MEP buildouts are generally relatively straightforward and are completed in the following steps: 1) each residential parcel classified by the town assessor as developable is identified and divided by minimum lot sizes specified in current 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, and 3) residential, commercial and industrial parcels with existing development and lot 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. Local knowledge and insights regarding future sewer connections, other land use restrictions, or future development are also incorporated into the MEP buildout scenario.

It should be noted that the MEP buildout approach is relatively simple and generally does not include any modifications/refinements for lot line setbacks, road construction, frontage requirements, parcel shape requirements, or other more detailed zoning provisions. The MEP buildout approach also does not include potential impacts associated with the higher densities usually associated with Chapter 40B affordable housing projects. However, buildout potential on individual lots in the Wareham River watershed was reduced by the removal of wetland areas, based on a MassDEP GIS coverage. Other provisions of the MEP buildout assessment include differentiated treatment of undevelopable lots, commercial and industrial properties, and lots less than the minimum areas specified by zoning. Properties classified by the town assessors as "undevelopable" (*e.g.*, MassDOR land use codes 132, 392, and 442) are not assigned any development at buildout (unless revised by a town review).

As an example of how the MEP approach might apply to an individual parcel, assume an 81,000 square foot lot is classified by the town assessor as a developable residential lot (land use code 130). Current zoning specifies that this lot is in an area where the minimum lot size is 40,000 square foot. For the MEP buildout, this lot is divided by a 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 sub-watershed in the MEP buildout scenario. Under the buildout, each of these lots would have the addition of nitrogen loads from wastewater, lawn fertilizers, and impervious surfaces (*i.e.*, roof and driveway). This addition could then be modified during discussion of town staff and incorporation of other factors, such as whether sewering is expected in the area.

Commercial and industrial properties classified as developable are not subdivided; the area of each parcel and zoning factors are used to determine a 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 (130 land use code) will be assigned an additional residential dwelling in the MEP buildout scenario even though the minimum lot size in the area is 40,000 square feet. 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.

Discussions with town planners, boards, and/or wastewater consultants can generate some additional insights on planned development, and often include discussion of developments planned for government or public service parcels, and updates to assessor classifications, including lands purchased by the town as open space. Refinements of the MEP buildout can continue as the Towns conduct nitrogen management planning and could include updates on parcels initially identified as developable or undevelopable and application of more detailed zoning provisions. As planning proceeds the Towns may request additional refined buildout scenarios to account for specific land-use shifts or projects that may be deemed likely within the watershed. All the parcels with additional buildout potential within the Wareham River watershed under the MEP buildout scenario are shown in Figure IV-6 and details for individual parcels are included in the MEP Data Disk that accompanies this report. The MEP buildout scenario includes 1,016 additional residential units (153 with sewer connections), 2.6 million square feet of commercial buildings, and 1.2 million square feet of industrial buildings.

The MEP buildout scenario also incorporates results of discussions with AD Makepeace (ADM) staff and consultants, as well as Town of Wareham sewer staff and consultants. ADM owns a number of large properties within the Wareham River watershed and is in the process of changing the land use on these properties. The development proposals are subject to review under the Massachusetts Environmental Policy Act (MEPA) and ADM has filed a number of MEPA documents detailing and modifying their development proposals. ADM is in the process of developing the project in a number of phases (Table IV-4) and these phases correspond to areas within the watershed (see Figure IV-6). The MEP buildout of the ADM phases is based on current plans, including the Expanded Environmental Notification Form (EENF) that was filed with MEPA in November 2012 (Beals and Thomas, 2012). MEP nitrogen loading factors were utilized in developing the ADM buildout nitrogen loads within the Wareham River watershed and these were reviewed with ADM consultants (personal communications, Stacy Minihane, Beals and Thomas, Inc.).

Among the ADM phases, Phase C is the most conceptual and, thus, is the most likely to change in the future. As currently proposed, this phase includes changes in cranberry bogs areas, conversion of flow through bogs to pump on bogs, development of a number of different land uses (*e.g.*, residential units and retail, office, and light industrial space), and the construction of a wastewater treatment facility. As an example of the changeable nature of this phase, however, an earlier iteration included 437 single-family residences on a portion of the Phase C development area in the Town of Plymouth. A subsequent modification reduced this count to 372 residences, and in the current EENF, these residences have been eliminated completely. Working with ADM staff and consultants, MEP staff used the current EENF proposal, MEP factors and Wareham-specific water uses to develop a nitrogen load for this phase. The nitrogen load for this phase is largely within the watershed to the Wankinco River and it is a little less than half of the overall MEP buildout nitrogen loading additions within the Wareham River watershed.

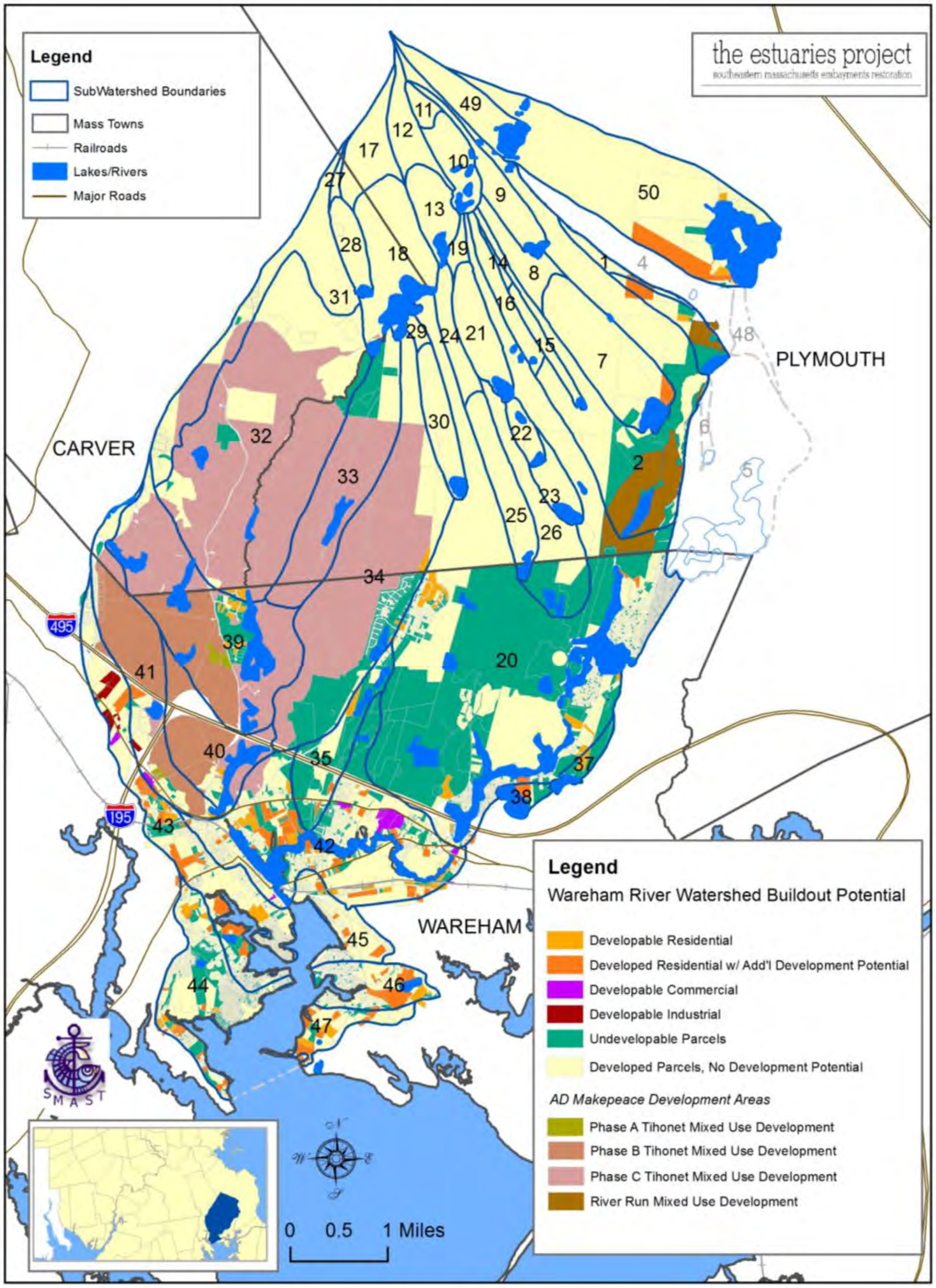


Figure IV-6. Developable Parcels in the Wareham River watershed. Residential, commercial, and industrial undeveloped parcels and developed parcels with additional development potential are shown. These parcels are assigned nitrogen loads in the MEP Buildout scenario for the Wareham River estuary with corrections for future projected town sewering. Also indicated are the AD Makepeace development areas, most of which are currently classified by town assessors as agricultural lands. Buildout nitrogen loads for the ADM areas are based on building areas or units specified in MEPA filings and MEP loading factors.

Table IV-4. AD Makepeace Loads Used MEP Buildout Scenario of Wareham River Watershed			
ADM Phase	MEP Sheds	MEP assigned unattenuated load (kg/yr)	Notes
River Run	2	67	80 estate houses; wastewater to ADM WWTF
A1	39	283	Mixed use bldg., Title 5 septic system
A2	40	26	Medical office bldg., connected to Wareham WWTF
A3	41	45	Bog expansion
B	40,41	203	Rosebrook Place (hotel, restaurant, retail, office), Rosebrook Business Park, Solar Arrays
C	32,33	10,507	Bog expansion, bog bypass channel, 929 single family residences, 380 condos, 110 apartments, retail, manufacturing, light industrial, office, R&D, ADM WWTF
ADM loads are based on current configuration of the project; only Phase A2 is completed at the time of this report is being written			

The MEP buildout also includes connection of additional properties to the Town of Wareham WWTF. Wareham's current Comprehensive Wastewater Management Plan (CWMP) includes the identification of a number of areas to be sewered in the future (Figure IV-7). Based on discussion with Town wastewater consultants, MEP staff converted these areas to conform to current parcel boundaries and existing and projected future buildout wastewater flows within these areas are assigned to the WWTF in the MEP buildout. The overall buildout flow for the WWTF is based on the CWMP year 2020 estimate: 1.47 million gallons per day (MGD) average year round flow. The WWTF effluent concentration at buildout is 5.67 mg/L total nitrogen, which is based on measured flow-weighted average effluent concentrations from July 2008 to April 2010. The total flow of 1.47 MGD is a 0.43 MGD increase over the 1.04 MGD used in the existing conditions modeling (see Table IV-1).

The MEP buildout scenario also includes changes in the areas or type of cranberry bogs. As mentioned in the Fertilized Areas section of nitrogen loading factors, bogs with continuous streamflow through the bogs have higher nitrogen loads (N losses per hectare per year) than those where the water needs to be pumped or diverted onto the bog. Review of aerial photographs show that a number of the bogs within the Wareham River watershed have been converted to pump on bogs through the use of stream bypasses over the past few decades, including the period since MEP streamflow readings were collected on the Agawam River and Wankinco River (April 1999 to June 2000). MEP consulted with USDA and BBNEP staff and reviewed current and available historic aerial photographs on Google Earth to classify the likely type of bog at the time of the stream water quality data used for the MEP modeling and whether changes in bog management or area have occurred since the MEP stream monitoring. Based on this review, over 150 acres of cranberry bogs in the watershed have been converted from flow through to pump on since the MEP Streamflow readings were collected. These changes are incorporated into the MEP buildout scenario.

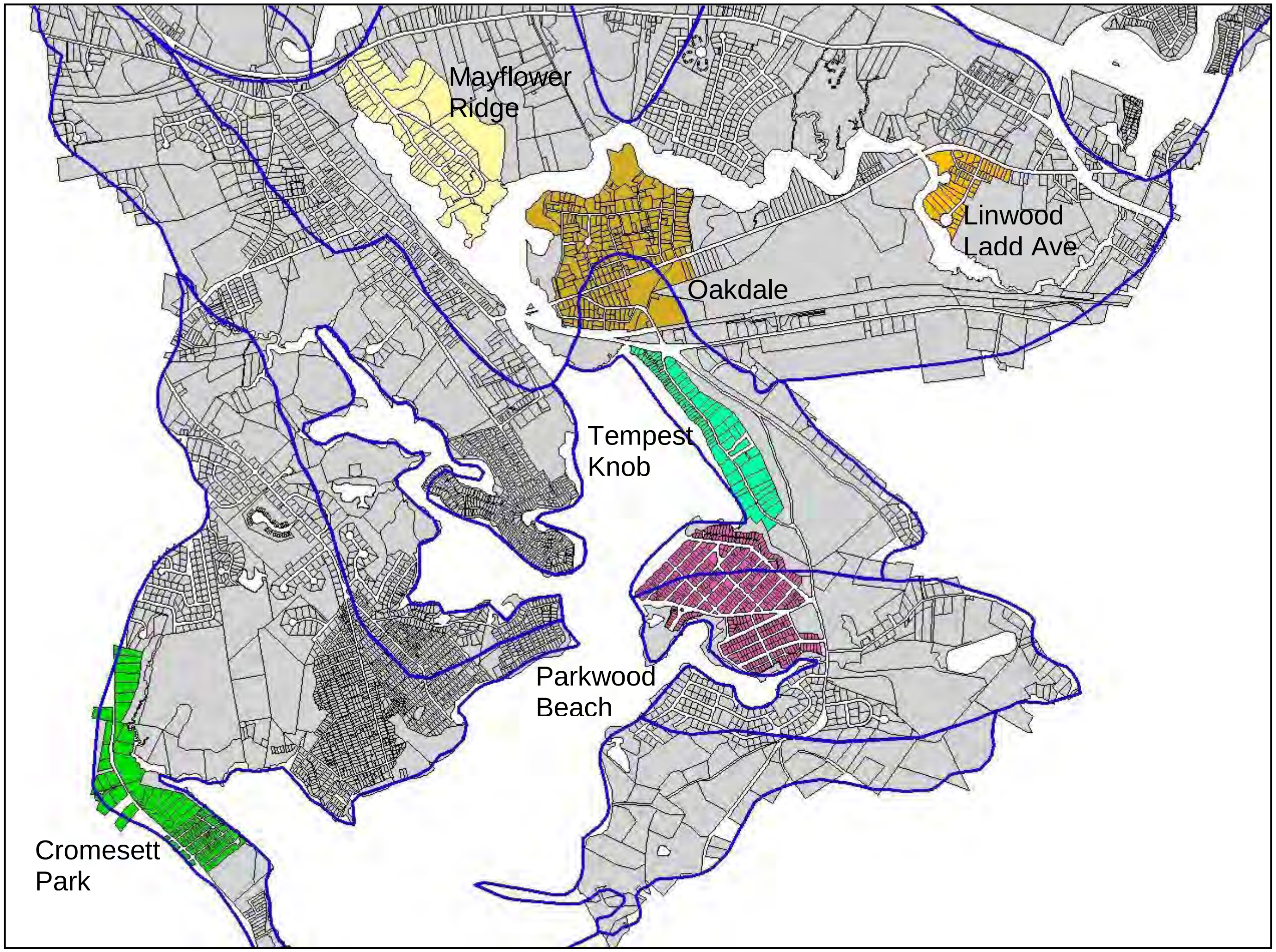


Figure IV-7. Future Sewer wastewater collection areas for Town of Wareham Wastewater Treatment Facility within the Wareham River MEP Watershed. Sewer collection areas are based on the Town of Wareham CWMP (2002). Areas within the Wareham River watershed were converted to corresponding parcels based on existing contracts for sewer pipes and future projected collection systems based on indicated areas and road layouts. Wastewater from these parcels is removed from the Wareham River buildout scenario.

Overall, there are a projected 1,945 additional residences at buildout within the Wareham River watershed (48% are within the current conceptual plan of ADM Phase C). Each additional residential, commercial, or industrial property added at buildout is assigned nitrogen loads for wastewater and impervious surfaces minus the sewer corrections to the Town of Wareham or ADM WWTF. All properties not connected to the sewers are assumed to utilize Title 5 on-site septic systems for wastewater treatment. Residential additions also include lawn fertilizer nitrogen additions. Cumulative unattenuated and attenuated buildout loads are indicated in separate columns in Table IV-2. Buildout additions within the Wareham River watersheds will increase the unattenuated nitrogen loading rate by 39%.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

IV.2.1 Background and Purpose

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out, sewering analysis, enhanced flushing, pond/wetland restoration for natural attenuation, etc.) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the sub-watersheds of the Wareham River-Broad Marsh-Marks Cove System being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1). If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such being the case in the developed region of southeastern Massachusetts but more so 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) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the case of the Wareham River embayment system watersheds, a portion of the freshwater flow and transported nitrogen passes through two major surface water systems (Agawam and Wankinco Rivers) prior to entering the Wareham River estuary, producing the opportunity for significant nitrogen attenuation.

Failure to determine the attenuation of watershed derived nitrogen overestimates the nitrogen load to receiving estuarine waters. If nitrogen attenuation is significant in one portion of a watershed and insignificant in another the result is that nitrogen management would likely be more effective in achieving water quality improvements if focused on the watershed region having unattenuated nitrogen transport (other factors being equal). In addition to attenuation by freshwater ponds (see Section IV.1.3, above), attenuation in surface water flows is also important. An example of the significance of surface water nitrogen attenuation relating to embayment nitrogen management was seen in the Marstons Mills River, where >60% of nitrogen originating within the upper watershed was attenuated prior to discharge to the Three

Bays Estuarine system (Howes et. al., 2006). Similarly, MEP analysis of the Quashnet River indicates that in the upland watershed, which has natural attenuation predominantly associated with riverine processes, the integrated attenuation was 39% (Howes et al. 2004). In addition, a preliminary study of Great, Green and Bournes Ponds in Falmouth, measurements indicated a 30% attenuation of nitrogen during stream transport (Howes and Ramsey 2001). An example where natural attenuation played a significant role in nitrogen management can be seen relative to West Falmouth Harbor (Falmouth, MA), where ~40% of the nitrogen discharge to the Harbor originating from the groundwater effluent plume emanating from the WWTF was attenuated by a small salt marsh prior to reaching Harbor waters. Clearly, proper development and evaluation of nitrogen management options requires determination of the nitrogen loads reaching an embayment, not just loaded to the watershed.

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP Approach. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the head of the Wareham River embayment system in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). This additional site-specific study was conducted in the 2 major surface water flow systems, the freshwater portion of the Agawam River as well as the Wankinco River, both discharging to the head of the Wareham River (Figure IV-8).

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 Agawam and Wankinco Rivers provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up-gradient from the gauging sites. Flow and nitrogen load were measured in each river starting in April of 1999 and continued to June 2000 for 15 months of continuous record (Figure IV-9 through 12). During the study period, velocity profiles were completed on both the rivers 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).

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

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

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

where by:

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

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

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

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

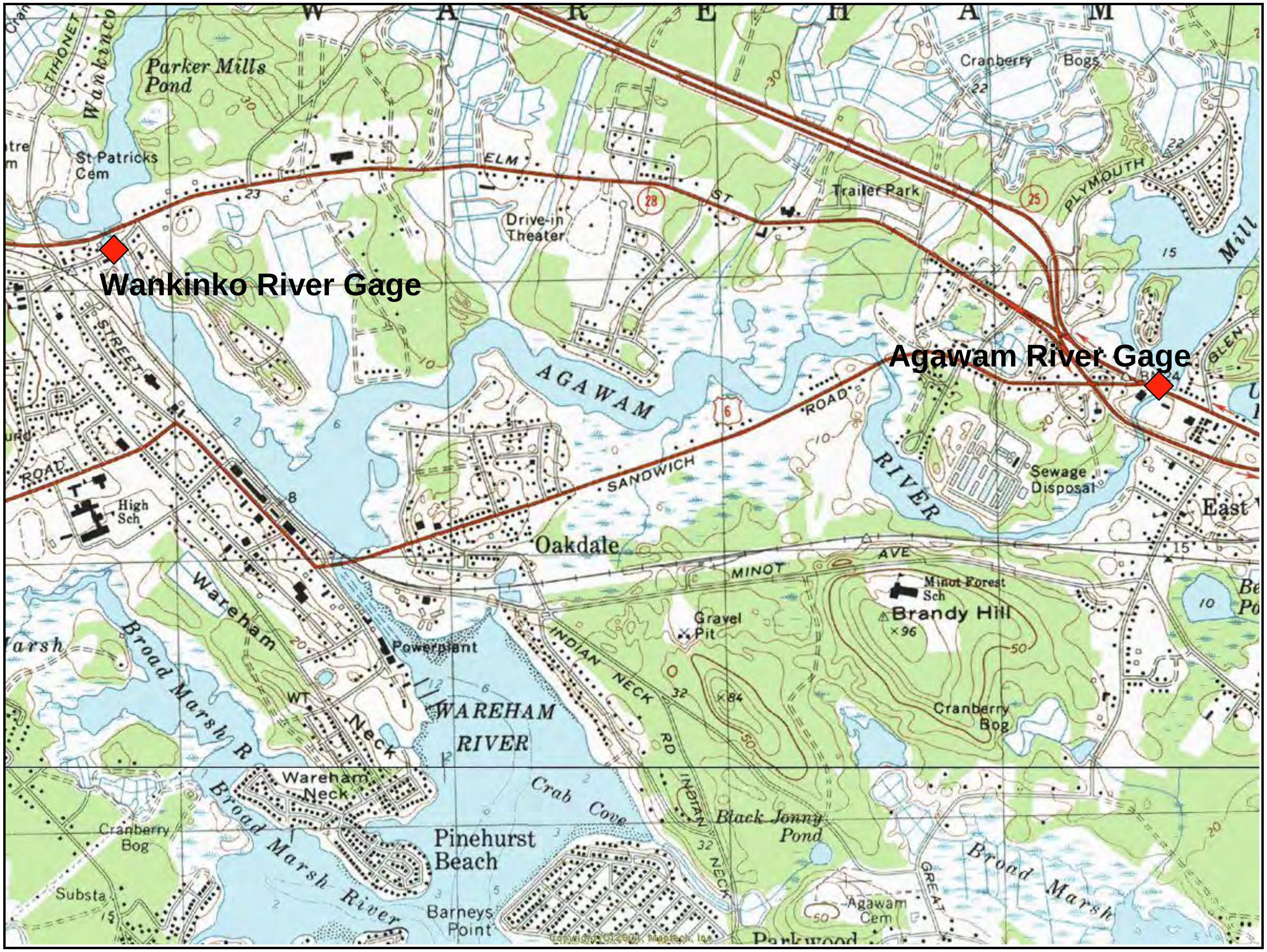


Figure IV-8. Location of Stream gage (red symbol) in the Wareham River-Broad Marsh embayment system.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Agawam River Discharge to the Wareham River-Broad Marsh Embayment System

The Mill Pond located up-gradient of the Agawam River gage site is a essentially a large freshwater pond and unlike many of the freshwater ponds in southeastern Massachusetts and Cape Cod, this pond has stream outflow rather than discharging solely to the aquifer along its down-gradient shore. This stream outflow, the Agawam River, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands and streambed associated with the freshwater portion of the Agawam River. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the Agawam River above the gage site and the measured annual discharge of nitrogen to the tidal portion of the Wareham River, Figure IV-8.

At the Agawam River (up-gradient Route 6) gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the Agawam River that carries the flows and associated nitrogen load to the head of the upper portion of the estuarine reach of the Wareham River. Stage was recorded in the Agawam River just downstream (ca. 20 feet) of the confluence of the 3 surface water outlets from Mill Pond (Rt. 6 dam). The vented transducer automatically corrects for changes in atmospheric pressure. The transducers were "fixed" within the deepest part of the river channel. The transducers were periodically calibrated in the laboratory and showed less than a 1% drift over the deployment interval. While the transducers were in the field, water levels at the sensor were measured at about weekly intervals to confirm the calibration during each deployment. Stage data was retrieved at 2-4 week intervals and the transducers checked for fouling without removing the recorders using a lap-top computer.

As the Agawam River is tidally influenced the gage was located above the saltwater reach such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average low tide salinity was determined to be no greater than 0.1 ppt (Agawam/Wareham River upper estuarine reach averages 23 ppt). Therefore, the gage location was deemed acceptable for making freshwater flow measurements. Calibration of the gage was checked monthly. The gage on the Agawam River was installed in April 1999 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued uninterrupted until June 24, 2000 for a total deployment of 15 months. The hydrologic year (12-month uninterrupted record from low flow conditions in one year to low flow conditions in the next year) used in this analysis encompasses the summer 1999 field season.

River flow (volumetric discharge) was initially measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter for a period of approximately 16 months. The volume of river flow was determined by making water depth and flow velocity measurements along a fixed transect across the river channel at the transducer location. The same fixed transect was used for all of the discharge measurements. The transect was set by attaching a meter tape between permanent posts on the river banks. At the Agawam River site, velocity measurements were made at 13-14 fixed points (from bank to bank) across the channel each separated by 0.5 meters. A rating curve was developed for the Agawam River site based upon these flow measurements and measured water levels at the gage site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume over the deployment period.

The Agawam River water sampling location was near the gage (transducer) site, but on the branch associated with the herring run and one of the dam overflows. Sampling of the freshwater was conducted by both grab sampling and continuous sampling (ISCO) from April 5, 1999 through November 5, 1999. Initially grab samples were collected nearly daily. Upon deployment of the automated samplers on June 1, grab sampling was reduced to approximately weekly intervals. The automated samplers integrated hourly water samples into 12 hour composites for chemical assay. To preserve the samples until return to the laboratory (maximum time 7 days), the sample bottles were pre-charged with sulfuric acid to lower the water to about pH 2. For quality assurance purposes, an additional grab sample was collected at the start of each automated sampler deployment and acidified and left in the sampler for comparison with the parallel grab sample (collected during each deployment) which was unacidified but assayed within hours of collection.

Nutrient samples were filtered upon return to the laboratory through 0.45 um membrane filters (GeoTech) for dissolved nutrients and pre-combusted GFF (Whatman) filters for particulate carbon and nitrogen analysis. All nutrient sample bottles were HCl leached and triple distilled water rinsed before use. Chlorophyll samples were collected in opaque bottles and transported cold (ca. 4C), dark filtered and extracted with acetone within hours of collection.

Water samples were collected both daily and weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the estuarine portion of the Agawam River (Figure IV-9, 10 and Table IV-5). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gage site.

The annual freshwater flow record for the Agawam River measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from the Agawam River was 0.4 % lower than the long-term average modeled flows (Table IV-6). This inconsequential difference between measured and modeled flow in the Agawam River surface water system is significant as the Agawam River is essentially a groundwater fed feature and as such should have flows comparable to those determined by recharge over the watershed area. Based upon the comparison of measured and modeled flows, it appears that the stream is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Agawam River outflow were relatively low averaging 0.44 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 34.14 kg/day and a measured total annual TN load of 12,461 kg/yr. In the Agawam River, nitrate was a very small fraction of the total nitrogen pool (4%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was completely taken up by plants within the pond or stream ecosystems up gradient of the gage. The concentration of inorganic nitrogen in the out-flowing stream waters also suggests that plant production within the up-gradient freshwater ecosystems is potentially nitrogen limited. In addition, the nitrate level in the Agawam River flow suggests the limited possibility for additional uptake by freshwater systems being achieved in this system either within the Mill Pond immediately up-gradient from the gage location or along the freshwater reach of the Agawam River further up in the watershed.

Table IV-5. Comparison of water flow and nitrogen discharges from the Agawam and Wankinco Rivers (freshwater) discharging to the estuarine reach of Wareham River. The "Stream" data is from the MEP stream gauging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	Agawam River Discharge[(a)]	Wankinko River Discharge[(a)]	Data Source
Total Days of Record	365[(b)]	365[(b)]	(1)
Flow Characteristics			
Stream Average Discharge (m3/day)	77817	71870	(1)
Contributing Area Average Discharge (m3/day)	78167	72688	(2)
Discharge Stream (MEP) relative Long-term Discharge	0.4%	1.1%	
Nitrogen Characteristics			
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.017	0.02	(1)
Stream Average Total N Concentration (mg N/L)	0.439	0.425	(1)
Nitrate + Nitrite as Percent of Total N (%)	4%	5%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	34.14	30.52	(1)
TN Average Contributing UN-attenuated Load (kg/day)	37.09	37.29	(3)
Attenuation of Nitrogen in Pond/Stream (%)	8%	18%	(4)

(a) Flow and N load to streams discharging to the Wareham River-Broad Marsh-Marks Cove system includes apportionments of Pond contributing areas.
(b) September to August, 1999 to 2000

(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 Agawam and Wankinko Rivers; and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates as applicable.
(4) Calculated based upon the measured TN discharge from the river vs. the unattenuated watershed load.

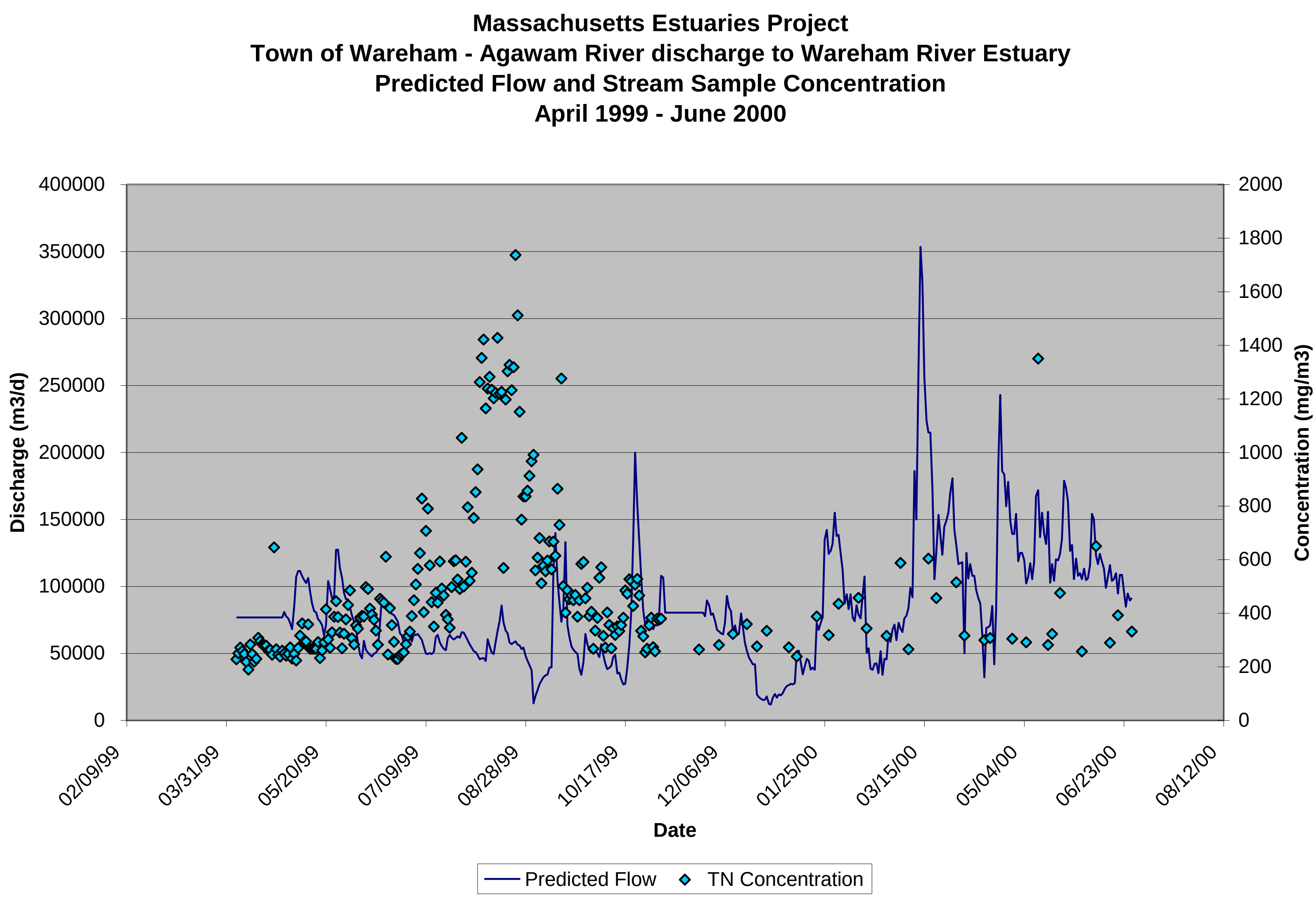


Figure IV-9. Agawam River discharge (solid blue line), Total Nitrogen (blue diamond) concentrations for determination of annual volumetric discharge and N-load from the upper watershed to the Wareham River Estuary (Table IV-6).

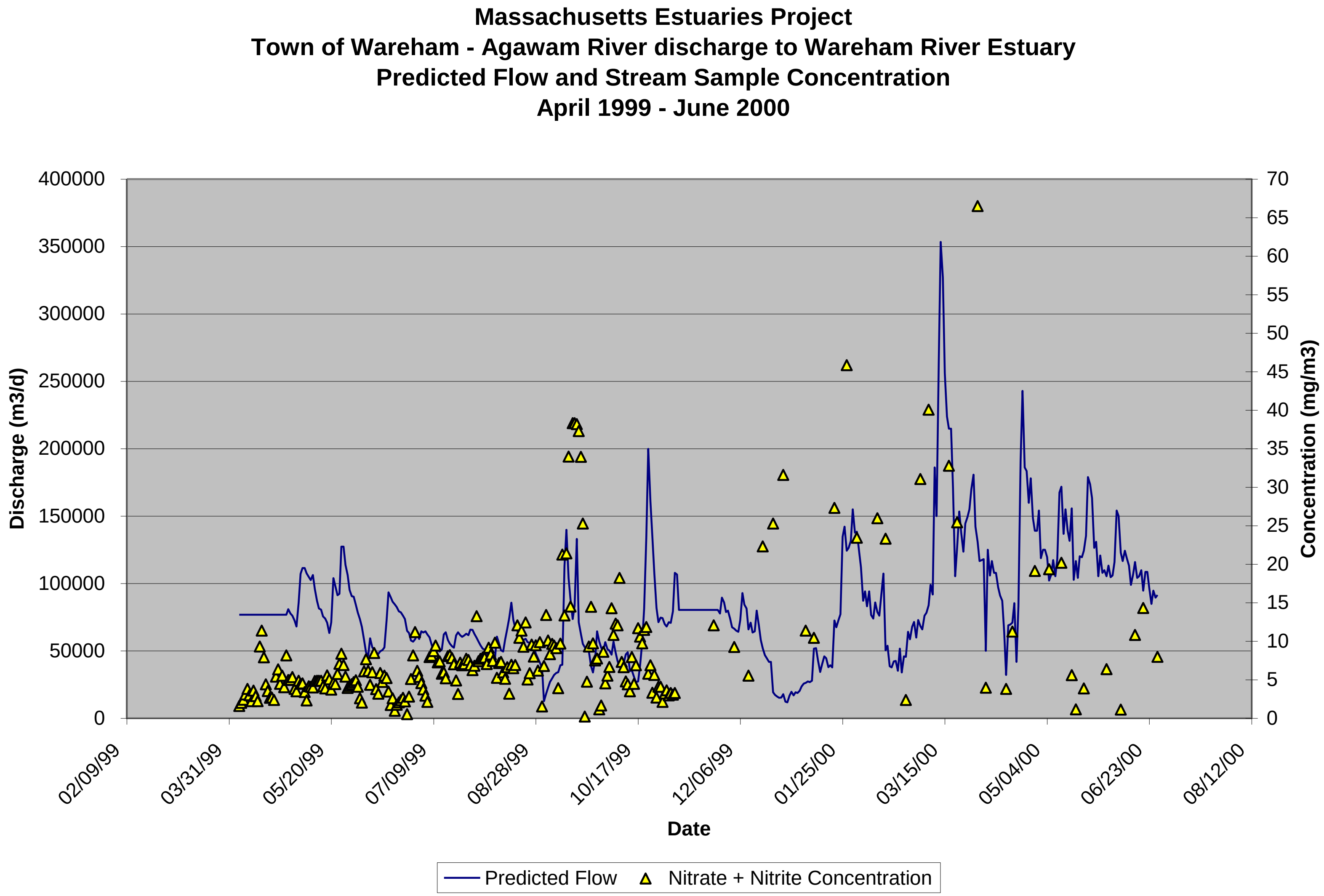


Figure IV-10. Agawam River discharge (solid blue line), nitrate+nitrite (yellow triangle) concentrations for determination of annual volumetric discharge and N-load from the upper watershed to the Wareham River Estuary (Table IV-6).

From the measured nitrogen load discharged by the Agawam River to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower nitrogen load (12,461 kg yr^{-1}) discharged from the freshwater Agawam River compared to that added by the various land-uses to the associated watershed (13,537 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 8% (i.e. 8% of nitrogen input to watershed does not reach the estuary). This level of attenuation is expected given the nature of the aquatic systems such as ponds and wetlands up-gradient of the Agawam River stream gage location. The directly measured nitrogen loads from the river was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Wankinco River Discharge to the Wareham River-Broad Marsh Embayment System

The Parker Mills Pond located up-gradient of the Wankinco River gage site is a essentially a large freshwater pond and unlike many of the freshwater ponds in southeastern Massachusetts and Cape Cod, this pond/reservoir has stream outflow rather than discharging solely to the aquifer along its down-gradient shore. This stream outflow, the Wankinco River, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands and streambed associated with the freshwater portion of the Wankinco River. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the Wankinco River above the gage site and the measured annual discharge of nitrogen to the tidal portion of the Wareham River, Figure IV-8.

