Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for West Falmouth Harbor, Falmouth, Massachusetts

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Massachusetts Department of Environmental Protection
Environmental Protection

FINAL REPORT –May 2006

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I. INTRODUCTION

The West Falmouth Harbor embayment system is located within the Town of Falmouth, on Cape Cod Massachusetts. The system exchanges tidal water with Buzzards Bay through an inlet fixed with jetties on its western shore (Figure I-1). The watershed for this embayment system is also distributed fully within the Town of Falmouth. West Falmouth Harbor is one of the Town of Falmouth's significant marine resources. At a time when many other coastal ponds and bays in the Town have been degraded, water quality in West Falmouth Harbor has until recently remained fairly high, as pockets of eelgrass and healthy animal populations demonstrate. However, the West Falmouth Harbor System has been undergoing rapid degradation of its resources over the past decade as a result of nutrient overloading primarily from recent entry of the plume of treated wastewater emanating from the effluent disposal at the Town's Wastewater Treatment Facility. While the embayment was becoming impaired due to nitrogen loading associated with landuse shifts within its watershed prior to the entry of the wastewater effluent plume, nitrogen related habitat quality decline has rapidly accelerated with the nitrogen load from the plume which has more than doubled nitrogen loading to this estuary over a period of several years (Howes et al. 2000). West Falmouth Harbor is presently a moderately to highly nutrient enriched shallow coastal estuarine system. Nitrogen enters the system through both surface and groundwaters.

Landuses within the watershed are more complex than other of Falmouth's embayment systems, although on areal basis the Harbor watershed is predominantly residential landuses (roads, lawns, on-site septic systems). However, the Harbor's watershed also includes a variety of other nutrient sources, among them the Town's Wastewater Treatment Facility and discharge, the Town landfill, old septage lagoons, composting installations, and the Town's industrial park.

West Falmouth Harbor, historically called Chappaquoit Harbor, is an enclosed tidal system comprised of multiple basins with a mean depth at MLW of 0.6 meters. The Harbor was originally an open basin with an island, what is now Chappaquoit Point, marking the outer boundary with Buzzards Bay. Deposition of a sand spit enclosed the present Harbor. During this century, jetties were placed at the Harbor inlet, further enclosing the outer basin. The upper watershed to West Falmouth Harbor is somewhat geologically complex, being composed primarily of Falmouth Glacial Moraine. At present, West Falmouth Harbor is a tidal embayment with a groundwater fed stream discharging to its inner reaches (Mashapaquit Creek).

The Harbor supports both salt marsh and eelgrass communities. The largest areas of salt marsh are found surrounding Mashapaquit Creek and Oyster Pond, with narrow fringing marsh bordering much of the inner Harbor. Eelgrass beds are highly sensitive to nutrient overloading. Eelgrass beds within West Falmouth Harbor have historically filled most of the sub-tidal area. Recent concern over the Harbor's health stems from the rapid loss of eelgrass beds and the fish and shellfish communities they support within the inner portions of this system. The presence of eelgrass is particularly important to the use of West Falmouth Harbor as bay scallop habitat. It is clear from the seed/harvest programs in 1995 and 1997 that scallop production within this embayment is still possible, although potentially declining. Scallops were observed by MEP Technical Staff within the outer portion of the Harbor during the fall of 1999 and in subsequent years through fall 2005.

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, West Falmouth Harbor, as well as other embayment systems in Falmouth (Little, Great, Green and Bournes Pond embayment systems along the southern Falmouth shoreline) are at risk of eutrophication from high nitrogen loads in the groundwater and runoff from their watersheds. However, the structure of the West Falmouth Harbor watershed and the relatively high tidal range and high water quality of adjacent Buzzards Bay, tend to make this system more able to tolerate watershed nitrogen loading than Falmouth's southern shore embayments. This is supported by the relatively high nitrogen related habitat quality in this system until the 1990's and the persistence of eelgrass beds in the outer basin today. However, nitrogen loading from residential land-uses was augmented by discharge of the Falmouth Wastewater Treatment Facility introducing effluent as a point source to Mashapaquit Creek via upgradient infiltration beds. This effectively expanded the contributing area of the Harbor. Critical in the nutrient threshold analysis for the West Falmouth Harbor is the import of this nutrient load from outside the system's watershed.

The primary ecological threat to West Falmouth Harbor resources is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters has been greatly increased over the past few decades with further increases certain unless nitrogen management is implemented. However, the Town of Falmouth has begun nitrogen management towards restoration of the Harbor habitats, by upgrading the WWTF to lower the nitrogen load from this dominant source to the estuary. Nonetheless, loads originating within the watershed itself continue to increase as development continues. Residential and commercial landuses within the West Falmouth Harbor watershed virtually all use on-site septic treatment and disposal systems. Fortunately, as West Falmouth Harbor watershed nitrogen loads (non-WWTF) are approaching their build-out rates, so management options can be clearly defined and implemented with a high degree of certainty for restoration so long as the WWTF discharges are appropriately factored into the nutrient analysis for the watershed and the harbor. To this end, as the primary stakeholder to the West Falmouth Harbor embayment systems, the Town of Falmouth was one of the first communities to become concerned over perceived degradation of embayment waters.

The Town of Falmouth (via the Planning Office) has long recognized the potential threat of nutrient over-enrichment of its coastal salt ponds and embayments. In the mid-1980's the Town enacted an innovative Nutrient Overlay By-law that tied watershed development to water quality within the adjacent embayment. Nutrient limits were set for nitrogen in each of the Town's embayments. The goal was to keep nitrogen concentrations in the receiving systems below thresholds that were projected to cause water quality shifts, much like the approach of MEP and the associated TMDL process. To acquire baseline water quality data necessary for ecological management of Falmouth's coastal salt ponds and harbors, a citizen-based water quality monitoring program was initiated by the Town of Falmouth. Falmouth PondWatch, was established to provide on-going nutrient related embayment health information in support of the By-law. The water quality monitoring program was based on a collaborative effort between scientists, citizens and representatives of the Town of Falmouth. As originally conceived, the monitoring program focused on data collection in three original ponds, Oyster Pond, Little Pond and Green Pond. By 1990, the scope of water quality data collection expanded to include two additional ponds, Great/Perch Pond and Bournes Pond. In 1992, the scope of data collection was once again expanded to include West Falmouth Harbor in order to evaluate the effects from the nutrient enriched wastewater plume generated by the Falmouth Wastewater Treatment Facility.

The Falmouth PondWatch Program partnered early on with the Coalition for Buzzards Bay's Baywatcher Program for monitoring West Falmouth Harbor nutrient related water quality. This partnership continues to play an active role in the collection of baseline water quality data to this day. These water quality data have supported other nutrient related efforts within West Falmouth Harbor including early modeling of water quality (Ramsey and Howes 1995), quantifying attenuation of watershed nitrogen within Mashapaquit Creek (Smith 1999, Hamersley and Howes 2004), and a habitat assessment and nitrogen thresholds analysis by DEP and SMAST (Howes et al. 2000). In addition, estimates of nitrogen loading to the Harbor from the watershed have been conducted by SMAST scientists, the Cape Cod Commission, Buzzards Bay Project and most recently as part of Wastewater Facilities Planning for the Town of Falmouth by Stearns & Wheler, LLC (see Chapter II).

Figure I-1. West Falmouth Harbor 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 1 surface water discharge (Mashapaquit Creek upgradient of Chase Road) and direct groundwater discharge.

The current MEP effort builds upon these previous efforts and includes additional high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the West Falmouth Harbor embayment system, and specifically its major sub-embayments (Snug Harbor, South Basin, Outer/Mid Harbor). Also, critical to the present MEP effort was access to the Falmouth's Planning Office's expertise and GIS database. Based on the wealth of information obtained over the many years of study of this system, in addition to the nutrient analyses undertaken as a precursor to the Massachusetts Estuaries Project, the West Falmouth Harbor embayment system was included in the first round prioritization of the Massachusetts Estuaries Project to provide state-of-the-art analysis and modeling. However, given that the MEP was able to fully integrate data and information from the Town of Falmouth's previous efforts and work by the Planning Department, only minimal municipal funds were required as direct matching funds to the MEP to complete the full MEP Linked Watershed-Embayment Management Approach.

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 Falmouth. 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 a 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 Falmouth to develop and evaluate the most cost effective nitrogen management alternatives to restore this valuable coastal resource which is currently being degraded by nitrogen overloading. It should be noted that the present MEP Technical Analysis, builds directly on a preliminary MEP assessment and nitrogen thresholds analysis conducted by SMAST and DEP (2000) to set nitrogen parameters for the upgrade of the Town's WWTF (which is underway).

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 Falmouth) 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 (MA DEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts.

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region’s coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the DEP 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, TMDL’s 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 each of the 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,

- keep each embayment's model "alive" to address future 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 >15 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.

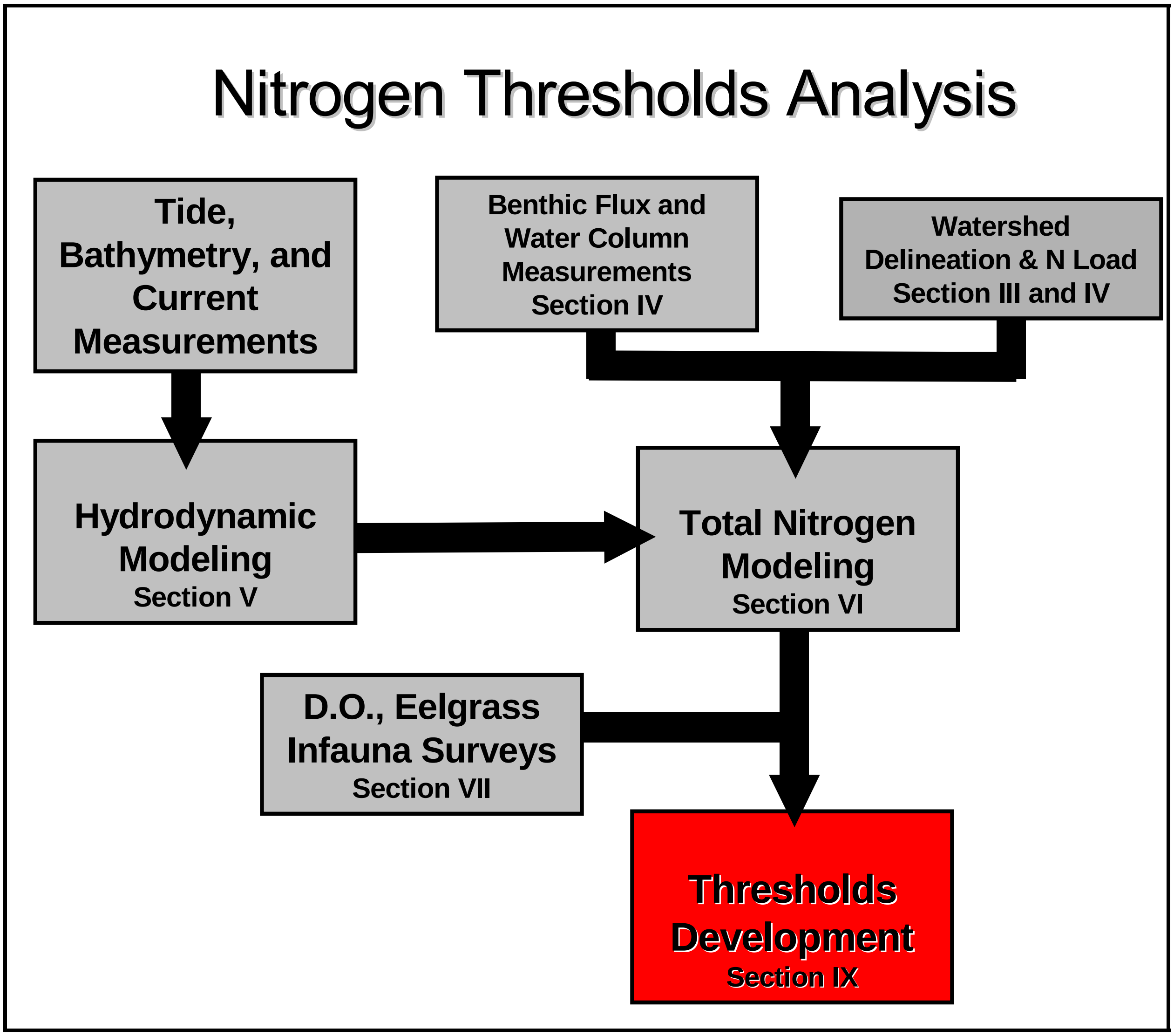


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

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

I.2 SITE DESCRIPTION

The Buzzards Bay embayments within the Town of Falmouth, including West Falmouth Harbor tend to be Lagoonal Estuaries with basins running parallel to the barrier beach. West Falmouth Harbor is a complex estuary formed primarily as a lagoon by the formation of the barrier beach (Chappaquoit Beach) with a small drown “river” valley (Mashapaquit Creek entering Snug Harbor). The system also includes a drown kettle pond (Oyster Pond) whose connection with the Harbor was modified in the late 1800’s by the construction of the railroad bed (Figure I-1).