At the Wankinco River (up-gradient Main Street) gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the freshwater portion of the Wankinco River that carries the flows and associated nitrogen load to the head of the upper portion of the estuarine reach of the Wareham River. The vented transducer automatically corrects for changes in atmospheric pressure. The transducer was “fixed” within the deepest part of the river channel. The transducer was periodically calibrated in the laboratory and showed less than a 1% drift over the deployment interval. While the transducer was in the field, water levels at the sensor were measured at about weekly intervals to confirm the calibration during each deployment. Stage data was retrieved at 2-4 week intervals and the transducers checked for fouling without removing the recorders using a lap-top computer.

Stage was recorded at 2 sites in the Wankinco River, both adjacent the Tremont Nail Factory property. An upper recorder was placed in the primary discharge weir which separates the freshwater from the uppermost portion of the estuary. The second recorder was placed in the channel about 100 feet downstream of the confluence of the 4 surface freshwater flows from the upper watershed. The recorder measured only freshwater outflow during low tide (as determined by salinity), but was influenced by estuarine water during high tide. Freshwater stage at the lower transducer site was determined from the low tide levels during tides that the channel was fully emptied of estuarine waters. These conditions were met during most tidal cycles. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average low tide salinity was determined to be <0.2 ppt (Wareham River upper estuarine reach averages 23 ppt). Therefore, the gage location was deemed acceptable for making freshwater flow measurements. Calibration of the gage was checked weekly to monthly. The gage on the Wankinco River was installed in April 1999 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued uninterrupted until June 24, 2000 for a total deployment of 15 months. The hydrologic year (12-month uninterrupted record from low flow conditions in one year to low flow conditions in the next year) used in this analysis encompasses the summer 1999 field season.

River flow (volumetric discharge) was initially measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter for a period of approximately 16 months. The volume of river flow was determined by making water depth and flow velocity measurements along a fixed transect across the river channel at the transducer location. The same fixed transect was used for all of the discharge measurements. The transect was set by attaching a meter tape between permanent posts on the river banks. The Wankinco River flow measurement site was at the lower transducer site and the transect had 12-13 fixed points across the river each separated by 1.0 meter. A rating curve was developed for the Wankinco River site based upon these flow measurements and measured water levels at the gage site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume over the deployment period.

The Wankinco River water sampling location was at the primary weir, before discharge to the tidal portion of the river. Initial sampling of the site showed that no estuarine water reached the sampling locations during any stage of both neap and spring tides (as measured by salinity). Furthermore, sampling showed no detectable difference in nutrients or chlorophyll levels between the individual weirs or overflows. Sampling of the freshwater was conducted by both grab sampling and continuous sampling (ISCO) from April 5, 1999 through November 5, 1999. Initially grab samples were collected nearly daily. Upon deployment of the automated samplers on June 1, grab sampling was reduced to approximately weekly intervals. The automated samplers integrated hourly water samples into 12 hour composites for chemical assay. To preserve the samples until return to the laboratory (maximum time 7 days), the sample bottles were pre-charged with sulfuric acid to lower the water to about pH 2. For quality assurance purposes, an additional grab sample was collected at the start of each automated sampler deployment and acidified and left in the sampler for comparison with the parallel grab sample (collected during each deployment) which was unacidified but assayed within hours of collection.

Nutrient samples were filtered upon return to the laboratory through 0.45 um membrane filters (GeoTech) for dissolved nutrients and pre-combusted GFF (Whatman) filters for particulate carbon and nitrogen analysis. All nutrient sample bottles were HCl leached and triple distilled water rinsed before use. Chlorophyll samples were collected in opaque bottles and transported cold (ca. 4C), dark filtered and extracted with acetone within hours of collection.

Water samples were collected daily to weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the estuarine portion of the Wareham River (Figure IV-11, 12 and Table IV-5). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gage site.

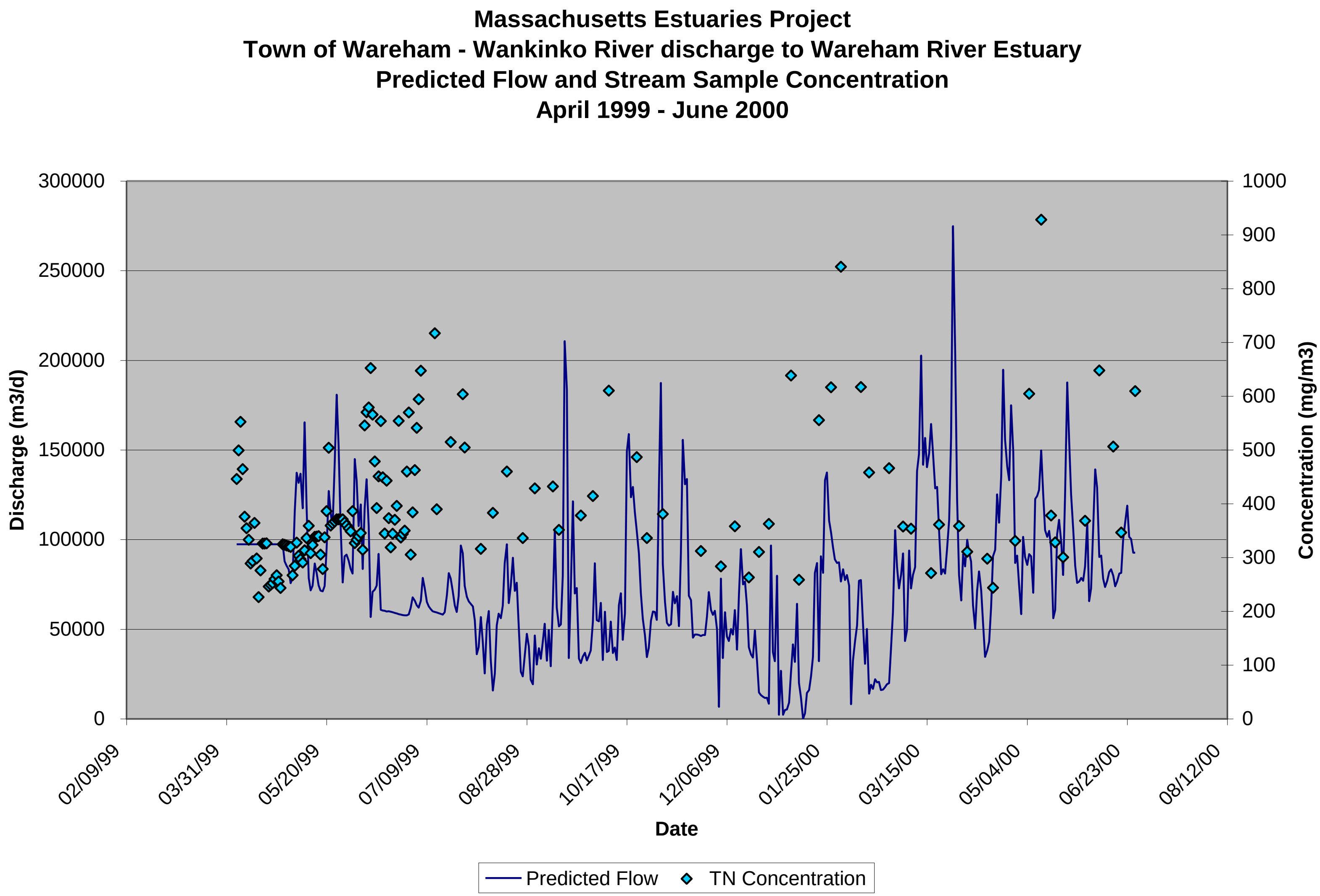


Figure IV-11. Wankinco River discharge (solid blue line), Total Nitrogen (blue diamond) concentrations for determination of annual volumetric discharge and N-load from the upper watershed to the Wareham River Estuary (Table IV-6).

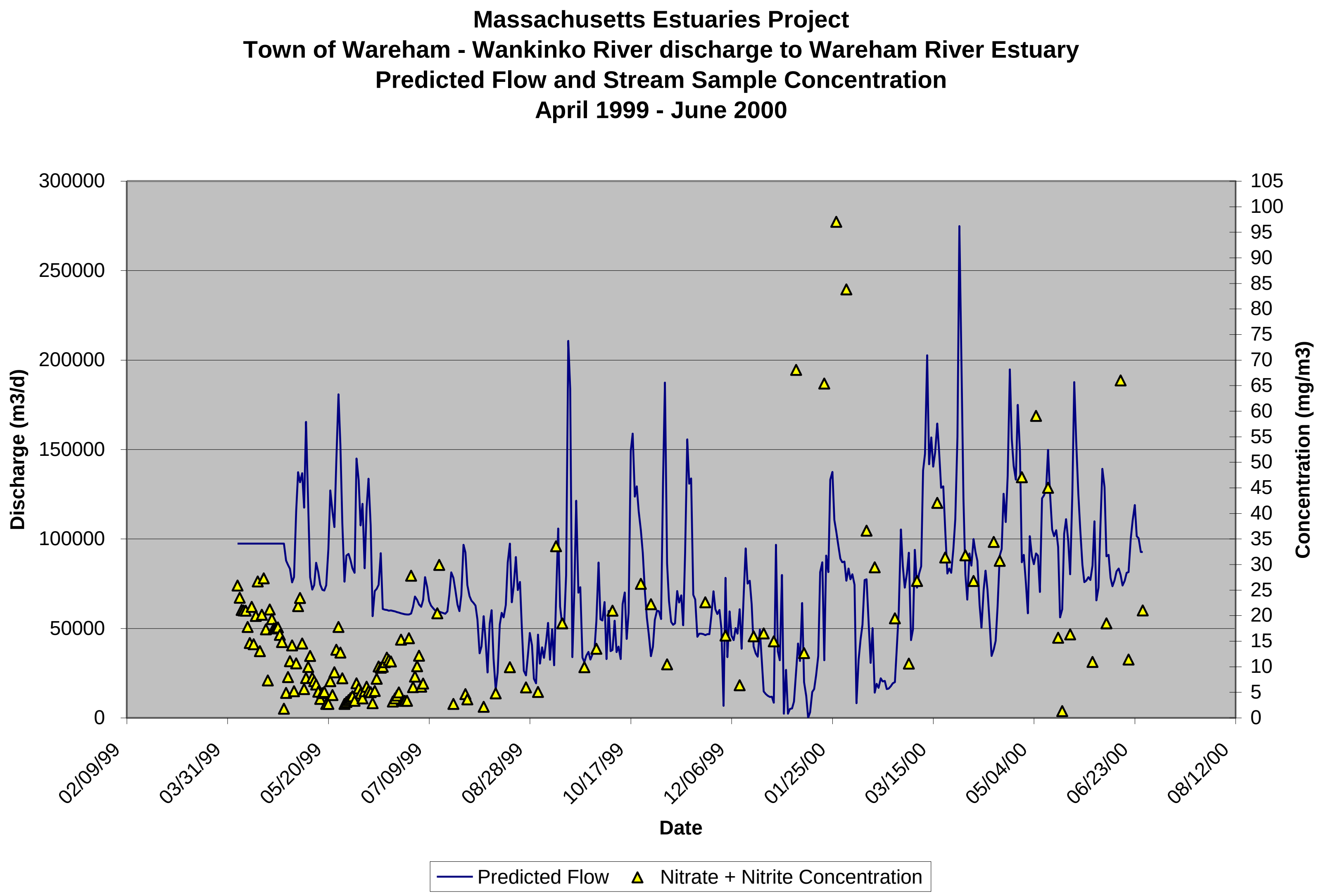


Figure IV-12. Wankinco River discharge (solid blue line), NOx (yellow triangle) concentrations for determination of annual volumetric discharge and N-load from the upper watershed to the Wareham River Estuary (Table IV-6).

The annual freshwater flow record for the Wankinco River measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from the Wankinco River was ~1% lower than the long-term average modeled flows (Table IV-6). This inconsequential difference between measured and modeled flow in the Agawam River surface water system is significant as the Wankinko River is essentially a groundwater fed feature and as such should have flows comparable to those determined by recharge over the watershed area. Based upon the comparison of measured and modeled flows, it appears that the stream is capturing the up-gradient recharge (and loads) accurately.

Table IV-6. Summary of annual volumetric discharge and nitrogen load (nitrate+nitrite and total nitrogen) from the Agawam and Wankinco Rivers (freshwater) discharging to the head of the estuarine reach of the Wareham River based upon the data presented in Figures IV-9 through 12 and Table IV-5.

Embayment System	Period of Record	Discharge (m^3/yr)	Attenuated Load (Kg/yr) NOx	TN
Agawam River (Freshwater)	September 1, 1999 to August 31, 2000	28,403,345	469	12,461
Agawam River (Freshwater)	Based on Watershed Area and Recharge	28,530,955	--	--
Wankinco River (Freshwater)	September 1, 1999 to August 31, 2000	26,232,595	580	11,139
Wankinco River (Freshwater)	Based on Watershed Area and Recharge	26,531,120	--	--

Total nitrogen concentrations within the Wankinco River outflow were relatively low averaging 0.425 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 30.52 kg/day and a measured total annual TN load of 11,139 kg/yr (based on one year record). In the Wankinco River, nitrate was a small fraction of the total nitrogen pool (5%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was almost completely taken up by plants within the pond or stream ecosystems up-gradient of the gage site. The concentration of inorganic nitrogen in the out-flowing stream waters also suggests that plant production within the up-gradient freshwater ecosystems is potentially nitrogen limited. In addition, the nitrate level in the Wankinco River flow suggests the limited possibility for additional uptake by freshwater systems being achieved in this system, either within the Parker Mills Pond immediately up-gradient from the gage location or along the freshwater reach of the Wankinco River further up in the watershed.

From the measured nitrogen load discharged by the Wankinco River to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower nitrogen load (11,139 kg yr^{-1}) discharged from the freshwater Wankinco River compared to that added by the various land-uses to the associated watershed (13,612 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 18% (i.e. 18% of nitrogen input to watershed does not reach the estuary). The directly measured nitrogen loads from the river 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 Wareham River Embayment System. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Water column Exchange of Nitrogen

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

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

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment water column for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, such as found within Crooked River. In contrast, regions of deposition like the Wareham River, Broad Marsh and Marks Cove, upper basins (Agawam and Wankinco) where the upper watershed nutrients are focused typically show the most organic sediments and highest levels of nitrogen release. The consequences of the high organic loading in the upper reaches (above the Route 6 Bridge) are unconsolidated sediments composed of fine material, organic rich and sulfidic in 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 Wareham River Embayment System. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for determining sediment-watercolumn nitrogen exchange

For the Wareham River 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 throughout the lower estuary from Broad Marsh River, Crooked River, Marks Cove and the main basins of the Wareham River (16 sites) in August 2002 and throughout the upper estuary, within the estuarine reaches of the Agawam and Wankinco Rivers (8 sites) in August 2007. The upper estuary was assayed in 2007 after the system had adjusted to the localized effects of the upgrade to the Wareham WWTF in 2005 (Figure IV-13). Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The number of core samples from each site (Figure IV-13) per incubation are as follows:

Wareham River Embayment System Benthic Nutrient Regeneration Cores

• Agawam River Upper-22	1 core	(Basin)
• Agawam River Upper-23	1 core	(Basin)
• Agawam River Upper-24	1 core	(Basin)
• Agawam River Lower-20	1 core	(Basin)
• Agawam River Lower-21	1 core	(Basin)
• Agawam/Wankinco-18	1 core	(Basin)
• Agawam/Wankinco-19	1 core	(Basin)
• Wankinco Basin-17	1 core	(Basin)
• Wareham River Upper-13	1 core	(Basin)
• Wareham River Upper-14	1 core	(Basin)
• Wareham River Upper-15	1 core	(Basin)
• Wareham River Upper-16	1 core	(Basin)
• Broad Marsh River-10	1 core	(Basin)
• Broad Marsh River-11	1 core	(Basin)
• Broad Marsh River-12	1 core	(Basin)
• Crooked River-9	1 core	(Basin)
• Wareham River Lower-4	1 core	(Basin)
• Wareham River Lower-5	1 core	(Basin)
• Wareham River Lower-6	1 core	(Basin)
• Wareham River Lower-7	1 core	(Basin)
• Wareham River Lower-8	1 core	(Basin)
• Marks Cove-1	1 core	(Basin)
• Marks Cove-2	1 core	(Basin)
• Marks Cove-3	1 core	(Basin)

Sampling was distributed throughout the primary embayment sub-basins of this system: the Agawam and Wankinco Rivers estuarine reaches, Broad Marsh River, Crooked River, Marks Cove and the Wareham River Estuary. and the results for each site combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

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

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

Figure IV-13. Wareham River-Marks Cove-Broad Marsh embayment system sediment sampling sites (red symbols) for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-7.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

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

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

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

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

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can “escape” to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-14).

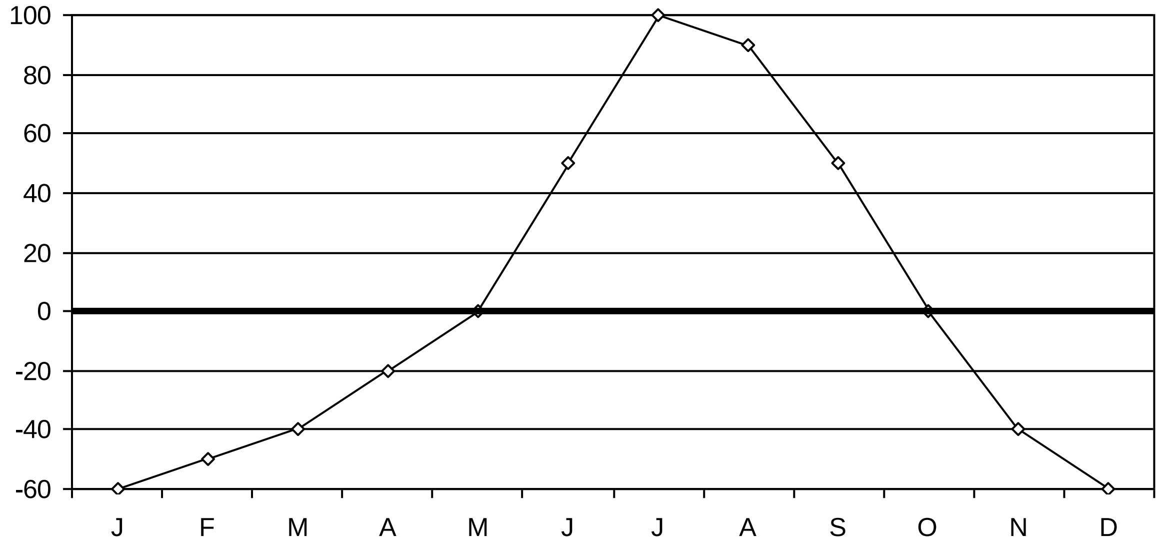


Figure IV-14. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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

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

Sediment sampling was conducted throughout the primary embayment sub-basins of this system: the Agawam and Wankinco Rivers estuarine reaches, Broad Marsh River, Crooked River, Marks Cove and the Wareham River Estuary, in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

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

Net nitrogen release or uptake from the sediments within the Wareham River Embayment System was comparable to other similar embayments with similar configuration and flushing rates in southeastern Massachusetts. In addition, the pattern of sediment N release was also similar to other systems, with the upper estuarine reaches where upper watershed nitrogen loads are focused and tidal flushing is lowest (Agawam and Wankinco River estuarine reaches) showing moderate release to net uptake, consistent with MEP Technical Team field observations of other estuaries. Net nitrogen uptake occurs in areas where deposition rates are sufficiently high to stimulate denitrification within the bottom sediments, but not so high as to reduce oxygen availability for nitrification. The estuarine reaches of the Agawam and Wankinco Rivers and the lower sub-basins (south of the Route. 6 Bridge) ranged from moderate nitrogen uptake to moderate nitrogen release rates found in similarly structured estuaries throughout the region, -13.8 to 14.1 mg N m^{-2} d^{-1}. However, on an areal basis, sediment nitrogen release in the main basins of the lower estuary showed little variation, ranging from 34.6 mg N m^{-2} d^{-1} in the lower Wareham River basin, Marks Cove, 7.7 mg N m^{-2} d^{-1}, and within the large Broad Marsh tributary basin 24.3 mg N m^{-2} d^{-1}. Areas with small rates of uptake were limited to small depositional sites of the upper Wareham River basin (below RR bridge), -0.2 mg N m^{-2} d^{-1}, Crooked River, -7.5 mg N m^{-2} d^{-1}, and the confluence of the lower portions of the Agawam/Wankinco Rivers, -13.8 mg N m^{-2} d^{-1},. These rates are consistent with the depositional nature of these basins. The observed levels of summer nitrogen release are common in southeastern Massachusetts estuaries. For example the main basins of Pleasant Bay were similar to the main basin of the Wareham River, -1.1 to 16.0 mg N m^{-2} d^{-1} as are comparable basins in Centerville River Estuary, -13.2 to 36.6 mg N m^{-2} d^{-1}.

Net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the Wareham River Embayment System (Chapter VI) are presented in Table IV-7. There was a clear spatial pattern of sediment nitrogen flux, with high rates of nitrogen release by the sediments of the upper estuary and low to moderate rates in the lower estuarine basins. The sediments within the Wareham River Embayment System showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to this system and its relatively high flushing rate.

Table IV-7. Rates of net nitrogen return from sediments to the overlying waters of the Wareham River 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})			i.d. *
	Mean	S.E.	# sites	
Wareham River Embayment System				
Agawam River - Upper Reach	14.1	19.0	3	WR 22-24
Agawam River - Lower Reach	2.2	6.2	2	WR 20,21
Agawam/Wankinco Basin	-13.8	12.6	2	WR 18,19
Wankinco Basin	5.6	0.2	1	WR 17
Wareham River - Upper	-0.2	5.0	4	WR 13-16
Broad Marsh River	24.3	10.2	3	WR 10-12
Crooked River	-7.5	1.8	1	WR 9
Wareham River - Lower	34.6	10.4	5	WR 4-8
Marks Cove	7.7	25.1	3	WR 1-3

* Station numbers refer to Figure IV-13.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

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

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

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

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

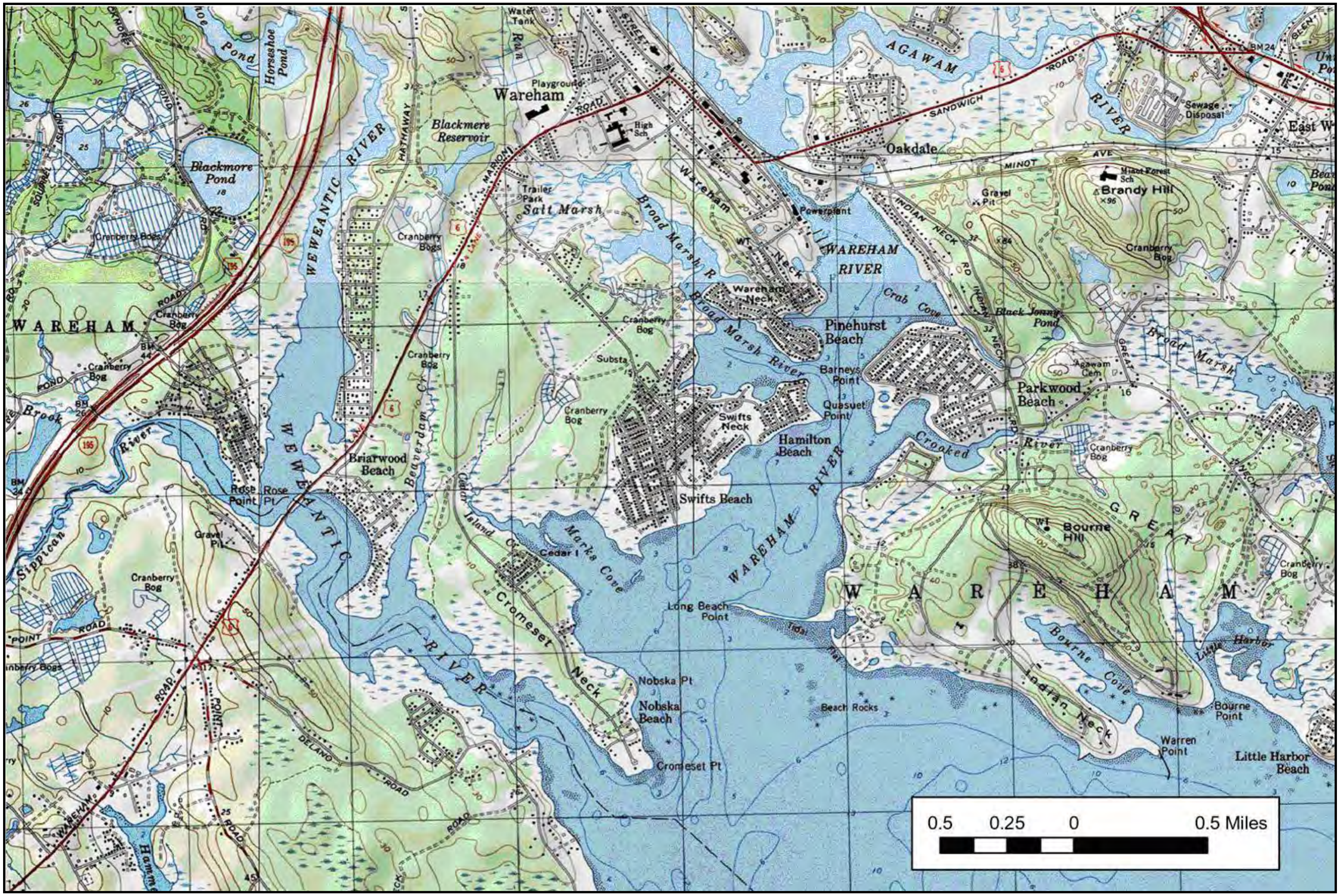


Figure V-1. Map of the Wareham River and Weweantic River estuary systems (from United States Geological Survey topographic map).

The Wareham River and Weweantic River estuaries (Figure V-1) are tidally dominated embayment systems open to the northern extent of Buzzards Bay. The lower Weweantic River (along with the Sippican River) defines a portion of the municipal boundary with the Town of Marion. Buzzards Bay's largest single freshwater point discharge is the Weweantic. The total length of the estuarine reach of the Weweantic River is approximately 4 miles, and it has a mean tide range of 4 ft.

The Wareham River system is a sinuous estuary, made up of several smaller tidal sub-embayments, including Broad Marsh River, Crooked River, and the Agawam River. From the farthest estuarine reach of the Agawam River it is approximately 5.5 miles to the mouth on Buzzards Bay. Mean tide ranges between the lower Agawam River and the mouth of the Wareham River are similar to observed tides in the Weweantic River and the upper portion of Buzzards Bay. The tide range of the upper Agawam is smaller (3 ft) due to tide attenuation the shallow, marshy condition of this area of the system.

Since the water elevation difference between Buzzards Bay and the inland reaches of each estuarine system is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) through the Weweantic system is negligible indicating a "well-flushed" system. In the Wareham River system, tidal damping reduces the tide range in the Agawam River by approximately 25% compared to the offshore tide. However, since the Agawam River is shallow relative to its tide range, the Wareham River system does in fact flush very efficiently, even to the upper reaches of the Agawam. Any issues with water quality, therefore, would likely be due to nutrient loading conditions from the system's watersheds.

The Weweantic and Wareham river systems were modeled together in a single model grid developed for the two systems. To calibrate the hydrodynamic model, field measurements of water elevations and bathymetry were required. For the Wareham systems, tide data were acquired within Buzzards Bay at a gage station installed offshore Great Hill, in Marion, and also at stations located along the length of the estuary. All temperature-depth recorders (TDRs or tide gages) were installed for a 50-day period to measure tidal variations through an entire neap-spring cycle. In this manner, attenuation of the tidal signal as it propagates through the various sub-embayments was evaluated accurately.

V.2 FIELD DATA COLLECTION AND ANALYSIS

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

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

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

Boundary conditions for the numerical model consist of variations of water surface elevation in Buzzards Bay. These variations result principally from tides, and provide the dominant hydraulic forcing for the system. A pressure sensor was installed near the mouths of the Weweantic and Wareham Rivers to measure the Buzzards Bay tides. Gauging locations are shown in Figure V-2. The tidal data recorded at this station were used as the principal forcing function, or boundary condition, to the model. Additional pressure sensors were installed at selected interior locations to measure variations of water surface elevation along the length of the two river systems. These measurements were used to calibrate and verify the model results, and to assure that the important physics were properly simulated.

To complete the field data collection effort for this study, and to provide model verification data, a survey of velocities was completed at three cross-channel transects. Survey transects were placed one each in the lower reach of the Weweantic River and Wareham River, and a third between Indian Neck and Great Hill Point, at the confluence of the two rivers in Buzzards Bay.

V.2.1. Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Weweantic River and Wareham River system were assembled from two main sources: (1) historical data from previous NOS surveys, and (2) a recent hydrographic survey performed specifically for this study. Historical NOS survey data, where available, were used for areas with little likely bathymetric change.

The hydrographic survey of March, 2004 (CRE, 2004) was designed to cover areas not covered by the NOS surveys (e.g., the upper portions of the Weweantic and Agawam Rivers), or where significant bathymetric change was expected (e.g., Long Beach Point, at the mouth of the Wareham River). For the shallow upper reaches of each system, the survey was completed using a johnboat equipped with a precision fathometer interfaced to a differential GPS receiver. In other deeper and more open areas, the survey was conducted from a larger, more sea-worthy craft. The fathometer had a depth resolution of approximately 0.1 foot, and the differential GPS provides position measurements accurate to approximately 1-3 feet. Digital data output from both the echo sounder and GPS were logged to a laptop computer, which integrated the data to produce a single data set consisting of water depth as a function of geographic position (latitude/longitude).

The raw bathymetry measurements were merged with water surface elevation measurements to correct the measured depths to the NAVD 1988 vertical datum. Once corrected, the finished processed data were archived as ‘xyz’ files containing x-y horizontal position (in Massachusetts State Plan 1983 coordinates) and vertical elevation of the bottom (z) relative to NAVD88. These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The interpolated bathymetric data, including the earlier NOS data, are presented in Figure V-3.

V.2.2 Tide Data Collection and Analysis

Variations in water surface elevation were measured at a station in Buzzards Bay, at five locations in the Wareham River, and at a single station in the Weweantic River (Figure V-2). Stations within the Wareham River system were located at Pinehurst Beach (WR-2), in Broad Marsh River (WR-3), at the railroad bridge over the Wareham River (WR-4), the mid-point (WR-5) and inland limit of the estuarine reach of the Agawam River (WR-6). TDRs were deployed in late November, 2003, and recovered in mid January, 2004 for the first deployment. Due to icing conditions on the river in early 2004, the ADCP survey of the inlet was not performed until March 30, 2004. Because of the long weather delay of the ADCP survey, a second gage deployment was necessary, with extended data records collected at the offshore, Weweantic River and Pinehurst Beach gauging locations.

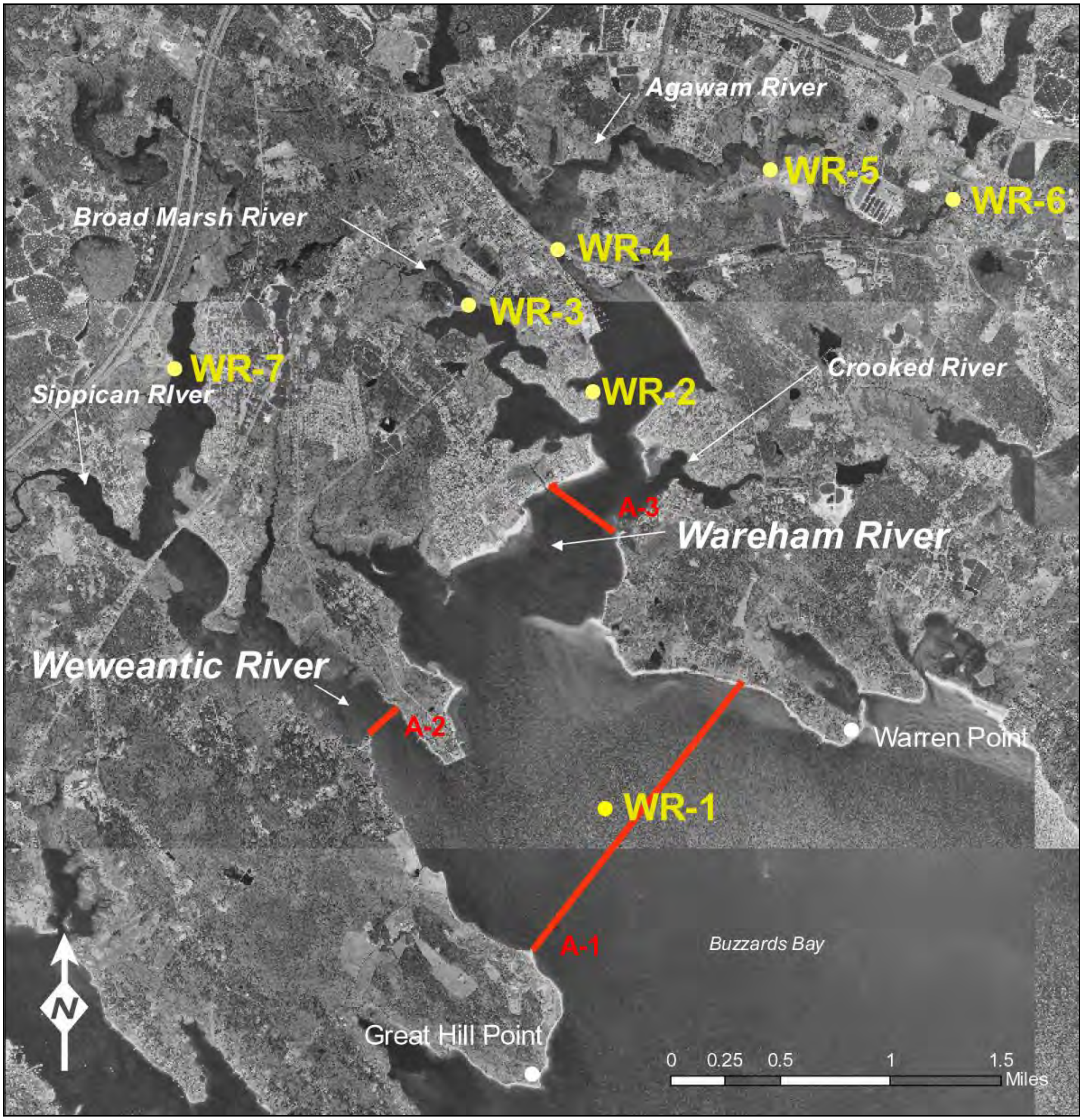


Figure V-2. Map of the study region identifying locations of the tide gages used to measure water level variations throughout the system. Six (6) gages were deployed for a 50-day period between November 2003 and January 2004. Each yellow dot represents the approximate locations of the tide gages: (WR-1) Offshore Great Hill Point, (WR-2) Wareham River, (WR-3) Broad Marsh River, (WR-4) the railroad crossing of the Wareham River, (WR-5) mid Agawam River, (WR-6) upper Agawam River, and (WR-7) the Weweantic River.

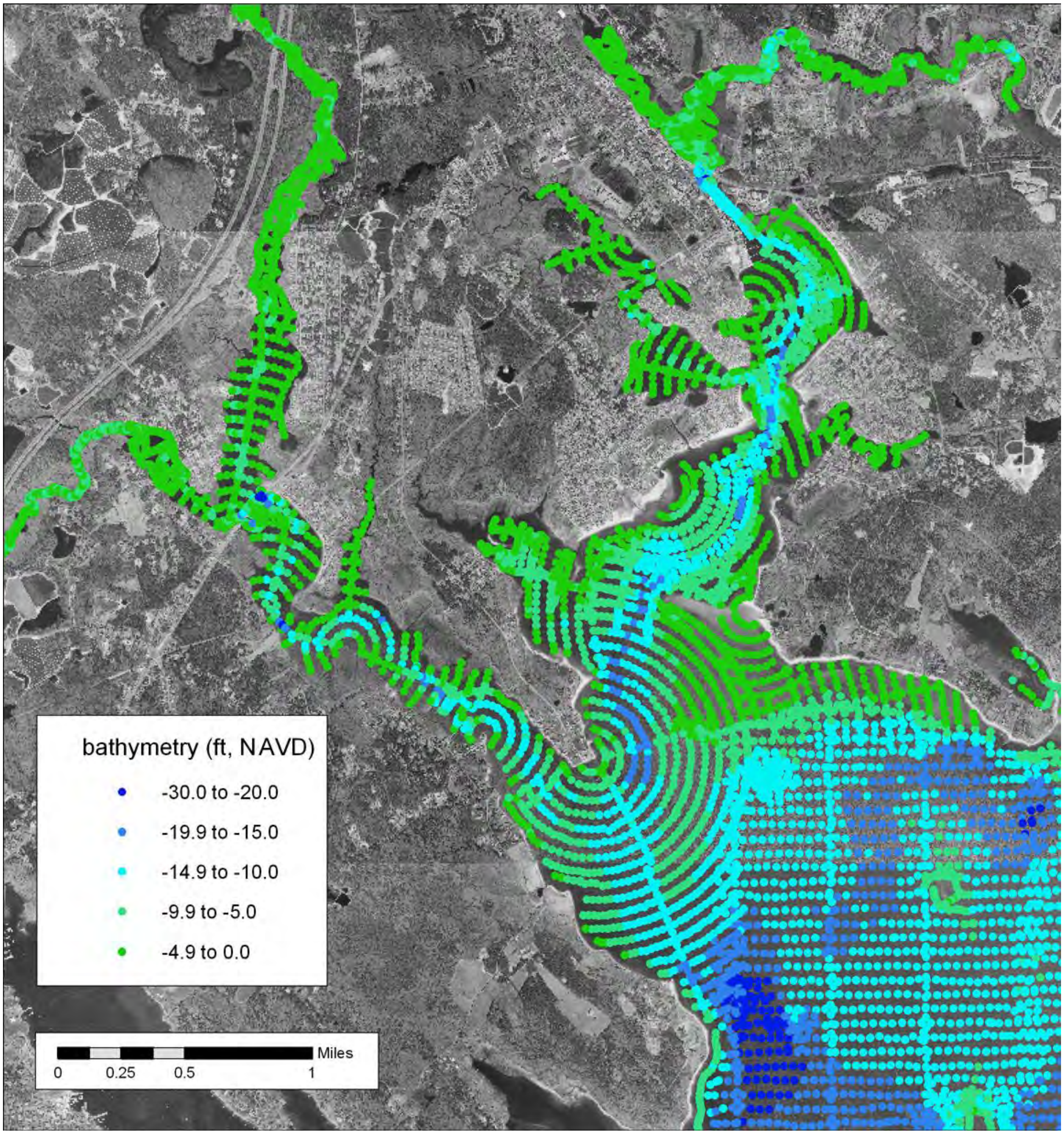


Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

The tide records from the Wareham and Weweantic River systems were corrected for atmospheric pressure variations and then rectified to the NAVD 88 vertical datum. Atmospheric pressure data, available in one-hour intervals from the NDBC Buzzards Bay C-MAN platform, were used to pressure correct the raw tide data. Final processed tide data from stations used for this study are presented in Figure V-4, for the complete 50-day period of the first deployment.

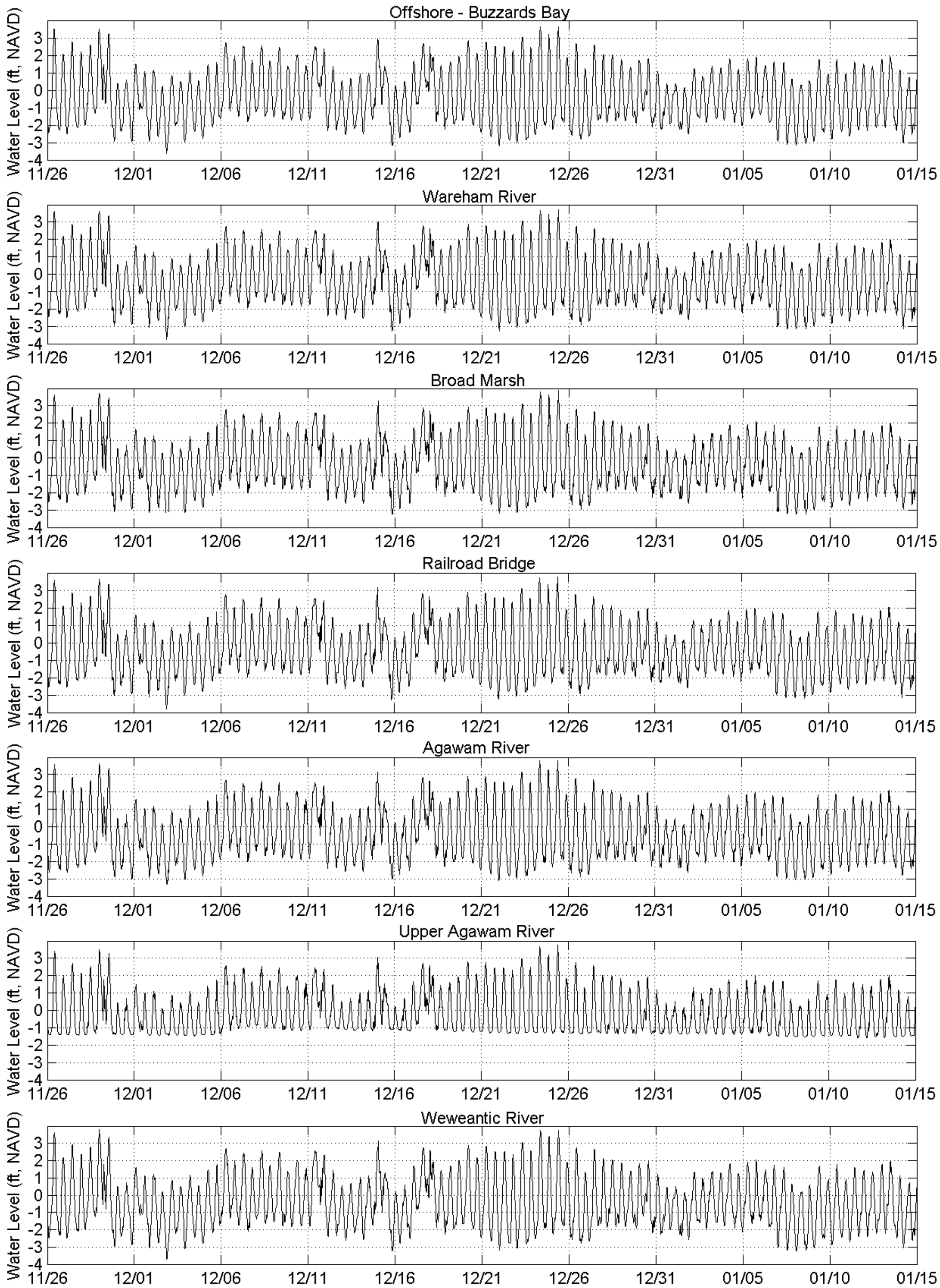


Figure V-4. Water elevation variations as measured at the seven locations within the Wareham River and Weweantic River systems, between November 26, 2003 and January 15, 2004. Atmospheric effects have been removed from the records.

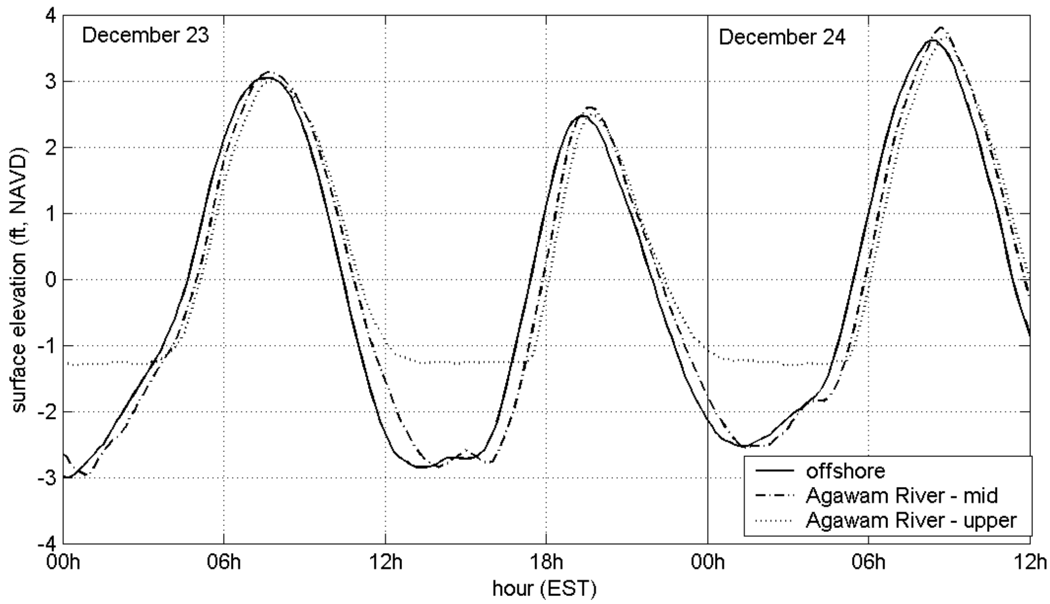


Figure V-5 Plot showing two tide cycles tides at three stations in the Wareham River system plotted together. Demonstrated in this plot is the phase delay effect caused by the propagation of the tide up the estuary (i.e., mid Agawam River data), and attenuation of the tide range due to marshy flats (i.e., upper Agawam River gage data).

Tide records longer than 29 days are necessary for a complete evaluation of spring and neap tidal conditions 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 gravitational attraction. For numerical modeling of hydrodynamics, the typical tide conditions associated with a one-month record are appropriate for driving tidal flows within the estuarine system.

The loss of amplitude and increasing phase delay with increasing distance from the inlet is described as tidal attenuation. In the modeled systems, attenuation of the tidal signal is caused by the geomorphology of the nearshore region. Channel restrictions (e.g., bridge abutments) and also the length of the estuaries are the primary factors which influence tidal damping in these systems. A visual comparison in Figure V-5 between tide elevations at the three stations in the Wareham River system demonstrates how the phase delay of the tide increases to the upper-most reaches of the Agawam River. Along with the delayed timing of high and low tide, a significant truncation of the tide is visible in the record from upper Agawam. This truncation is due to the shallow marshy condition of the upper river. The river channel is shallow enough in its upper reaches that it effectively goes dry during most low tides.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 50-day 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 Water (MHHW) and Mean Lower Low Water (MLLW) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW. The tides in Buzzards Bay are semi-diurnal, meaning that there are typically two tide cycles in a day. There is usually a small variation in the level of the two daily tides. This variation can be seen in the differences between the MHHW and MHW, as well as the MLLW and MLW levels.

From the computed datums, it is apparent that there is little tide damping throughout these systems. The only exception is the upper Agawam River, where the mean tide range is reduced by approximately one foot. The small level of tide damping exhibited in the Weweantic and Wareham River estuaries gives an initial indication that they flush efficiently.

A more thorough harmonic analysis was also performed on the time series from each gage location in an effort to separate the various tidal components. The analysis allows an understanding of the relative contribution that various physical processes (i.e. tides, winds, etc.) have on water level variations within the estuary. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 tidal constituents, with periods between 4 hours and 2 weeks, result from this procedure. The observed astronomical tide is therefore the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-6.

Table V-2 presents the amplitudes of significant eight tidal constituents. The M_2, or the familiar twice-a-day lunar semi-diurnal, tide is the strongest contributor to the signal with an amplitude of 1.75 feet in Buzzards Bay. The range of the M_2 tide is twice the amplitude, or about 3.5 feet. The diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar), possess amplitudes of approximately 0.27 and 0.19 feet respectively. The N_2 tide, a lunar constituent with a semi-diurnal period, rivals the diurnal constituents with an amplitude of 0.47 feet. The M_4 tide, a higher frequency harmonic of the M_2 lunar tide (twice the frequency of the M_2), results from frictional dissipation of the M_2 tide in shallow water.

Table V-1. Tide datums computed from records collected in the Wareham and Weweantic River systems November 26, 2003 to January 15, 2004. Datum elevations are given relative to NAVD 88.

Tide Datum	Offshore (feet)	Wareham River (feet)	Broad Marsh River (feet)	Agawam River (feet)	Upper Agawam River (feet)	Weweantic River (feet)
Maximum Tide	3.64	3.73	3.89	3.80	3.75	3.78
MHHW	2.04	1.99	2.10	2.07	2.06	1.95
MHW	1.69	1.71	1.76	1.73	1.71	1.65
MTL	-0.22	-0.28	-0.27	-0.25	0.21	-0.30
MLW	-2.13	-2.27	-2.30	-2.23	-1.29	-2.27
MLLW	-2.39	-2.50	-2.50	-2.47	-1.32	-2.50
Minimum Tide	-3.64	-3.75	-3.24	-3.32	-1.59	-3.72

Table V-2. Tidal Constituents, Wareham and Weweantic River systems December-January 2004.

	Amplitude (feet)							
Constituent	M_2	M_4	M_6	S_2	N_2	K_1	O_1	Msf
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Offshore	1.75	0.28	0.03	0.35	0.47	0.27	0.19	0.13
Wareham River	1.76	0.29	0.03	0.35	0.47	0.27	0.19	0.12
Broad Marsh	1.78	0.29	0.04	0.35	0.47	0.26	0.19	0.12
Rail Road Bridge	1.75	0.30	0.04	0.35	0.47	0.27	0.19	0.12
Agawam River	1.75	0.27	0.06	0.34	0.48	0.27	0.19	0.12
Upper Agawam	1.35	0.36	0.05	0.25	0.35	0.21	0.17	0.14
Weweantic River	1.75	0.29	0.05	0.35	0.46	0.26	0.19	0.12

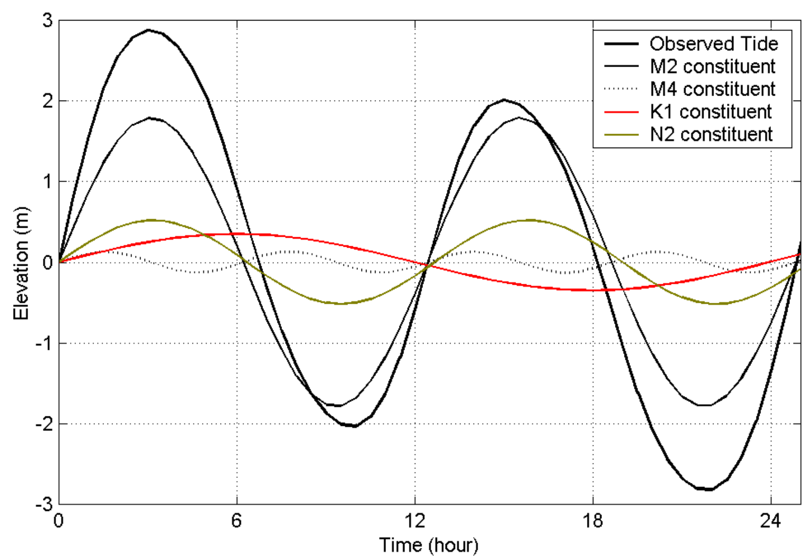


Figure V-6. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-2 also shows how the constituents vary as the tide propagates into the estuaries. Most estuaries exhibit tidal damping, that is, a reduction of the tide range relative to the offshore forcing tide. Note the reduction in the M_2 amplitude between Buzzards Bay and the upper portion of the Agawam River (M_2 amplitude of 1.75 feet in Buzzards Bay versus 1.35 feet in the Agawam). In other portions of the Wareham River and the Weweantic River, there is little amplitude difference

Table V-3 presents the phase delay (in other words, the travel time required for the tidal wave to propagate throughout the system) of the M_2 tide at all tide gage locations. The propagation speed of tides in a shallow estuary can be expressed by the shallow water form of the wave dispersion relationship, $C=(gh)^{0.5}$, where C is the tide propagation speed, g is the gravitational constant, and h is the average depth of the estuary. By this equation, the phase delay of the tide would be approximately 32 minutes from the mouth of the Wareham River to the uppermost tidal portion of the Agawam River. Measured data indicate that it takes approximately 31 minutes for the tide wave to travel from Buzzards Bay to the upper portion of the Agawam River. Because the phase delay of the tide can be accounted for by the computed propagation speed of the tidal wave through the estuary, the comparison of measured results from Table V-3 and the delay calculated using linear wave theory is another indication that hydrodynamic circulation is efficient within the system.

Table V-3. M_2 Phase Delays from Nantucket Sound through the Popponesset Bay System.

Location	Delay (minutes)
Wareham River	4.7
Agawam River	18.9
Agawam River - upper	31.0
Weweantic River	15.2

The tide data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. Non-tidal processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow. The results of an analysis to determine the energy distribution (or variance) of the original water elevation time series for the two river systems is presented in Table V-4 compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 23 constituents determined by the harmonic analysis). Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes are relative to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from Buzzards Bay, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual. The largest tide residuals occurred on December 11, 15 and 17. These are storm-induced surges caused by low pressure fronts moving through the area at those times, as indicated in regional meteorological data records.

Table V-4 shows that the percentage contribution of tidal energy was essentially equal in all parts of the system, which indicates that local effects due to winds and other non-tidal processes are minimal throughout the systems. The analysis also shows that tides are responsible for approximately 83% of the water level changes in the Wareham and Weweantic River systems. The remaining 17% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the water surface of Buzzards Bay. The total energy content of the tide signal from each gauging station does not change significantly, except at the upper Agawam River station, were the tide flats truncate the tide range.

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

Table V-4. Percentages of Tidal versus Non-Tidal Variance Wareham and Weweantic River systems.			
Location	Total Variance (ft^2)	Tidal Variance	Residual Variance
Offshore	2.03	83.3%	16.7%
Wareham River	2.07	83.1%	16.9%
Broad Marsh	2.13	82.2%	17.8%
Rail Road Bridge	2.07	82.6%	17.4%
Agawam River	2.05	82.4%	17.6%
Upper Agawam	1.30	81.5%	18.5%
Weweantic River	2.06	82.0%	18.0%

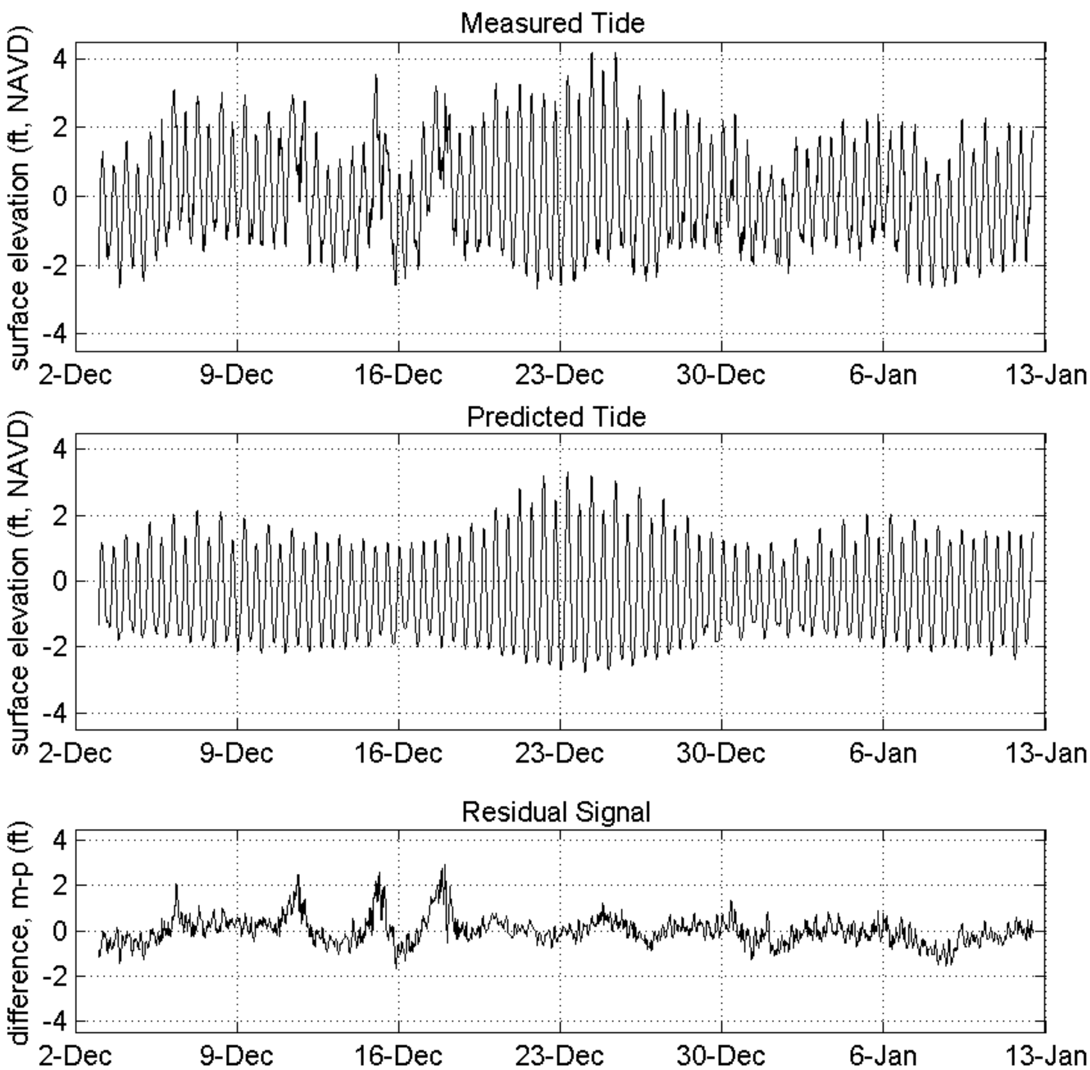


Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured in the Agawam River (WR-5).

V.2.3 ADCP Data Analysis

Cross-channel current measurements were surveyed through a complete tidal cycle in the Wareham River and Weweantic River on March 30, 2004 to resolve spatial and temporal variations in tidal current patterns. The survey was designed to observe tidal flow across three transects in the system at hourly intervals. These transects (indicated in Figure V-2) were located at the separate mouths of the two systems, and also at their confluence in Buzzards Bay. The data collected during this survey provided information that was necessary to model properly the hydrodynamics of the two riverine estuary systems.

Figures V-8 through V-13 show color contours of the current measurements observed during the flood and ebb tides at each of the three transects. 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. For example, at the Wareham River mouth transect, positive along-channel flow is to the northeast, and positive cross-channel flow is moving to the southeast. In Figure V-8, the lower left panel shows depth-averaged currents across the channel projected onto a 1997 aerial photograph of the transect vicinity. The lower right panel of each figure indicates the stage of the tide that the survey transect was taken by the vertical line plotted with the tide elevation curve.

Maximum measured currents in the water column were 1.1 ft/sec during the flood portion of the tide and 0.6 ft/sec during the ebb across the inlet to the Wareham River. At the Weweantic River transect, maximum velocities were similar, with a 1.1 ft/sec maximum measured velocity during the flood tide, and a 0.8 ft/sec maximum ebb velocity. Measured tidal flow rates (computed using the ADCP velocity data) for both river systems were roughly the same during the measured tide cycle. Maximum measured flood flows during flooding portions of the tide were 4500 ft^3/sec at the Wareham River mouth, and 3900 ft^3/sec at the Weweantic River mouth. During ebbing portions of the tide maximum flows were 2300 ft^3/sec and 3400 ft^3/sec at the Wareham River and Weweantic River transects, respectively.

V.3 HYDRODYNAMIC MODELING

The focus of this study was the development of a numerical model capable of accurately simulating hydrodynamic circulation within the Wareham River and Weweantic River estuary systems. Once calibrated, the model was used to calculate water volumes for selected subembayments (e.g., Broad Marsh River, and the upper portions of the Weweantic River) as well as determine the volumes of water exchanged during each tidal cycle. These parameters are used to calculate system residence times, or flushing rates. The ultimate utility of the hydrodynamic model is to supply required input data for the water quality modeling effort described in Chapter VI.

V.3.1 Model Theory

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

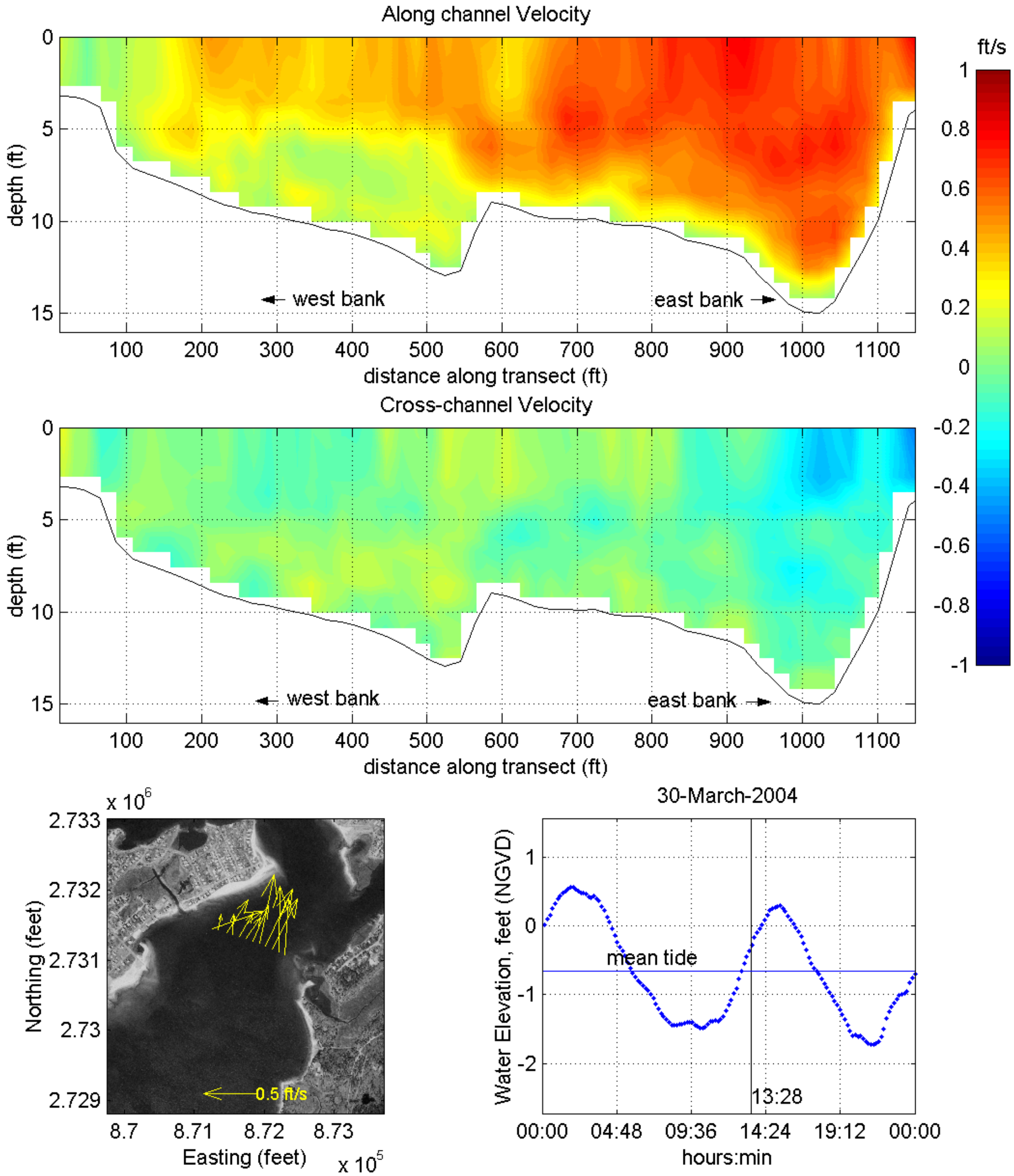


Figure V-8. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across the Wareham River, measured at 13:28 EST on March 30, 2004 during the period of maximum flood tide currents. Positive along-channel currents (top panel) indicate the flow is 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 1997 aerial photo of the survey area. A tide plot for the survey day is also given.

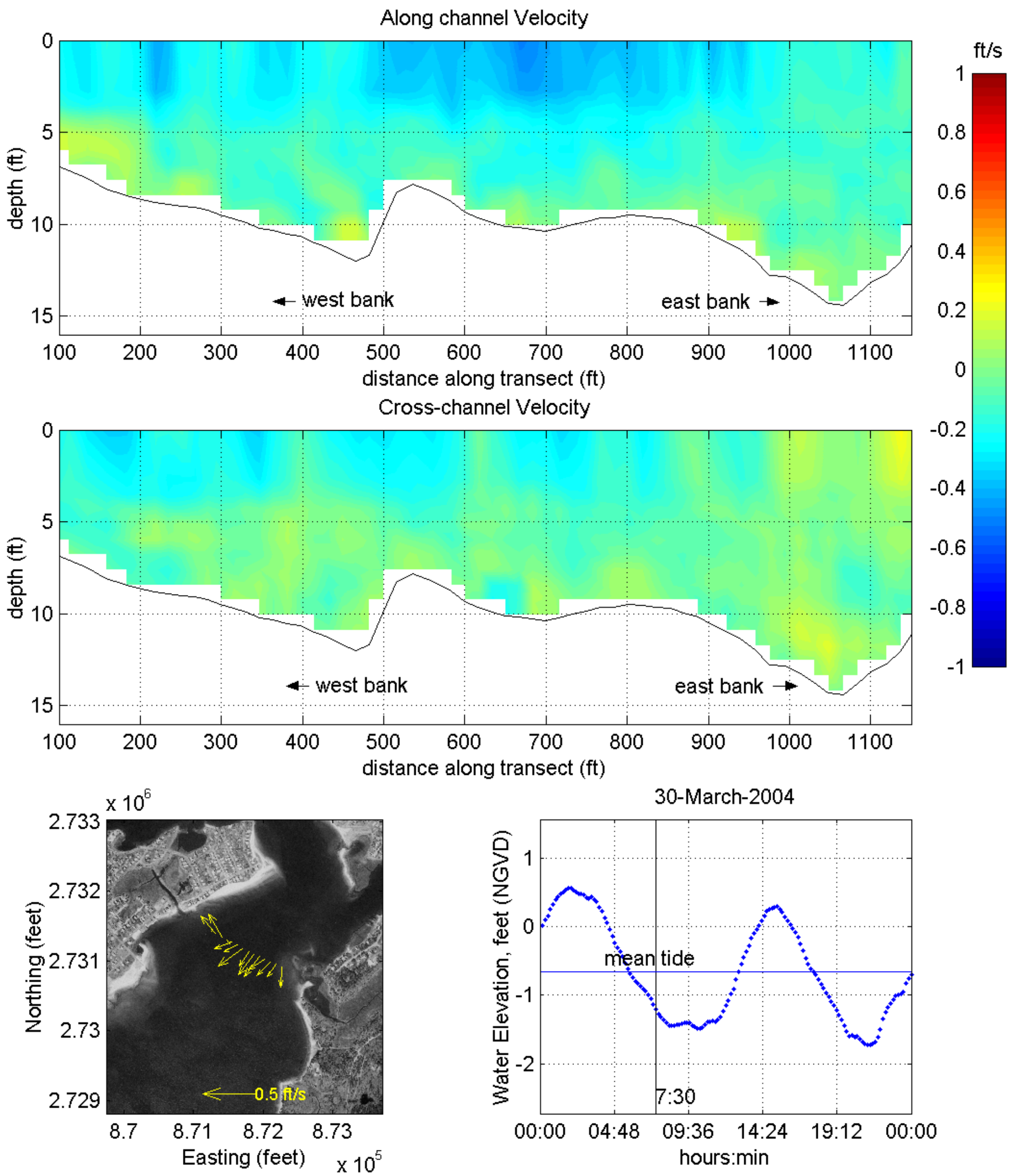


Figure V-9. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across the Wareham River, measured at 07:30 EST on March 30, 2004 during the period of maximum ebb tide currents. Positive along-channel currents (top panel) indicate the flow is 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 1997 aerial photo of the survey area. A tide plot for the survey day is also given.

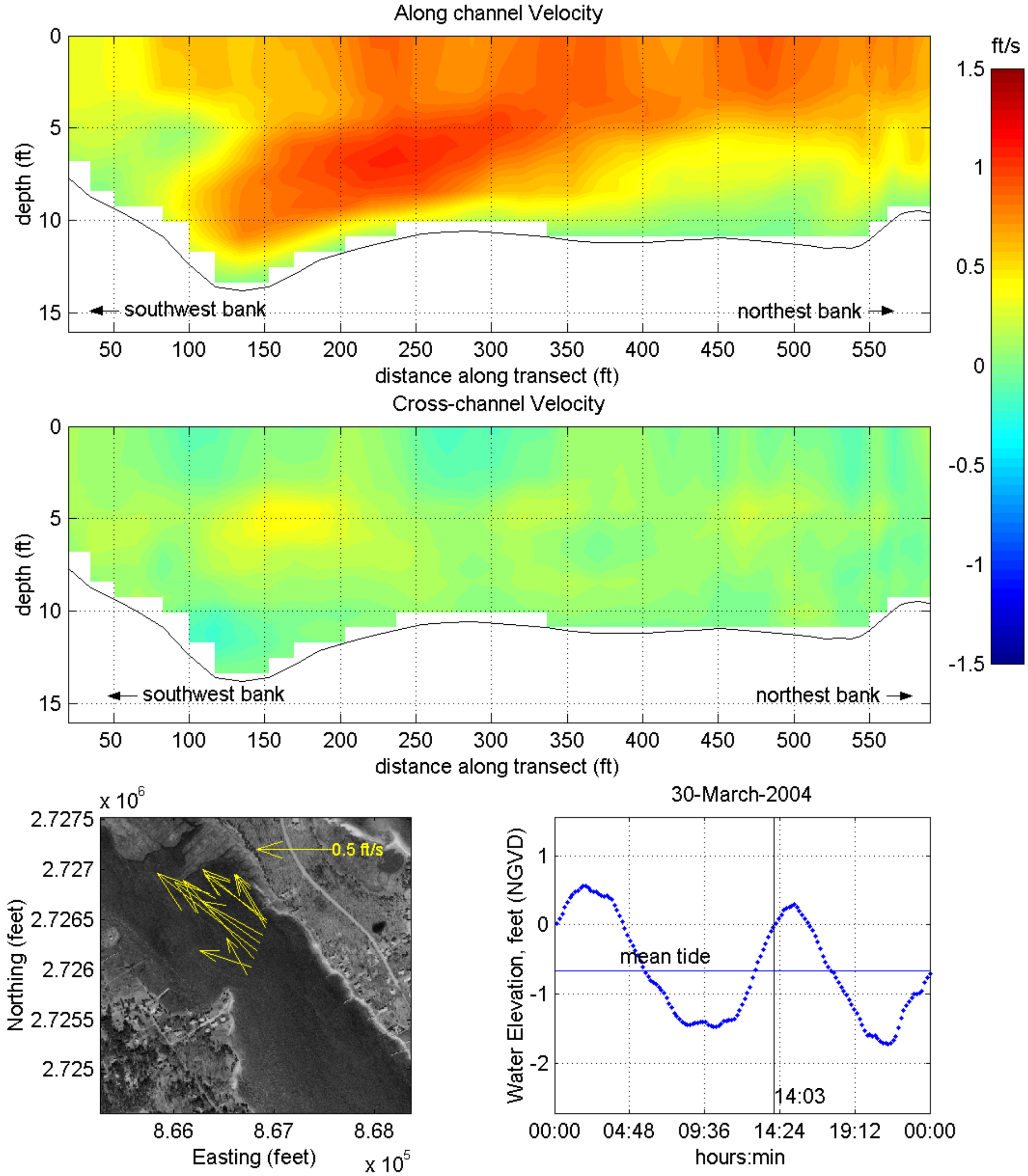


Figure V-10. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across the Weweantic River, measured at 14:03 EST on March 30, 2004 during the period of maximum flood tide currents. Positive along-channel currents (top panel) indicate the flow 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 1997 aerial photo of the survey area. A tide plot for the survey day is also given.