West Falmouth Harbor is situated within the Buzzards Bay terminal moraine deposited after the retreat of the Buzzards Bay Lobe of the Laurentide Ice sheet and consisting of glacial till, as opposed to the sandy outwash deposits typical of Falmouth’s southern shore. As post-glacial sea-level rose, Buzzards Bay and then West Falmouth Harbor became marine systems. The West Falmouth Harbor Estuary is a relatively recent formation, first requiring inundation with marine waters (4,500-3,000 years B.P.) followed by barrier beach formation by coastal processes.

The habitat quality of West Falmouth Harbor is linked to the level of tidal flushing through its inlet to Buzzards Bay, which exhibits a moderate tide range of about 5 ft. Since the water elevation difference between the Bay and Harbor 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 is presently armored with jetties.

Like the Harbor itself, the watershed to the West Falmouth Harbor Estuary is also distributed fully within the Town of Falmouth. West Falmouth Harbor is one of the Town of Falmouth's significant marine resources. At a time when many other coastal ponds and bays in the Town have been degraded, water quality in West Falmouth Harbor has until recently remained fairly high, as pockets of eelgrass and healthy animal populations demonstrate. However, the West Falmouth Harbor System has been undergoing rapid degradation of its resources over the past decade as a result of nutrient overloading primarily from recent entry of the plume of treated wastewater emanating from the effluent disposal at the Town’s Wastewater Treatment Facility. While the embayment was becoming impaired due to nitrogen loading associated with land-use shifts within its watershed prior to the entry of the wastewater effluent plume, nitrogen related habitat quality decline has rapidly accelerated with the addition of the nitrogen load from the plume which has more than doubled nitrogen loading to this estuary over a period of several years (Howes et al. 2000).

West Falmouth Harbor, historically called Chappaquoit Harbor, is an enclosed tidal system comprised of multiple basins with a mean depth at MLW of 0.6 meters. The Harbor was originally an open basin with an island, what is now Chappaquoit Point, marking the outer boundary with Buzzards Bay. Deposition of the sand spit (Chappaquoit Beach) enclosed the present Harbor. During this century, jetties were placed at the Harbor inlet, further enclosing the outer basin. The upper watershed to West Falmouth Harbor is somewhat geologically complex, being composed primarily of Falmouth Glacial Moraine. At present, West Falmouth Harbor is a tidal estuary with a groundwater fed stream discharging to its headwaters (Mashapaquit Creek).

The Harbor is moderate in size, 197 acres, and composed of an outer region between the jetties and Old Field Point (the spit between Snug Harbor and the outer basin), the inner Harbor consisting of the Snug Harbor and South (Chappaquoit) basins and 3 tributary systems, Mashapaquit Creek Marsh, Harbor Head and Oyster Pond (Figure I-1). Each of these systems has its own sensitivity to nitrogen loading. Oyster Pond, a kettle pond now tidally connected to the Bay, is the deepest part of the West Falmouth Harbor marine system, more than 8 meters (26 feet) in depth. This 7 acre salt pond has a small channel for tidal flow and typically maintains a salinity throughout the water column above 25 parts per thousand. However, because of its depth, Oyster Pond periodically stratifies and oxygen depletion of bottom waters results. Harbor Head is a shallow basin between Oyster Pond and the primary basins of the Harbor and therefore receives nutrients from its surrounding watershed as well as nutrients from the Oyster Pond watershed which leave the Pond in ebb tidal flows. Similarly, South Basin receives ebb tidal waters from both Harbor Head and Oyster Pond. Snug Harbor, 37 acres, averages 1.2 m depth (at mid-tide) and is the most heavily nutrient loaded basin within the System. Snug Harbor and its upper portion, Mashapaquit Creek (14 acres) form a sub-estuary to the Harbor which began receiving nitrogen when the groundwater effluent plume from the Falmouth WWTF reached its shores in ca. 1994.

The Harbor is important for recreational boating and supports over 350 moorings. The Inner Harbor has both a Town Dock, which consists of a pier with floats, and a public boat ramp. Boat fueling activities at the Town Dock have been discontinued. West Falmouth Harbor remains an important habitat for quahogs, soft-shell clams, and oysters and to some extent scallops. In 1993 the Harbor supplied over 8% of Falmouth's commercial and recreational catch of clams, quahogs, and scallops, some 1200 bushels valued at about $90,000 (Town of Falmouth, 1993). In addition, the inner Harbor supports an “up-weller” for shellfish propagation, maintained by the Town Shellfish Department. The Town of Falmouth Shellfish Department in 1997 used the Harbor for transfer of 1158 bushels of quahogs and 100,000 of seed, while MA Division of Marine Fisheries planted seed bay scallops in 1995 (1.5 million) followed by 75,000 seed by the Town in 1997. Additional seeding efforts continued to be undertaken after 1997. The Harbor supports diverse areas for shellfish harvest which are Conditional/Prohibited. In November of 1998, the Harbor was reclassified as “Seasonally Approved”; this allows shellfish harvest from November 1 through April 30 only. However, the region of Snug Harbor and Mashapaquit Creek is Prohibited (permanently closed). Bacterial contamination to the Harbor appears to be primarily via tidal outflows from the Mashapaquit Creek Marsh, which is likely to be at least in part due to “natural” contamination from wildlife.

The Harbor currently supports both salt marsh and eelgrass communities. Of the 38 acres of salt marsh the largest areas are found surrounding Mashapaquit Creek and Oyster Pond. Narrow fringing marsh is found bordering much of the inner Harbor. Eelgrass beds are highly sensitive to nutrient overloading. Eelgrass beds within West Falmouth Harbor have historically filled most of the sub-tidal area. Recent concern over the Harbor’s health stems from perceptions that eelgrass beds and the fish and shellfish communities they support are declining within the inner portions of this system. The presence of eelgrass is particularly important to the use of West Falmouth Harbor as bay scallop habitat. It is clear from the seed/harvest programs in 1995 and 1997 that scallop production within this system is still possible, although potentially declining. Scallops were observed by MEP Technical Staff within the outer portion of the Harbor during the fall of 1999 and in subsequent years through fall 2005.

Similar to other embayments in the Town of Falmouth (Great and Bournes Pond embayment systems), West Falmouth Harbor is a mesotrophic (moderately nutrient impacted) to eutrophic (nutrient-rich) shallow estuarine system. Although the embayment is located within a glacial moraine, consisting of glacial till, the material is moderately to highly permeable and as such, direct rainwater run-off is typically rather low for this type of coastal system. Therefore, most freshwater inflow to the estuarine system is via groundwater discharge or groundwater fed surface water flow (e.g. Mashapaquit Creek upgradient of Chase Road). West Falmouth Harbor acts as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Buzzards Bay, however, the salinity characteristics of the system varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with Buzzards Bay.

For the MEP analysis, the West Falmouth Harbor system was analyzed individually as a stand-alone system within its watershed. Similar to other embayments in Falmouth (e.g. Great/Perch Pond, Green Pond, and Bournes Pond) West Falmouth Harbor is an estuary with surface and groundwater inputs primarily in its inner reaches and tidal exchange of marine waters from Buzzards Bay (tide range of approximately 1.5 m) at the mouth. The West Falmouth Harbor estuarine system was partitioned into several regions: 1) Harbor Head, 2) Oyster Pond, 3) a southern “Chappaquoit” basin (behind Chappaquoit Beach), 4) Snug Harbor which receives a freshwater stream discharge (Mashapaquit Creek), 5) outer/mid basins reaching from Old Field Point to the Inlet (see Figure I-1). West Falmouth Harbor is a true estuary, acting as the mixing zone of terrestrial freshwater inflow and saline tidal waters from Buzzards Bay. Salinity in the harbor ranges from approximately 30 ppt at the Buzzards Bay inlet to ~ 20 ppt at the mouth of Mashapaquit Creek.

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

Nitrogen loading to the West Falmouth Harbor embayment system was determined relative to the regions of the estuary as depicted in Figure I-1. Based upon land-use and the watershed being fully within the Town of Falmouth, it appears that nitrogen management for harbor restoration may likely be more rapidly developed and implemented than otherwise. Restoration of Harbor habitats is already underway with the upgrade to the Falmouth WWTF, which will reduce the load from the largest nitrogen source to this estuary. As management alternatives are being developed and evaluated, it is important to note that strong gradients define the nutrient characteristics of the Harbor and as such the associated habitat impacts. There is a strong gradient in nitrogen level and health in West Falmouth Harbor, with highest nitrogen levels and lowest environmental health within the inner basins and lowest nitrogen levels and highest health near the inlet to Buzzards Bay. The upper reaches of West Falmouth Harbor are presently showing poor water quality and “Eutrophic” conditions. Eelgrass beds have been lost from these regions and oxygen depletion of bottom waters periodically occurs.

I.3 NITROGEN LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In sandy glacial outwash aquifers, such as in the watershed to the West Falmouth Harbor embayment system, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer mineral (Weiskel and Howes 1992). Since Cape Cod "rivers" are primarily groundwater fed, watersheds tend to release little phosphorus to coastal waters. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through oxygenated groundwater systems on Cape Cod (DeSimone and Howes 1998, Weiskel and Howes 1992, Smith *et al.* 1991). The result is that terrestrial inputs to coastal waters tend to be higher in plant available nitrogen than phosphorus (relative to plant growth requirements). However, coastal estuaries tend to have algal growth limited by nitrogen availability, due to their flooding with low nitrogen coastal waters (Ryther and Dunstan 1971). Tidal reaches within the West Falmouth Harbor system follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

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

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

Protection and restoration of coastal embayments from nitrogen overloading has resulted in a focus on determining the assimilative capacity of these aquatic systems for nitrogen. While this effort is ongoing (e.g. USEPA TMDL studies), southeastern Massachusetts has been the site of intensive efforts in this area (Eichner et al., 1998, Costa et al., 1992 and in press, Ramsey et al., 1995, Howes and Taylor, 1990, and the Falmouth Coastal Overlay Bylaw). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the "allowable N concentration increase" or "threshold nitrogen concentration" used in previous studies had a significant uncertainty due to the need for direct linkage of watershed and embayment models and site-specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout the West Falmouth Harbor system monitored by the Falmouth PondWatch 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, almost all of the estuarine reach within West Falmouth Harbor is near or beyond its ability to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated throughout the system and eelgrass beds have been lost throughout the inner basins and into the outer basins with the only remaining beds near the mouth of the harbor. 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, "cultural eutrophication". Although the influence of human-induced changes has clearly increased nitrogen loading to the system and contributed to the degradation of its ecological health, it is sometimes possible that eutrophication within a given subembayment could potentially occur without man's 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 subembayment into a "pristine" system.

I.4 WATER QUALITY MODELING

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

The MEP water quality evaluation examined the potential impacts of nitrogen loading into West Falmouth Harbor. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the system. Once the hydrodynamic properties of the estuarine system was computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations by USGS using a modification of the West Cape model for sub-watershed areas designated by MEP. Almost all nitrogen entering Cape Cod embayment systems is transported by freshwater, predominantly groundwater, either through direct discharge or after discharging to streams flowing to estuarine waters. Concentrations of total nitrogen and salinity of Buzzards Bay source waters and throughout the West Falmouth Harbor system was taken from the Falmouth PondWatch Monitoring Program (supported by the Town of Falmouth and associated with the Coastal Systems Program at SMAST). Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of the system were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the West Falmouth Harbor system for the Town of Falmouth. 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 salt pond. 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 West Falmouth Harbor system. Finally, analyses of the West Falmouth Harbor 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. The results of the nitrogen modeling for each scenario have been presented (Section IX).