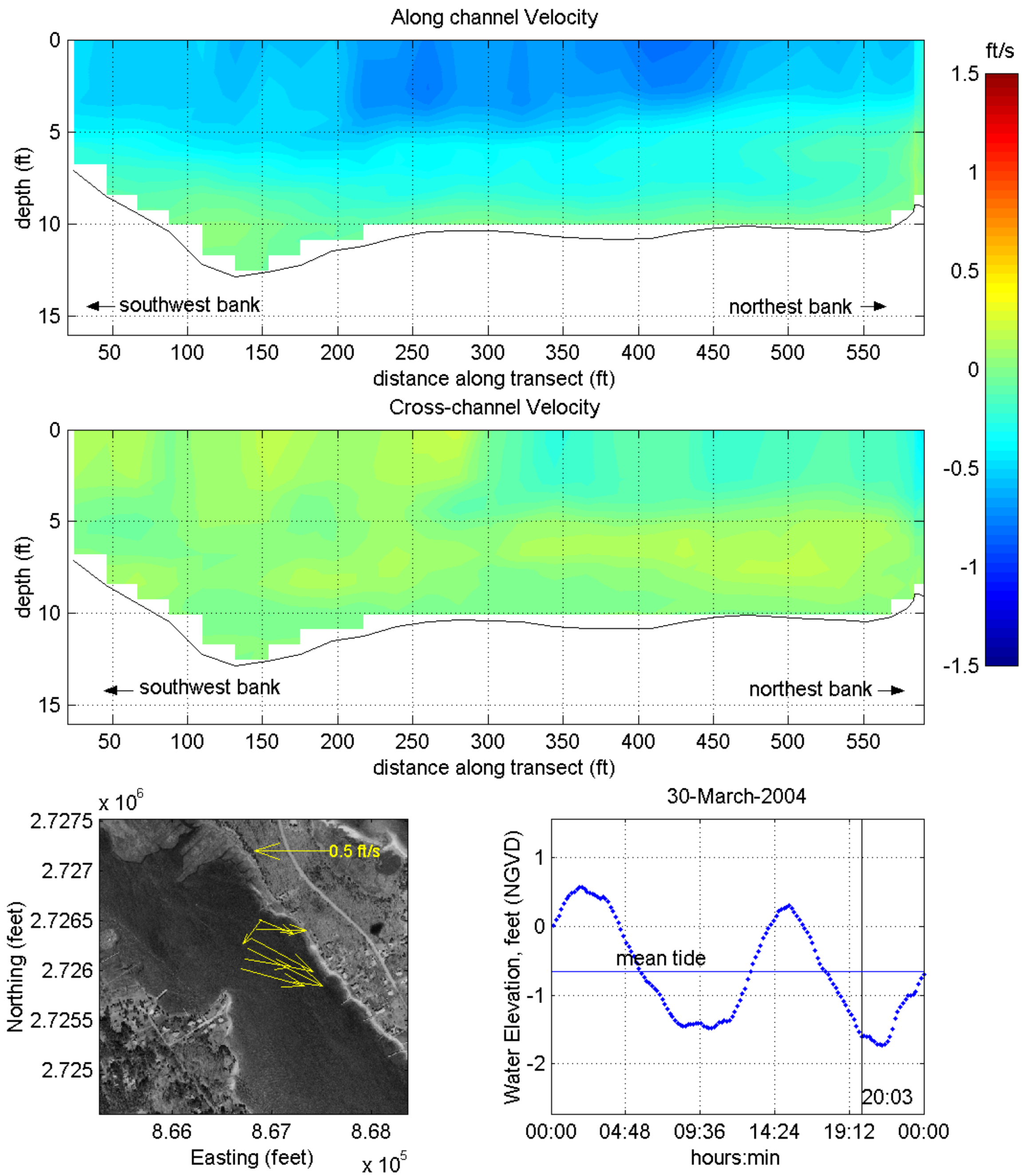


Figure V-11. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across the Weweantic River, measured at 20:03 EST on March 30, 2004 during the period of maximum ebb tide currents. Positive along-channel currents (top panel) indicate the flow 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 1997 aerial photo of the survey area. A tide plot for the survey day is also given.

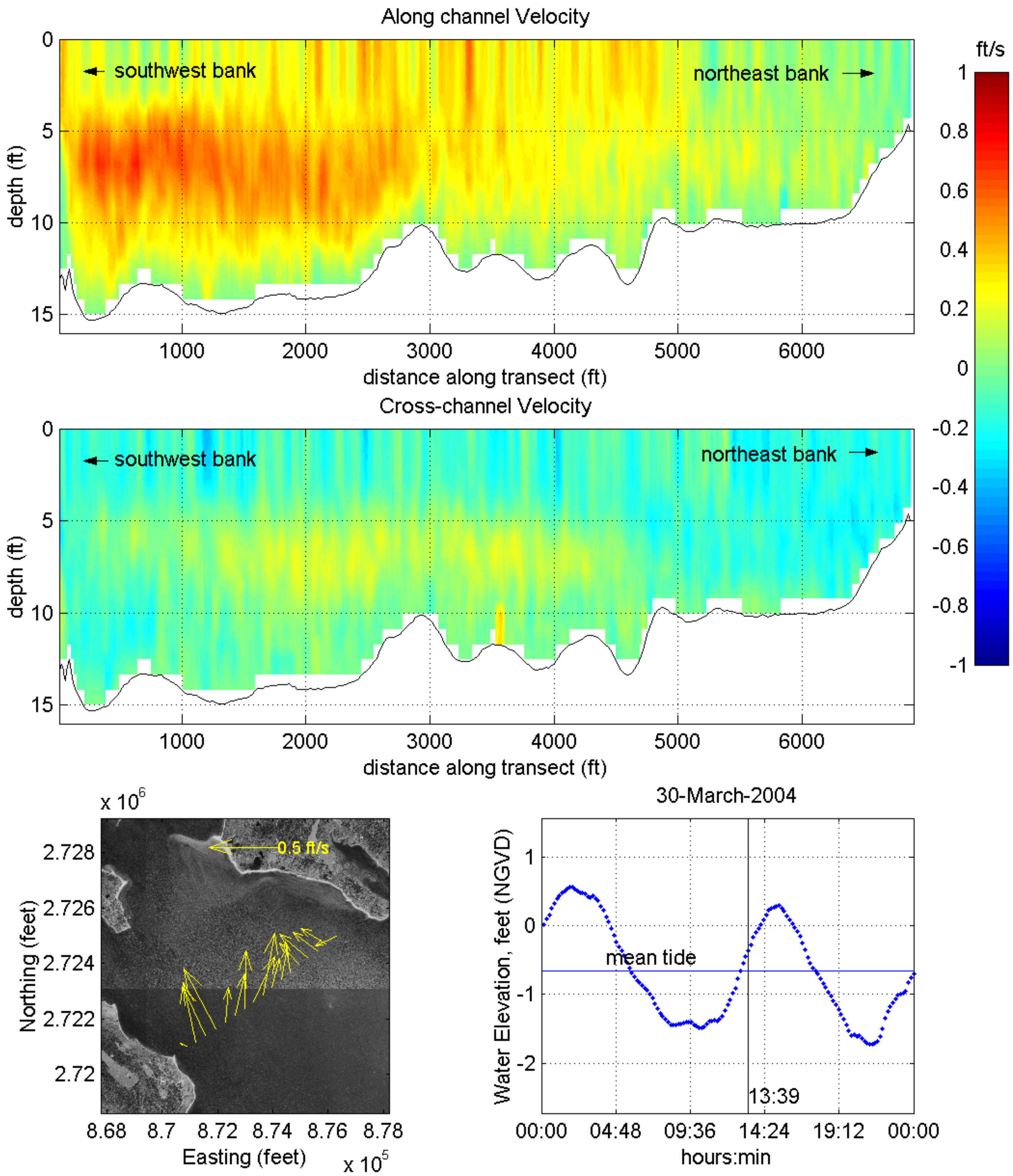


Figure V-12. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across the confluence of the Wareham River and Weweantic River, in Buzzards Bay, measured at 13:39 EST on March 30, 2004 during the period of maximum flood tide currents. Positive 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 1997 aerial photo of the survey area. A tide plot for the survey day is also given.

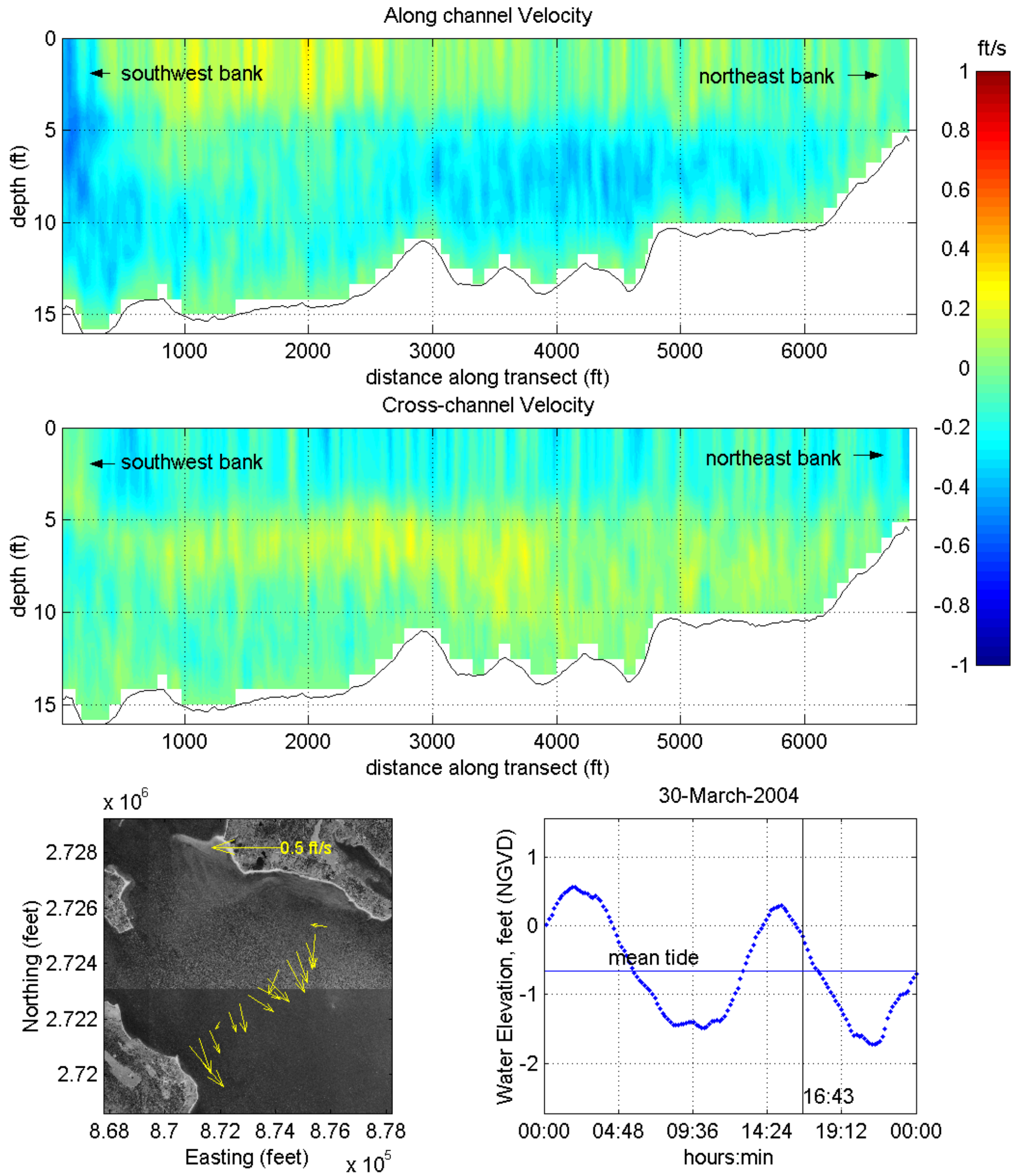


Figure V-13. Color contour plots of along-channel and cross-channel velocity components for transect line run east-to-west across the confluence of the Wareham River and Weweantic River, in Buzzards Bay, measured at 16:43 EST on March 30, 2004 during the period of maximum ebb tide currents. Positive 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 1997 aerial photo of the survey area. A tide plot for the survey day is also given.

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

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

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

V.3.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

The extent of the finite element grid was generated using digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of the system based on the tide gage data collected in Buzzards 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 (15+) model calibration simulations for each system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid Generation

The grid generation process for the model was assisted through the use of the SMS package. The digital shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary with 3435 elements and 9319 nodes (Figure V-14). All regions in the system were represented by two-dimensional (depth-averaged) elements. The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties within the estuary. Fine resolution was required to simulate the numerous channel constrictions (e.g., at the bridge crossings over the two Rivers) that significantly impact the estuarine hydrodynamics. The completed grid is made up of quadrilateral and triangular two-dimensional elements. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the recent field surveys and the

NOS data archive. The model computed water elevation and velocity at each node in the model domain.

Grid resolution is governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each region. Smaller cross channel node spacing in the river channels was designed to provide a more detailed analysis in these regions of rapidly varying velocities and bathymetry. Widely spaced nodes were utilized in areas where velocity gradients were likely to be less acute; for example, on marsh plains and in broad, deep channel sections in the model domain. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

V.3.2.2 Boundary Condition Specification

Three types of boundary conditions were employed for the RMA-2 model: 1) "slip" boundaries, 2) freshwater inflow, and 3) tidal elevation boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. Freshwater inflows were specified at the estuarine terminus of the Weweantic River, Sippican River, and Agawam River. Although the Weweantic River is the largest single freshwater input into Buzzards Bay, this flow is small relative to the tidal prism (approximately 5% of the prism).

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

V.3.3 Calibration

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

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

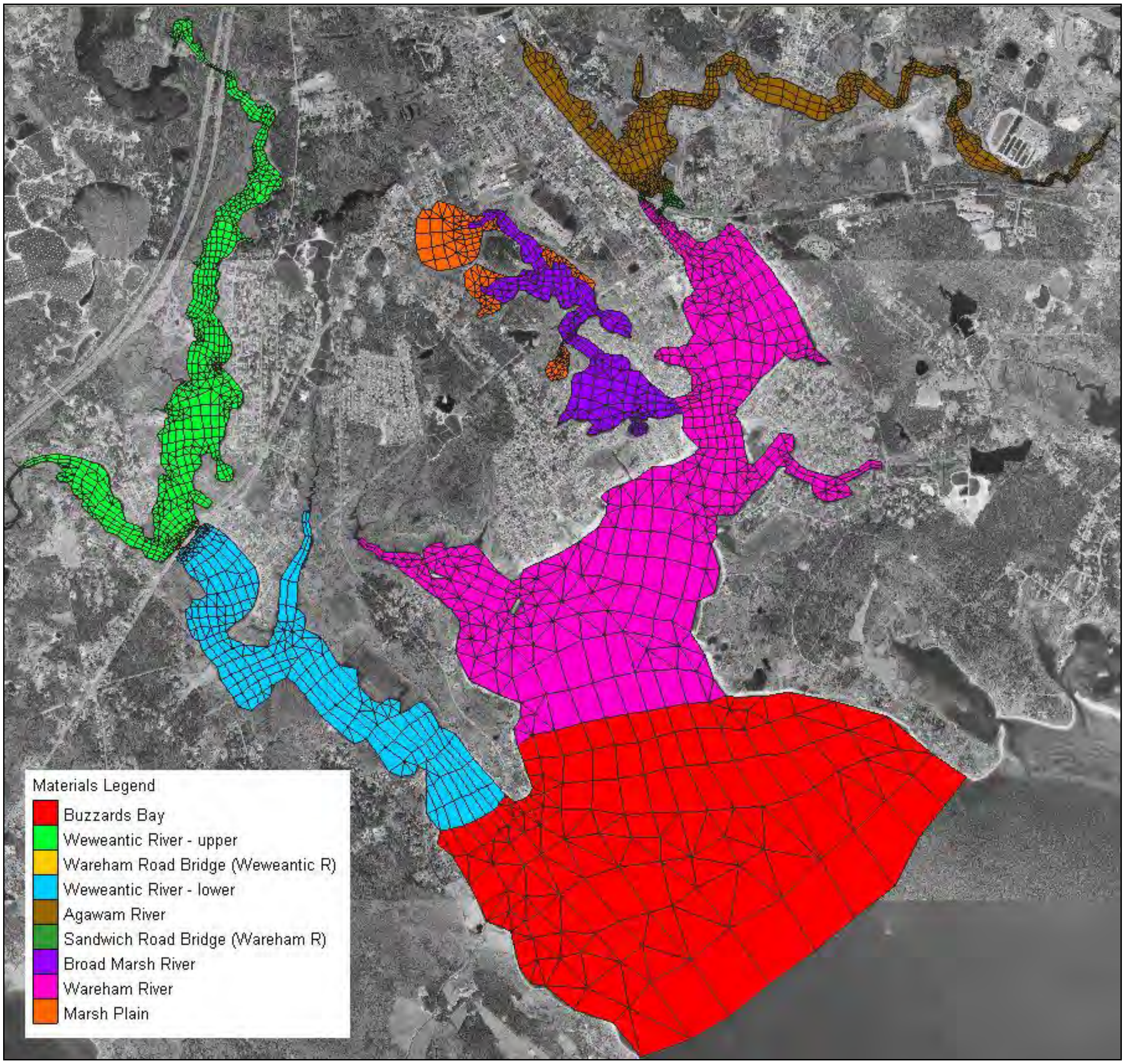


Figure V-14. The model finite element mesh developed for the combined Wareham River and Weweantic River systems. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained in Nantucket Sound.

The calibration was performed for an approximate eight-day period, beginning 0730 hours EST December 21, 2003 and ending December 31, 2003. This time period included a 24-hour model spin-up period, and a 14-tide cycle period used for calibration. This representative time period was selected because it included tidal conditions where the wind-induced portion of the signals (i.e. the residual) was minimal, hence more typical of tidal circulation within the estuary. The selected time period also spanned the transition from neap (bi-monthly minimum) to spring (bi-monthly maximum) tide ranges, which is representative of average tidal conditions in the embayment system. Throughout the selected seven-day period, the tide ranged approximately 6.5 feet from minimum low to maximum high tides. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. Modeled tides were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.3.3.1 Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where water depths can become shallow and velocities relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude attenuation and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient. First, Manning's friction coefficient values of 0.025 were specified for all elements. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels with pools and shoals with higher friction (Henderson, 1966). On the marsh plains, damping of flow velocities typically is controlled more by “form drag” associated with marsh plants than the bottom friction described above. However, simulation of this “form drag” is performed using Manning’s coefficients as well, with values ranging from 2-to-10 times friction coefficients used in sandy channels. Final calibrated friction coefficients (listed in Table V-5) were largest for marsh plain area, where values were set at 0.07. Small changes in these values did not change the accuracy of the calibration.

Table V-5. Manning’s Roughness coefficients used in simulations of modeled embayments.

Embayment	Bottom Friction
Buzzards Bay	0.025
Weweantic River – upper	0.025
Wareham Road Bridge	0.040
Weweantic River - lower	0.025
Agawam River – upper	0.025
Sandwich Road Bridge	0.050
Broad Marsh River	0.030
Wareham River	0.025
Marsh Plain	0.070

V.3.3.2 Turbulent Exchange Coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swift, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). The model was mildly sensitive to turbulent exchange coefficients, with areas of marsh plain being most sensitive. In other regions where the flow gradients were not as strong, the model was much less sensitive to changes in the turbulent exchange coefficients. Typically, model turbulence coefficients (D) were set between 50 and 100 lb-sec/ft^2 (as listed in Table V-6. Higher values (up to 500 lb-sec/ft^2) were used on the marsh plain, to ensure solution stability.

Table V-6. Turbulence exchange coefficients (D) used in simulations of modeled embayment system.

Embayment	D (lb-sec/ft$^{2)}$
Buzzards Bay	50.0
Weweantic River – upper	50.0
Wareham Road Bridge	50.0
Weweantic River - lower	50.0
Agawam River – upper	50.0
Sandwich Road Bridge	50.0
Broad Marsh River	100.0
Wareham River	50.0
Marsh Plain	500.0

V.3.3.3 Wetting and Drying/Marsh Porosity Processes

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

V.3.3.4 Comparison of Modeled Tides and Measured Tide Data

Several calibration model runs were performed to determine how changes to various parameters (e.g. friction and turbulent exchange coefficients) affected the model results. These trial runs achieved excellent agreement between the model simulations and the field data. Comparison plots of modeled versus measured water levels at the seven gage locations is presented in Figures V-15 through V-21 Errors between the model and observed tide constituents were less than 0.5 inch for all locations, suggesting the model accurately predicts tidal hydrodynamics within the Wareham River and Weweantic River systems. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the calibration time period are shown in Table V-7. The constituent values in for the calibration time period differ from those in Tables V-2 because constituents were computed for only seven days, rather than the entire 50-day period represented in Tables V-2. Errors associated with tidal constituent height were on the order of hundredths of feet, which was of the same order of magnitude as the accuracy of the tide gage gages ($\pm$0.12 ft). Time lag errors were typically less than the time increment resolved by the model (1/6 hours or 10 minutes), indicating good agreement between the model and data.

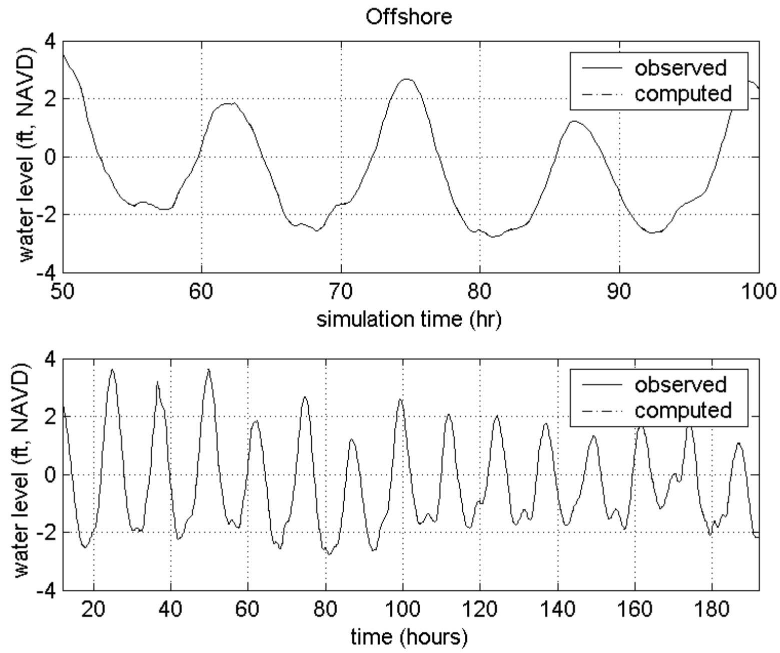


Figure V-15. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the calibration time period, for the offshore gauging station. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

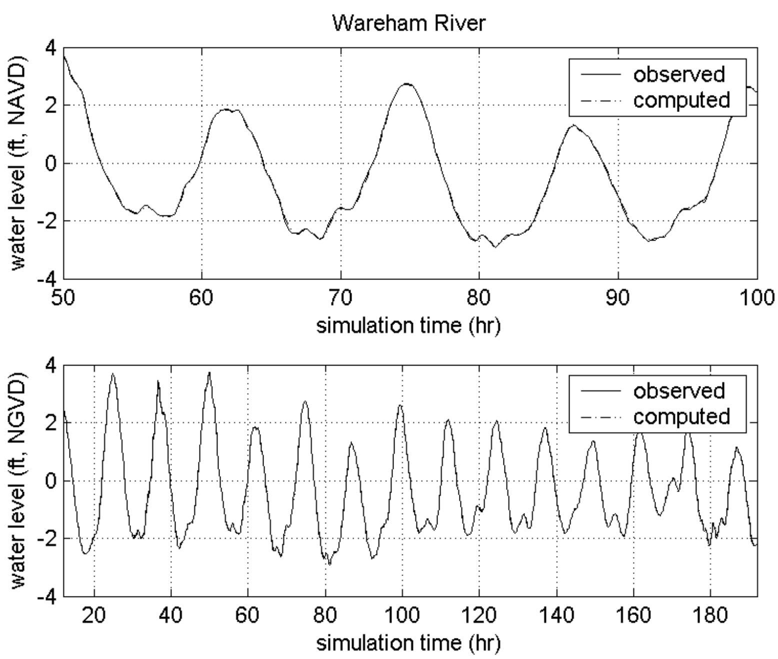


Figure V-16. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Wareham River gauging station (WR-2). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

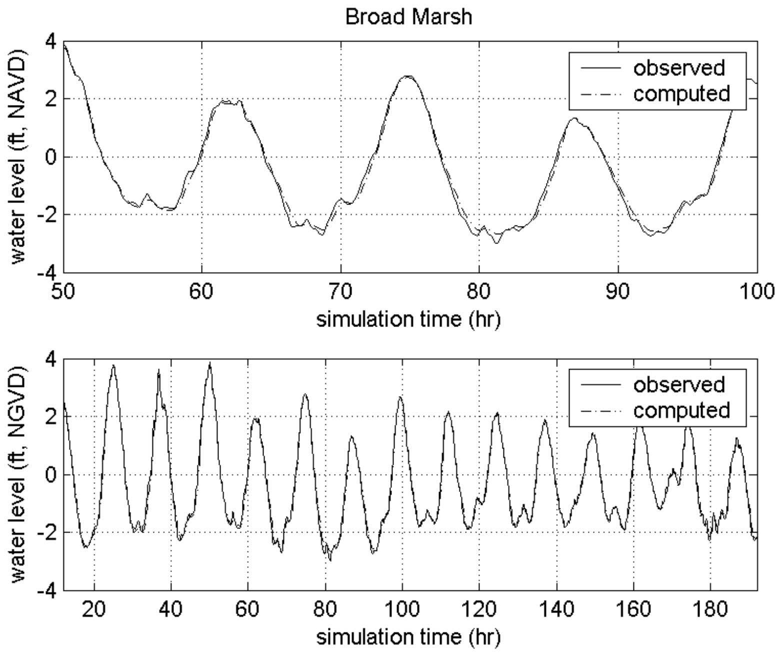


Figure V-17. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Broad Marsh River gauging station (WR-3). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

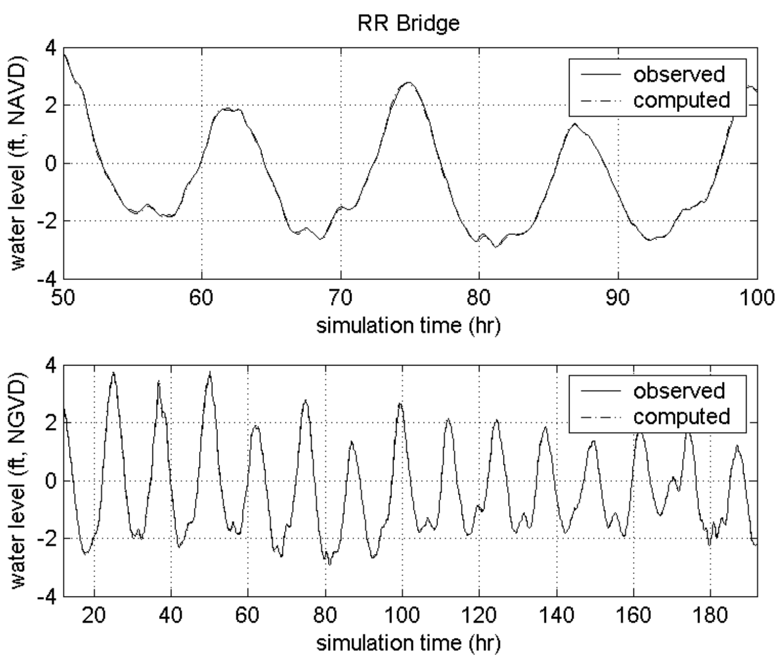


Figure V-18. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Sandwich Road crossing of the Wareham River (WR-4). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

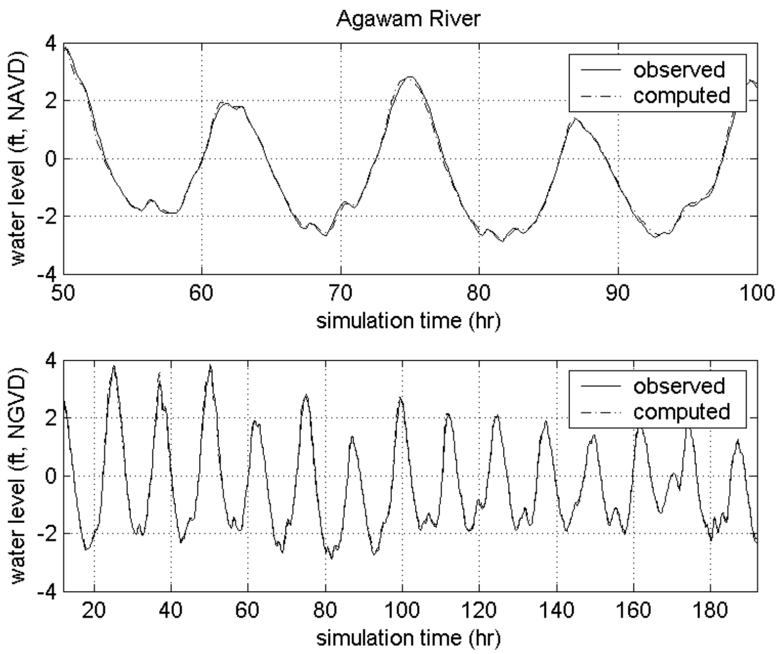


Figure V-19. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the mid-Agawam River gauging station (WR-5). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

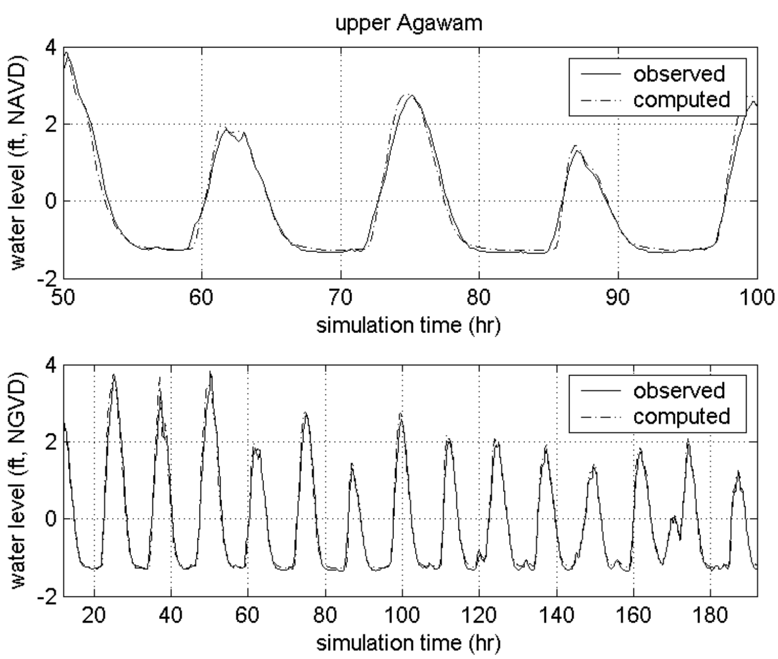


Figure V-20. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the upper Agawam River gauging station (WR-6). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

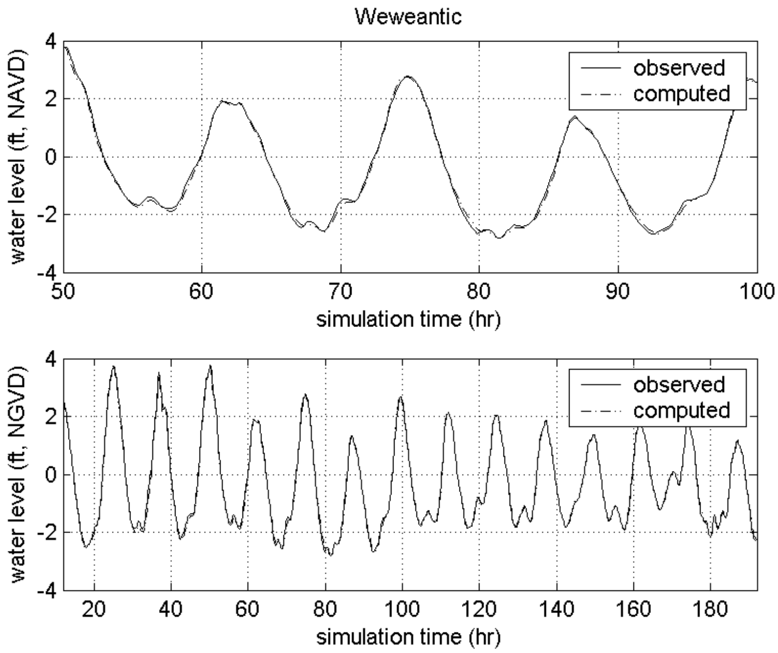


Figure V-21. Comparison of water surface variations simulated by the model (dashed line) to those measured within the system (solid line) for the verification time period at the Weweantic River gauging station (WR-7). The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

V.3.4 ADCP verification of the Agawam-Wareham River System

An additional model verification check was possible by using collected ADCP velocity data to verify the performance of the two river systems included in the 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.2.3. For the model ADCP verification, the Wareham model was run for the period covered during the ADCP survey on March 30, 2004. Model flow rates were computed in RMA-2 at continuity lines (channel cross-sections) that correspond to the actual ADCP transects followed in the survey (i.e., across the mouths of the two rivers, and at their confluence in Buzzards Bay).

Comparisons of the measured and modeled volume flow rates at each survey transect are shown in Figures V-22 through V-24. For each figure, the top plot shows the flow comparison, and the lower plot shows the time series of tide elevations for the same period. Each ADCP point (blue triangles 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 mostly to the peculiar nature of the forcing tide in this region of Buzzards Bay (due to the influence of the Cape Cod Canal), but also to the effects of winds (i.e., atmospheric effects) on the water surface and friction across the seabed periodically retarding or accelerating the flow through the inlets, 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 river mouth ADCP transects show good agreement with the model predictions, with R^2 correlation coefficients between data and model results are 0.88.

The calibrated model accurately describes the discharge magnitude at each line. At the offshore transect, the comparison is less precise. Larger errors in calculated flows from the ADCP data at the offshore line are possibly due to difficulties measuring velocities along this transect, which is across a very broad embayment (8,500 ft cross-channel distance), where tidal currents are weaker and less coherent than those measured at the two river mouth transects.

Table V-7. Comparison of Tidal Constituents calibrated RMA2 model versus measured tidal data for the period December 23 through 31, 2003.

Model Verification Run						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Wareham River	1.98	0.55	0.10	0.34	19.0	54.9
Broad Marsh River	1.99	0.55	0.11	1.34	20.6	57.4
Sandwich Road Bridge	1.97	0.56	0.11	0.34	21.6	60.3
Agawam River	1.99	0.54	0.15	0.35	27.4	66.7
Agawam River - upper	1.60	0.59	0.14	0.28	34.3	66.4
Weweantic River	1.96	0.55	0.13	0.34	23.9	63.5
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Wareham River	1.99	0.55	0.12	0.34	19.7	55.4
Broad Marsh River	1.98	0.54	0.15	0.34	24.1	59.7
Sandwich Road Bridge	1.99	0.56	0.13	0.34	21.1	57.6
Agawam River	1.99	0.54	0.18	0.35	26.5	60.7
Agawam River - upper	1.63	0.66	0.18	0.29	32.4	58.4
Weweantic River	1.99	0.54	0.17	0.35	24.8	59.4
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	M_6	K_1	ΦM_2	ΦM_4
Wareham River	-0.01	0.00	-0.02	0.00	-1.5	-0.4
Broad Marsh River	0.00	0.01	0.01	-0.04	-7.3	-2.4
Sandwich Road Bridge	-0.02	0.00	-0.02	0.00	1.1	2.8
Agawam River	0.01	0.00	0.01	-0.02	1.8	6.2
Agawam River - upper	-0.03	-0.01	-0.06	-0.01	3.9	8.4
Weweantic River	-0.02	0.01	-0.04	-0.01	-1.9	4.2

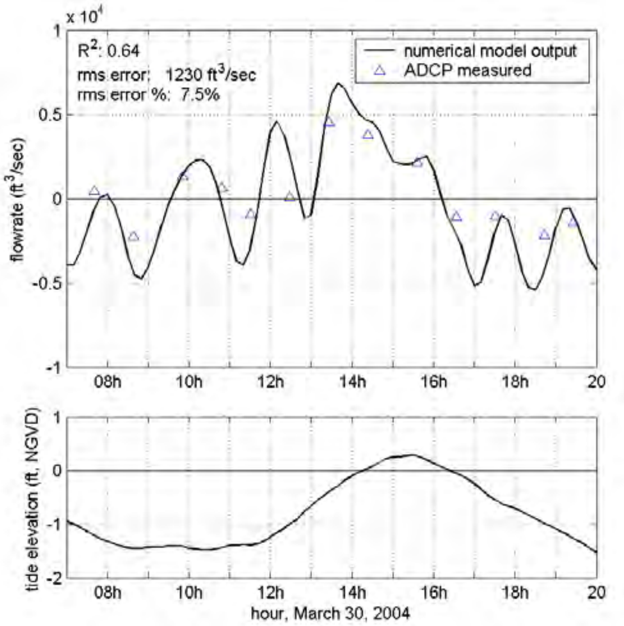


Figure V-22. Comparison of measured volume flow rates versus modeled flow rates (top plot) across the Wareham River mouth, over a tidal cycle on March 30, 2004. Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Buzzards Bay

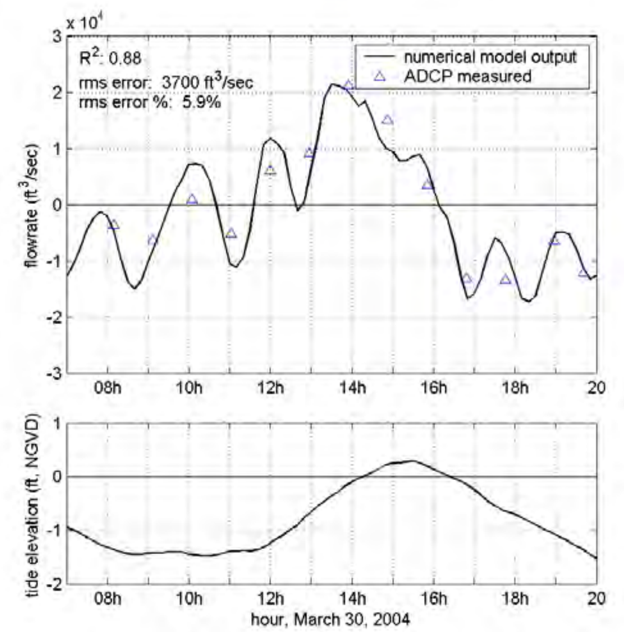


Figure V-23. Comparison of measured volume flow rates versus modeled flow rates (top plot) across the confluence of the Wareham and Weweantic Rivers, over a tidal cycle on March 30, 2004. Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Buzzards Bay

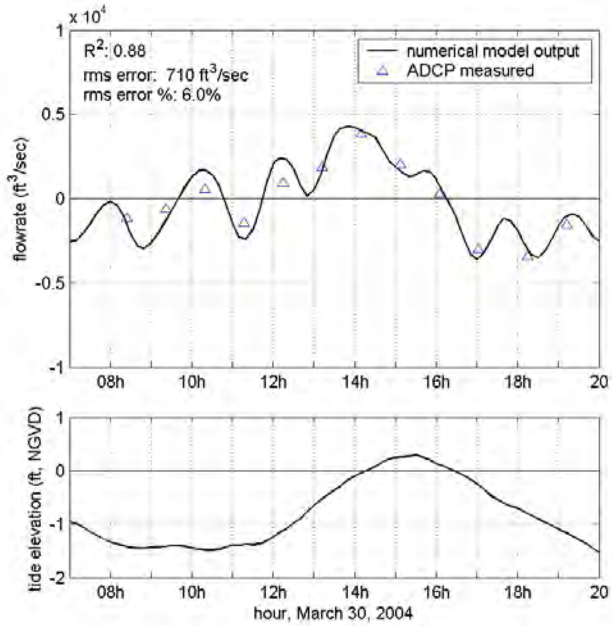


Figure V-24. Comparison of measured volume flow rates versus modeled flow rates (top plot) across the Weweantic River mouth, over a tidal cycle on March 30, 2004. Flood flows into the inlet are positive (+), and ebb flows out of the inlet are negative (-). The bottom plot shows the tide elevation offshore, in Buzzards Bay

V.3.4.1 Model Circulation Characteristics

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

From the model run of the two riverine estuary systems, ebb velocities in the channels are slightly larger than velocities during maximum flood. In the Weweantic River the maximum depth-averaged velocities in the model are approximately 1.7 feet/sec. For the Wareham River, maximum velocities are approximately 2.0 ft/sec at the railroad bridge. A close-up of the model output is presented in Figure V-25, which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow, for a single model time-step, at the portion of the tide where maximum flood velocities occur in the Wareham River.