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

Nutrient additions to aquatic systems cause shifts in a series of biological processes that can result in impaired nutrient related habitat quality. Effects include excessive plankton and macrophyte growth which in turn leads to: 1) reduced water clarity, 2) organic matter enrichment of waters and sediments, 3) concomitant increased rates of oxygen consumption and periodic depletion of dissolved oxygen, especially in bottom waters, and 4) 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 marine resource and a loss of productivity to both the local shellfisherman and to the sport-fishery and offshore finfishery. A viable and sustainable coastal fishery is dependant upon these highly productive estuarine systems as a habitat and food resource during migration or during different life cycle phases. The degenerative process sketched above 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 West Falmouth Harbor, 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 West Falmouth Harbor System. As the MEP approach requires substantial amounts of site specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of “data mining” and to gather additional information on an estuary’s habitat quality and unique features.

To this end, there are a number of studies that relate to the nutrient related health of West Falmouth Harbor. The Town of Falmouth was one of the first communities to become concerned over the perceived degradation of its estuaries. The Town of Falmouth (via the Planning Office) has long recognized the potential threat of nutrient over-enrichment of its coastal salt ponds and embayments. In the mid-1980's the Town enacted an innovative Nutrient Overlay By-law that tied watershed development to water quality within the adjacent embayment. Nutrient limits were set for nitrogen in each of the Town’s embayments. The goal was to keep nitrogen concentrations in the receiving systems below thresholds that were projected to cause water quality shifts, much like the approach of MEP and the associated

TMDL process. To acquire baseline water quality data necessary for ecological management of Falmouth's coastal salt ponds and harbors, a citizen-based water quality monitoring program was initiated by the Town of Falmouth. Falmouth PondWatch, was established in 1987 to provide on-going nutrient related embayment health information in support of the By-law. The water quality monitoring program was based on a collaborative effort between scientists, citizens and representatives of the Town of Falmouth. In 1992, PondWatch partnered with the Coalition for Buzzards Bay's BayWatcher Program to collect nutrient related water quality data throughout the West Falmouth Harbor System. The partnership between the two water quality monitoring programs enabled the evaluation of the estuarine effects of the nutrient enriched wastewater plume generated by the Falmouth Wastewater Treatment Facility and continuing watershed build-out.

The Falmouth PondWatch Program, as the water quality monitoring effort came to be known, continues to play an active role in the collection of baseline water quality data to this day. Over time, however, it has evolved beyond its original mandate of providing basic environmental data relative to the Coastal Pond Overlay Bylaw (Nutrient Bylaw). The Pond Watch Program brings together, as requested by Town boards, ecological information relative to specific water quality issues. Additionally, as remediation plans for various systems are implemented, the continued monitoring satisfies demands by State regulatory agencies and provides quantitative information to the Town relative to the efficacy of remediation efforts. This multi-year effort has also provided the baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. The PondWatch Program in West Falmouth Harbor has elucidated the long-term trend of declining water quality and its relation to watershed based nutrient loading (see Chapter VII).

Numerous studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the West Falmouth Harbor System over the past 10 years. In the late 1980's and early 1990's local concern over the health of the sub-embayments to West Falmouth Harbor (particularly in the upper reaches) focused future impacts of Town of Falmouth activities within the watershed. Future impacts ranged from activities such as the siting of the West Falmouth WWTF and the opening of the Falmouth Technology Park. Field measurements by the Falmouth PondWatch and Coalition for Buzzards Bay's BayWatchers in the mid/late 1990's indicted that the greater issue of habitat degradation from nitrogen enrichment was occurring, particularly in the region of Snug Harbor.

Initial studies to predict changes in embayment health related to increasing watershed nitrogen loads and indicated that harbor resources would be degraded at levels of nitrogen loading that are now entering the estuary. Habitat decline would result primarily from nitrogen inputs from the WWTF, continuing development within the watershed, and entry of the Landfill plume. Nitrogen management particularly for the inner Harbor was recommended as development continued. The authors stated that major water quality declines were not expected to result as long as there were no major additional sources of nitrogen added to the Harbor over the existing development pattern and the 1993 WWTF discharges (Ramsey et al. 1995). The initial and subsequent studies revealed that the Falmouth WWTF nitrogen loading was the single major nitrogen source to the estuary. Furthermore the WWTF loading was not constant but was increasing significantly since the beginning of effluent discharge in October 1986 (Costa 1996, Eichner et al. 1998, Smith 1999). Unfortunately loading increased far beyond 1993 levels, and habitat degradation has subsequently been documented throughout the inner harbor basins.

The concern about nutrient related habitat declines resulted in a nitrogen loading and flushing analysis by the Cape Cod Commission (CCC) under the Cape Cod Coastal Embayment Project (Eichner et al. 1998). In that study the major sub-watersheds to the West Falmouth Harbor System were delineated based upon available water table measurements. A land-use nitrogen loading model was implemented to determine nitrogen inputs to bay waters and a numerical hydrodynamic model was used to evaluate flushing rates of the estuary's sub-basins. The CCC study synthesized the available habitat health, water quality and hydrodynamic information in the context of projecting future resource quality. The analysis revealed that some of the inner basins were currently impaired and as the WWTF approached its capacity of 880,000 gpd (it was at 447,000 in the study), nitrogen loads would cause degradation of the inner harbor basins. Watershed buildout would further exacerbate the habitat decline. While the analysis did not use a water quality model to project a nitrogen loading threshold, the overall conclusions appear to have been qualitatively correct (see Chapter VII).

The CCC study supported earlier analyses indicating that the WWTF was the single largest source of nitrogen to West Falmouth Harbor waters with on-site septic disposal of wastewater being second. In addition, the Harbor's watershed includes a variety of other nutrient sources, among them the Town's landfill, old septage lagoons, composting installations, runoff from roads and lawns, as well as the Town's industrial park. While the overall results of the CCC study have held true, the analysis is insufficient to simulate changes in nitrogen within the estuary under different management alternatives. In addition, as the landuse model did not account for nitrogen attenuation by the wetland ecosystems (no data available at the time), it over estimated the role of nitrogen sources in upper (inland most) sub-watersheds compared to the direct groundwater watersheds to the estuary. While base data from this earlier study was incorporated by the MEP, direct use of the modeling results was problematic. Since the landuse model was based upon the 1996 watershed delineations from well data, rather than the MEP's USGS West Cape Model (see Chapter III), the contributing areas are slightly different. 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 from the MEP are different and supercede the earlier studies.

Given the significance of the WWTF nitrogen load to the embayment health (accounts for ~70% of total N load), studies have been undertaken to determine the attenuation of WWTF nitrogen by activities at the facility (Jordan et al., 1997) and by the down-gradient salt marsh (Smith, 1999). The original WWTF was designed to reduce its nitrogen load to the Harbor by incorporating spray irrigation of vegetation, whereby nutrients would be denitrified or absorbed by growing plants. However, this system has been only partially effective. In the initial study, nitrogen uptake by the spray irrigation system was important to the nitrogen balance in the first year of discharge, but diminished significantly in the second year. More recent data by MEP indicates that attenuation declined further and has remained low (see Chapter IV). The nitrogen-rich plume created by this source has entered the groundwater in the northeast section of the watershed and is currently discharging to the Snug Harbor/Mashapaquit Creek sub-estuary. However, the Mashapaquit Marsh creek bottom provides a significant attenuation of nitrogen during transport to the embayment waters of Snug Harbor. Attenuation of nitrogen from the WWTF plume and other watershed sources was determined through a variety of techniques, including tidal mass balance, watershed modeling, direct measures of freshwater inflow, and incubations of creek bottom sediments (Smith 1999, Smith and Howes Unpublished, Hamersley and Howes, 2003). All of the approaches support an annualized nitrogen attenuation of ~40% for watershed nitrogen transiting this salt marsh.

Most recently a habitat assessment and nitrogen thresholds analysis was conducted by DEP and SMAST relative to the upgrade of the West Falmouth WWTF (Howes et al. 2000). This analysis concluded that the data indicate a system in which nitrogen levels are rising, the frequency and magnitude of bottom water oxygen depletion is increasing, and biotic communities (eelgrass and benthic animals) are declining and being replaced by stress-tolerant species. This is the classical example of the response of shallow embayments to nutrient over-enrichment. In addition, the ecological shifts appear to have taken place relatively rapidly, apparently coinciding with the entry of a new significant nitrogen load from the WWTF plume.

The DEP/SMAST study further indicated that “the mass of nitrogen discharged by the WWTF has been increasing since its start-up in October 1986. From 1991-92 to 1996-98 alone, nitrogen loading to the watershed from WWTF effluent discharge nearly doubled. The increasing mass of nitrogen discharged from the WWTF results from increased use of the Facility for septage, additional hook-ups within sewered areas, and increased occupancy. This rising rate of loading from the WWTF is much higher than from continued development within the West Falmouth Harbor watershed for the same interval. While all sources of nitrogen contribute to fertilization of the Harbor, the WWTF clearly presents the largest source and is increasing at the highest rate. The study further underscored the difficulty in assessing West Falmouth Harbor watershed-embayment relationships, since the nitrogen load from the WWTF has a significant time-delay from discharge to entry into the Harbor System. The time lag results from vertical and groundwater flow times of ca. 6 years, based on the travel times predicted by the West Cape Model. The 6-year lag time between discharge at the WWTF and entry to the Harbor waters is a critical part of the nitrogen issue for West Falmouth Harbor. This time lag means that even if the discharges were to have ceased in 2000, total nitrogen loading to the entire Harbor would continue to increase by ca. 50% over 1998 levels by the year 2004.

Two of the key recommendations of the DEP/SMAST study were:

- A nitrogen threshold of 0.35 (to possibly 0.37) mg N L^{-1} within the waters of the inner Harbor basins (South Basin and Snug Harbor) should support the recovery of eelgrass and associated animal and plant communities throughout West Falmouth Harbor’s sub-tidal basins.

- Land-disposal of WWTF Effluent should maximize discharge to the Mashapaquit Creek Marsh. Large areas of forested land are located just north of the existing WWTF infiltration beds. Ratios of DIN to Na in groundwater under the existing vegetated spray irrigation areas seem to indicate that the vegetation acts as a sink for effluent nitrogen. In addition, these unused areas are within the subwatershed to Mashapaquit Creek Marsh, which has been shown to remove 40 to 50% of watershed nitrogen.

All of the above efforts were part of the decision to upgrade the West Falmouth WWTF to include nitrogen removal and sewering of portions of the watershed. These decisions are further evaluated in the MEP synthesis and modeling in the following chapters using the Linked Watershed-Embayment Modeling Approach (Chapters VI, VII). In addition, the nitrogen loading threshold for the estuary is refined based upon the additional data from the MEP effort.

The PondWatch effort provided the quantitative watercolumn nitrogen data (1992-2004) required for the implementation of the MEP’s Linked Watershed-Embayment Approach. The MEP effort also builds upon the previous hydrodynamic and water quality analyses, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the West Falmouth Harbor embayment system. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the West Falmouth Harbor System and to reduce costs to the Town of Falmouth.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). These USGS groundwater modelers were central to the development of the groundwater modeling approach used by the Estuaries Project. The USGS has a long history of developing regional models for the six-groundwater flow cells on Cape Cod. Through the years, advances in computing, lithologic information from well installations, water level monitoring, stream flow measurements, and reconstruction of glacial history have allowed the USGS to update and refine the groundwater models. The MODFLOW and MODPATH models used by the USGS to organize and analyze the available data utilize 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 West Falmouth Harbor embayment system located in Falmouth, Massachusetts.

In the present investigation, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the West Falmouth Harbor embayment system under evaluation by the Project Team. The West Falmouth Harbor estuarine system is composed of a complex estuary, originating from sea level flooding of a knob and kettle landscape formed by a terminal moraine and a small river valley (Mashapaquit Creek). As sea level rose the harbor was originally an open basin with an island that is now known as Chappaquoit Point, marking the outer boundary with Buzzards Bay. With the progression of coastal processes the main basins were formed as a lagoonal estuary by deposition of the sand spit (Chappaquoit Beach) enclosing the present Harbor.

Watershed modeling was undertaken to sub-divide the overall watershed to the West Falmouth Harbor system into functional sub-units based upon: (a) defining inputs from contributing areas to each major portion within the embayment system, (b) defining contributing areas to major freshwater aquatic systems which generally attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands), and (c) defining 10 year time-of-travel distributions within each sub-watershed as a procedural check to gauge the potential mass of nitrogen from “new” development, which has not yet reached the receiving estuarine waters. The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in the Sagamore flow cell on Cape Cod. Model assumptions for calibration were matched to surface water inputs and flows from historic (1989, 1990 and 2003) stream flow measurements.