In addition to depth averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. For the flushing analysis in the next section, flow rates were computed across three separate transects in the greater Wareham River system: at the mouth to the Wareham River, at the mouth of the Weweantic River, and at a constriction point in the Wareham River channel. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-26. During spring tides, the maximum flow rates are approximately 15,000 ft^3/sec at the mouth of the Wareham River, and 10,000 ft^3/sec at the Weweantic River mouth. The minimum typical flow rates during neap tides are approximately 7,000 ft^3/sec at the Wareham River mouth, and 5,000 ft^3/sec for the Weweantic.

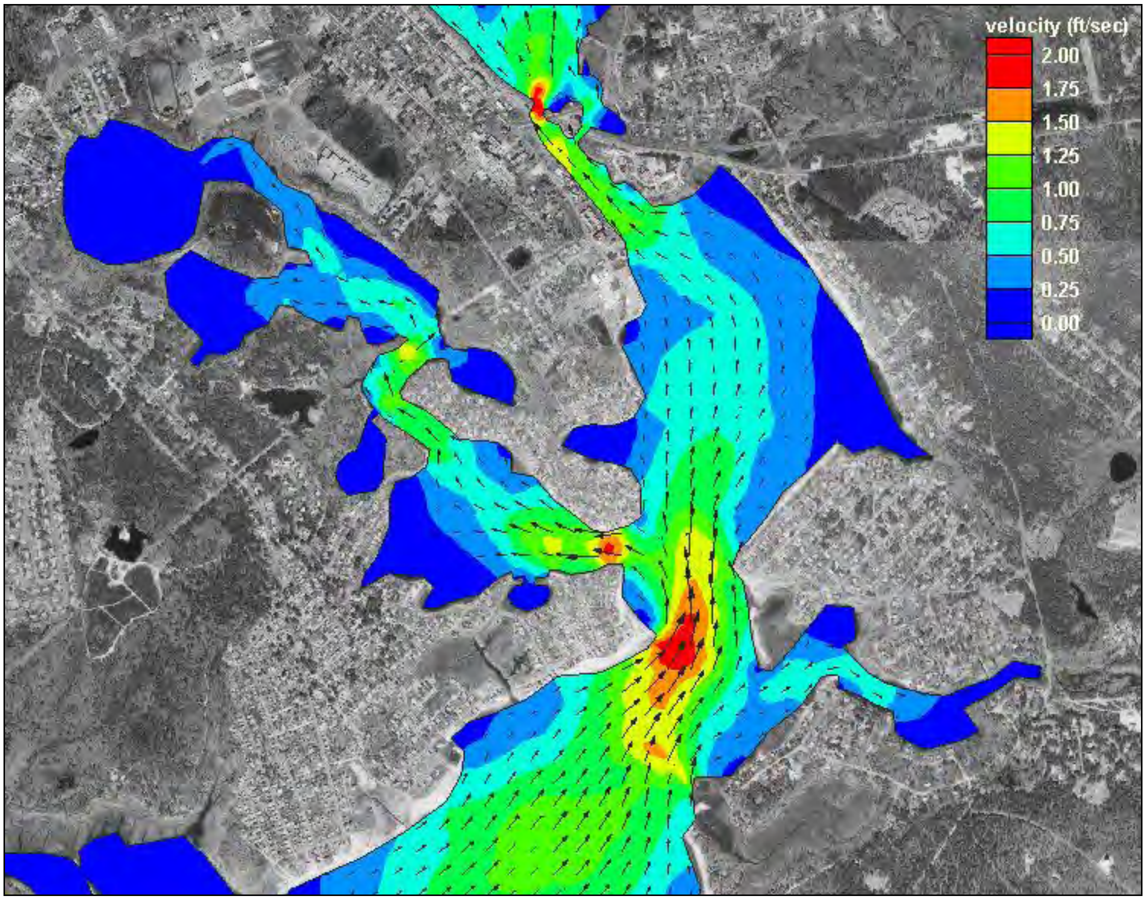


Figure V-25. Example of hydrodynamic model output in the Wareham River for a single time step where maximum flood velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

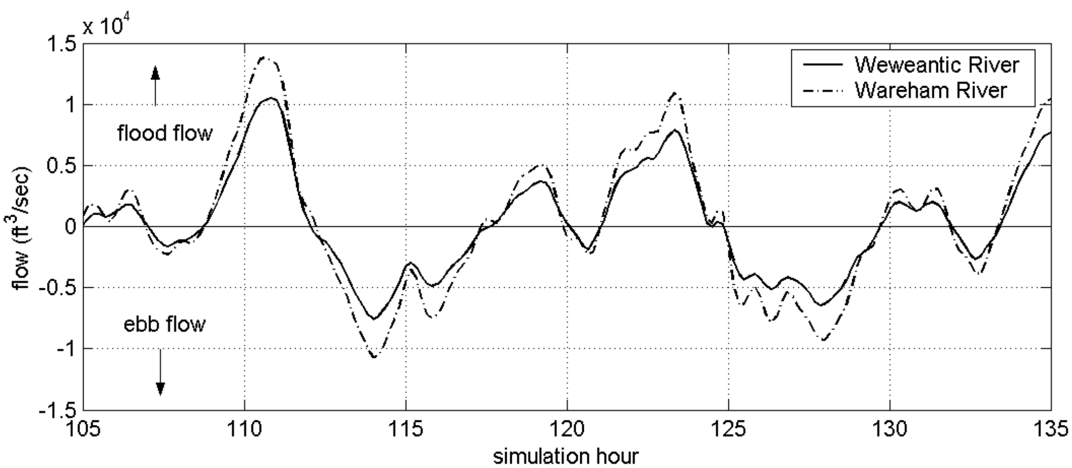


Figure V-26. Time variation of computed flow rates for two transects at the mouths of the Wareham and Weweantic River systems. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flow indicates flooding tide, while negative flow indicates ebbing tide.

V.5 FLUSHING CHARACTERISTICS

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

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

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

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

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using the upper Agawam River as an example, the **system residence time** is the average time required for water to migrate from the upper Agawam River, through the lower portions of the Agawam and Wareham Rivers, and finally into Buzzards Bay, where the **local residence time** is the average time required for water to migrate from the upper Agawam River to just the lower Agawam River (not all the way to the Bay). Local residence times for each sub-embayment are computed as:

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

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

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

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

The volume of the each sub-embayment, as well as their respective tidal prisms, were computed as cubic feet (Table V-8). Model divisions used to define the system sub-embayments for the two systems include 1) the entire Weweantic River, 2) upper Weweantic River (north of the Wareham Road Bridge) , 3) the complete Wareham River estuary (including the Agawam River, and Broad Marsh River), 4) Broad Marsh River, and 5) Agawam River. The model computed total volume of each sub-embayment (using the divisions shown in Figure V-14), at every time step, and this output was used to calculate mean sub-embayment volume and average tide prism. 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.

Residence times were averaged for the tidal cycles comprising a representative 7.25 day period (14 tide cycles), and are listed in Table V-9. Residence times were computed for the entire estuary, as well selected sub-embayments within the two systems. In addition, **system** and **local residence times** were computed to indicate the range of conditions possible for the system. Residence times were calculated as the volume of water (based on mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days.

The computed flushing rates for both the Wareham and Weweantic River systems show that as a whole, they flush well. A flushing time of under 0.7 days for both estuaries shows that on average, water is resident in the system less than one day. All system sub-embayments have local flushing times that are equal to or less than 0.7 days. The Agawam River has the shortest local flushing time, because of its small mean sub-embayment volume (due to its shallow marshy channel), relative to its tide prism.

The low local residence times in all areas of the both river systems and their sub-embayments show that they would likely have good water quality if the system water with which they exchange also has good water quality, and if they were not overloaded by nutrient inputs. For example, the water quality of the upper Agawam River would likely be good as long as the water quality of the lower portion of the Wareham River was also good, and as long as it did not receive a large nitrogen influx.

For the upper reaches of the Wareham River system, computed system residence times are typically one order of magnitude greater 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. Again as an example, the Agawam

River, with a system residence time of 5.7 days, is likely very sensitive to the quality of the water in the Wareham River. Because of the long, winding morphology of the Wareham River system, it is likely that tidal exchange with high quality water offshore in Buzzards Bay is not efficient, and therefore, the calculated system residence times are probably better indicators of the flushing conditions that affect water quality in the upper portion of this system.

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

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

Table V-8. Embayment mean volumes and average tidal prism of the Wareham River and Weweantic River systems during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Wareham River (system)	243,574,000	191,430,000
Broad Marsh River	26,553,000	30,228,000
Agawam River	16,965,000	22,304,000
Weweantic River (system)	103,831,000	87,266,000
Weweantic River - upper	31,920,000	38,952,000

Table V-9. Computed System and Local residence times for embayments in the Wareham River and Weweantic River systems.

Embayment	System Residence Time (days)	Local Residence Time (days)
Wareham River (system)	0.66	0.66
Broad Marsh River	4.17	0.45
Agawam River	5.65	0.39
Weweantic River (system)	0.62	0.62
Weweantic River - upper	1.38	0.42

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 Wareham River 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 embayments were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated hydrodynamic model representing the transport of water within the Wareham River 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 7.2 day (14 tide cycle) period beginning December 21, 2003 2030 EST. This period corresponds to 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 sub-embayments are recognized in this modeling study: external loads from the watersheds, nitrogen load from direct rainfall on the embayment surface, and internal loads from the sediments. Additionally, there is a fourth load to the Wareham River system's sub-embayments, consisting of the background concentrations of total nitrogen in the waters entering from Buzzards 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 Embayments

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. Seven years of data (collected between 2005 and 2011) were available for some stations.

Table VI-1. Measured data and modeled nitrogen concentrations for the Wareham River 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 the separate yearly means. Data represented in this table were collected in the summers of 2005 through 2011. The Buzzards Bay boundary condition was developed using data from station MC-3, and represents the lowest quartile of measurements.

Sub-Embayment	MEP monitoring station	data mean	s.d. all data	N	model min	model max	model average
Marks Cove	MC-3	0.420	0.082	22	0.344	0.445	0.370
Marks Cove	MC-2	0.440	0.090	24	0.347	0.451	0.396
Marks Cove	MC-1	0.464	0.093	24	0.432	0.502	0.468
Lower Wareham R	WR-7	0.408	0.065	21	0.348	0.497	0.407
Lower Wareham R	WR-6	0.453	0.072	23	0.358	0.536	0.442
Upper Wareham R	WR-5	0.459	0.084	22	0.372	0.549	0.464
Upper Wareham R	WR-4	0.469	0.091	25	0.392	0.551	0.477
Upper Wareham R	WR-3	0.477	0.098	23	0.428	0.560	0.494
Upper Wareham R	WR-1,2	0.490	0.078	68	0.448	0.588	0.524
Lower Broad Marsh	BMR-5/6	0.541	0.094	47	0.371	0.630	0.479
Lower Broad Marsh	BMR-4	0.560	0.121	25	0.403	0.703	0.529
Upper Broad Marsh	BMR-3	0.586	0.118	48	0.448	0.812	0.603
Upper Broad Marsh	BMR-1	0.649	0.117	24	0.487	0.907	0.666
Lower Agawam R	AG-2	0.533	0.137	22	0.554	0.597	0.573
Mid Agawam R	AG-1	0.554	0.178	26	0.558	0.595	0.573
Buzzards Bay - boundary	MC-3	**0.345**	-	-	-	-	-

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 Wareham River 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 the Wareham River. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. The MEP Technical Team has utilized this model in water quality studies of other Cape Cod embayments, including systems other Massachusetts estuarine systems such as Falmouth (Howes *et al*., 2005); Mashpee, MA (Howes *et al*., 2004) and Chatham, MA (Howes *et al*., 2003).

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

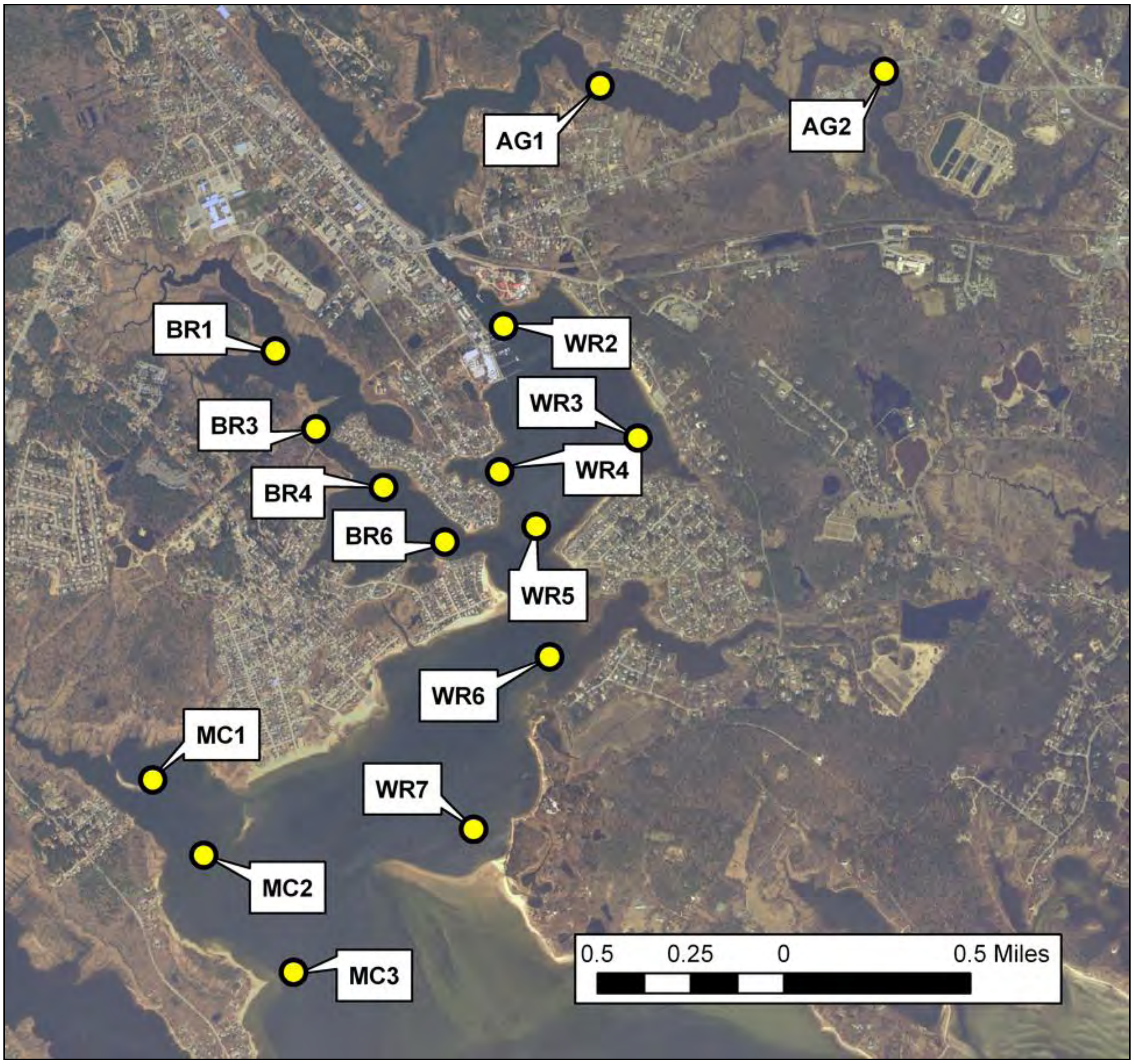


Figure VI-1. Estuarine water quality monitoring station locations in the Wareham River estuary system. Station labels correspond to those provided in Table VI-1.

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 sub-embayments. The governing equation of the RMA-4 constituent model can be most simply expressed as a form of the transport equation, in two dimensions:

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

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

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

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

VI.2.2 Water Quality Model Setup

Required inputs to the RMA-4 model include a computational mesh, computed water elevations and velocities at all nodes of the mesh, constituent mass loading, and spatially varying values of the dispersion coefficient. Because the RMA-4 model is part of a suite of integrated computer models, the finite-element meshes and the resulting hydrodynamic simulations previously developed for the Wareham River 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 7 tidal-day (174 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the Wareham River 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-embayment watershed were distributed across the sub-embayment. For example, the combined watershed and direct atmospheric deposition loads for Broad Marsh River were evenly distributed at grid cells that formed the perimeter of the sub-embayment. Benthic regeneration loads were distributed among another sub-set of grid cells which are in the interior portion of each basin.

The loadings used to model present conditions in the Wareham River system are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For some areas of the Wareham River (e.g., the mid river basin, at Crab Cove), the net benthic flux is negative which indicates a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in the Buzzards Bay region offshore the River was set at 0.345 mg/L, based on the lowest quartile of SMAST data collected at monitoring station MC-3.

Table VI-2. Sub-embayment and surface water loads used for total nitrogen modeling of the Wareham River 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)
Broad Marsh	7.945	1.681	15.656
Marks Cove	4.874	0.959	2.987
Crab Cove	3.548	1.614	-0.125
Crooked River	5.351	0.333	-0.745
Wareham River lower	0.718	5.180	73.028
Wareham River Upper	42.189	1.803	-1.431
Agawam River from Mill Pond	34.268	-	-
Wankinco River from Parker Mills Pond	30.586	-	-
System Total	129.479	11.570	89.369

VI.2.4 Model Calibration

Calibration of the total nitrogen model of the Wareham River proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (*E*) values were varied through the modeled system by setting different values of *E* for each grid material type, as designated in Section V. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent estuarine embayments encircling Buzzards Bay 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.

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

For model calibration, the 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 near the modeled mean because the monitoring data are collected, as a rule, during mid ebb tide.

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

Embayment Division	E m^2/sec
Lower Wankinco River	5.0
Upper Agawam River	70.0
Wankinco/Agawam River confluence	10.0
Route 6/Railroad Bridge crossings	5.0
Mid Wareham River – Crab Cove	10.0
Broad Marsh River	5.0
Broad Marsh River - marsh	0.5
Lower Wareham River	15.0
Crooked River	10.0
Marks Cove	0.6

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for each system. Computed root mean squared (rms) error is less than 0.03 mg/L, which demonstrates a skillful fit between modeled and measured data for this system.

A contour plot of calibrated model output is shown in Figures VI-4. In this figure, color contours indicate nitrogen concentrations throughout the model domain. The output in these figures show average total nitrogen concentrations, computed using the full 7-tidal-day model simulation output period.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Wareham River system using salinity data collected at the same stations as the nitrogen data. Comparisons of modeled and measured salinities are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. The rms error of the model is 2.3 ppt.

The only required inputs into the RMA4 salinity model of the system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundaries. The open boundary salinity (to Buzzards Bay) was set at 30.3 ppt, while salinities at the two rive inputs was set at 0 ppt. The average summer surface water discharges of the Wankinco River (24.4 ft^3/sec, or 59,800 m^3/day) and the Agawam River (24.3 ft^3/sec, or 59,500 m^3/day) were included in the model. Groundwater inputs used for the model were 6.2 ft^3/sec (15,000 m^3/day) for the estuarine reach of the Agawam River, 3.1 ft^3/sec (7,600 m^3/day) for the Broad Marsh River, 2.0 ft^3/sec (4,900 m^3/day) for the Crooked River watershed, 0.8 ft^3/sec (2,000 m^3/day) for the Wankinco River estuarine reach and 1.6 ft^3/sec (3,900 m^3/day) for the lower basin of the Wareham River. River inputs were added to the model using designated boundary nodestrings placed at the head of tide. Groundwater flows were distributed in the model by introducing water at several 2-D elements within the grid designated as fresh water inputs.

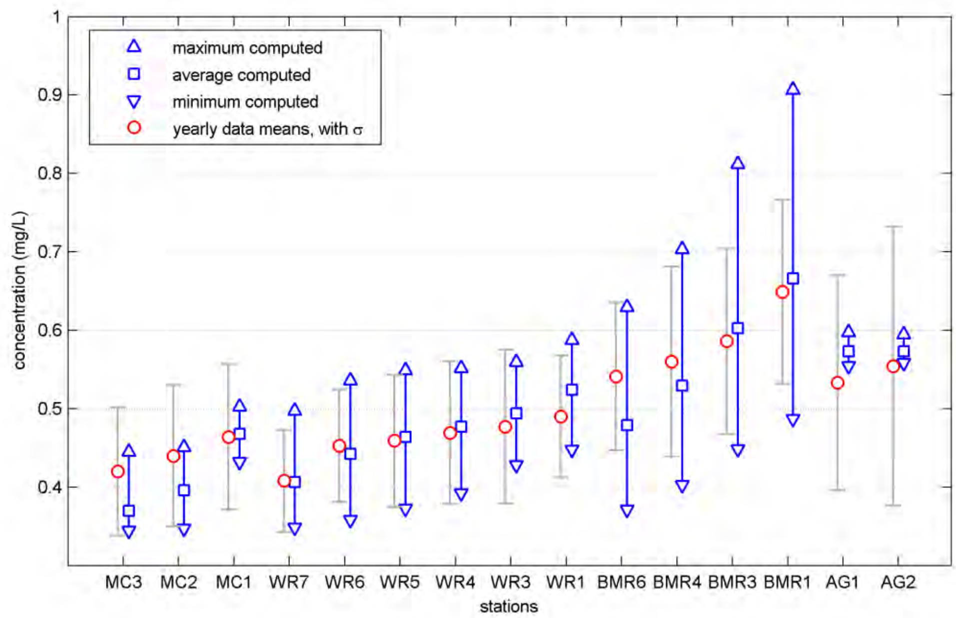


Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the Wareham River system. Station labels correspond with the MEP IDs provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation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

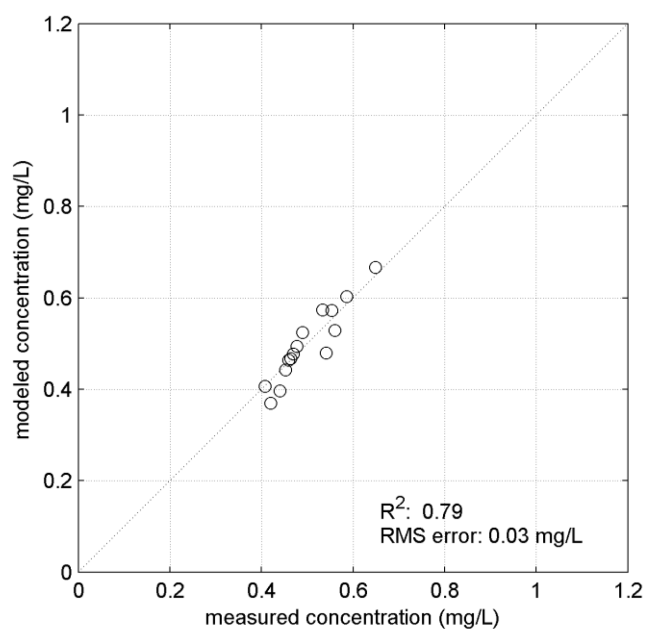


Figure VI-3. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are 0.79 and 0.03 mg/L respectively.

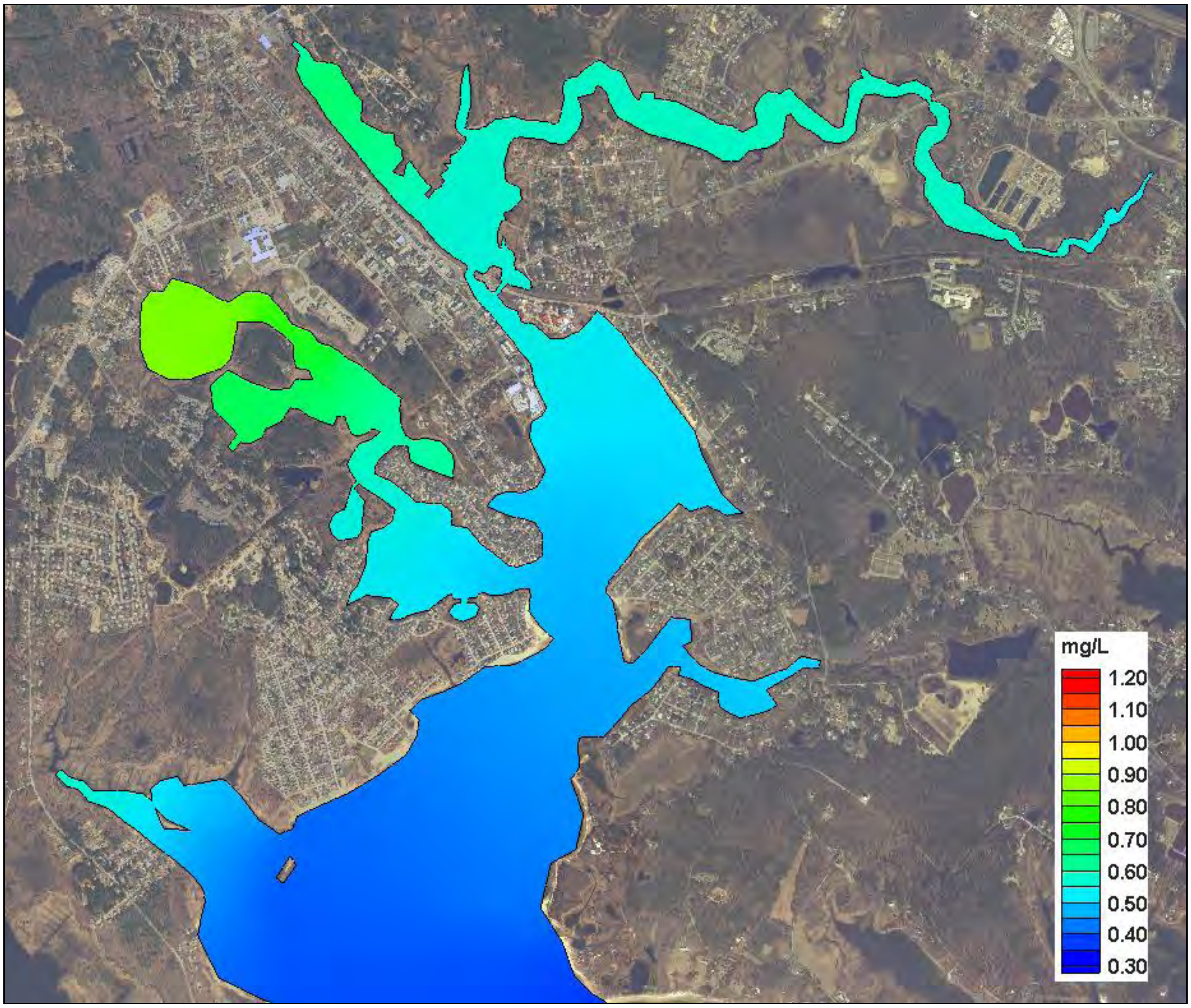


Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the Wareham River system.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

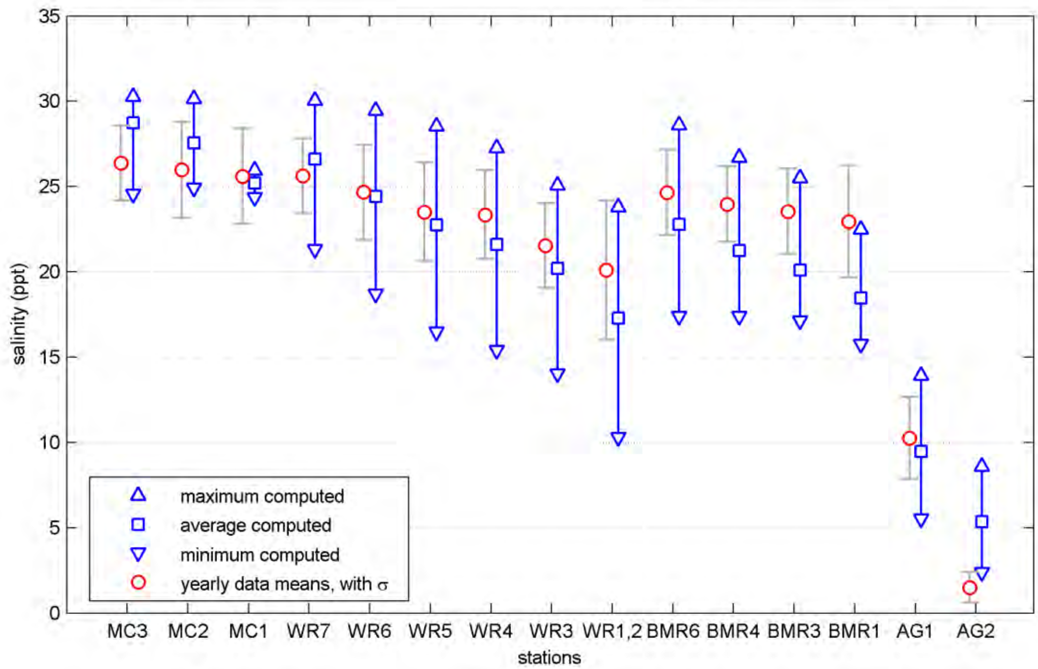


Figure VI-5. Comparison of measured and calibrated model output at stations in the Wareham River. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along 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.

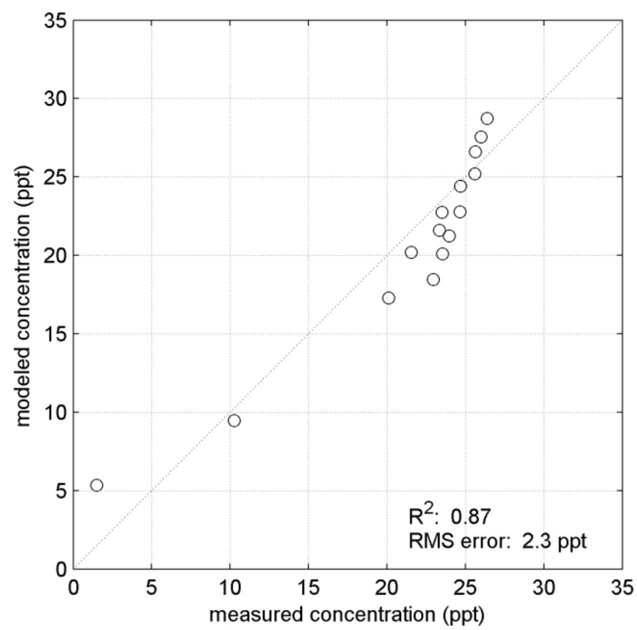


Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. The R^2 correlation is 0.87. RMS error for this model verification run is 2.3.

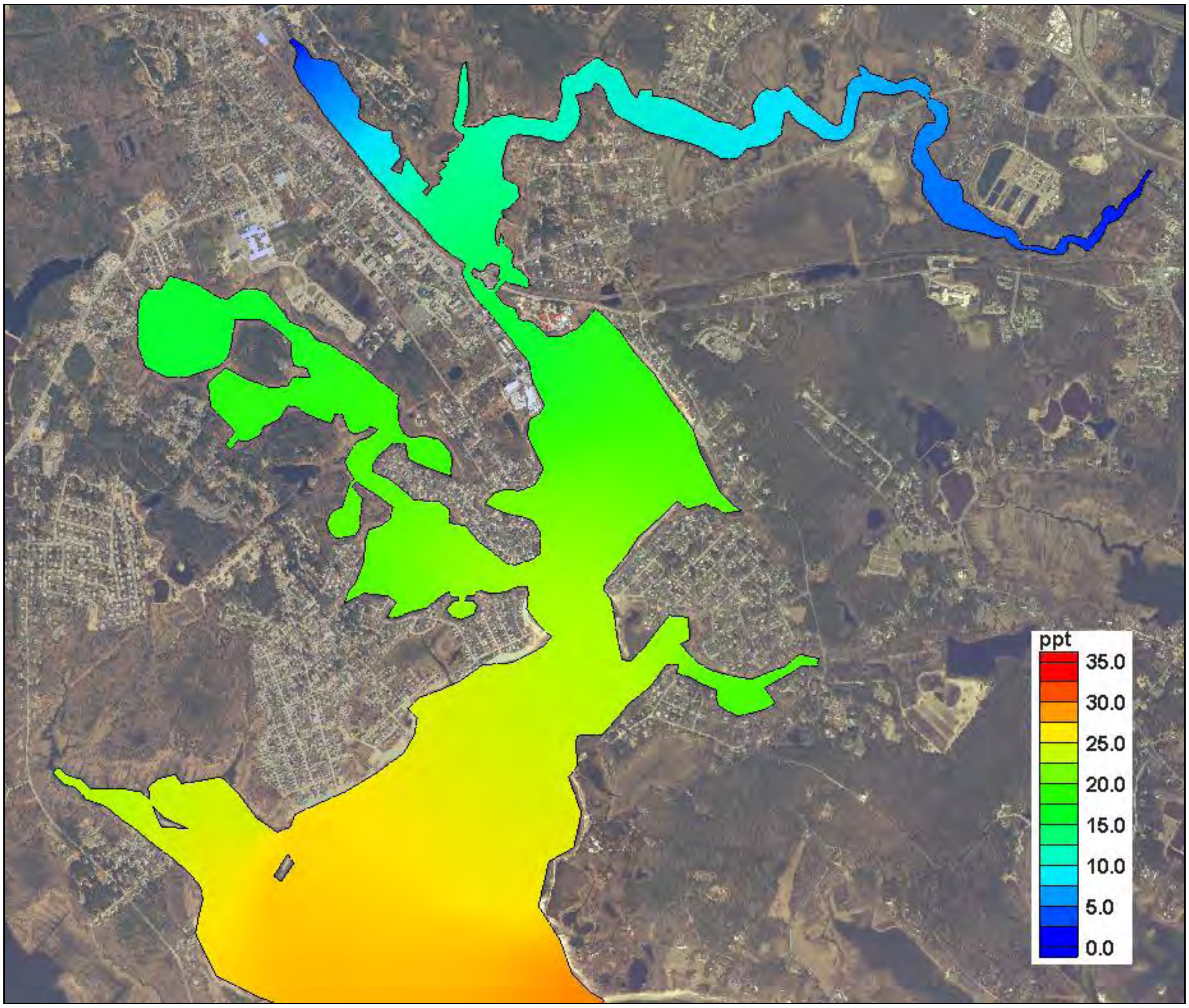


Figure VI-7. Contour Plot of average modeled salinity (ppt) in the Wareham River system.

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 *vise versa*.