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

III.2 MODEL DESCRIPTION

Contributing areas to the West Falmouth Harbor system and local freshwater bodies were delineated using a regional model of the Sagamore Lens (Walter and Whealan, 2005). The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, et al., 2000) was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4 (Pollock, 2000), which uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies. This approach was used to determine the contributing areas to the main basins of the West Falmouth Harbor system and also to determine portions of recharged water that may flow through freshwater ponds and streams prior to discharging into coastal water bodies.

The Sagamore Flow Model grid consists of 246 rows, 365 columns and 20 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top 17 layers of the model extend to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft. Layers 1-7 are stacked above NGVD 29 and layers 8 to 20 extend below. Layer 18 has a thickness of 40 feet and layer 19 extends to 240 feet below sea level. The bottom layer, layer 20, extend from 240 feet below sea level to the bedrock surface and has a variable thickness depending upon site characteristics. The rewetting capabilities of MODFLOW-2000, which allows drying and rewetting of model cells, was used to simulate the top of the water table, which varies in elevation depending on the location in the Lens. In the portion of the Sagamore Lens in which the West Falmouth Harbor system resides, groundwater elevations are generally less than +40 ft and, therefore, over much of the study area the uppermost layers of the model are inactive.

The glacial sediments that comprise the aquifer of the Sagamore Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The sediments generally show a fining downward with sand and gravel deposits deposited in glaciofluvial (river) and near-shore glaciolacustrine (lake) environments underlain by fine sand, silt and clay deposited in deeper, lower-energy glaciolacustrine environments. Most groundwater flow in the aquifer occurs in shallower portions of the aquifer dominated by coarser-grained sand and gravel deposits. The West Falmouth Harbor watershed extends from the Buzzards Bay outwash deposits near the Harbor to the Buzzards Bay Moraine; modeling and field measurements of contaminant transport at the Massachusetts Military Reservation (MMR) has shown that both moraine and outwash materials are highly permeable (*e.g.*, Masterson, *et al*., 1996). Given their high permeability, direct rainwater run-off is typically rather low for this type of coastal system. Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from USGS, local Town records and data from previous investigations. Final aquifer parameters were determined through calibration to observed water levels and stream flows. Hydrologic data used for model calibration included historic water-level data obtained from USGS and town records and stream flow data collected in 1989-1990 as well as 2003.

The model simulates steady state, or long-term average, hydrologic conditions including a long-term average recharge rate of 27.25 inches/year and the pumping of public-supply wells at average annual withdrawal rates for the period 1995-2000 with a 15% consumptive loss. This recharge rate is based on the most recent USGS information for the Sagamore Lens. Large withdrawals of groundwater from pumping wells may have a significant influence on water tables and watershed boundaries and therefore the flow and distribution of nitrogen within the aquifer. After accounting for the consumptive loss and measured discharge at municipal treatment facilities, water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within designated residential areas utilizing on-site septic systems. In the West Falmouth Harbor watershed area, return flow is included in the non-sewered residential areas close to the harbor and additional water from outside the watershed is included by the discharge of the Town of Falmouth Wastewater Treatment Facility.

III.3 WEST FALMOUTH HARBOR CONTRIBUTORY AREAS

Revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the West Falmouth Harbor embayment system (Figure III-1). Model outputs of MEP watershed boundaries were “smoothed” to (a) correct for the grid spacing, (b) to enhance the accuracy of the characterization of the pond and coastal shorelines, and (c) 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. Overall, thirteen sub-watershed areas were delineated within the watershed to the West Falmouth Harbor embayment system. The MEP sub-watershed delineation includes 10 yr time of travel boundaries as part of assessing the watershed nitrogen loading model and its ability to resolve present nitrogen inputs to the estuary.

Table III-1 provides the daily discharge volumes for various sub-watersheds as calculated by the groundwater model; these volumes were used to assist in the salinity calibration of the tidal hydrodynamic model and for comparison to measured surface water discharges. The overall estimated groundwater flow into West Falmouth Harbor from the MEP delineated watershed is 14,436 m^3d^{-1}. The long-term average freshwater discharges from the sub-watersheds to Upper (1,877 m^3d^{-1}) and Lower (3,544 m^3d^{-1}) Mashapaquit Creek are consistent with direct measurements of discharge made in 1998-99 of 1,693 m^3d^{-1} and 4,377 m^3d^{-1}) respectively (Smith 1999) or ~10% difference overall.

West Falmouth Harbor has been the subject of a number of watershed delineation efforts. Each of these efforts has utilized information collected during the prior effort and the delineations completed for the MEP project benefit from information developed by the Cape Cod Commission (Eichner, *et al.*, 1998) and additional information developed during the regulatory review of the proposed expansion of the Town of Falmouth WWTF (e.g., Howes, *et al.*, 2000). Figure III-2 compares the delineation completed under the current effort with the delineation completed by the Cape Cod Commission. The CCC delineation completed in 1995 was defined based on regional water table measurements collected over a number of years and normalized to average conditions; delineations based on this effort were incorporated into the Commission’s regulations through the Regional Policy Plan (CCC, 1996 & 2001).

The MEP watershed area for the West Falmouth Harbor system as a whole is 25% smaller (566 acres) than the 1995 CCC delineation. This significant change is largely due to the more western location and more northeast/southwest orientation of the Buzzards Bay/Vineyard Sound groundwater divide. The change in location has the greatest impact on the more southern portions of the watershed delineation; the combined Oyster Pond/Harbor Head delineation is 60% smaller than the 1995 CCC delineation. On the other hand, the Snug Harbor plus Mashapaquit Creek delineation, which includes the WWTF, is only 5% (45 acres) smaller.

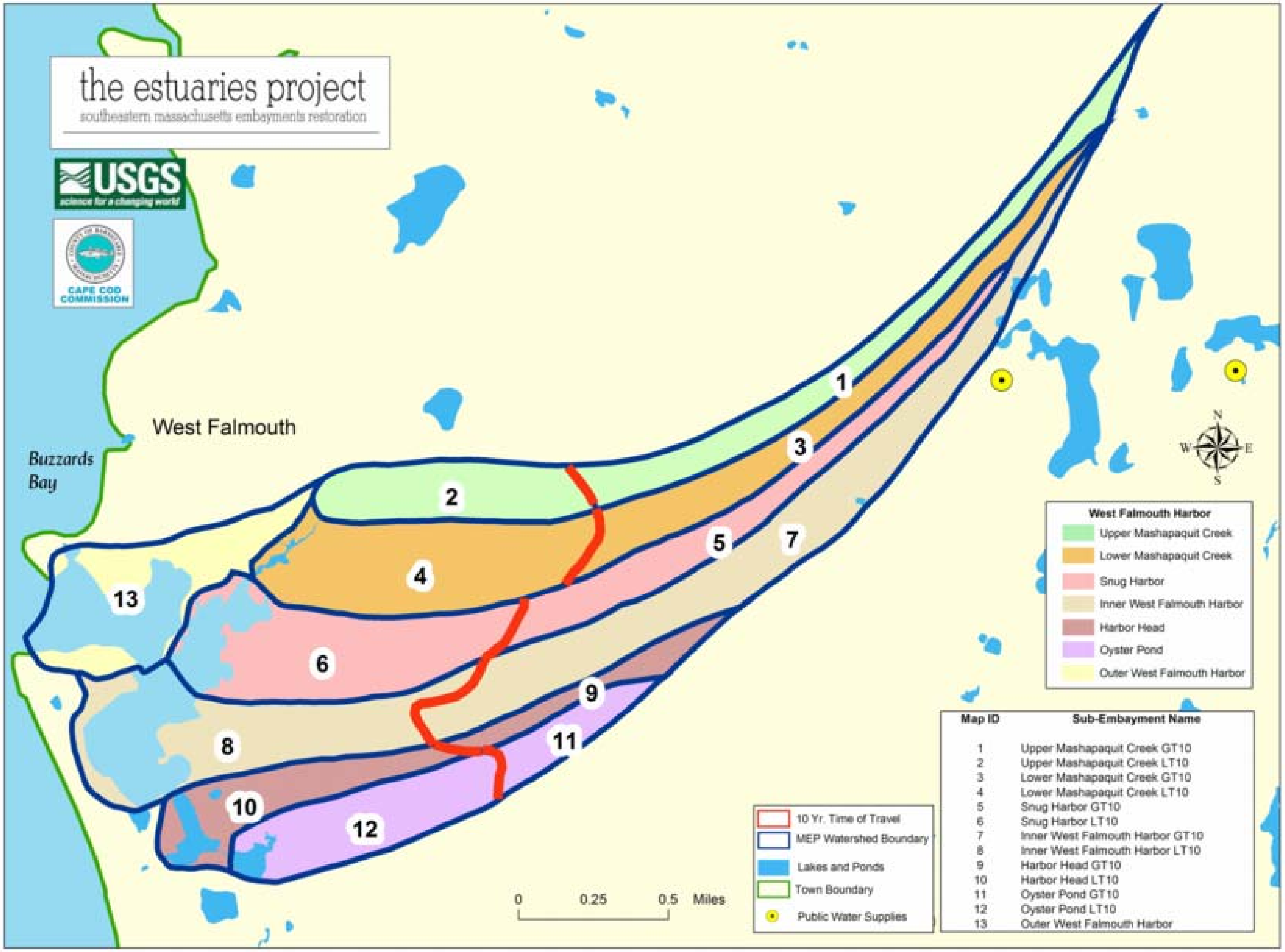


Figure III-1. Watershed and sub-watershed delineations for the West Falmouth Harbor estuary system. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names (above). Sub-watersheds to embayments were selected based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

Table III-1. Daily groundwater discharge from each of the sub-watersheds to the West Falmouth Harbor Estuary, as determined from the USGS groundwater model.

Watershed	Watershed #	Discharge	
		ft^3/day	m^3/day
Upper Mashapaquit Creek GT10	1	36,818	1,043
Upper Mashapaquit Creek LT10	2	29,471	835
Lower Mashapaquit Creek GT10	3	39,046	1,106
Lower Mashapaquit Creek LT10	4	86,106	2,438
Snug Harbor GT10	5	41,347	1,171
Snug Harbor LT10	6	48,157	1,364
Inner West Falmouth Harbor GT10	7	83,086	2,353
Inner West Falmouth Harbor LT10	8	39,962	1,132
Harbor Head GT10	9	12,543	355
Harbor Head LT10	10	23,730	672
Oyster Pond GT10	11	12,535	355
Oyster Pond LT10	12	31,501	892
Outer West Falmouth Harbor	13	25,508	722
Whole System		509,811	14,436

Note: 100% of Oyster Pond flow discharges into the Inner West Falmouth Harbor watershed.

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

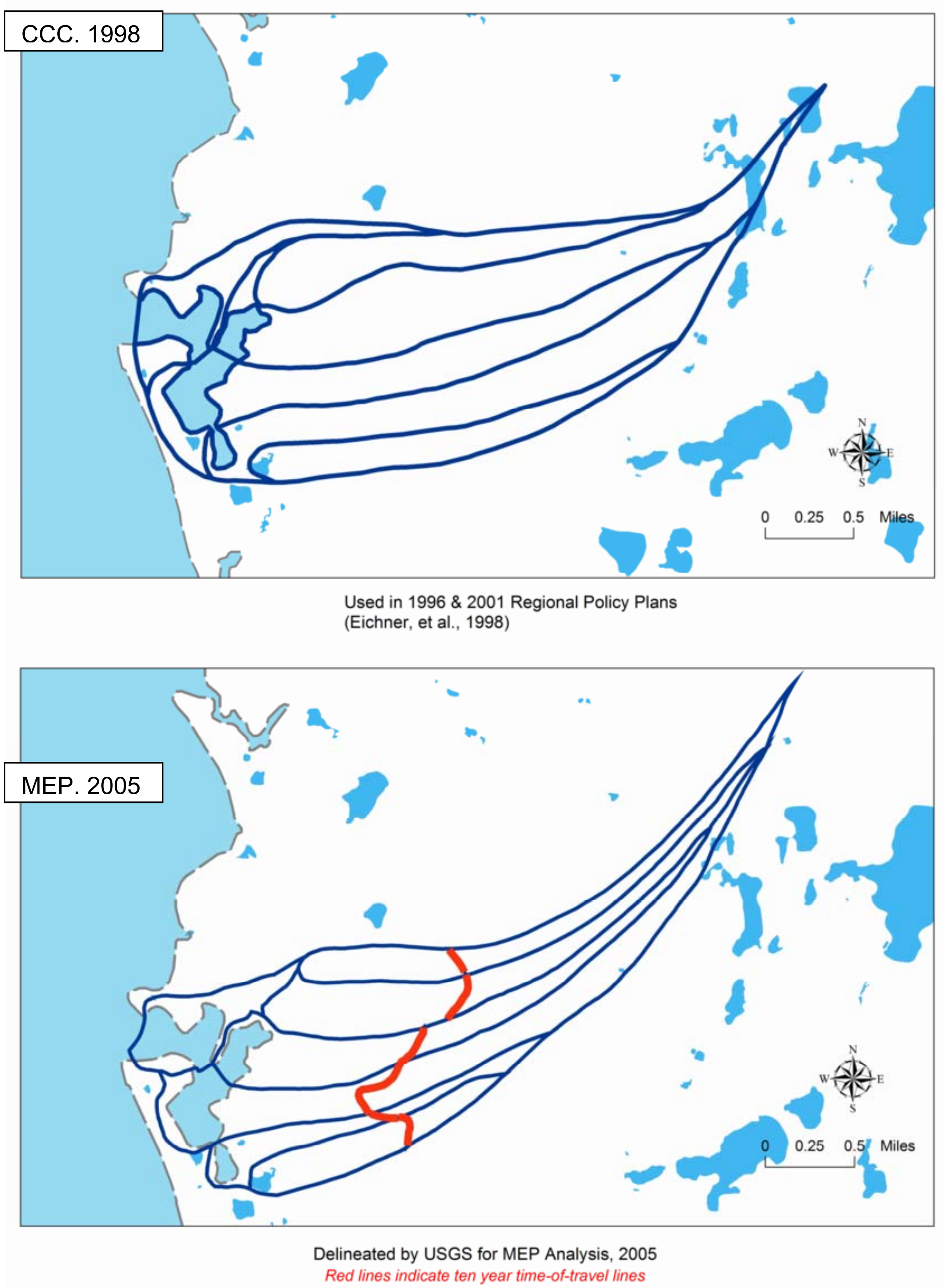


Figure III-2. Comparison of 1998 Cape Cod Commission and current West Falmouth Harbor watershed and subwatershed delineations.

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 West Falmouth Harbor system. Determination of watershed nitrogen inputs to these embayment systems requires the (a) identification and quantification of the nutrient sources and their loading rates to the land or aquifer, (b) confirmation that a groundwater transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes. This latter natural attenuation process results from biological processes that naturally occur within ecosystems. Failure to account for attenuation of nitrogen during transport results in an over-estimate of nitrogen inputs to an estuary and an underestimate of the sensitivity of a system to new inputs (or removals). In addition to the nitrogen transport from land to sea, the amount of direct atmospheric deposition on each embayment surface must be determined as well as the amount of nitrogen recycling within the embayment, specifically nitrogen regeneration from sediments. Sediment nitrogen recycling results primarily from the settling and decay of phytoplankton and macroalgae (and eelgrass when present). During decay, organic nitrogen is transformed to inorganic forms, which may be released to the overlying waters or lost to denitrification within the sediments. Burial of nitrogen is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source or sink of nitrogen to embayment waters and leads to errors in predicting water quality if it is not included in determination of summertime nitrogen load.

The MEP Technical Team includes technical staff from the Cape Cod Commission (CCC). In coordination with other MEP technical team staff, CCC staff developed nitrogen loading rates to the West Falmouth Harbor embayment system (Section IV.1) for the sub-watersheds delineated by the groundwater modeling effort (Chapter III). The watershed was sub-divided to define contributing areas to each major sub-embayment within West Falmouth Harbor and further sub-divided into regions greater and less than 10 year groundwater travel time from the receiving estuary, a total of 13 sub-watersheds in all. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to the embayment (see Chapter III).

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the embayment. This involves a temporal review of land use changes and the time of groundwater travel provided by the USGS watershed model. After reviewing the percentage of nitrogen loading in the less than 10 year time of travel (LT10) and greater than 10 year time of travel (GT10) watersheds (Table IV-1), previous nitrogen loading assessments (Eichner, et al., 1998), land use development records, and water quality modeling, it was determined that West Falmouth Harbor is currently in balance with its watershed load. The bulk (67%) of the entire watershed nitrogen load is within 10 years flow to the Harbor. Equally important, the nitrogen load to the WWTF reaching the Harbor in 2004 from 1996-1998 discharges will be relatively constant until they diminish as a result of the current upgrade to the facility. The WWTF accounts for more than half of the total watershed nitrogen loading. In addition, analysis of the major sources in the greater than 10 year sub-watersheds indicates that they have been extant for sufficient time for their nitrogen loads to have reached the estuary. Therefore, the distinction of less than 10 year and greater than 10 year time of travel regions within a subwatershed (Figure III-1) was eliminated and the number of subwatersheds was reduced to seven (Figure IV-1) for the water quality modeling effort. The overall result of the timing of development relative to groundwater travel times is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuaries (after accounting for natural attenuation, see below).

Table IV-1. Percentage of unattenuated nitrogen loads in less than 10 time of travel subwatersheds to West Falmouth Harbor

WATERSHED		LT10	GT10	TOTAL	%LT10
Name	#	kg/yr	kg/yr	kg/yr	
Upper Mashapaquit Creek	1	2,109	431	2,541	83%
Lower Mashapaquit Creek	2	7,133	1,064	8,197	87%
Snug Harbor	3	1,629	2,029	3,658	45%
Inner Harbor	4	1,026	3,081	4,106	25%
Harbor Head	5	411	41	452	91%
Oyster Pond	6	418	109	527	79%
Outer West Falmouth Harbor	7	953	0	953	100%
TOTAL	8	13,679	6,754	20,434	67%

In order to determine nitrogen loads from the watershed, 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 of the watershed. The Linked Watershed-Embayment Management Model (Howes & Ramsey 2001) uses a land-use Nitrogen Loading Sub-Model based upon subwatershed-specific land-uses and pre-determined nitrogen loading rates. For the West Falmouth Harbor embayment system, the model used Town of Falmouth specific land-use data transformed to nitrogen loads using both regional nitrogen load factors and local watershed-specific data (such as parcel by parcel water use). Determination of the nitrogen loads required obtaining watershed-specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the “potential” 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 was determined based upon a site-specific study within the freshwater (Section IV.2.2) and tidal (Section IV.2.3) portions of Mashapaquit Creek. Natural attenuation was not included in the nitrogen loading analysis for the small freshwater ponds located in the eastern portion of the system watershed. 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. However, even if attenuation of nitrogen is occurring during transport, given the distribution of the nitrogen sources and small ponds that do exist within the watershed, nitrogen loading to the estuary would only be slightly (~10%) overestimated. Based upon these considerations, the MEP Technical Team used the conservative estimate of nitrogen loading based upon direct groundwater discharge. Internal nitrogen recycling was also determined throughout the tidal reaches of the West Falmouth Harbor embayment; 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).

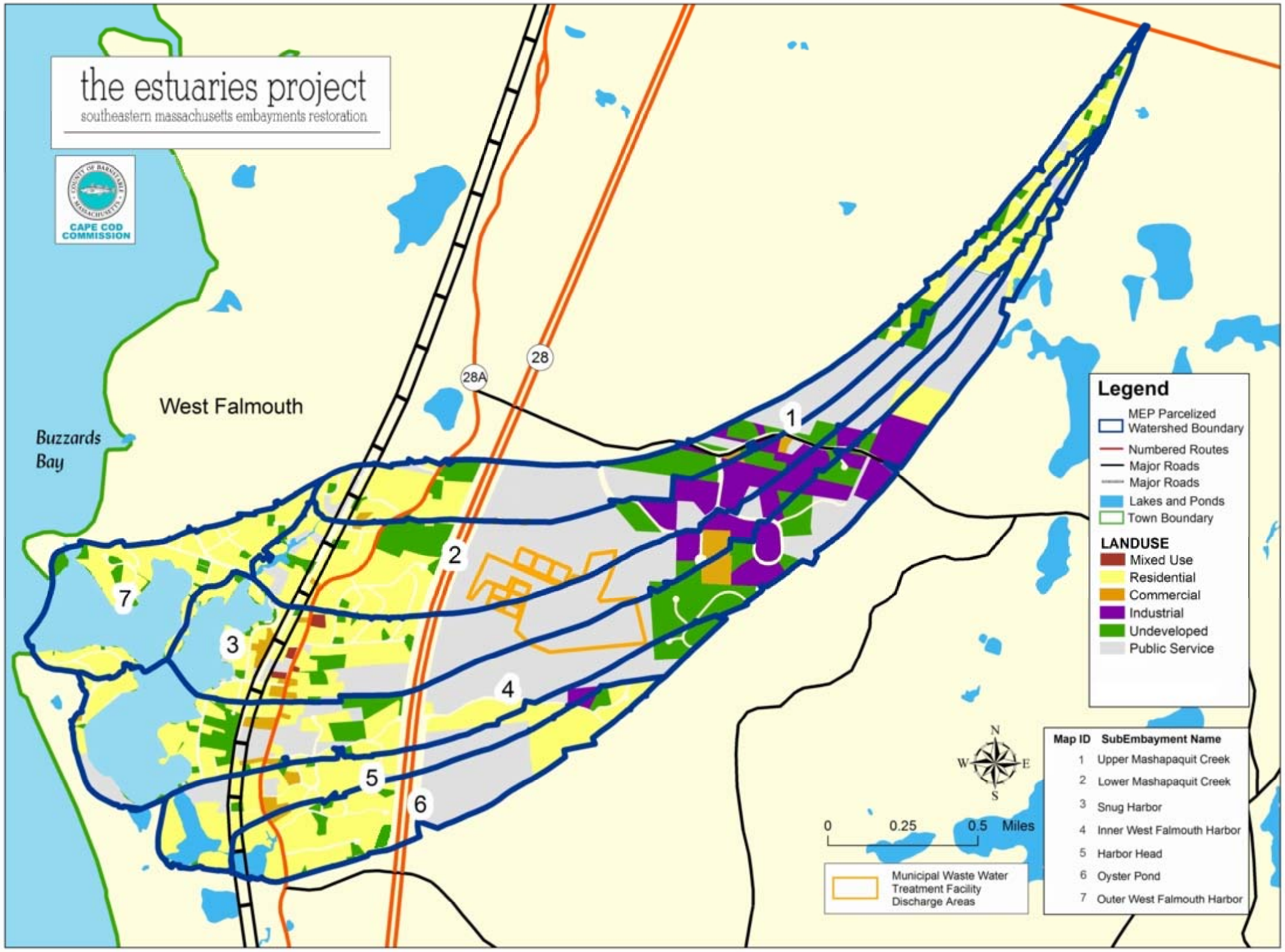


Figure IV-1. Land-use coverage in the West Falmouth Harbor watershed. Land use classifications are based on assessors' records provided by the Town of Falmouth.

IV.1.1 Land Use and Water Use Database Preparation

Estuaries Project staff obtained digital parcel and tax assessors data from the Town of Falmouth. Digital parcels and land use data are from 2001 and 2003, respectively, and were obtained from the Town of Falmouth Planning Department. The land use database contains traditional information regarding land use classifications (MADOR, 2002) plus additional information developed by the Town about impervious surfaces (building area, driveways, and parking area) on individual lots. The parcel coverages and assessors database were combined for the MEP analysis by using the Cape Cod Commission Geographic Information System (GIS).

Figure IV-1 shows the land uses within the study area. Land use in the study area is one of seven land use types: 1) residential, 2) commercial, 3) industrial, 4) undeveloped, 5) mixed use, 6) public service/government, including road rights-of-way, and 7) ponds. “Public service” is the land classification assigned by the Massachusetts Department of Revenue to tax exempt properties, including lands owned by government (*e.g.*, wellfields, schools, open space, roads) and private groups like churches and colleges. Massachusetts Assessors land uses classifications (MADOR, 2002), which are common throughout Massachusetts, are aggregated into these six land use categories.

In the West Falmouth Harbor watershed, the predominant land use based on area is public service/right of way, which accounts for 47% (787 acres) of the watershed area (almost all east of Rte. 28); residential land is the second highest percentage (33%) of the watershed (almost all west of Rte. 28; Figure IV-2). The majority of the public service land is the parcels occupied by and surrounding the town’s municipal wastewater treatment facility (WWTF). When the number of parcels is considered, 67% of the parcels in the system watershed are classified as single family residences (MADOR land use code 101) and single family residences account for 93% of developed properties classified as residential. It is notable that there is more land in the industrial classification than the commercial classification; this is largely due to the presence of the Falmouth Industrial Park in the watershed.