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

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

and the present PON concentration above background,

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

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Wareham River 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
Broad Marsh	7.945	12.395	+56.0%	0.627	-92.1%
Marks Cove	4.874	4.466	-8.4%	0.411	-91.6%
Crab Cove	3.548	1.614	-54.5%	0.156	-95.6%
Crooked River	5.351	3.693	-31.0%	0.296	-94.5%
Wareham River lower	0.718	1.038	+44.7%	0.123	-82.8%
Wareham River Upper	42.189	57.145	+35.5%	1.332	-96.8%
Agawam River from Mill Pond	34.268	35.937	+4.9%	8.584	-75.0%
Wankinco River from Parker Mills Pond	30.586	64.973	+114.7%	8.110	-73.2%
System Total	129.479	181.261	+40.0%	19.638	-84.8%

Table VI-5. **Build-out** scenario sub-embayment and surface water loads used for total nitrogen modeling of the Wareham River 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)
Broad Marsh	12.395	1.681	19.631
Marks Cove	4.466	0.959	3.670
Crab Cove	1.614	1.614	-0.144
Crooked River	3.693	0.333	-0.919
Wareham River lower	1.038	5.180	89.090
Wareham River Upper	57.145	1.803	-1.769
Agawam River from Mill Pond	35.937	-	-
Wankinco River from Parker Mills Pond	64.973	-	-
System Total	181.261	11.570	109.558

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). Total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. For build-out, the increase in modeled TN concentrations is greatest in the upper basin, where TN concentrations increase more than 25% above monitoring station AG-2, in the mid-river basin. A contour plot showing average TN concentrations throughout the river is presented in Figure VI-8 for the model of build-out loading.

Table VI-6. Comparison of model average total N concentrations from present loading and the **build-out scenario**, with percent change, for the Wareham River system. The sentinel threshold station is in bold print.

Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	build-out (mg/L)	% change
Marks Cove	MC-3	0.370	0.381	+3.2%
Marks Cove	MC-2	0.396	0.414	+4.5%
Marks Cove	MC-1	0.468	0.494	+5.5%
Lower Wareham River	WR-7	0.407	0.439	+7.9%
Lower Wareham River	**WR-6**	0.442	0.495	+11.9%
Upper Wareham River	WR-5	0.464	0.535	+15.3%
Upper Wareham River	WR-4	0.477	0.560	+17.4%
Upper Wareham River	WR-3	0.494	0.591	+19.6%
Upper Wareham River	WR-1,2	0.524	0.653	+24.6%
Lower Broad Marsh	BMR-5/6	0.479	0.550	+14.8%
Lower Broad Marsh	BMR-4	0.529	0.621	+17.4%
Upper Broad Marsh	BMR-3	0.603	0.726	+20.5%
Upper Broad Marsh	BMR-1	0.666	0.817	+22.6%
Lower Agawam River	AG-2	0.573	0.720	+25.5%
Mid Agawam River	AG-1	0.573	0.692	+20.8%

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 §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., Buzzards Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from “no load” was large, with the upper areas of the system experiencing reductions greater than 30%. A contour plot showing TN concentrations throughout the system is shown pictorially in Figure VI-9.

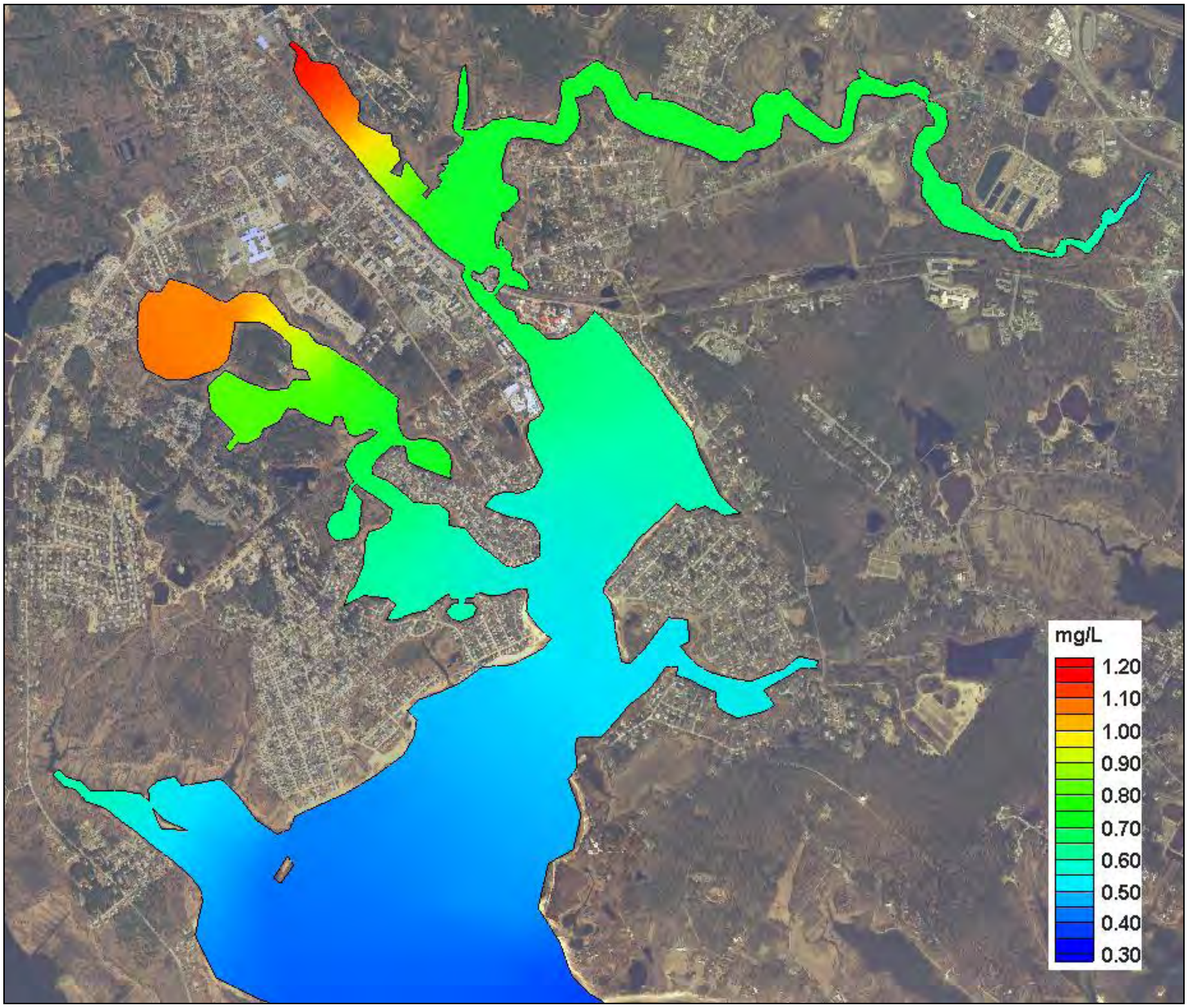


Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the Wareham River system, for projected build-out scenario loading conditions.

Table VI-7. “**No anthropogenic loading**” (“no load”) sub-embayment and surface water loads used for total nitrogen modeling of the Wareham River 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)
Broad Marsh	0.627	1.681	7.823
Marks Cove	0.411	0.959	1.684
Crab Cove	0.156	1.614	-0.063
Crooked River	0.296	0.333	-0.406
Wareham River lower	0.123	5.180	41.073
Wareham River Upper	1.332	1.803	-0.761
Agawam River from Mill Pond	8.584	-	-
Wankinco River from Parker Mills Pond	8.110	-	-
System Total	19.638	11.570	49.350

Table VI-8. Comparison of model average total N concentrations from present loading and the “**No anthropogenic loading**” (“no load”), with percent change, for the Wareham River system. The sentinel threshold station is in bold print.				
Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	no-load (mg/L)	% change
Marks Cove	MC-3	0.370	0.347	-6.1%
Marks Cove	MC-2	0.396	0.353	-10.9%
Marks Cove	MC-1	0.468	0.372	-20.5%
Lower Wareham River	WR-7	0.407	0.347	-14.6%
Lower Wareham River	**WR-6**	0.442	0.345	-21.9%
Upper Wareham River	WR-5	0.464	0.337	-27.3%
Upper Wareham River	WR-4	0.477	0.331	-30.6%
Upper Wareham River	WR-3	0.494	0.324	-34.5%
Upper Wareham River	WR-1,2	0.524	0.304	-42.0%
Lower Broad Marsh	BMR-5/6	0.479	0.351	-26.7%
Lower Broad Marsh	BMR-4	0.529	0.364	-31.1%
Upper Broad Marsh	BMR-3	0.603	0.384	-36.3%
Upper Broad Marsh	BMR-1	0.666	0.401	-39.8%
Lower Agawam River	AG-2	0.573	0.249	-56.6%
Mid Agawam River	AG-1	0.573	0.219	-61.7%

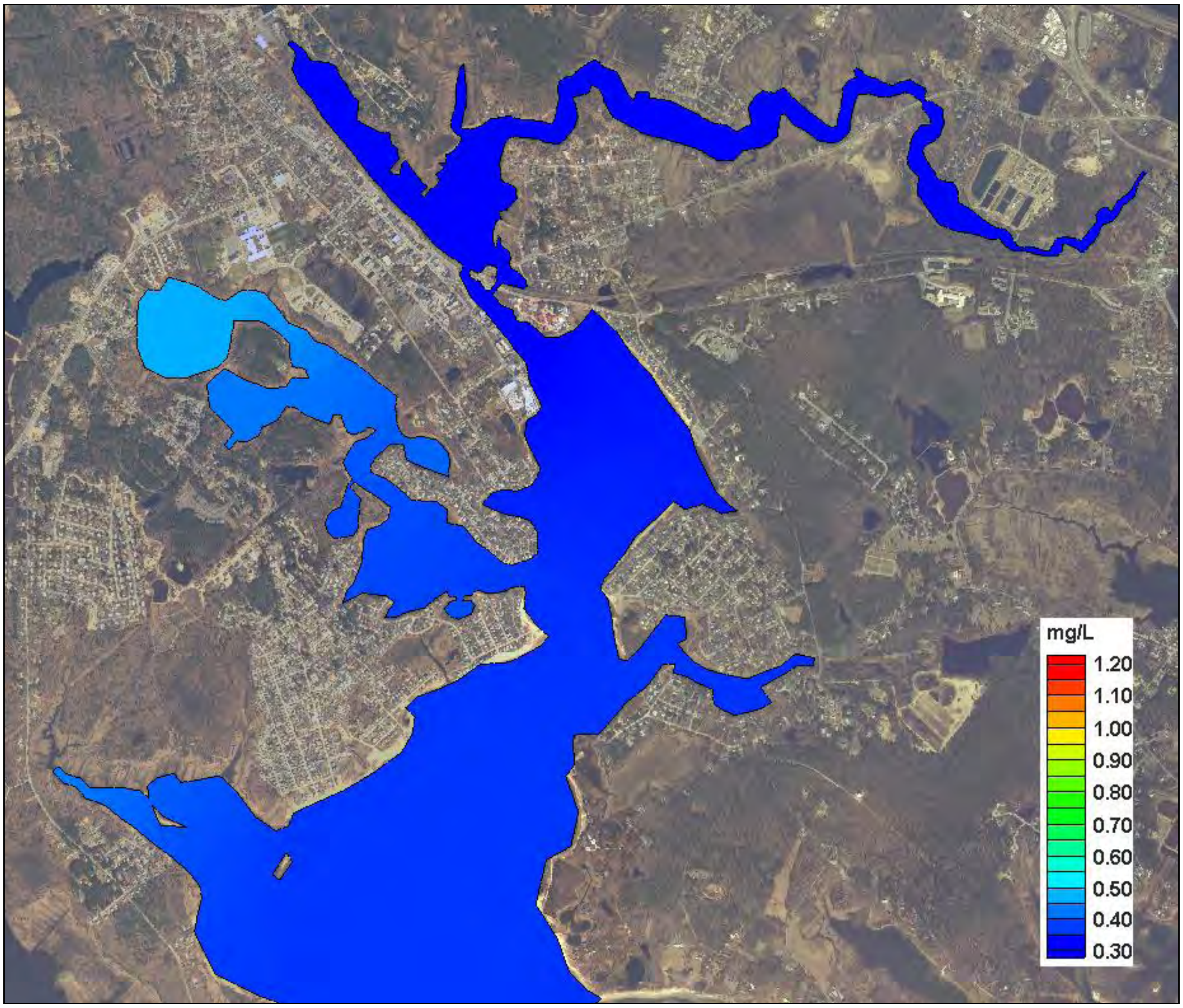


Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in the Wareham River, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gaged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Agawam / Wareham River embayment system in the Town of Wareham, MA, our assessment is based upon data from the water quality monitoring database developed by the Coalition for Buzzards Bay and our surveys of eelgrass distribution, benthic animal communities and sediment characteristics, and dissolved oxygen records conducted during the summer and fall of 2002. These data were analyzed relative to recent changes within the watershed and have been used to form the basis of an assessment of this system's present health. When coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, the full data set supports complete nitrogen threshold development for this system (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen thresholds determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll a (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed dissolved oxygen sensors within the upper portions of the Agawam / Wareham River system, as well as in the tributary embayment (Broadmarsh River) and closer to the inlet of the overall system (Hamilton Beach), to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Agawam / Wareham River system was conducted for comparison to historic records (DEP Eelgrass Mapping Program, C. Costello). These results were combined with other eelgrass surveys (Costa 1988) to refine temporal trends in eelgrass coverage, which are then used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the Agawam / Wareham River system, temporal changes in eelgrass distribution provide a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet; nitrogen management) in nutrient enrichment.

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

VII.2 BOTTOM WATER DISSOLVED OXYGEN

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

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (see Figure VII-1 for example). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Wareham River Embayment System (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the Agawam / Wareham River embayment system was collected during the summer of 2002.

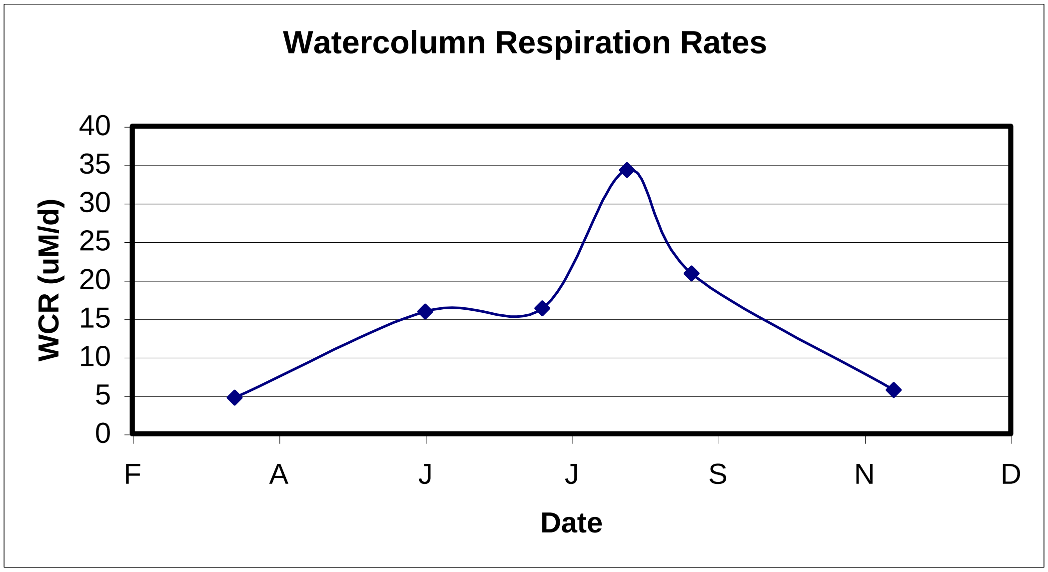


Figure VII-1. As an example, average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System are presented(Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter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

Similar to other embayments in southeastern Massachusetts, the Wareham River Embayment System evaluated in this assessment showed high frequency variation, apparently related to diurnal and sometimes tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration at 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 33-39 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions. The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate highly nutrient enriched waters and impaired habitat quality at all mooring sites within each estuary (Figures VII-3 through VII-10). The oxygen data is consistent with high organic matter loads from phytoplankton production (chlorophyll a levels) indicative of nitrogen enrichment and eutrophication of these estuarine systems. The oxygen records further indicate that the upper tidal reaches of the estuarine system has the largest daily oxygen excursion, which further supports the assessment of a high degree of nutrient 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 upper tidal reaches of the Agawam/Wareham River system is eutrophic.

Overall, the dissolved oxygen records throughout the Wareham River Embayment System generally showed little to moderate depletions during the critical summer period. Oxygen depletions were generally associated with the wetland dominated tributary basins, with higher oxygen levels maintained in the main embayment basin. The continuous D.O. records indicate that the upper region of the Wareham River Embayment System, defined by the Agawam River estuarine reach, shows periodic oxygen depletion during summer, consistent with its nitrogen and organic matter enrichment (Table VII-1, Figures VII-3). It appears that the organic matter enrichment results in part from the system's role as a tidal river bordered by extensive wetlands and from in situ phytoplankton production supported by nitrogen inputs as seen by the high levels of chlorophyll a, >25 µg/L 48% of the time. (cf. Agawam River, Table VII-2). Oxygen conditions and chlorophyll a levels improved with decreasing distance to the tidal inlet.

Oxygen levels in the region of The Narrows are influenced by outflows from the estuarine reaches of the Agawam and Wankinco Rivers, but only rarely showed oxygen depletions to <5 mg L^{-1}, while the lower Wareham River consistently maintained oxygen levels of >5 mg L^{-1}. The lower basin of the Broad Marsh River also supported oxygen levels > 5 mg L^{-1}, except for brief excursions slightly below 5 mg L^{-1}. The Broad Marsh River record is from the lower basin of this sub-embayment, where the upper basin is dominated by extensive tidal salt marshes and is naturally nutrient and organic matter enriched. The pattern of oxygen excursions was consistent with the observed chlorophyll a levels at each site, with only the Agawam River estuarine reach indicating high phytoplankton levels. Chlorophyll levels showed a gradient with increasing distance from the head waters toward the tidal inlet to Buzzards Bay. These results are consistent with the eelgrass coverage and infaunal animal community composition and distribution as noted in Sections VII-3 and VII-4, below.

***Agawam River* (Figures VII-3 and VII-7):**

The Agawam River station was located about mid-way along the estuarine reach (Figure VII-2). There was clear tidal and diurnal variation in dissolved oxygen levels, with lowest dissolved oxygen typically occurring at high tide. Highest dissolved oxygen was observed when low tide occurred at the end of the photocycle (ca. 1500 hrs). While dissolved oxygen only rarely dropped below 4 mg L^{-1} (1%, Table VII-1) levels often climbed above 10 mg L^{-1} and occasionally above 12 mg L^{-1}, consistent with the high phytoplankton biomass. Chlorophyll a exceeded the 25 ug L^{-1} benchmark 48% of the time (Table VII-2, Figure VII-7). Peak concentrations always occurred near low tide indicating in situ production as the source for the high chlorophyll a levels.

The Agawam River is bordered by many areas of fringing marsh as well as more extensive pocket marshes, which by their nature are rich in organic matter. In addition, the upgraded Wareham waste water treatment facility, which discharges into the head of the estuary, along with the upper watershed nitrogen load entering via the Agawam River (freshwater), are major sources to this tidal river.

This assessment is justified in that the oxygen declines to ca. 4 mg L^{-1} are the largest within the entire system, consistent with its function as primarily a tidal river with significant bordering wetland area. The low oxygen levels are also consistent with a salt marsh tidal creek, where the organic matter enriched sediments support high levels of oxygen uptake at night that deplete the overlying waters. While oxygen depletion to 4 mg/L would indicate impairment in an embayment like the Wareham River sub-basin, it is consistent with the organically enriched nature of tidal creeks. These observations are typical of other tidal creeks and rivers assessed by the MEP, for example the nearby Back River (Bourne, MA), where periodic oxygen depletions to 3 mg L-1 were measured, but it was functioning as a healthy wetland river system. Given the significant wetland areas in the mid and lower Agawam Estuary, and observed oxygen levels, it appears that this reach of the embayment system is moderately impaired.

Wareham Narrows **(Figures VII-4 and VII-8):**

The Wareham Narrows (The Narrows) station was located downstream of the confluence of the Agawam and Wankinco Rivers in an average of 1.6m of water. Oxygen concentrations were typically >5 mg L^{-1} and only very rarely dropped into the 5-4 mg L^{-1} range (~2%). The instantaneous minimum recorded oxygen level was 4.8 mg L^{-1}. Salinities, though variable, remained above 20 ppt throughout the deployment indicating a dominance of estuarine processes at this site. During the first 10 days of the deployment, oxygen levels were at or above air equilibration and showed some depletion for the remainder of the deployment. The relative shift in oxygen concentration appeared to be the result of a moderate phytoplankton bloom, which occurred throughout the embayment system. Chlorophyll a concentrations averaged ca. 15ug L^{-1} over the bloom period. Following the phytoplankton bloom, oxygen levels declined slightly and were generally at or below air equilibration. The lack of large diurnal oxygen excursions suggests that much of the organic matter entering through The Narrows, does not settle within the upper Wareham River sub-basin. Rather, it is transported to the lower estuary where current velocities are smaller. The Wareham Narrows moored instrument data indicates moderate nutrient enrichment and moderate oxygen related habitat impairment.

Broad Marsh River **(Figures VII-5 and VII-9):**

The Broad Marsh River station was located in the main lower basin of the Broad Marsh River tributary embayment at a depth of 3.8m. The Broad Marsh River has 2 sub-basins, with the upper basin functioning primarily as a salt marsh pond, and the lower basin acting more as a typical sub-embayment (like Marks Cove, Upper Wareham River). In this lower basin, oxygen concentrations were generally high, falling to 6-5 mg L^{-1} and 5-4.5 mg L^{-1} only 16% and 2% of the time, respectively. Diurnal changes in oxygen ranged from 2-4 mg L^{-1} and oscillated around air equilibration; the magnitude of the oscillations, in general, reflected the magnitude of the moderate chlorophyll a levels which averaged 6-8 ug L^{-1}. As with the Agawam River and the Wareham Narrows stations, peak chlorophyll concentrations occurred during the last half of the deployment. The combined effects of relatively deep water and potential organic loading from marshes located in the upper reaches of this tributary system did not exert as strong an effect on oxygen levels water quality as expected. The result is that oxygen levels are consistent with a high quality salt marsh basin and a moderately impaired embayment basin.

Hamilton Beach **(Figures VII-6 and VII-10):**

Hamilton Beach is within the uppermost portion of the Wareham River lower basin. The dissolved oxygen measurements were made at the basin's deeper point, 2.8m. Even so, oxygen concentrations were consistently high, generally showing >1mg L-1 below air equilibration and showing only a brief (2 hr) decline below 5 mg L^{-1} over the 33 day (800 hr) record (Figure VII-6, Table VII-1). There was no apparent correlation between tide and either dissolved oxygen or chlorophyll a. Chlorophyll concentrations were lower than measured at The Narrows site, but were moderately high average ~10 ug L^{-1} over the deployment period. The generally high oxygen levels with modest depletions indicate that the uppermost portion of the lower Wareham River basin is supporting habitat of high quality to moderate impairment.

Figure VII-2. Aerial Photograph of the Wareham/Agawam River system in Wareham showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2002.

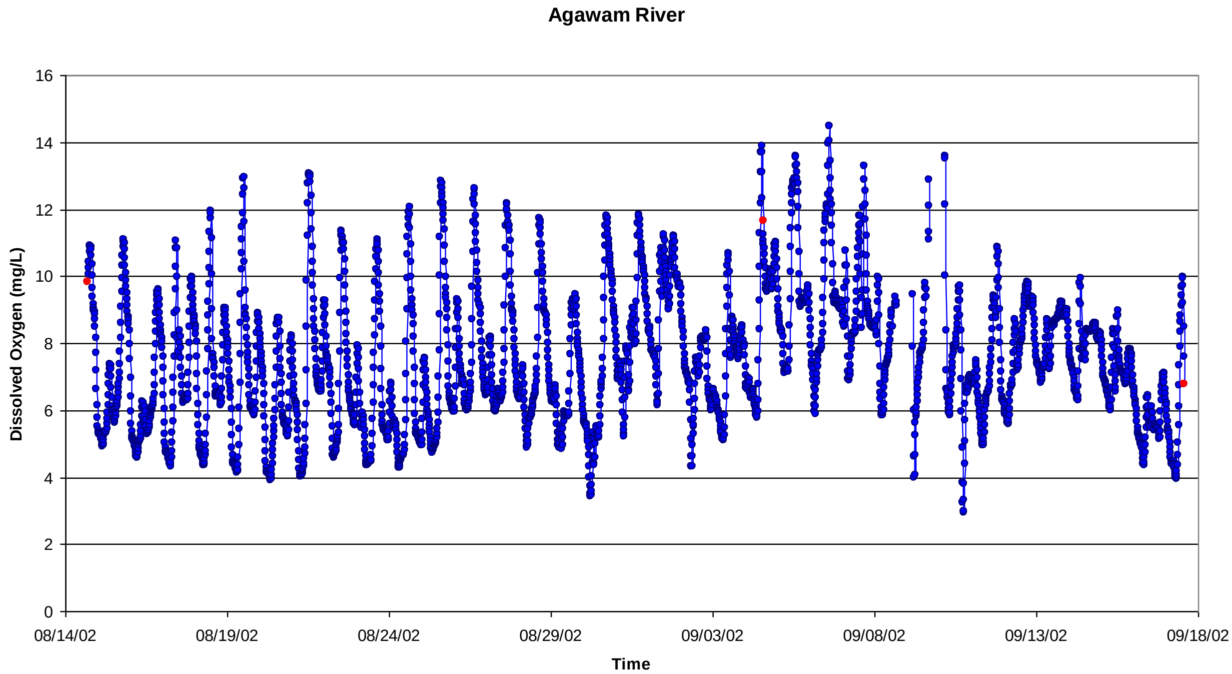


Figure VII-3. Bottom water record of dissolved oxygen at the Agawam River station, Summer 2002. Calibration samples represented as red dots.

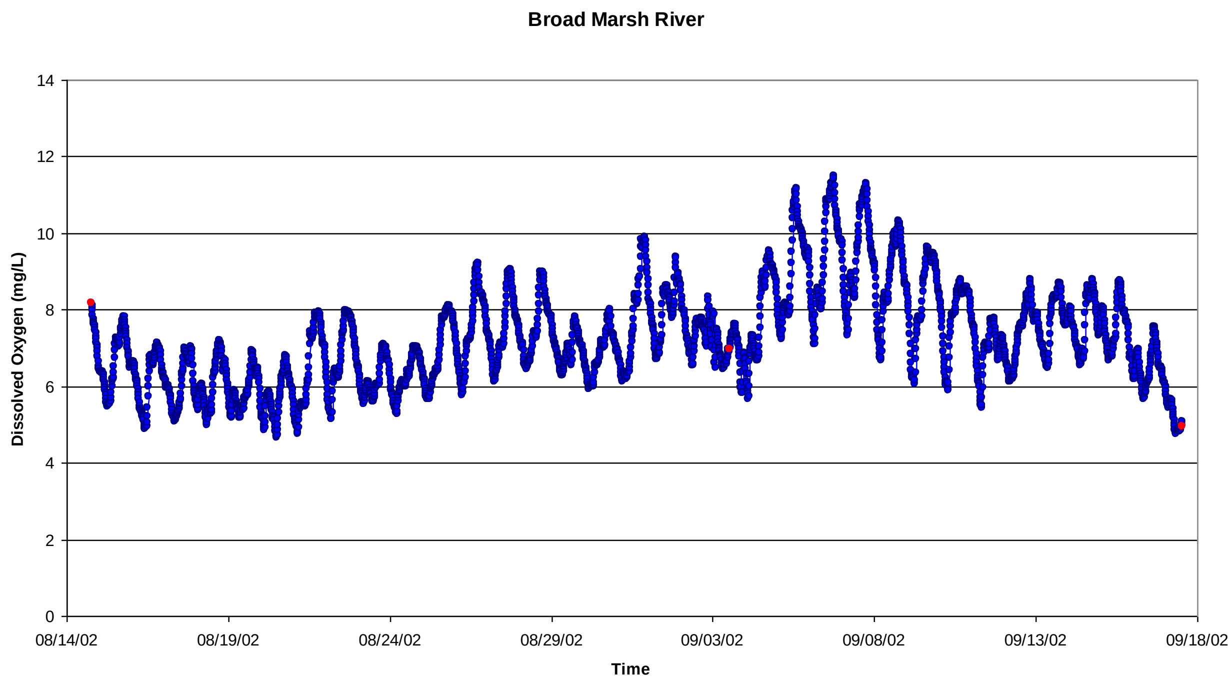


Figure VII-4. Bottom water record of dissolved oxygen at the Broadmarsh River station, Summer 2002. Calibration samples represented as red dots.

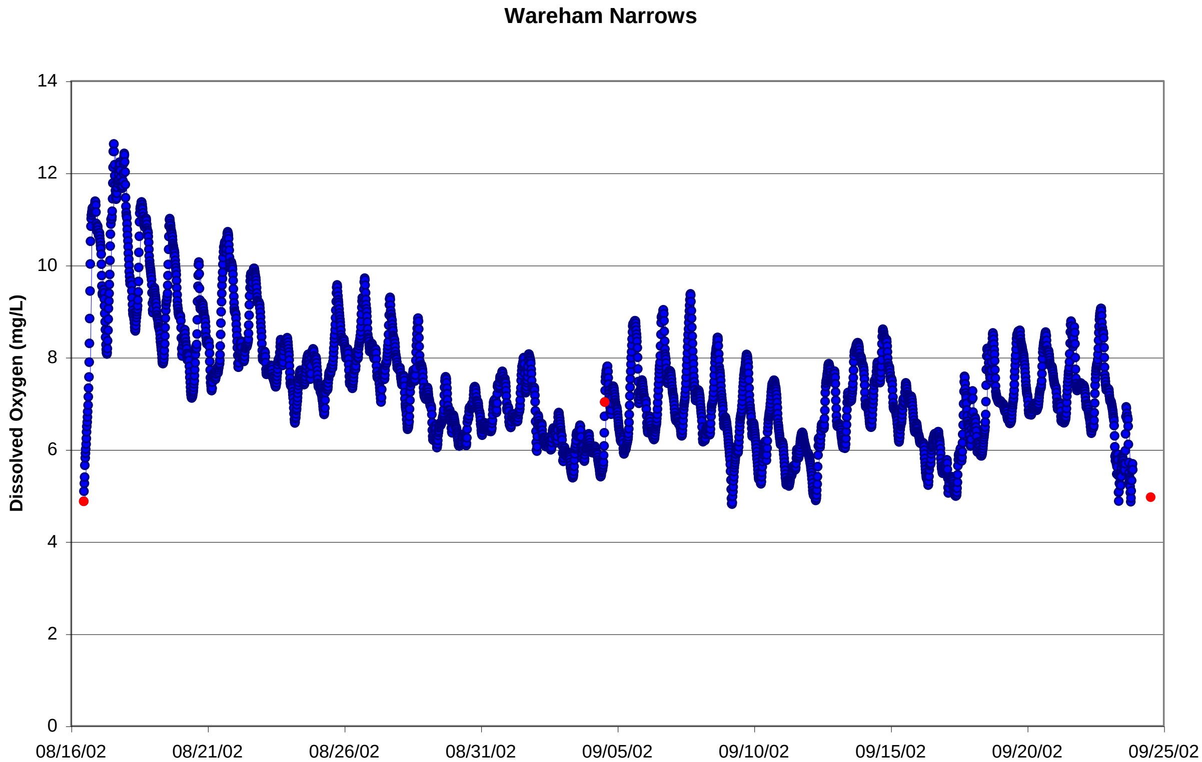


Figure VII-5. Bottom water record of dissolved oxygen at the Wareham River station, Summer 2002. Calibration samples represented as red dots.

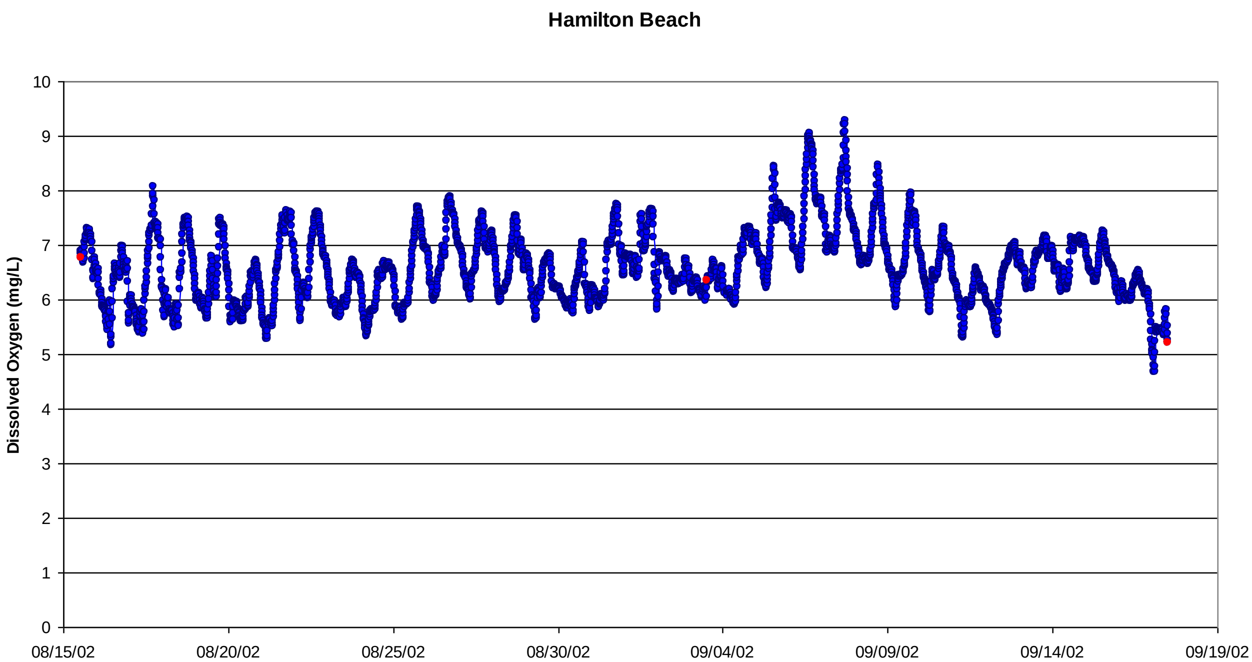


Figure VII-6. Bottom water record of dissolved oxygen at the Hamilton Beach station, Summer 2002. Calibration samples represented as red dots.

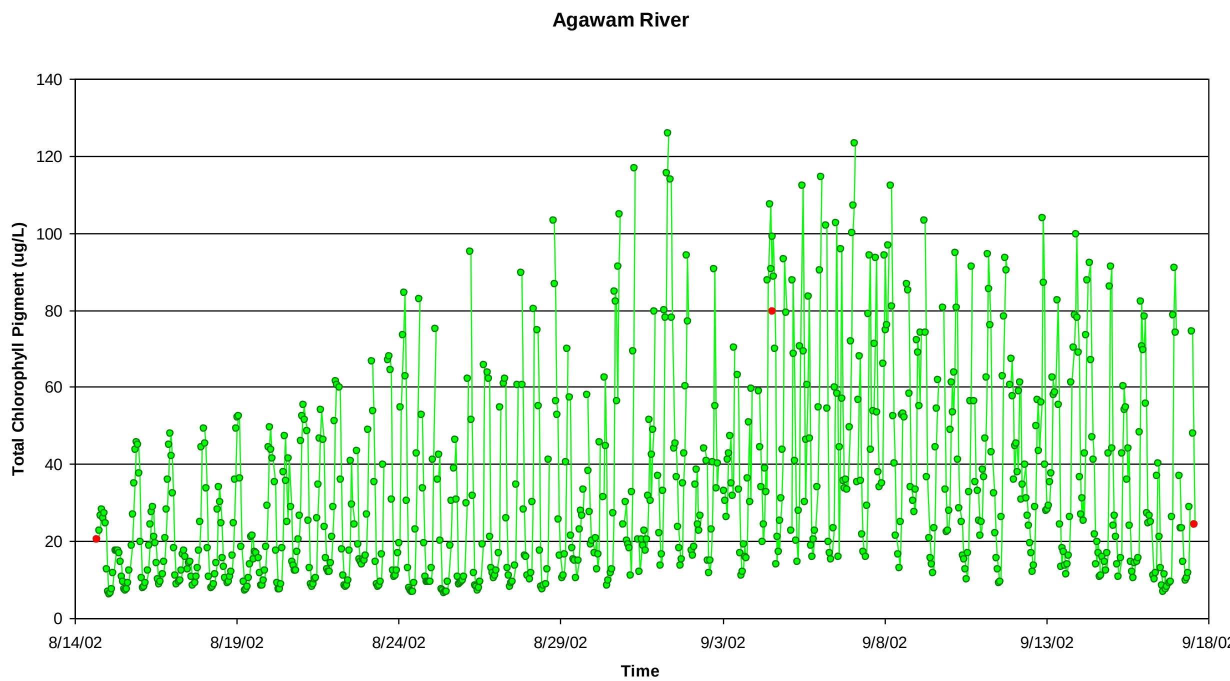


Figure VII-7. Bottom water record of Chlorophyll-*a* in Agawam River, Summer 2002. Calibration samples represented as red dots.