In order to estimate wastewater flows within the West Falmouth Harbor watershed, MEP staff also obtained parcel-by-parcel water use information from the Town of Falmouth Water Department. This information included two years of water use information with the final reading in May 2003. Water use information was linked to the parcel and assessors data using GIS techniques. Water use for each parcel was converted to an annual volume for purposes of the nitrogen loading calculations. Developed parcels, except for the Town WWTF, utilize on-site septic systems for wastewater treatment and discharge effluent to the groundwater. The Town WWTF imports wastewater from a collection system outside of the watershed and discharges effluent in areas shown in Figure IV-1 and discussed in greater detail below (Section IV.2.3). Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the measured water-use, nitrogen concentration, and an assumed consumptive loss of water before the remainder is treated in a septic system.

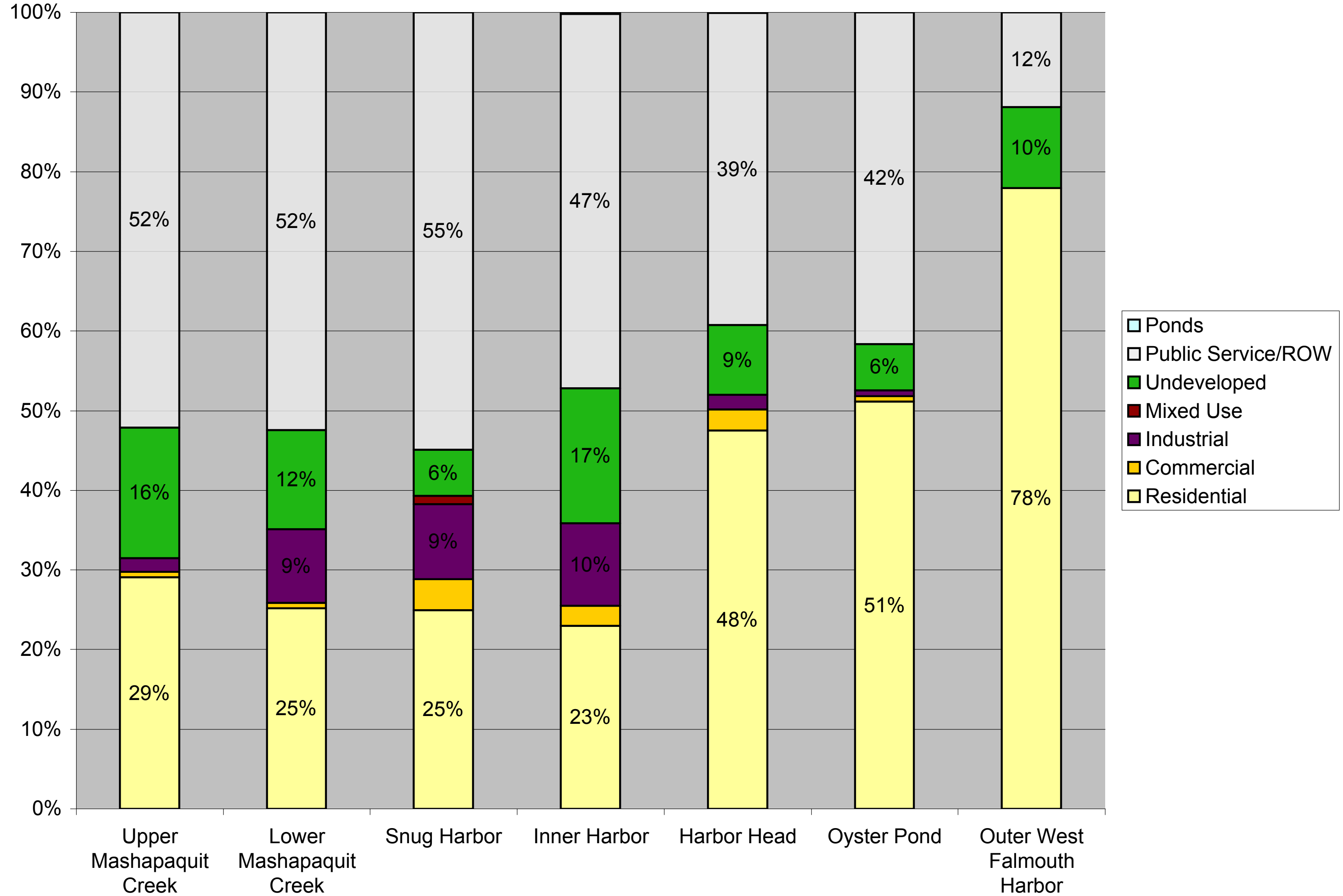


Figure IV-2. Distribution of land uses within the West Falmouth Harbor subwatersheds. Only land uses with percentages greater than 5% are labeled.

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

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

All nitrogen losses within the septic system are incorporated. For example, information developed at the DEP Alternative Septic System Test Center at the Massachusetts Military Reservation on Title 5 septic systems have shown nitrogen removals between 21% and 25%. Multi-year monitoring from the Test Center has revealed that nitrogen removal within the septic tank was small (1% to 3%), with most (20 to 22%) of the removal occurring within five feet of the soil adsorption system (Costa et al. 2001). Aquifer studies indicate that further nitrogen loss during aquifer transport is negligible (Robertson et al. 1991, DeSimone and Howes 1996).

In its application of the water-use approach to septic system nitrogen loads, the MEP has ascertained for the Estuaries Project region that while the per capita septic load is well constrained by direct studies, the consumptive use and nitrogen concentration data are less certain. As a result, the MEP has derived a combined term the effective N Loading Coefficient (consumptive use times N concentration) of 23.63, to convert water (per cubic meter) to nitrogen load (N grams). 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, etc.).

The nitrogen loads developed using this approach have been validated in a number of long and short term field studies where integrated measurements of nitrogen discharge from watersheds could be directly measured. Weiskel and Howes (1991, 1992) conducted a detailed watershed/stream tube study that monitored septic systems, leaching fields and the transport of the nitrogen in groundwater to adjacent Buttermilk Bay. This monitoring resulted in estimated annual per capita nitrogen loads of 2.17 kg (as published) to 2.04 kg (if new attenuation information is included). Modeled and measured nitrogen loads were determined for a small sub-watershed to Mashapaquit Creek in West Falmouth Harbor (Smith and Howes 2006) 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 and under the ecological situation (Samimy and Howes unpublished data).

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

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

In order to provide an independent validation of the residential water use average within the West Falmouth Harbor study area, MEP staff reviewed US Census population values in the

Town of Falmouth. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so each person generates 55 gpd of wastewater. Average occupancy within the Town of Falmouth during the 2000 US Census was 2.36 people per household. If the Falmouth average of 2.36 is multiplied by 55 gpd, the average residential wastewater flow in the West Falmouth Harbor watershed would be 130 gpd. In the West Falmouth Harbor watershed, the adjusted average water use among the 680 single family residences is 126 gpd; this average includes the removal of one property from the town database that had an average water use of 25,0963 gpd. The adjusted flow in the West Falmouth Harbor watershed is a good match with this simple check on the water use data.

In order to complete the estimate of existing nitrogen loads to West Falmouth Harbor, MEP staff needed to develop water use estimates for properties that are thought to utilize private wells. Although water use information exists for 99% of the residential properties in the West Falmouth Harbor watershed, there are 13 developed residential properties that do not have water use accounts and are thought to utilize private wells for drinking water. MEP staff used the average residential water use derived from the 680 residences (99% of the units) for these properties (Table IV-2). The ten existing commercial, industrial, and government properties within the watershed without water use were also assigned flows derived from parcels with water-use data of similar State Class Code.

Table IV-2. Average Water Use in West Falmouth Harbor Watershed

Land Use	State Class Codes	# of Parcels with Water Use in Watershed	Water Use (gallons per day)	
			Watershed Average	Subwatershed Average Range
Residential	101	680	126	33 to 762
Commercial	300 to 389	17	354	35 to 753
Industrial	400 to 439	26	659	88 to 1,299

Note: All data for analysis supplied by town.

Town of Falmouth Wastewater Treatment Facility

The Town of Falmouth maintains a municipal wastewater treatment facility (WWTF) with discharge basins and spray irrigation areas within the watershed to West Falmouth Harbor (Figure IV-1, IV-10 shows the discharge areas). The WWTF imports wastewater from a sewer collection system generally concentrated in the main town center and the village of Woods Hole, treats it, and discharges it within the West Falmouth Harbor watershed. MEP staff obtained three years (2001-2003) worth of influent and effluent flow information, including effluent total nitrogen concentrations and percent discharge to discharge basins and spray irrigation areas, from the DEP (B. Dudley, personal communication, 2/20/04) to review the current nitrogen loading from the WWTF. This information was supplemented with water quality information from wells downgradient of the WWTF that is regularly submitted to the Cape Cod Commission by the Town. Historic WWTF discharges were also evaluated relative to long term nitrogen loading rates (Section IV.2.3).

Flow monitoring data presented significant differences between influent and effluent (effluent averaged 14% higher); MEP staff, in consultation with DEP and town staff, determined that the influent flows were more appropriate for estimating nitrogen loading from the WWTF. Influent into the WWTF is composed of wastewater collected by the sewer system and septage delivered to the plant for treatment. The sewer flow is continuously monitored by a meter prior to delivery to the WWTF and septage disposal is assigned a per gallon charge at delivery. Effluent flow, on the other hand, is based on a single morning reading at a WWTF weir. Based on the flow measurement methods, the influent flows data was deemed to give the most accurate estimate of effluent volume discharge from the WWTF. Note that there is little process water added at the facility.

The MEP analysis utilizes averages for the WWTF nitrogen loading analysis, but there are fluctuations in some of the components. The WWTF began discharging to effluent in October 1986. Water quality monitoring data collected in West Falmouth Harbor by the Falmouth Pond Watchers, partnered with The Coalition for Buzzards Bay, has allowed scientists in previous analyses (e.g., Eichner, *et al*., 1998, Howes et al. 2000) to estimate that it takes approximately six to seven years for effluent from the WWTF to reach West Falmouth Harbor. Under the conditions of the state wastewater discharge permit for the Town's WWTF, the Town has maintained a monitoring well network downgradient of the WWTF. MEP staff reviewed monitoring data from 1997 through 2005 for wells downgradient of the WWTF that have high specific conductivity and chloride concentrations (Figure IV-3). After correcting total nitrogen using an available effluent chloride concentration, the overall dilution corrected average TN concentration was 26.5 ppm (SD=29.1; n=132). Total nitrogen concentrations in the effluent between 2001 and 2003 varied between 6.6 and 40.3 ppm, but flow weighted average for the three years was 18.9, 26.9, and 24.7 ppm, respectively. The average of these concentrations is 23.5 ppm. After considering the available data, MEP staff selected 23.5 ppm TN as the appropriate TN concentration for WWTF load to West Falmouth Harbor.

Between 2001 and 2003, annual influent to the Falmouth WWTF varied between 143.6 and 159.3 million gallons with a peak in flow in June, July, and August (Figure IV-4). In the Town's Needs Assessment study for their Facilities Plan (Stearns and Wheler, 1999), the average daily influent flow to the WWTF (1995 to 1998) and the 1998 average daily influent to the WWTF are both 0.463 million gallons per day (MGD). Conversion of the 2001 to 2003 annual influent flows to average daily flows yields 0.436, 0.393, and 0.399 MGD, respectively. This finding suggests that the annual influent flow of 149.5 million gallons is an appropriate flow for calculating the WWTF load given the observed variability (coefficient of variation (s.d./mean) of 6%).

The division of effluent discharge among the spray irrigation areas and the discharge basins is subject to more variability than the other factors used in determining the nitrogen load from the WWTF. The spray irrigation areas were first utilized in 1988 and they were used for an average of 82% of the effluent flow during 1988 and 1989 (Jordan et al. 1991). During the years 2001 through 2003, the irrigation areas were used for 34%, 44%, and 51% of the annual flow, respectively. No information on division of effluent discharge was included in the Needs Assessment report (Stearns and Wheler, 1999). Given that the majority of the area of the discharge basins is located in the Mashapaquit Creek subwatershed and, thus, effluent flows to these are subject to the attenuation in the Creek system, while the majority of the irrigation areas are not, the high variability in this factor is a cause for some concern. However, the similar nitrogen concentrations observed in the monitoring wells and in the effluent suggest that the distinction between the spray irrigation and discharge basins is more important in terms of their location.