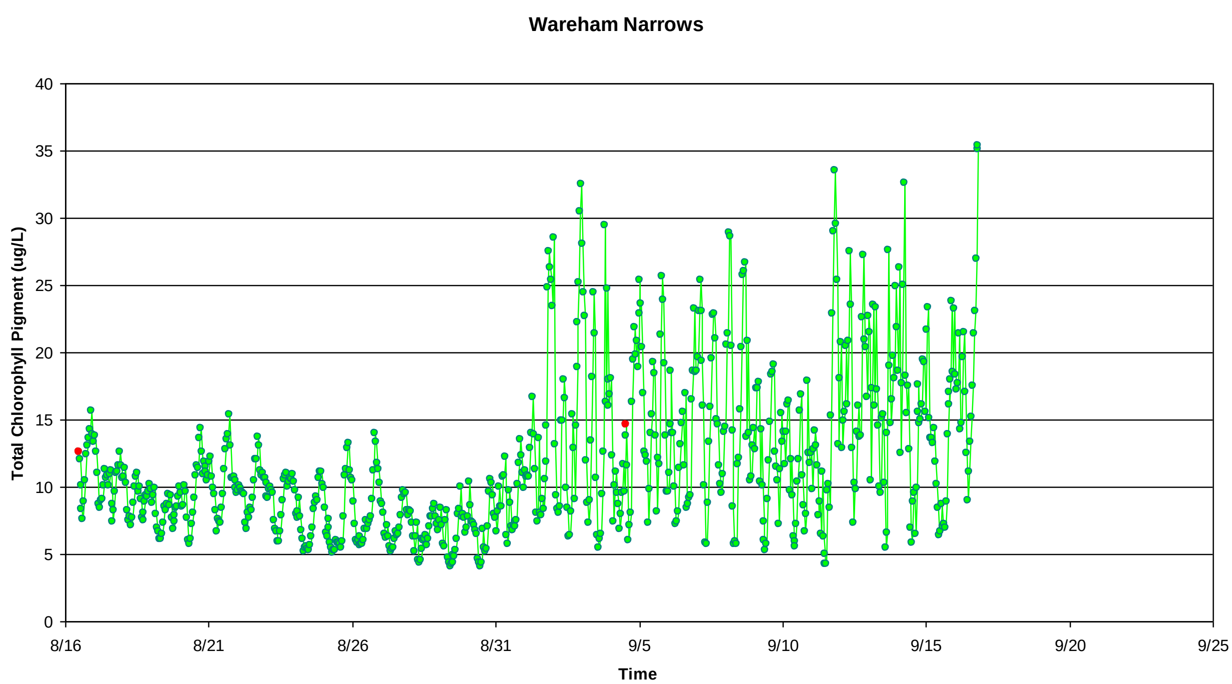


Figure VII-8. Bottom water record of Chlorophyll-*a* in Wareham River station, Summer 2002. Calibration samples represented as red dots.

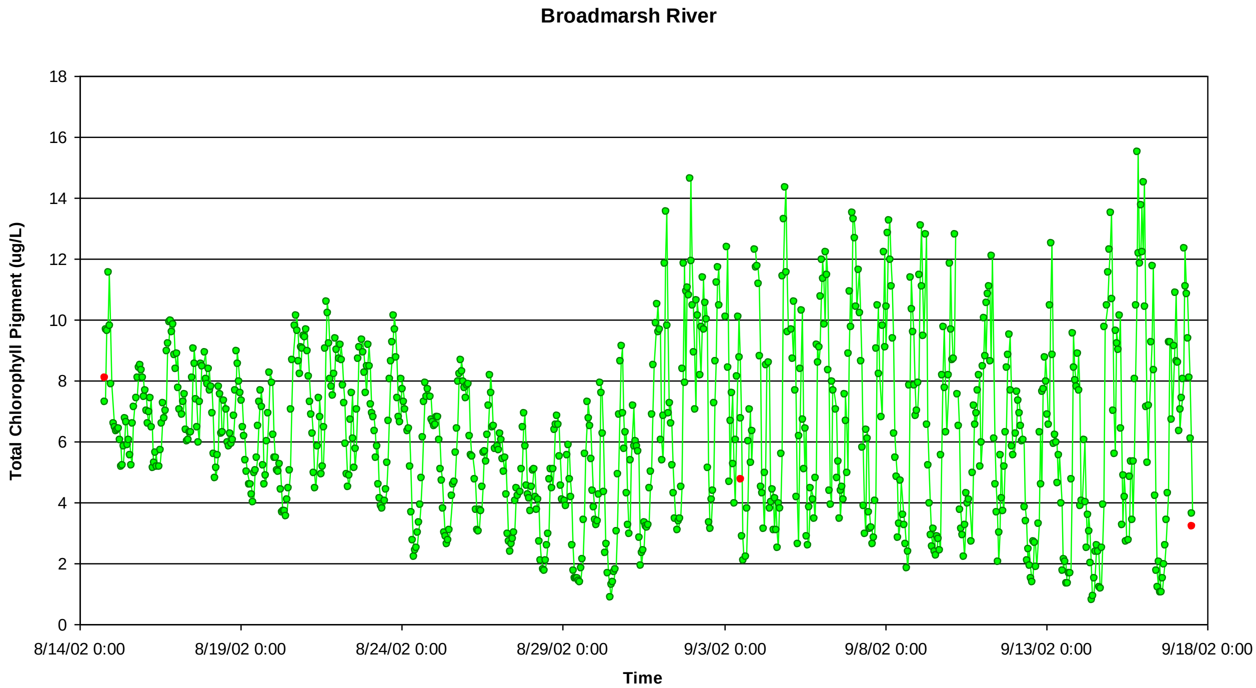


Figure VII-9. Bottom water record of Chlorophyll-*a* in Broadmarsh River station, Summer 2002. Calibration samples represented as red dots.

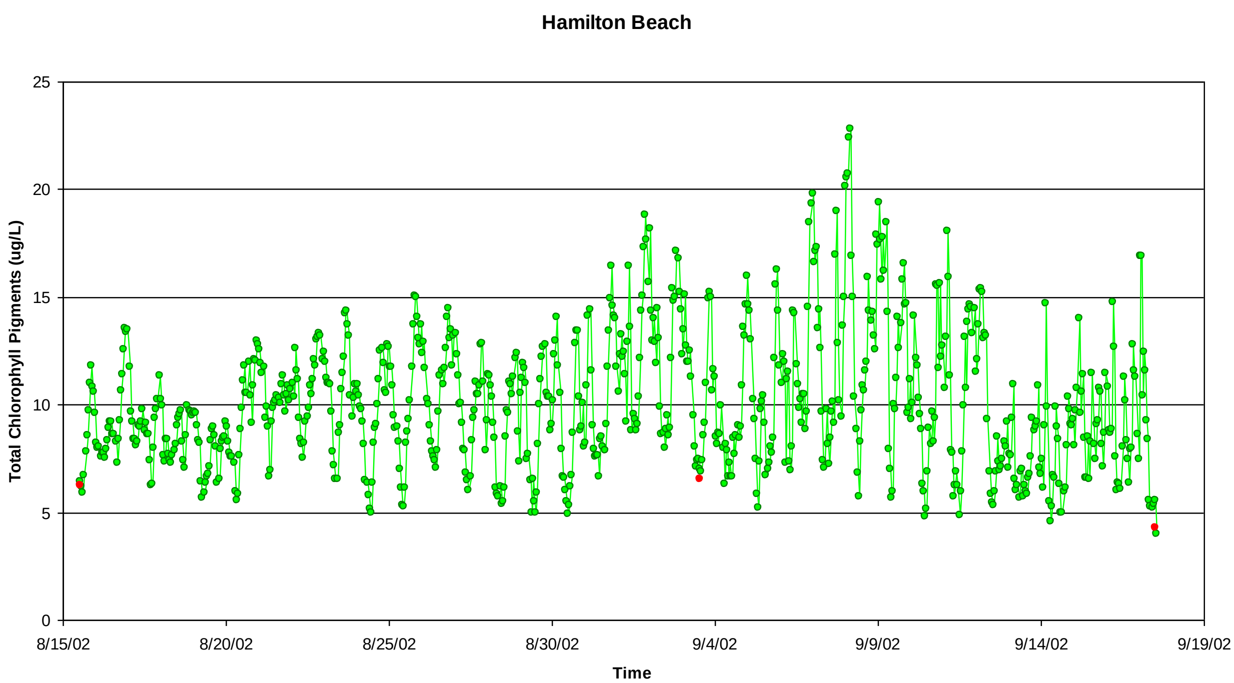


Figure VII-10. Bottom water record of Chlorophyll-*a* in Hamilton Beach station, Summer 2002. Calibration samples represented as red dots.

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

Massachusetts Estuaries Project Town of Wareham: 2002	Dissolved Oxygen: Continuous Record, Summer 2002				
	Deployment Days	< 6 mg/L (% of days)	< 5 mg/L (% of days)	< 4 mg/L (% of days)	< 3 mg/L (% of days)
Agawam River	33.9	24%	9%	1%	0%
Wareham Narrows	39.1	13%	2%	0%	0%
Broad Marsh River	33.8	16%	2%	0%	0%
Hamilton Beach	33.0	17%	0%	0%	0%

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data was conducted for the Wareham River Embayment System by the DEP Eelgrass Mapping Program as part of the MEP technical effort. Field surveys were conducted in 1995 and 2001 by MassDEP, as part of this program, with additional observations during summer and fall 2002 by the MEP Technical Team. Analysis of available high resolution aerial photos from 1951 was conducted to reconstruct the eelgrass distribution prior to any substantial development of the watershed. In addition the MEP Technical Team has incorporated an additional survey of the Wareham River System (Costa 1988) based upon aerial photography (1971, 1974, 1975, 1981) and field surveys (1985, 1986). This data provides a field validated 1985 benchmark, greatly enhancing assessment of temporal changes in eelgrass throughout the Wareham River Embayment System. The primary use of the eelgrass data is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 (Figure VII-11 and 12) and 1985; the 1985 to 2001 period being the time in which watershed nitrogen loading significantly increased to its present level. This temporal information can be used to determine the stability of the eelgrass community.

At present, eelgrass is present within only a very small portion of the Wareham River System. Only 2 decades ago, eelgrass was found throughout much of the Wareham River basin, from Pinehurst Beach to south of Long Beach Point. Based on the 2001 eelgrass survey conducted by the DEP Eelgrass Mapping Program the remaining eelgrass is limited to a small area just down gradient of The Narrows, where the estuarine reaches of the Agawam and Wankinco Rivers enter the Wareham River basin. In addition, to the DEP mapping, this distribution has been confirmed by the multiple MEP staff conducting the infaunal and sediment sampling and the mooring studies. The decline of eelgrass beds relative to historical distributions is expected given the high chlorophyll a and low dissolved oxygen levels and water column nitrogen concentrations within this system.

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

Embayment System	**Start Date**	**End Date**	**Total Deployment (Days)**	**> 5 ug/L Duration (Days)**	**> 10 ug/L Duration (Days)**	**> 15 ug/L Duration (Days)**	**> 20 ug/L Duration (Days)**	**> 25 ug/L Duration (Days)**
Agawam/Wareham River								
Agawam River	8/14/2002	9/17/2002	33.9	92%	81%	67%	55%	48%
		Mean		0.80	0.42	0.24	0.19	0.17
		S.D.		1.05	0.59	0.19	0.16	0.14
Wareham Narrows	8/16/2002	9/24/2002	39.1	79%	42%	18%	8%	3%
		Mean		6.15	0.28	0.17	0.10	0.08
		S.D.		5.55	0.23	0.12	0.07	0.05
Broad Marsh River	8/14/2002	9/17/2002	33.8	65%	11%	0%	0%	0%
		Mean		0.39	0.09	0.04	N/A	N/A
		S.D.		0.49	0.07	N/A	N/A	N/A
Hamilton Beach	8/15/2002	9/17/2002	33.0	99%	45%	7%	1%	0%
		Mean		3.62	0.26	0.11	0.21	N/A
		S.D.		3.89	0.21	0.09	N/A	N/A

The eelgrass surveys indicated that eelgrass habitat within this estuary is limited to the Wareham River and Marks Cove Basins, with potential limited areas at the mouths of the Broad Marsh River and Crooked River sub-basins. There is no evidence that eelgrass has colonized either the Wankinco or Agawam River sub-basins (i.e. north of The Narrows). The 1985 survey data indicated eelgrass beds colonizing most of the lower Wareham River basin (south of Pinehurst Beach). The beds appeared to be restricted to the margins of the basin and were not observed in the deeper channel which runs from Cromset Point to The Narrows. Larger beds were found in the lower sub-basins of Marks Cove and south of Long Beach. This depth distribution is similar to that observed in nearby Phinneys Harbor, where within the 1951-1985 time-frame, eelgrass appears to have colonized most of the basin to depths of ~2 meters, but not the deeper waters of the basin.

The presence of eelgrass in the upper region of the Wareham River (southeast of the Narrows) in the recent surveys suggests that coverage in this region of the Wareham River was likely greater in the 1950's. However, the sparse eelgrass in this basin in the 1985 survey and the distribution in the lower basin suggests that eelgrass in this upper basin would likely have been restricted to the shallow margins.

The temporal surveys also indicate that eelgrass habitat loss within the Wareham River Embayment System is a relatively recent phenomenon. The decline of eelgrass beds appears to have occurred primarily between 1985 and 1995 and continued to 2001. The current absence of eelgrass throughout virtually all of the Wareham River is consistent with the depth of the basin and the chlorophyll levels measured by the BayWatcher Program >10 ug/L and the basin-wide total nitrogen levels >0.44 mg N/L (higher than the 0.35 threshold for eelgrass in nearby West Falmouth Harbor). The timing of the eelgrass habitat loss is also consistent with changes in land-use within the watershed. In addition, the spatial pattern of bed loss is consistent with the typical pattern of habitat decline related to increasing nitrogen loading from a watershed. The pattern is for highest nitrogen levels to be found within the innermost basins, with concentrations declining as one moves toward the tidal inlet. This pattern is also observed in nutrient related habitat quality parameters, like phytoplankton, turbidity, oxygen depletion, etc. The consequence is that eelgrass bed decline typically follows a pattern of loss in the innermost basins (and sometimes also from the deeper waters of other basins) first. The temporal pattern is a “retreat” of beds toward the region of the tidal inlet. This appears to be the pattern of retreat observed within the Wareham River System. Although some regions presently support healthy infaunal habitat (tolerant of higher levels of enrichment), it appears to have become sufficiently nutrient enriched to impair its eelgrass habitat. However, it is likely that if nitrogen loading were to decrease that eelgrass could first be restored in the lower portion of the main basin and with further reductions, be restored to the 1985 pattern.

It is significant that there is no record of significant eelgrass in the Wankinco and Agawam River tidal sub-basins. It is likely that these areas may not be supportive of eelgrass habitat due to the structure of these water bodies and the low salinities in their upper reaches. Much of this region of the Wareham River System is more of a tidal river with extensive fringing salt marsh. As a result of the discharge from the extensive up-gradient watershed and the estuarine wetlands, these basins would not be expected to support significant eelgrass habitat (no anthropogenic loading analysis, Chapter VI). Therefore, nutrient management related to these upper basins should focus on infaunal animal habitat, rather than eelgrass habitat.

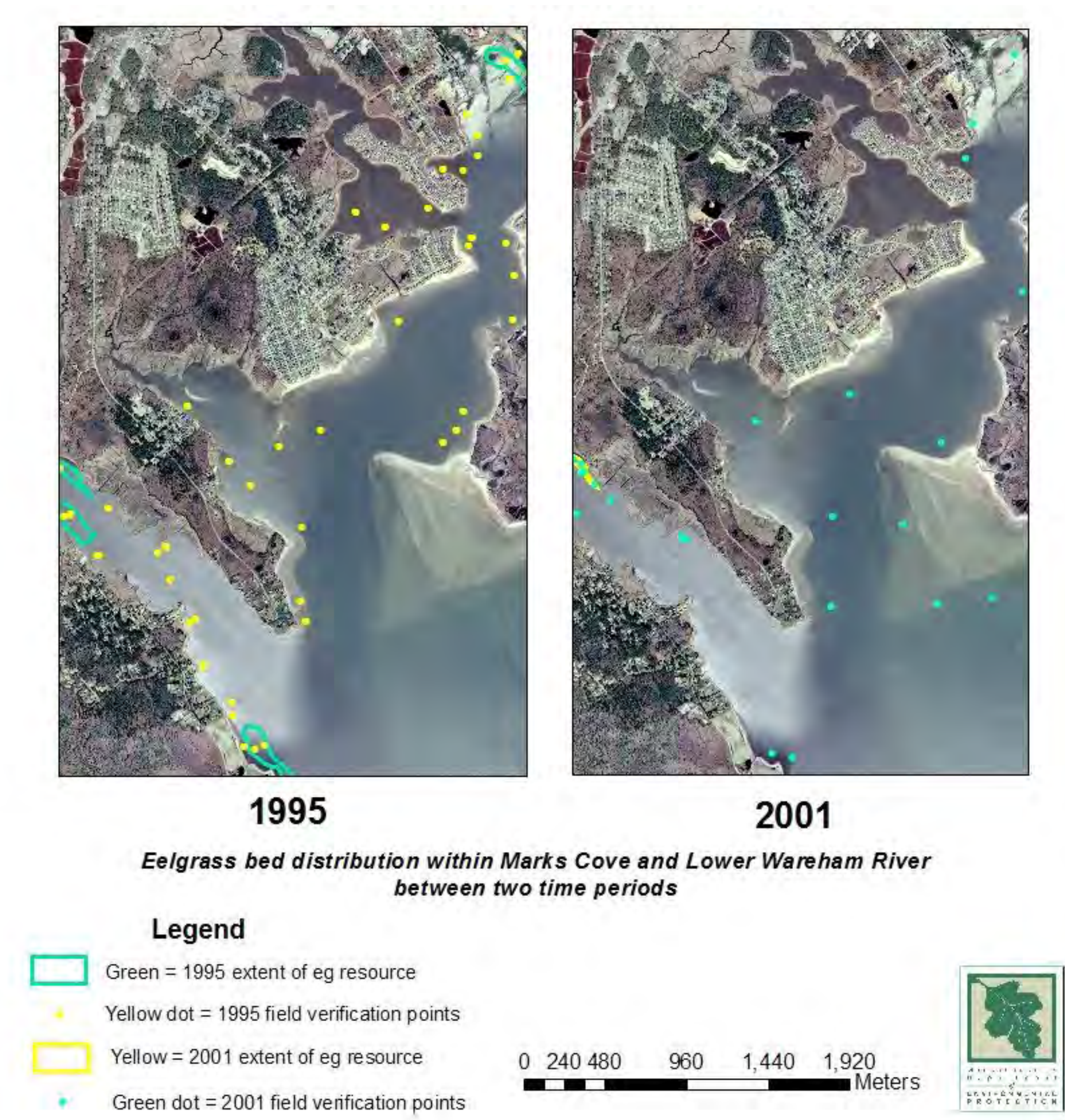


Figure VII-11. Eelgrass bed distribution within the Wareham/Agawam River System. The 1995 coverage is depicted by the green outline inside of which circumscribes the eelgrass beds. The yellow (2001) areas were mapped by DEP. The is no record of eelgrass beds in the Wankinco and Agawam River Sub-Basins. All data was provided by the DEP Eelgrass Mapping Program.

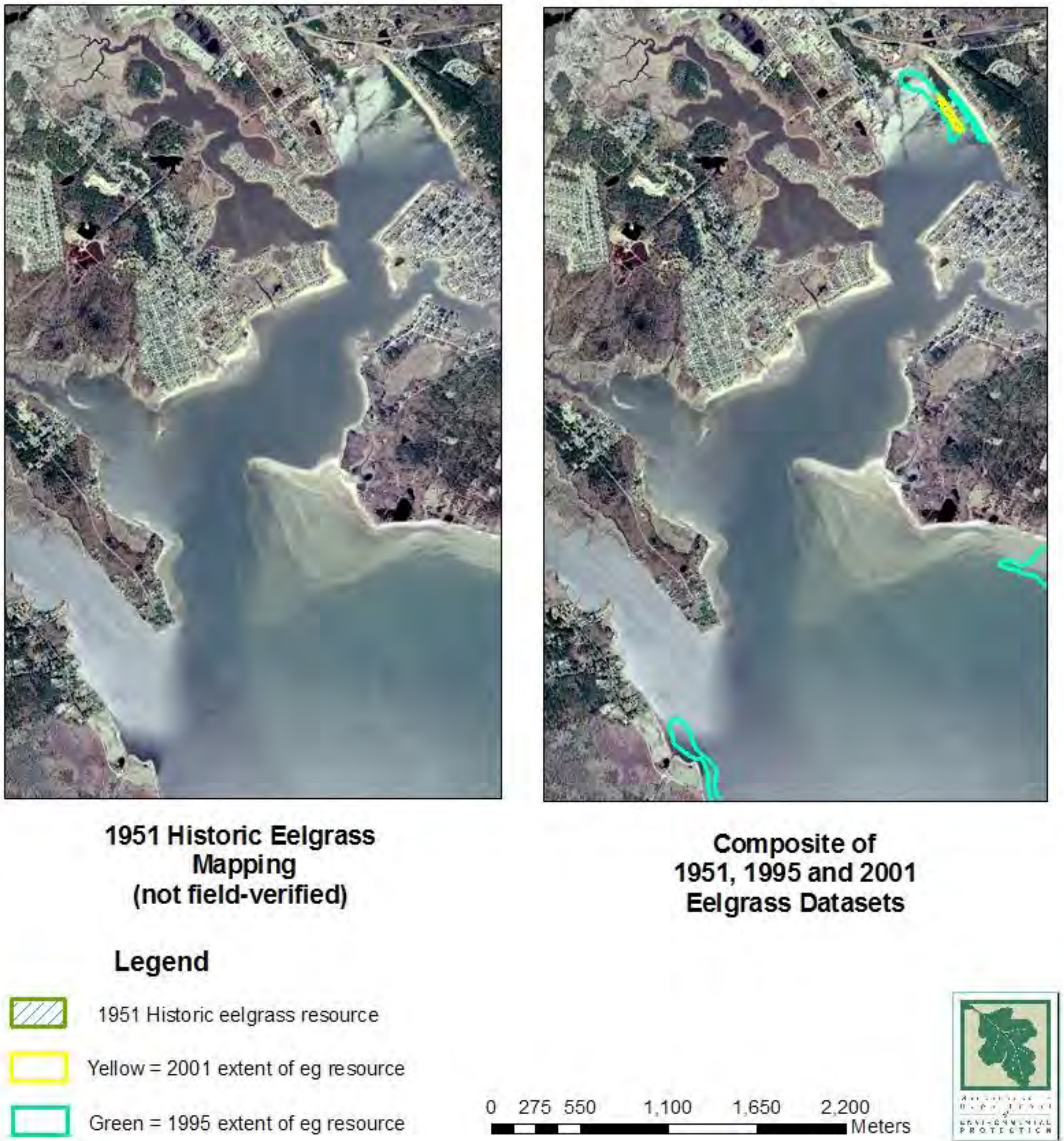


Figure VII-12. Eelgrass bed distribution within the Wareham River Embayment System. In the composite photograph, coverage as depicted by the light green outline shows the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. Coverage data for 1951 is unavailable for this system. The 1995 and 2001 areas were mapped by DEP. The is no record of eelgrass within the Wankinco and Agawam River sub-basins. All data was provided by the DEP Eelgrass Mapping Program.

Other factors which influence eelgrass bed loss in embayments may also be at play in the Wareham River Embayment System, though the loss seems completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, as the region of documented eelgrass loss, generally supports a low density of boat moorings, although there are a number of moorings within the system overall. Similarly, pier construction and boating pressure may be adding additional stress but seem to be relatively minor factors in the overall system. It is not possible at this time to determine the potential effect of shell fishing on eelgrass bed distribution, although it is mediated by periodic closures in some of the shallower areas.

Based on the available data, it is possible to make a conservative estimate of the extent of eelgrass habitat that can be recovered through watershed nitrogen management. Eelgrass coverage in 1951 is typically used by the MEP, as the benchmark for recovery from nitrogen enrichment, since watershed nitrogen loading to most of the regions estuaries was relatively low until recent decades. Unfortunately, the 1951 data is unavailable for this system (C. Costello, MassDEP). However, the 1985 eelgrass survey data shows eelgrass coverage throughout much of the potential eelgrass habitat within the Wareham River Basin (from the mouth of Broad Marsh River to south of Long Beach Point and within Marks Cove). Although significant eelgrass beds have not been mapped within the upper Wareham River Basin, from Pinehurst Beach to the Narrows, eelgrass has been observed in multiple surveys, including recently by the MEP Technical Team. The persistence of an eelgrass bed within the upper basin to the southeast of the entrance to the Narrows, suggests a greater coverage in this region at one time. Based upon the 1995 and 1985 coverage data, it appears that a conservative estimate of the amount of eelgrass habitat that would be restored if nitrogen management alternatives were implemented would be a minimum of three acres (relative to 1995 acreage calculations) and possibly more if one were to try and attain the acreages that existed as far back as the mid-1980's. Note that restoration of this habitat will necessarily result in lower nitrogen levels in Broad Marsh River and Crooked River, as well (see Chapter VIII). Based upon the documented eelgrass coverage in the lower basin of the Wareham River sub-embayment (Barneys Point to Marks Cove) and the shallow marginal bed in the upper Wareham River sub-embayment (south of The Narrows), these basins are classified as significantly impaired (SI) and moderately impaired (MI) for eelgrass habitat. This classification follows the concept that loss of eelgrass, but still some remaining coverage, is less impaired than total loss of eelgrass from a basin. The difference between the basins most likely stems from the basin depth and configuration as it influences response of eelgrass to nutrient enrichment.

The relative pattern of these data is consistent with the results of the benthic infauna analysis and the observed eelgrass loss is typical of nutrient enriched shallow embayments (see below).

Table VII-3. Changes in eelgrass coverage in the Wareham River Embayment System within the Town of Wareham as mapped by MassDEP (C. Costello).

EMBAYMENT	1951 (acres)	1995 (acres)	2001 (acres)	% Difference (1995 to 2001)
Wareham River / Agawam River Mark's Cove / Broad Marsh	Unmapped (imagery unsuitable for mapping)	11.23	8.13	28%
That the 1951 time point remain unmapped does not indicate that there was no eelgrass for that period.				

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 16 locations throughout the Wareham River Embayment System (Figure VII-13). In almost all cases multiple assays were conducted at each site. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the loss of eelgrass beds, the Wareham River System is clearly impaired by nutrient overloading. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). Areas of the Wareham River Embayment System do not contain documented eelgrass habitat (Broad Marsh River, Agawam and Wankinco River estuarine reaches) and as such, management is focused upon infaunal habitat quality in these basins. This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

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

Benthic animal communities were surveyed throughout the Wareham River Estuary in fall 2007. Samples were collected by Young modified Van Veen Grab, immediately sieved on site and preserved for later sorting and analysis. Samples are collected in the fall to gage the effects of any summertime low oxygen events or elevated organic matter loading that may have occurred associated with nitrogen enrichment.

The Infauna Study indicated that most areas, with the exception of the uppermost stations in the Agawam River estuarine reach are presently supporting healthy to moderately impaired habitat for infaunal animal communities (Table VII-4). The habitat quality of the uppermost reach of the Agawam River Estuary is somewhat uncertain, as it contains fresh/brackish water invertebrates and appears to be transitional between fresh and estuarine habitat. The stress indicator species present included *Cyathura polita,* which is tolerant of the stress associated with widely varying changing salinity, such as occurs between low tide when the upper-most reach is dominated by freshwater and high tide when it is dominated by saline flood waters (this specie was found in similar environment in the Mashpee River, Popponesset Bay). However, given the low numbers of species and individuals in this estuarine reach, it appears to be presently supporting a moderately impaired benthic habitat.

The remaining basins are all clearly estuarine. The lower Agawam River/Wankinco River estuarine reaches and confluence have infaunal communities consistent with a wetland influenced organic matter enriched estuarine sediment. In contrast to the uppermost estuarine reach of the Agawam River, the communities showed a relatively high number of species (22-28) and individuals (177-538), with diversity indices generally $\geq$ 3, although organic enrichment species were generally dominant (*Mediomastus, Streblospio*, various amphipods). The high number of species and diversity in these areas indicate a moderate and in some cases high quality benthic habitat, with the presence of organic tolerant species. However, this habitat appears to have significantly improved due to the lowering of "local" loading from the Wareham WWTF which saw a 62% reduction in nitrogen discharge after the 2005 upgrade.

The upper basin of the Wareham River showed a clear difference from the entrance to The Narrows (moderately impaired compared to its lower portion which showed high quality benthic habitat). This gradient is consistent with the oxygen gradient and the likely transport of lower quality waters from the Agawam/Wankinco basin on the ebbing tides. The lower basin of the Wareham River showed moderate to high numbers of individuals, with high diversity composed of polychaetes, crustaceans and mollusks, indicative of a high quality habitat. This was also the case for associated sites in Crooked River and lower Broad Marsh River. This is to be expected as the lower reaches of both tributary areas have similar sediments, oxygen and nutrient levels. The mid region of the Wareham River, while transitional between upper and lower reaches, generally supported high numbers of species and individuals, consistent with its oxygen status and higher watercolumn nutrients and organic matter (hence high quality to moderate impairment). Upper Broad Marsh showed infaunal communities consistent with a salt marsh basin, with moderate numbers of species and individuals, and species indicative of an organic rich environment, but not contamination (i.e. not Capitella). Head down deposit feeders were observed at these sites with mollusks and crustaceans.

Overall, the infaunal habitat quality was consistent with the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in this system. Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to whether a basin area is wetland dominated or tidal embayment dominated. Based upon this analysis it is clear that the upper regions of the Wareham River Embayment System are moderately impaired by nitrogen and organic matter enrichment, although the lower reaches are currently supporting high quality benthic animal habitat.

Figure VII-13. Aerial photograph of the Agawam / Wareham River system showing location of benthic infaunal sampling stations (red symbol).

Table VII-4. Benthic infaunal community data for the Wareham/Agawam River embayment system. Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m2). Stations refer to map in figure VII-9, (N) is the number of samples per site.

Location	Sta ID (N)	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Agawam and Wankinco Estuarine Reach						
Upper Agawam	Sta. 24 (2)	3	144	3	1.00	0.63
	Sta. 23 (2)	8	855	6	1.75	0.58
Lower Agawam	Sta. 22 (2)	12	126	10	2.15	0.62
	Sta. 21 (2)	26	290	19	3.55	0.76
Agawam &	Sta. 17 (2)	22	177	16	3.28	0.74
Wankinco Basin	Sta. 19 (2)	28	217	20	3.48	0.73
	Sta. 20 (2)	23	538	14	2.99	0.67
Broad Marsh River & Crooked River						
Upper BMR	Sta. 10 (1)	10	160	10	2.64	0.79
Lower BMR	Sta. 11 (1)	11	98	10	2.83	0.82
Lower CR	Sta. 9 (1)	23	177	11	2.41	0.53
Wareham River Central Basins						
Upper Basin	Sta. 16 (3)	22	155	18	3.43	0.77
Mid Basin	Sta. 8 (1)	27	253	14	2.95	0.62
Lower Basin	Sta. 4 (1)	32	574	11	1.99	0.40
	Sta. 5 (1)	24	284	12	2.28	0.50
Marks Cove						
Upper	Sta. 1 (2)	17	241	13	3.10	0.79
Lower	Sta. 2 (2)	26	428	12	2.32	0.50

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

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

The Wareham River Embayment System is a complex estuary composed of 3 functional types of component basins: an embayment (Wareham River-Marks Cove), a salt marsh pond/embayment (Broad Marsh River) and a tidal river with significant marginal wetlands (Agawam-Wankinco estuarine reaches). Each of these 3 functional components has different natural sensitivities to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of each system and their respective ability to support eelgrass beds and the types of infaunal communities that they support. At present, the Wareham River Embayment System is showing variations in nitrogen enrichment and habitat quality among its various component basins. In general the system is showing healthy to moderately impaired benthic habitat. However, the lower basins (e.g. lower Wareham River, Marks Cove) are clearly significantly impaired based on eelgrass criteria, as historical eelgrass beds have been lost and eelgrass is no longer present within these areas of the System. The upper Wareham River basin is moderately impaired based upon eelgrass criteria, as it still supports some eelgrass, but the prior beds have been reduced to sparse coverage at the basin's northeast margin.

Eelgrass: The present virtual absence of eelgrass throughout the Wareham River Embayment System is consistent with the observed nitrogen and the chlorophyll levels and functional basin types comprising this estuary. The upper estuarine reaches and most of the Broad Marsh River are strongly influenced by surrounding wetlands and do not typically support eelgrass habitat, due to their naturally nutrient enriched shallow waters and salt marsh function. However, basins like the Wareham River and Marks Cove (from The Narrows to Cromset Point and especially the lower basin of the Wareham River) typically do support eelgrass habitat under low to moderate nitrogen loading conditions. The distribution of eelgrass in 1985 is fully consistent with this functional analysis and the conclusion that the lower region of this Estuary (e.g. Barneys Point to Cromset Point), as well as the upper basin (The Narrows to Barneys Point) are currently over their nitrogen threshold level that supports healthy eelgrass habitat.

Analysis of the MassDEP mapped eelgrass beds which have persisted just outside of the tidal inlet in the large boundary basin between Cromset Point and Buzzards Bay (e.g. Bourne Point), supports the contention that the recent loss of eelgrass within the Wareham River is the result of nitrogen enrichment, as the well flushed outermost beds have been extremely stable over the past decades. These beds are at similar water depths and have the same tidal excursion as the historical bed areas within the lower estuary, so the major environmental differences between the sites appear to be directly related to nitrogen enrichment.

It appears from the eelgrass and water quality information that eelgrass beds within the lower basin of the Wareham River (inclusive of Marks Cove) and in the shallow margins of the upper basin should be the target for restoration and that this habitat should be recovered with appropriate nitrogen management. From the historical analysis, it appears that on the order of 3 acres of eelgrass habitat could be recovered, if nitrogen management alternatives were implemented. Note that restoration of this habitat will necessarily result in restoration of other resources throughout the Wareham River Embayment System. Since the Wareham River basins are influenced by waters ebbing from both the estuarine reaches of the Agawam and Wankinco Rivers, its nitrogen management will de facto result in a lowering of nitrogen levels throughout the estuarine system. As such, an improvement of infaunal habitats in the upper regions and in the Broad Marsh River, both of which have traditionally only supported infaunal habitat is expected. Based upon the above analysis, eelgrass habitat should be the primary nitrogen management goal for the Wareham River basins and infaunal habitat quality the management target for the upper reaches.

Water Quality: Overall, the oxygen levels within the major sub-basins to the Wareham River System are indicative of relatively healthy or only moderately impaired conditions, since the upper reaches are defined as infaunal habitats (e.g. historically have not supported eelgrass) and considering their physical structure and natural biogeochemical cycling. Similar to other embayments in southeastern Massachusetts, the upper estuarine reaches of the Agawam and Wankinco Rivers, Broad Marsh Cove and the Wareham River basins of the Wareham River Embayment System evaluated in this assessment showed high frequency variation, apparently related to diurnal and tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration at each mooring site, underscores the need for continuous monitoring within these systems.

Overall, the dissolved oxygen throughout the Wareham River Embayment System generally showed moderate depletions during the critical summer period. Oxygen depletions were generally associated with the wetland dominated tributary basins, with higher oxygen levels maintained in the main embayment basin. The continuous D.O. records indicate that the upper region of Wareham River Embayment System, defined by the Agawam River estuarine reach, shows periodic oxygen depletion during summer given its nitrogen and organic matter enrichment. It appears that the organic matter enrichment results in part from the system's role as a tidal river bordered by extensive wetlands and from in situ phytoplankton production supported by nitrogen inputs. Oxygen conditions and chlorophyll a levels tend to improve with decreasing distance to the tidal inlet. Oxygen levels in the region of The Narrows are influenced by outflows from the estuarine reaches of the Agawam and Wankinco Rivers, but only rarely showed oxygen depletions to <5 mg L^{-1}, while the lower Wareham River consistently maintained oxygen levels of >5 mg L^{-1}. The lower basin of the Broad Marsh River also supported oxygen levels >5 mg L^{-1}, except for brief excursions slightly below 5 mg L^{-1}. The Broad Marsh River record is from the lower basin of this sub-embayment, as the upper basin is dominated by extensive tidal salt marshes and is naturally nutrient and organic matter enriched. The pattern of oxygen excursions was consistent with the observed chlorophyll a levels. Chlorophyll levels showed a parallel gradient to dissolved oxygen, decreasing through the estuary from the head waters toward the tidal inlet to Buzzards Bay.

Sub-basins with significant wetland areas typically show oxygen depletions during the warmer summer months, as part of their functioning as nitrogen and organic matter rich systems. The Agawam River showed oxygen declines to ca. 4 mg L^{-1} and the greatest depletion within the estuarine complex. This is consistent with its function as primarily a tidal river with significant bordering wetland area. The low oxygen levels are also consistent with a salt marsh tidal creek, where the organic matter enriched sediments support high levels of oxygen uptake at night and deplete the overlying waters. While oxygen depletion to 4 mg/L would indicate impairment in an embayment like the Wareham River sub-basin, it is consistent with the organically enriched nature of tidal creeks. These observations are typical of other tidal creeks and rivers assessed by the MEP, such as the nearby Back River (Bourne, MA), where periodic oxygen depletions to 3 mg L-1 were measured in a functioning healthy wetland river system.

Overall, oxygen depletion within the embayment system followed the spatial pattern of chlorophyll a (phytoplankton biomass). This pattern of higher oxygen and lower chlorophyll from the headwaters to the tidal inlet parallels the gradient in total nitrogen (TN), as recorded by the water quality monitoring effort. The upper estuarine reaches support nitrogen levels approaching 0.7 mg TN L^{-1}, which is indicative of a nitrogen enriched system and one that should support the observed phytoplankton blooms and oxygen depletion. The upper basin of the Wareham River shows significantly lower TN levels, ca. 0.50-0.55 mg TN L^{-1}, consistent with the loss of eelgrass and the moderately impaired infaunal habitat. Broad Marsh River, with its extensive wetland, but limited chlorophyll levels and modest oxygen depletion also has TN levels generally ca. 0.55 mg TN L^{-1}. The gradient in nitrogen through the lower basin of the Wareham River and Marks Cove of 0.55 to 0.44 is completely consistent with the observed limited oxygen depletion and only recent loss of eelgrass and high quality infaunal habitat. In other similarly structured embayments in southeastern Massachusetts, TN levels below 0.5 mg TN L^{-1}, have been repeatedly found to support high quality infaunal habitats, as seen in the present assessment.

Infaunal Communities: The infaunal study indicated an overall system generally supportive of healthy to moderately impaired infaunal habitat relative to the ecosystem types represented (i.e. embayment versus salt marsh creek/pond).

The Lower Basin of the Wareham River supports healthy infaunal animal habitat for a coastal embayment in southeastern Massachusetts. This basin supports moderate numbers of individuals (100-300) and species (ca. 20/sample), with very high diversity (H = 3.2-3.7) and Eveness (>0.75).

The Infauna Study indicated that most areas, with the exception of the uppermost stations in the Agawam River estuarine reach are presently supporting healthy to moderately impaired habitat for infaunal animal communities. The habitat quality of the uppermost reach of the Agawam River Estuary is uncertain, as it contains fresh/brackish water invertebrates and appears to be transitional between fresh and estuarine habitat. The stress indicator species present included *Cyathura polita,* which is tolerant of the salinity stress and helps to define this as a wetland influenced sub-basin. The low species numbers and moderate density of individuals with low diversity and eveness indicated a stressful environment, but the cause nutrient enrichment versus salinity versus wetland influences could not be differentiated.

Of the remaining clearly estuarine basins, the lower Agawam River estuary supported infaunal communities consistent with a wetland dominated, organic matter enriched estuarine sediment, with moderate to high numbers of individuals and a moderate number of species, hence moderate diversity and eveness. An oyster reef was encountered in the lowermost reach. These characteristics are typical of a healthy to moderately impaired condition. In contrast, the Wankinco/Agawam basin and the down-gradient region of the upper Wareham River (basin south of The Narrows) show clear impairment of their communities as assessed by numbers, diversity and eveness and as such are classified as significantly to moderately impaired. The upper basin of the Wareham River showed a clear difference from the entrance to The Narrows (Significantly Impaired) compared to its lower portion (Moderately Impaired). This gradient is consistent with the observed oxygen gradient and the likely transport of low quality water from the Agawam/Wankinco basin on the ebbing tides. The lower basin of the Wareham River showed moderate to high numbers of individuals, with high diversity composed of polychaetes, crustaceans and mollusks, all of which are indicative of a high quality habitat (consistent with its watercolumn TN of <0.5 mg L^{-1}). This was also the case for associated sites in Crooked River and the lower basin of Broad Marsh River. These regions generally had similar sediments, oxygen and nutrient levels. The northern portion of the lower basin (or southern portion of the upper basin), showed reduced numbers of species, diversity and eveness, consistent with its oxygen status and higher watercolumn nutrients and organic matter, hence the designation of moderate impairment (as discussed above). Upper Broad Marsh showed infaunal communities consistent with a salt marsh basin, with moderate numbers of species and individuals, and species indicative of an organic rich environment, but not contamination (i.e. not Capitella). Head down deposit feeders were observed at these sites with mollusks and crustaceans indicative of a healthy salt marsh environment.

The overall results indicate a system generally supportive of high quality to moderately impaired infaunal community habitat, relative to each of the 3 component functional basin types comprising the Wareham River Embayment System, each with its different sensitivity to nitrogen enrichment and organic matter loading. The infaunal habitat quality within the Wareham River-Marks Cove ranges from high quality near Long Beach to moderately impaired near the mouth of Broad Marsh River and within the upper Wareham River Basin. The upper basin of Broad Marsh River is supportive of high quality infaunal habitat based upon its salt marsh structure. Similarly, the Agawam and Wankinco River estuarine regions showed a range of high quality to moderately impaired habitat quality, with the exception of the upper Agawam River reach which clearly indicated poor benthic habitat. However, as this upper reach contained freshwater tolerant invertebrates, it is likely that at least a portion of the "stress" results from the nearly freshwater overlying the sediments at low tide and ranging to estuarine waters at high tide. Variations in infaunal habitat quality paralleled variations in oxygen depletion, organic matter enrichment, chlorophyll and watercolumn TN, consistent with nutrient enrichment being the primary driver in determining habitat quality within this estuary.

Although there are some moderately impaired infaunal habitats in this system, restoration needs to also target eelgrass habitat. While the lower basins (e.g. lower Wareham River, Marks Cove) show high quality infauna habitat, they are clearly significantly impaired based on eelgrass criteria, since historical eelgrass beds have been recently lost. Similarly, the upper Wareham River basin is moderately impaired based upon eelgrass criteria, as it still supports some eelgrass, but the prior beds have been reduced to sparse coverage. As a result, both eelgrass and infaunal animal habitats are impaired in this estuary, and nitrogen management is required for their restoration.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Wareham River Embayment System, a sub-embayment to Buzzards Bay within the Town of Wareham, MA, based upon assessment data presented in Chapter VII. The upper estuarine reach is primarily a tidal river with significant wetlands, while upper Broad Marsh River operates as a salt marsh pond. The main reach of the Wareham River (from The Narrows to Cromset Point, inclusive of Marks Cove) is comprised of typical sub-embayment basins.

Health Indicator	Wareham River Embayment System						
	Wareham River Reach			Agawam River		Agawam-Wankinco	Broad Marsh River
	Upper	Lower	Marks Cove	Upper	Lower		
Dissolved Oxygen	H-MI[3]	H-MI[3]	H-MI[4]	--	H-MI[1]	MI[3]	H-MI[2]
Chlorophyll	MI[6]	--[13]	--[13]	MI-SI[6]	MI-SI[6]	MI-SI[6]	H[5]
Macroalgae	--[7]	--[7]	--[7]	--[7]	MI[8]	MI[8]	H[9]
Eelgrass	MI[10]	SI[12]	SI[12]	--[11]	--[11]	--[11]	--[11]
Infaunal Animals	MI-SI[16]	H-MI[17]	--[13]	--[19]	H-MI[16,18]	MI-SI[14]	H-MI[15]
Overall:	**MI[9]**	**SI[11]**	**SI[11]**	**MI**	**MI**	**MI**	**H-MI**

1 – salt marsh tidal creek, periodic oxygen depletions to 4-5 mg/L, rarely <4 mg/L.
2 – salt marsh basin oxygen depletions periodically to 5 mg/L., generally >6 mg/L.
3 – embayment basin periodically to 5-6 mg/L, rarely <5 mg/L generally >6 mg/L.
4 -- BayWatcher grab samples, periodically 5-6 mg L, rarely 4.5-5 mg/L, generally >6 mg/L.
5 – chlorophyll a levels <12 ug/L, but generally daily averages of 7 ug/L or less.
6 – elevated chlorophyll levels, mean >25 ug/L.
7 – very sparse or absence of drift algae, no surficial microphyte mat
8-- drift algae, primarily Ulva and filamentous red.
9 -- no drift algae, small patches of Codium in lower basin.
10 -- moderate impairment (MI): eelgrass present, but marginal bed declining 1985-2001
11-- no evidence this basin is supportive of eelgrass.
12-- significant impairment (SI): historical eelgrass beds were lost between 1985-2001.
13 -- insufficient data.
14 -- Infauna: low numbers of individuals, low-moderate species, organic enrichment indicator species typical of salt marshes.
15 -- Infauna: moderate numbers of individuals, high-moderate species, organic enrichment indicator species typical of salt marshes.
16 -- moderate-high numbers of individuals and moderate species, moderate diversity and Eveness; organic enrichment indicator species typical of salt marshes.
17 -- high numbers of species and moderate numbers of individuals. High diversity and eveness; with polychaetes, mollusks and crustaceans
18 -- oyster reef at lower reach, Sta. 20, not counted in grab sample.
19 -- samples contain mixture of fresh/brackish and estuarine species

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

VIII.2. THRESHOLD NITROGEN CONCENTRATIONS

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

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

The Wareham River Embayment System is presently supportive of infaunal habitat throughout its 3 component basin types. However, there is a moderate impairment of infauna habitat within the upper and middle regions of the Wareham River, lower basin of Broad Marsh River, and within portions of the Wankinco and Agawam River estuarine reaches, thus requiring nitrogen management for restoration. However, the primary habitat issue within the Wareham River Embayment System relates to the loss of eelgrass from the lower estuary, specifically from the mouth of the Broad Marsh River to Cromset Pond. This loss of eelgrass classifies these areas as "significantly impaired", although they presently support healthy to moderately healthy infaunal communities. The impairment to both the infaunal habitat and the eelgrass habitat is supported by the variety of other indicators, oxygen depletion, chlorophyll, and TN levels, which justify the conclusion that the overall impairment of the system is the result of nitrogen enrichment, primarily from watershed nitrogen loading.

The present lack of eelgrass throughout the Wareham River System is consistent with the observed oxygen depletions in each basin and the chlorophyll levels and functional basin types comprising this estuary. The basins, like the margins of the upper Wareham River basin and the extent of the lower Wareham River basin and Marks Cove, typically do support eelgrass habitat in other embayments with low to moderate nitrogen levels. These basins supported eelgrass in the relatively recent 1985 analysis. The earlier presence of beds within the lower reaches of the Wareham River Embayment System is consistent with the lower nitrogen loading and the resultant higher sustained oxygen levels and lower chlorophyll levels (high light penetration) that should have existed 2-3 decades ago, Estimates suggest that the population density of Wareham doubled between 1960 and 1990 (WHRC 2007).

The eelgrass and water quality information supports the conclusion that eelgrass beds within the Wareham River lower basin should be the primary target for restoration of the Wareham River Embayment System and that restoration requires appropriate nitrogen management. From the historical analysis, it appears that on the order of 3 acres of eelgrass habitat could be recovered, if nitrogen management alternatives are implemented. Therefore, the sentinel station (WR-6) for the Wareham River Embayment System was selected based upon its location within the uppermost reach of documented established eelgrass coverage in this estuary, with only fringing beds in shallow waters north of this point. The sentinel station is within the Wareham River lower basin, near the mouth of Broad Marsh River and is a long-term BayWatcher Water Quality Monitoring station.

The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location within the lower reach of the Wareham River was determined to be 0.40 mg TN L^{-1} and 0.42 mg TN L^{-1} within the marginal regions (shallows) north of this region (adjacent to WR-5). Since water depth is important in determining the criteria for eelgrass restoration, as the same phytoplankton concentration that results in shading of eelgrass in deep water, will allow sufficient light to support eelgrass in shallow water, the shallower water at the upper basin site allowed for a higher TN level compared to the sentinel station. This secondary level to check restoration of marginal beds in lower reach of Wareham River (0.42 mg TN L^{-1}) is consistent with the analysis of restoration of fringing eelgrass beds in Great Pond (Falmouth), and analysis where eelgrass beds in deep waters could not be supported at a tidally averaged TN of 0.412 mg TN L^{-1} at depths of 2 m. Similarly prior MEP analysis in Bournes Pond indicated that tidally averaged TN levels of 0.42 mg TN L^{-1} excluded beds from all but the shallowest water. The MEP Technical Team cannot specify the exact extent of marginal beds to be restored in the upper deep basins. At tidally averaged TN levels of 0.42 mg TN L^{-1} the eelgrass habitat would be restricted to very shallow waters, while at 0.40 mg TN L^{-1} the eelgrass habitat should reach to 1-2 meters depth, based upon the data from regional systems. The sentinel station under present loading conditions supports a tidally corrected average concentration of 0.443 mg TN L^{-1}, so watershed nitrogen management will be required for restoration of the estuarine habitats within this system.

In addition to the primary nitrogen threshold at the sentinel station and secondary check associated with restoration of marginal eelgrass beds, the MEP establishes additional criteria, to ensure that all impaired regions are restored if the threshold at the sentinel station is achieved. These values merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station. Secondary criteria were established at two locations within the Wareham River System: a TN level of <0.5 mg N L^{-1} within the Agawam/Wankinco basin (measured at WR-1) and within Broad Marsh River (BMR-4) to ensure restoration of infaunal habitat throughout these sub-embayments.

Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fin fisher resources), benthic infaunal habitat quality must also be supported as a secondary condition. At present, in the regions with moderately impaired infaunal habitat within the Wareham River and lower Broad Marsh basins, there exists total nitrogen (TN) levels in the range of 0.535 - 0.600 mg N L^{-1}, while in the Agawam-Wankinco basin water column concentrations are ca. 0.66 mg TN L^{-1}. The observed moderate impairment at these sites is consistent with observations by the MEP Technical Team in other enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay). In tributary systems to Buzzards Bay, where certain basins are characterized as deep, enclosed, depositional environments, TN levels <0.5 mg N L^{-1} were found to be supportive of healthy infaunal habitat (e.g. Eel Pond in Bourne). These deep basins appeared to have healthy infaunal habitat at the slightly lower threshold level of 0.45 mg N L^{-1}. Similarly, the Centerville River system showed moderate impairment at tidally averaged TN levels of 0.526 mg N L^{-1} in Scudder Bay and at 0.543 mg TN L^{-1} in the middle reach of the Centerville River. Equally important, the high quality infaunal animal habitat areas within the Wareham River System existed at TN levels of 0.444-0.463 mg TN L^{-1}. Based upon these observations, the MEP Technical Team concluded that an upper limit of 0.50 mg N L-1 tidally averaged TN would support healthy infaunal habitat in this system.

It should be noted that these secondary criteria values were not used for setting nitrogen thresholds in this embayment system. These values merely provide a check on the acceptability of conditions within the tributary basins at the point that the threshold level is attained at the sentinel station. The results of the Linked Watershed-Embayment modeling are used to ascertain that when the nitrogen threshold is attained, TN levels in these regions are within the acceptable range. The goal is to achieve the nitrogen target at the sentinel location and restore eelgrass habitat throughout the lower Wareham River basin and infaunal habitat throughout the System.

It must be stressed that the nitrogen threshold for the Wareham River Embayment System is set at the sentinel location. The secondary criteria (infaunal habitat) should be met when the threshold is met at the sentinel station. These secondary criteria are not used for setting the nitrogen threshold, but serve as a "check". The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations are discussed in Section VIII.3, below.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Wareham River Embayment System. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel station chosen for Wareham River lower basin and at the secondary stations in the Wareham River upper basin (e.g. Agawam/Wankinco basin, Broad Marsh River lower basin). It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required a combined 79% removal of septic load (associated with direct groundwater discharge to the embayment) for the river watershed. In addition, the Wareham WWTF load was reduced to 4,300 kg/yr, from the present discharge of 6,761 kg/yr, to simulate further possible upgrades to the facility. In addition, the ongoing reduction in nitrogen load from the existing landfill (1214 kg yr^{-1}, attenuated) within the Wankinco River watershed is modeled to go to background as the groundwater flushes out. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-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 removal of septic loads depicted in Table VIII-2. For Example, removal of 90% of the septic load from the Broad Marsh River watershed results in a -48% reduction in total watershed nitrogen load. 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 Buzzards Bay, as discussed in Section VI.2.6.1.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, reductions in TN concentrations of typically greater than 10% is required in the system, between the main harbor basin and the marsh.

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

sub-embayment	present load (kg/day)	threshold (kg/day)	threshold % change
Broad Marsh	4.27	0.43	-90%
Marks Cove	1.60	0.80	-50%
Crab Cove	2.50	1.25	-50%
Crooked River	4.00	1.20	-70%
Wareham River lower	0.50	0.25	-50%
Wareham River Upper	18.14	1.81	-90%
Agawam River from Mill Pond	12.16	0.00	-100%
Wankinco River from Parker Mills Pond	4.68	3.27	30%
System Total	47.85	9.01	-79%

Table VIII-3. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer, CSOs and the WWTF) used for modeling of present and threshold loading scenarios of the Wareham River system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms. The threshold loads reflect improvement to the WWTF (Wareham River Upper) and reduction of Landfill Load (Wankinko River).

sub-embayment	present load (kg/day)	threshold (kg/day)	threshold % change
Broad Marsh	7.95	4.10	-48.4%
Marks Cove	4.87	4.07	-16.4%
Crab Cove	3.55	2.30	-35.2%
Crooked River	5.35	2.55	-52.3%
Wareham River lower	0.72	0.47	-34.7%
Wareham River Upper	42.19	19.12	-54.7%
Agawam River from Mill Pond	34.27	22.11	-35.5%
Wankinco River from Parker Mills Pond	30.59	25.85	-15.5%
System Total	129.48	80.58	-37.8%

Table VIII-4. **Threshold** scenario sub-embayment and surface water loads used for total nitrogen modeling of the Wareham River 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)
Broad Marsh	4.101	1.681	12.168
Marks Cove	4.073	0.959	2.407
Crab Cove	2.299	1.614	-0.097
Crooked River	2.551	0.333	-0.594
Wareham River lower	0.468	5.180	58.800
Wareham River Upper	19.121	1.803	-1.133
Agawam River from Mill Pond	22.112	-	-
Wankinco River from Parker Mills Pond	25.851	-	-
System Total	80.576	11.570	71.551

Table VIII-5. Comparison of model average total N concentrations from present loading and the **threshold scenario**, with percent change, for the Wareham River system. The primary sentinel threshold station is in bold print.				
Sub-Embayment	monitoring station (MEP ID)	present (mg/L)	threshold (mg/L)	% change
Marks Cove	MC-3	0.370	0.360	-2.7%
Marks Cove	MC-2	0.396	0.379	-4.2%
Marks Cove	MC-1	0.468	0.436	-6.7%
Lower Wareham River	WR-7	0.407	0.381	-6.4%
Lower Wareham River	**WR-6**	0.442	0.399	-9.7%
Upper Wareham River	WR-5	0.464	0.408	-12.0%
Upper Wareham River	WR-4	0.477	0.413	-13.4%
Upper Wareham River	WR-3	0.494	0.420	-15.1%
Upper Wareham River	WR-1,2	0.524	0.429	-18.2%
Lower Broad Marsh	BMR-5/6	0.479	0.422	-11.9%
Lower Broad Marsh	BMR-4	0.529	0.455	-14.1%
Upper Broad Marsh	BMR-3	0.603	0.502	-16.8%
Upper Broad Marsh	BMR-1	0.666	0.542	-18.7%
Lower Agawam River	AG-2	0.573	0.421	-26.5%
Mid Agawam River	AG-1	0.573	0.398	-30.5%

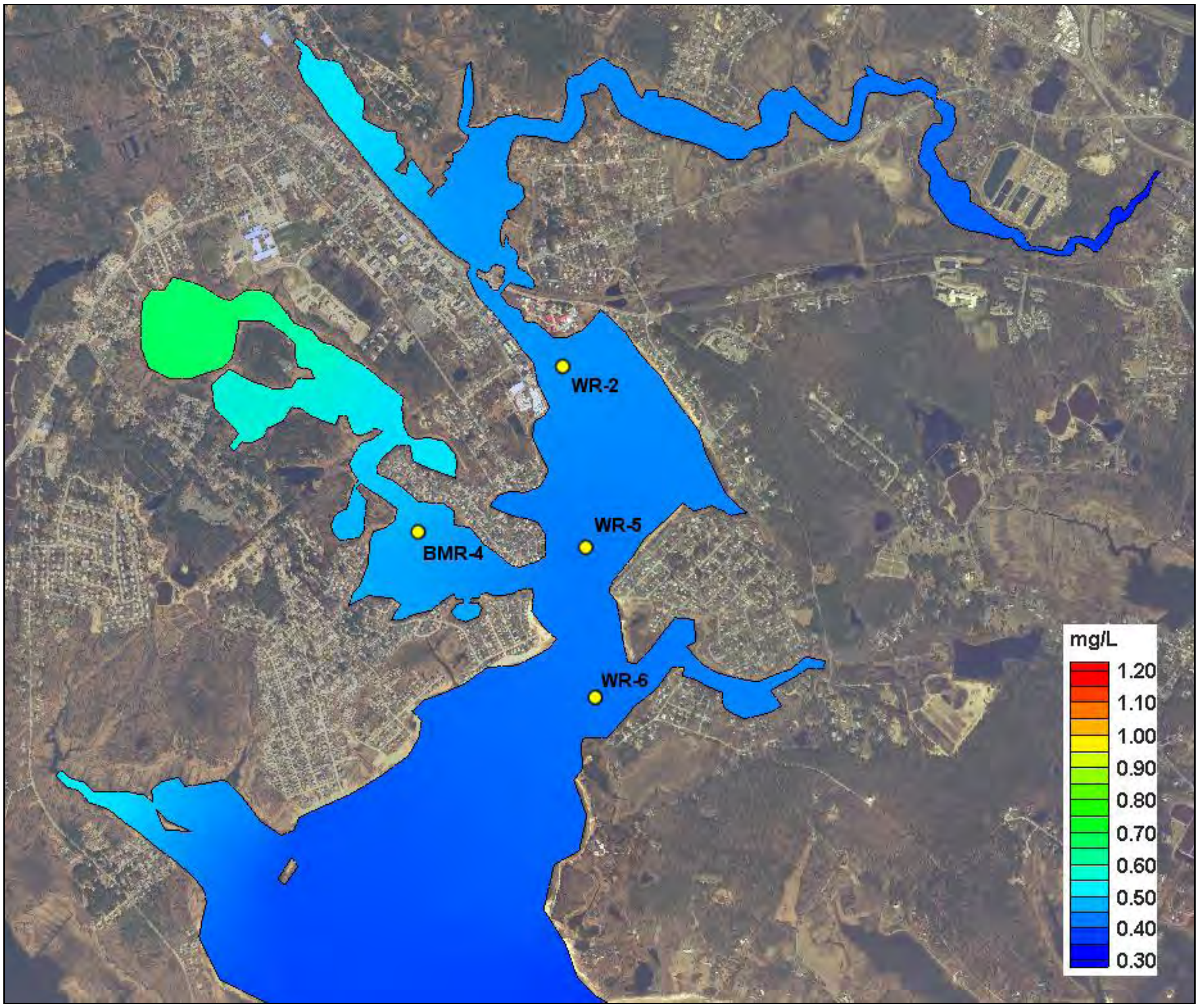


Figure VIII-1. Contour plot of modeled average total nitrogen concentrations (mg/L) in the Wareham River Embayment System, for threshold conditions of 0.40 mg/L at the sentinel station (WR-6), 0.42 mgTN/L at the secondary station (WR-5), and 0.50 mgTN/L at water quality monitoring stations average WR-2 and BMR-4. The sentinel station is at the uppermost the uppermost reach of documented established eelgrass coverage in this estuary, with only fringing beds in shallow waters north of this point

IX. REFERENCES

AFCEE (with Howes, B.L. & Jacobs Engineering). 2000. Ashumet Pond Trophic Health Technical Memorandum. AFCEE/MMR Installation Restoration Program, AFC-J23-35S18402-M17-0005, 210pp.

Aubrey Consulting Inc., 1996. Tidal Flushing within the East Bay/Centerville River Estuary: Existing Conditions and Effects of Proposed Dredging. Final Report, prepared for the Town of Barnstable, MA., 41 pp.

Beals and Thomas, Inc. October, 2012. Phase C2-Proposed Cranberry Bogs/Infrastructure Tihonet Mixed Use Development Project. Plymouth, Carver and Wareham, Massachusetts. Expanded Environmental Notification Form for ADM Development Services LLC. EEA No. 13940. Plymouth, MA.

Bent, G., Streamflow, Groundwater Recharge and Discharge, and Characteristics of Surficial Deposits in the Buzzards Bay Basin, Massachusetts: US Geological Survey Water Resources Investigations Report 95-4234.

Brawley, J.W., G. Collins, J.N. Kremer, C.-H. Sham, and I. Valiela. 2000. A time-dependent model of nitrogen loading to estuaries form coastal watersheds. Journal of Environmental Quality 29:1448-1461.

Brigham Young University, 1998. “User’s Manual, Surfacewater Modeling System.”

Burns, K., M. Ehrhardt, B. Howes and C. Taylor., 1993. Subtidal benthic community respiration and production rates near the heavily oiled coast of Saudi Arabia. Marine Pollution Bull. 27:199-205.

Buzzards Bay Project, Buzzards Bay Comprehensive Conservation and Management Plan (CCMP), US Environmental Protection Agency and Massachusetts Executive Office of Environmental Affairs, 1991. 234 p.

Buzzards Bay NEP National Estuary Program and the Coalition for Buzzards Bay, Report of the Buzzards Bay Citizens' Water Quality Monitoring Program 1992-1995.

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

CDM and Howes, B.L., 2000 Water Quality Evaluation of the Wareham River Estuary Complex. Final Report to the Town of Wareham. Camp, Dresser and McKee Inc. 300pp.

Camp Dresser and McKee, Inc. March, 2002. Town of Wareham, Massachusetts Comprehensive Wastewater Management Plan/Single Environmental Impact Report.

Costa, J. E. 1988a. Eelgrass in Buzzards Bay: Distribution, Production, and Historical Changes in Abundance. EPA 503/4/88-002 204 pp

Costa, J. E. 1988b. Distribution, production, and historical changes in abundance of eelgrass (Zostera marina L.) in Southeastern MA. Ph. D. Thesis, Boston University, 395 pp.

Cape Cod Commission, 1998. “Cape Cod Coastal Embayment Project.” Barnstable, MA.

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

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

Cape Cod Commission, 1998. Cape Cod Coastal Embayment Project: A Nitrogen Loading Analysis of Popponesset Bay. Cape Cod Commission Technical Report.

Cape Cod Commission. 1996. Regional Policy Plan. Cape Cod Commission, Barnstable, MA.

Cape Cod Commission. 2001. Regional Policy Plan. Cape Cod Commission, Barnstable, MA.

Costa, J.E., B.L. Howes, I. Valiela and A.E. Giblin. 1992. Monitoring nitrogen and indicators of nitrogen loading to support management action in Buzzards Bay. In: McKenzie et al. (eds.) Ecological Indicators, Chapter. 6, pp. 497-529.

Costa, J. E., B. Howes, and E. Gunn. 1996. Use of a geographic information system to estimate nitrogen loading to coastal watersheds. Buzzards Bay Project Technical Report. Draft, March 2, 1994, 21 p

Costa, J.E., G. Heufelder, S. Foss, N.P. Millham, B.L. Howes. 2002. Nitrogen Removal Efficiencies of Three Alternative Septic System Technologies and a Conventional Septic System. Environment Cape Cod 5(1): 15-24.

D’Elia, C.F, P.A. Steudler and N. Corwin. 1977. Determination of total nitrogen in aqueous samples using persulfate digestion. Limnology and Oceanography 22:760-764.

DeMoranville, C., Howes, B., Schlezinger, D. and White, D. 2009. Cranberry Phosphorous Management: How Changes in Practice can Reduce Output in Drainage Water. Acta Hort. (ISHS) 810:633-640

DeSimone, L.A. and B.L. Howes. 1996. Denitrification and nitrogen transport in a coastal aquifer receiving wastewater discharge. *Environmental Science and Technology* 30:1152-1162.

DeSimone, L.A. and B.L. Howes. 1998. Nitrogen Transport and Transformations in a shallow Aquifer Receiving Wastewater Discharge: A Mass Balance Approach. *Water Resources Research* Vol. 34, No. 2 271-285.

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

Eichner, E.M. and T.C. Cambareri, 1992. Technical Bulletin 91-001: Nitrogen Loading. Cape Cod Commission, Water Resources Office, Barnstable, MA. Available at:

http://www.capecodcommission.org/regulatory/NitrogenLoadTechbulletin.pdf

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

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

Eichner, E., B. Howes, and C. DeMoranville. 2012. White Island Pond Water Quality and Management Options Assessment. Completed for the Cape Cod Cranberry Growers Association. Coastal Systems Program, School of Marine Science and Technology, University of Massachusetts Dartmouth. 108 pp.

Fischer, H. B., List, J. E., Koh, R. C. Y., Imberger, J., and Brooks, N. H. (1979). *Mixing in inland and coastal waters*. Academic. San Diego.

FitzGerald, D.M., 1993. "Origin and Stability of Tidal Inlets in Massachusetts." In: Coastal and Estuarine Studies: Formation and Evolution of Multiple Tidal Inlets, Volume 29, Symposium on Hydrodynamics and Sediment Dynamics of Tidal Inlets (D. G. Aubrey and G.S. Geise, eds.). American Geophysical Union, Washington, D.C. pp. 1-61.

Frimpter, M. 1974 Groundwater management of Buzzards Bay coastal streams, Mass. and R.I. USGS Open-file Report (prepared for SENE Study).

Frimpter, M.H., J.J. Donohue, M.V. Rapacz. 1990. A mass-balance nitrate model for predicting the effects of land use on groundwater quality. U.S. Geological Survey Open File Report 88:493.

Griffith, G.E., Omernik, J.M., Bryce, S.A., Royte, J., Hoar, W.D., Homer, J.W., Keirstead, D., Metzler, K.J., and Hellyer, G., 2009, Ecoregions of New England (color poster with map, descriptive text, summary tables, and photographs): Reston, Virginia, U.S. Geological Survey (map scale 1:1,325,000).

Hansen, B.P., Lapham, W.W., Geohydrology and Simulated Ground-Water Flow in the Plymouth-Carver Aquifer, Southeastern Massachusetts USGS Water-Resources Investigations Report 90-4204, 1992. 69p, 30 fig, 28 tab, 2 pl, 53 ref.

Harbaugh, A.W. and McDonald, M.G., 1996. User's Documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model: U.S. Geological Survey Open-File Report 96-485, 56p.

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

Horsley Witten Group. 2009. Evaluation of Turfgrass Nitrogen Fertilizer Leaching Rates in Soils on Cape Cod, Massachusetts. Prepared for Brian Dudley, Department of Environmental Protection. Sandwich, MA.

Howes BL. 1998. Sediment metabolism within Massachusetts Bay and Boston Harbor relating to rates and controls of sediment-water column exchanges of nutrients and oxygen in 1997. Boston: Massachusetts Water Resources Authority. Report 1998-20. 80 p

Howes, B.L. and D.D. Goehringer. 1997. Falmouth's Coastal Salt Ponds. Falmouth Pondwatch Program, 1987-1996.

Howes, B.L., T. Williams, M. Rasmussen, 1999. Baywatchers II Nutrient related water quality of Buzzards Bay embayments: a synthesis of Baywatchers monitoring 1992-1998, pp. 126.

Howes, B.L., R.I. Samimy and B. Dudley, 2003. Massachusetts Estuaries Project, Site-Specific Nitrogen Thresholds for Southeastern Massachusetts Embayments: Critical Indicators Interim Report

Howes, B.L., J.S. Ramsey and S.W. Kelley, 2001. Nitrogen modeling to support watershed management: comparison of approaches and sensitivity analysis. Final Report to MA Department of Environmental Protection and USEPA, 94 pp. Published by MADEP.

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

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

Howes B.L., J. Ramsey, E.M. Eichner, R.I. Samimy, S. W. Kelley, D.R. Schlezinger (2005). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Oyster Pond System, Falmouth, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B.L., J. Ramsey, E.M. Eichner, R.I. Samimy, S. W. Kelley, D.R. Schlezinger (2005). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Three Bays System, Barnstable, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes, B.L. and J.M. Teal. 1995. Nitrogen balance in a Massachusetts cranberry bog and its relation to coastal eutrophication. Environmental Science and Technology 29:960-974.

Jorgensen, B.B. 1977. The sulfur cycle of a coastal marine sediment (Limfjorden, Denmark). Limnology Oceanography, 22:814-832.

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

Klump, J. and C. Martens. 1983. Benthic nitrogen regeneration. In: Nitrogen in the Marine Environment, (Carpenter & Capone, eds.). Academic Press.

Koppelman, L.E. (Ed.). 1978. The Long Island comprehensive waste treatment management plan. Vol II. Summary documentation report, Long Island Regional Planning Board, Hauppage, N.Y.

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

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

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

Massachusetts Department of Revenue. March, 2012. Property Type Classification Codes, Non-arm's Length Codes and Sales Report Spreadsheet Specifications. Prepared by the Bureau of Local Assessment. Division of Local Services. Boston, MA. http://www.mass.gov/dor/docs/dls/bla/classificationcodebook.pdf

MassGIS Data - Impervious Surface. February 2007. Available at: http://www.mass.gov/anf/research-and-tech/it-serv-and-support/application-serv/office-of-geographic-information-massgis/datalayers/impervioussurface.html

Masterson, J.P., C.S. Carlson, A.J. Massey, and D.A. Walter. 2009. Hydrogeology and simulation of ground-water flow in Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts. USGS Scientific Investigations Report 2009-5063. US Geological Survey, Marlborough, MA.

Masterson, J.P., Walter, D.A., Savoie, J., 1996, Use of particle tracking to improve numerical model calibration and to analyze ground-water flow and contaminant migration, Massachusetts Military Reservation, western Cape Cod, Massachusetts: U.S. Geological Survey Open-File Report 96-214, 50 p.

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

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

Murphy, J. and J.P. Reilly, 1962. A Modified Single Solution Method for the Determination of Phosphate in Natural Waters. Analytica Chemica Acta, v. 27, p. 31-36

Nelson, M.E., S.W. Horsley, T.C. Cambareri, M.D. Giggey and J.R. Pinnette. 1998. Predicting nitrogen concentrations in groundwater- An analytical model. Focus Conference on Eastern Groundwater Issues, National Water Well Association, Stamford, CT.

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

Natural Resources Conservation Service (NRCS). 1986. Urban Hydrology for Small Watersheds. Technical Release No. 55. USDA. Washington D.C.

Pollock, D.W., 1994. User's Guide to MODPATH/MODPATH_PLOT, version 3 – A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey modular three dimensional finite-difference ground-water-flow-model: U.S. Geological Survey Open-File Report 94-464, [variously paged].

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

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

Ramsey, J.S., B.L. Howes, N.P. Millham, and D. Bourne. 1995. Hydrodynamic and water quality study of West Falmouth Harbor, Falmouth MA. Aubrey Consulting Inc. Technical Report for Town of Falmouth, pp. 81.

Rhoads, D.C. and J.D. Germano. 1986. Interpreting long-term changes in benthic community structure: a new protocol. Hydrobiologia 142:291-308

Robertson, W.D., J.D. Cherry, and E.A. Sudicky. 1991. ³Ground-Water Contamination from Two Small Septic Systems on Sand Aquifers.² Ground Water. 29(1): 82-92.

Ryther, J.H., and W.M. Dunstan. 1971. Nitrogen, phosphorous and eutrophication in the coastal marine environment. Science, 171:1008-1012.

Scheiner, D. 1976. Determination of ammonia and Kjeldahl nitrogen by indophenol method. Water Resources 10: 31-36.

Smith, R.L., B.L. Howes and J.H. Duff. 1991. Denitrification in nitrate-contaminated groundwater: occurrence in steep vertical geochemical gradients. Geochimica Cosmochimica Acta 55:1815-1825.

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

Stone, B.D., J.D. Peper, 1982. Topographic Control of Deglaciation of Eastern Massachusetts: Ice Lobation and the Marine Incursion. In *Late Wisconsinan Glaciation of New England*. Pp. 145-166. Kendal/Hunt, Dubuque, Iowa.

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

US Army Corps of Engineers, Engineer Research and Development Center, Waterways Experiment Station, Coastal and Hydraulics Laboratory, Users Guide To RMA4 WES Version 4.5, June 05, 2001.

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

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

Weiskel, P.K. and B.L. Howes, 1991. Quantifying Dissolved Nitrogen Flux Through a Coastal Watershed. Water Resources Research, Volume 27, Number 11, Pages 2929-2939.

Weiskel, P.K. and B.L. Howes, 1992. Differential Transport of Sewage-Derived Nitrogen and Phosphorous through a Coastal Watershed. Environmental Science and Technology, Volume 26. Pages 352-360

Williams, J.R., G.D. Tasker, Water Resources of the Coastal Drainage Basins of Southeastern Massachusetts, Northwest Shore of Buzzards Bay: US Geological Survey Hydrologic Investigations Atlas HA-560.

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

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