As a result of the review of available information on the Town of Falmouth WWTF, MEP staff selected the following values for calculating the nitrogen load from the WWTF: annual effluent flow is 149.5 million gallons, effluent nitrogen concentration is 23.5 ppm, and 57% is discharged through the basins with the remainder to the spray irrigation areas. Based on these factors the WWTF annually adds 13,300 kg to West Falmouth Harbor. Of this total watershed loading, 8100 kg is within the Mashapaquit Creek sub-watershed which was intensively studied by SMAST scientists from 1997-2000. The nitrogen load projected to reach the Creek in 2003-2004 derived from this earlier study was ~8000 kg per year indicating that the load to this sub-basin has been relatively constant over this interval (see Section IV.2.3).

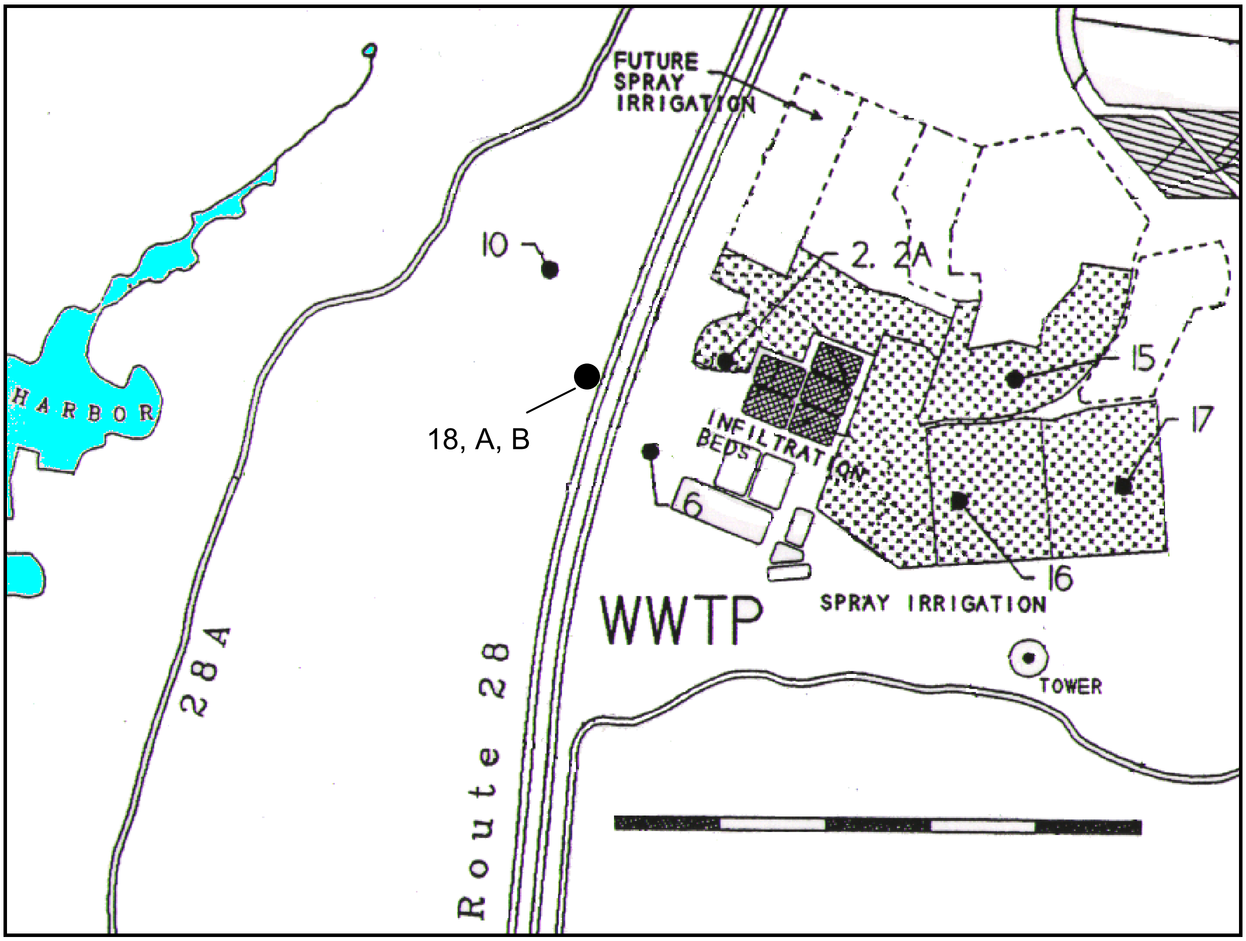
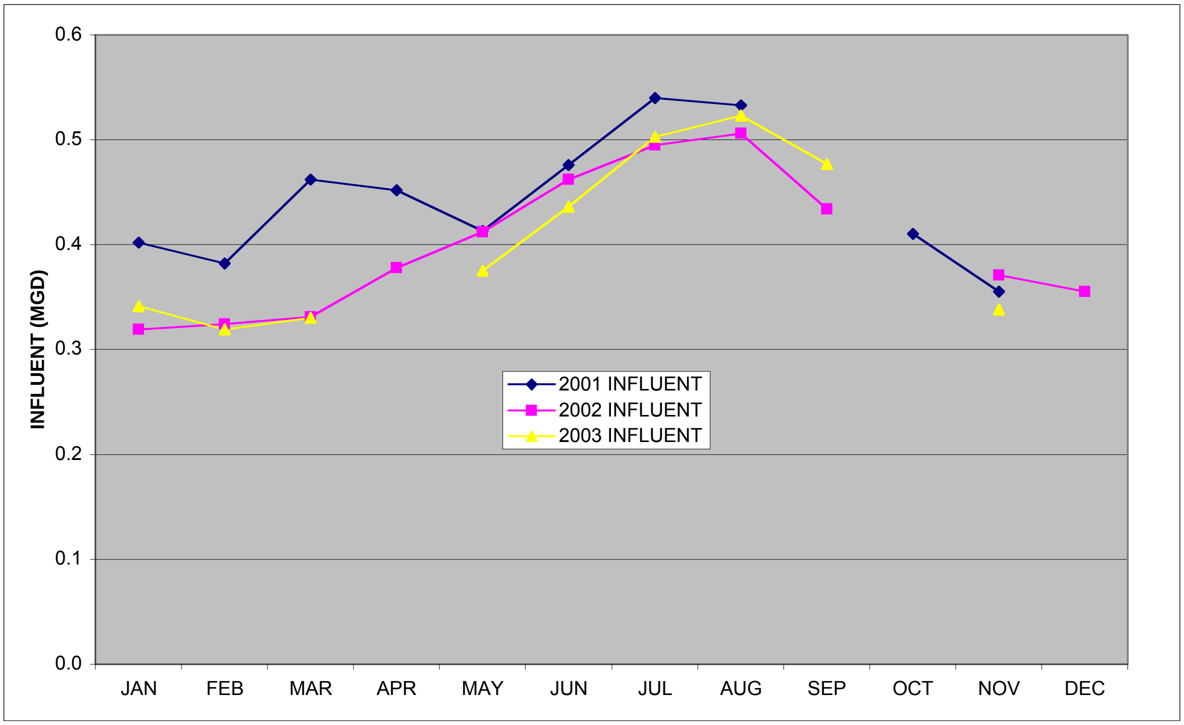
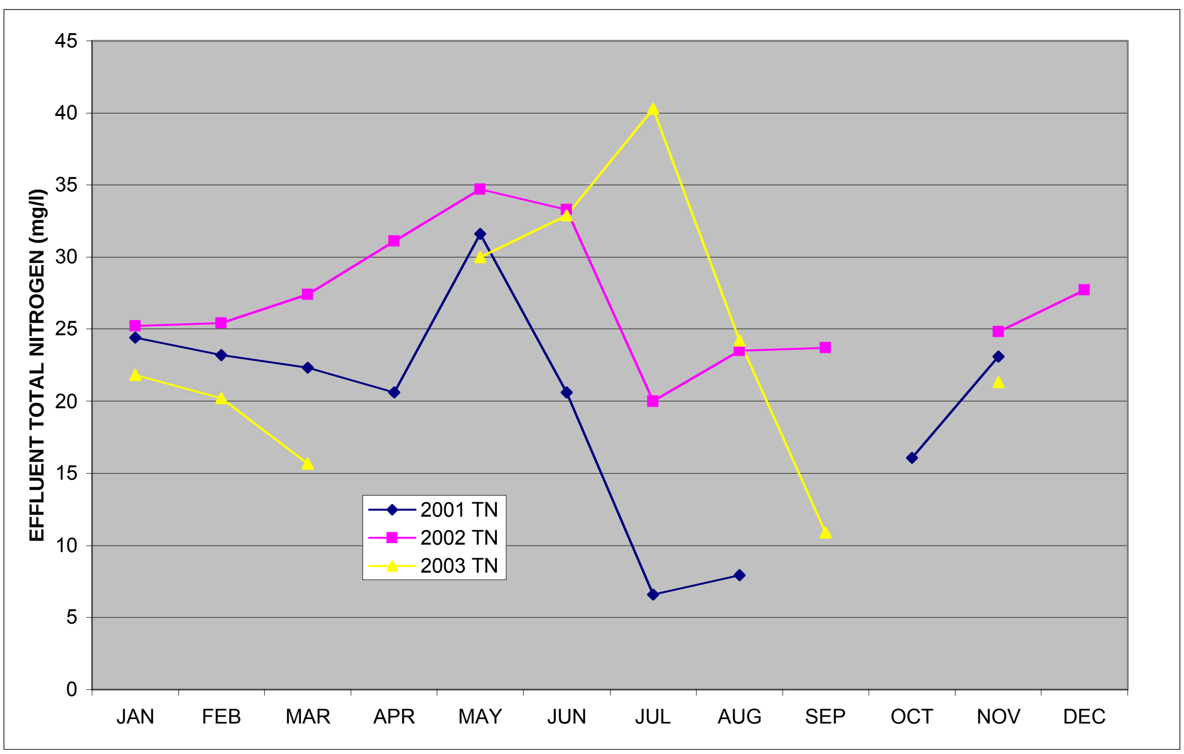


Figure IV-3. Monitoring wells with high specific conductivity and high chloride concentrations used to check the total nitrogen concentrations associated with the Falmouth WWTF. Monitoring data from 1997-2005 and supplied by the Town of Falmouth was reviewed. (Graphic modified from Howes, et al., 1992) .



A. Town of Falmouth WWTF Influent Flows



B. Town of Falmouth WWTF Effluent Total Nitrogen Concentrations

Figure IV-4. Monitoring data from Town of Falmouth Wastewater Treatment Facility (2001-03).

Nitrogen Loading Input Factors: Fertilized Areas

After wastewater, the next largest source of estuary watershed nitrogen loading is usually fertilized lawns and golf courses, with lawns being the predominant source within this category. In order to add this source to the nitrogen loading model for the West Falmouth Harbor system, MEP staff reviewed available information about residential lawn fertilizing practices.

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

The initial effort 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% resulted in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn for use in the nitrogen loading calculations. It is likely that this still represents a conservative estimate of nitrogen load from residential lawns. It should be noted that professionally maintained lawns were found to have the higher rate of fertilization application and hence higher estimated loss to groundwater of 3 lb/lawn/yr. Only residential fertilizer applications are included in the West Falmouth Harbor nitrogen loading as site surveys indicated minimal lawn areas associated with commercial and industrial parcels and there are not golf courses.

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 nitrogen loading analysis for the West Falmouth Harbor watershed are summarized in Table IV-3.

Table IV-3. Primary Nitrogen Loading Factors used in the West Falmouth Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from the Town of Falmouth. *Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.

Nitrogen Concentrations:	mg/l	Recharge Rates:	in/yr
Road Run-off	1.5	Impervious Surfaces	40
Roof Run-off	0.75	Natural and Lawn Areas	27.25
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:	
Natural Area Recharge	0.072	Existing residential and commercial parcels wo/water accounts:	126 gpd
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (ft^2)*	5,000		
Residential Watershed Nitrogen Rate (lbs/lawn)*	1.08	Existing parcels w/water accounts:	Measured annual water use
Town of Falmouth Wastewater Treatment Facility:		Buildout Parcels Assumptions:	
Effluent Flow (10^6 gal/y)	149.5	Residential parcels:	126 gpd
Effluent TN concentration (ppm)	23.5	Commercial parcels:	18 gpd/1,000 ft2 of building
Flow to discharge basins (%)	57	Commercial building coverage	40%
Flow to irrigation areas (%)	43	Industrial parcels	All parcels in Falmouth Industrial Park; used Development Agreement limits
Buildout flow (1 MGD) and treatment level (3 ppm TN) based on Cape Cod Commission decision			

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, parcels were assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel was located within a respective watershed. Following the assigning of boundary parcels, all large parcels were examined individually and were split (as appropriate) in order to obtain less than a 2% difference between the total land area of each subwatershed and the sum of the area of the parcels within each subwatershed. The resulting "parcelized" watersheds to West Falmouth Harbor are shown in Figure IV-5.

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, WWTFs, etc.) were 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 West Falmouth Harbor estuary. The assignment effort was undertaken to better define the sub-embayment loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Following the assignment of all parcels, subwatershed modules were generated for each of the thirteen sub-watersheds summarizing water use, parcel area, frequency, sewer connections, private wells, and road area. As mentioned above, these results were then condensed to seven subwatersheds based upon the time of travel analysis (<10 yr vs. > 10 yr) discussed above. The individual sub-watershed modules were then integrated to create the West Falmouth Harbor Watershed Nitrogen Loading module with summaries for each of the individual subembayments. The subembayments represent the functional embayment units for the Linked Watershed-Embayment Model's water quality component.

For management purposes, the aggregated embayment watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the West Falmouth Harbor System, the major types of nitrogen loads are: wastewater (both septic systems and the town WWTF), fertilizer, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-4). The output of the watershed nitrogen loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-6). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model. However, as noted above, the West Falmouth Harbor watershed nitrogen input is not subject to attenuation within the watershed, as there are no fresh great ponds. Attenuation of watershed nitrogen was only considered within the fresh and salt water portions of Mashapaquit Creek (Sections IV.2.2, IV2.3).

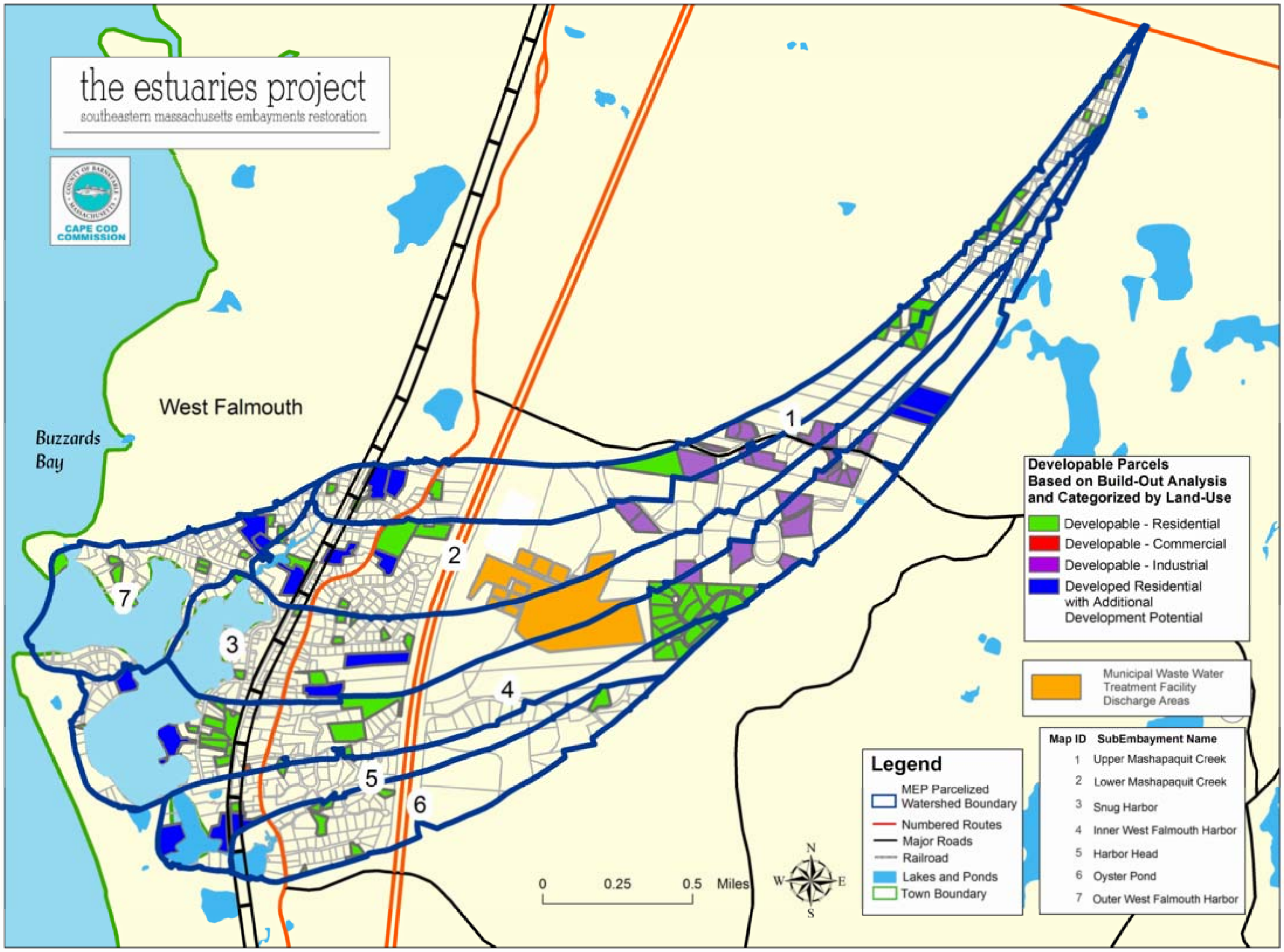
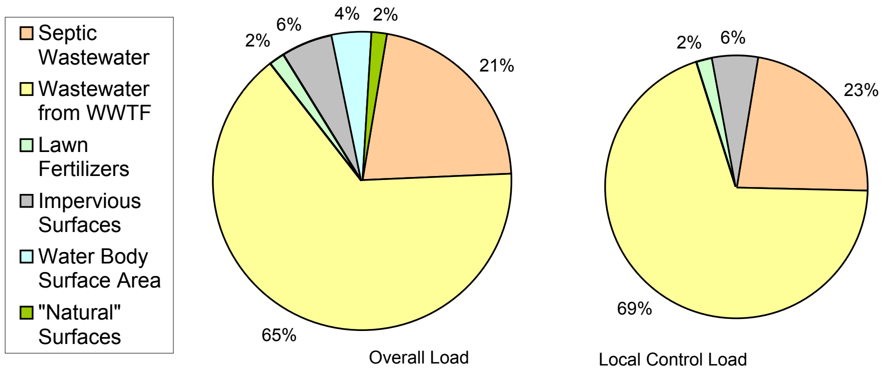


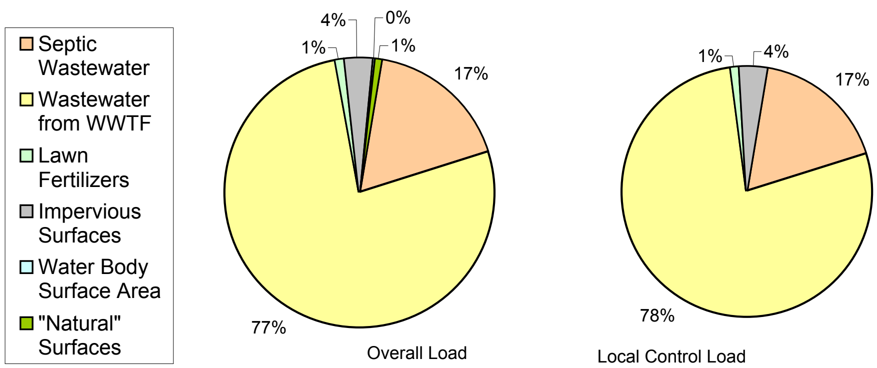
Figure IV-5. Parcels, Parcelized Watersheds, and Developable Parcels in the West Falmouth Harbor watershed.

Table IV-4. Nitrogen Loads to the West Falmouth Harbor Estuary. Attenuation of system nitrogen loads occurs as nitrogen moves through Mashapaquit Creek during transport to the estuary. Wastewater loads represents on-site septic treatment and discharge from the Town of Falmouth Wastewater Treatment Facility. Note that the "Inner Harbor" is also called South Basin or Chappaquoit Basin and the "Outer Harbor" is the region between Old Field Point and the Harbor inlet.

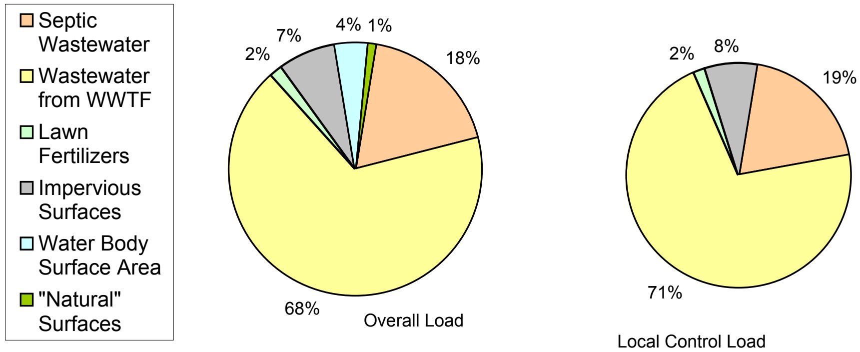
		Present W Falmouth Hbr N Loads by Input:						*Buildout by Input:*			*Present N Loads*			*Buildout N Loads*		
Name	Watershed ID#	Septic System Wastewater	Wastewater from WWTF	Lawn Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Buildout Septic System Wastewater	Buildout Wastewater from WWTF	Buildout other	UnAtten N Load	Atten %	Atten N Load	UnAtten N Load	Atten %	Atten N Load
West Falmouth Harbor System	1 to 13	4389	13300	365	1139	919	322	1451	4145	2829	20434		16210	8425		7693
Mashapaquit Crk	1,2,3,4	1810	8120	120	394	12	101	918	2530	656	10558	40%	6335	4104	40%	2470
Upper Mashapaquit Crk	1,2	563	0	52	109	0	45	392	0	223	769		769	615		615
Upper Mashapaquit Crk GT10	1	310	0	30	66	0	25	392	0	135	431		431	527		527
Upper Mashapaquit Crk LT10	2	253	0	22	43	0	20	0	0	88	338		338	88		88
Lower Mashapaquit Creek	3,4	1247	8120	68	285	12	56	526	2530	433	9789		9789	3502		3502
Lower Mashapaquit Creek GT10	3	509	317	17	200	0	21	526	99	240	1064		1064	865		865
Lower Mashapaquit Creek LT10	4	738	7803	51	85	0	36	0	2432	193	8712		8712	2624		2624
Mashapaquit Crk Estuary surface deposition						12					12		12	12		12
Snug Harbor	5,6	698	2582	66	279	166	47	42	805	565	3838		3838	1578		1578
Snug Harbor GT10	5	38	1809	2	161	0	20	42	564	183	2029		2029	789		789
Snug Harbor LT10	6	660	774	64	119	0	27	0	241	382	1643		1643	623		623
Snug Harbor Estuary surface deposition						166					166		166	166		166
Inner Harbor	7,8	761	2598	60	282	320	87	352	809	773	4106		4106	2251		2251
Inner Harbor GT10	7	237	2598	19	176	4	48	352	809	261	3081		3081	1423		1423
Inner Harbor LT10	8	524	0	41	106	0	39	0	0	512	710		710	512		512
Inner Harbor Estuary surface deposition						316					316		316	316		316
Harbor Head	9,10	296	0	29	44	56	27	49	0	167	452		452	272		272
Harbor Head GT10	9	24	0	3	5	0	9	49	0	20	41		41	69		69
Harbor Head LT10	10	271	0	26	39	0	18	0	0	146	355		355	146		146
Harbor Head Estuary surface deposition						56					56		56	56		56
Oyster Pond	11,12	359	0	35	74	29	30	89	0	173	527		527	291		291
Oyster Pond GT10	11	85	0	7	8	0	9	89	0	24	109		109	114		114
Oyster Pond LT10	12	274	0	28	66	0	21	0	0	149	389		389	149		149
Oyster Pond Estuary surface deposition						29					29		29	29		29
Outer West Falmouth Harbor	13	465	0	55	66	336	30	0	0	496	953		953	832		832
Outer West Falmouth Harbor	13	465	0	55	66	0	30	0	0	496	617		617	496		496
Outer West Falmouth Harbor Estuary surface deposition						336					336		336	336		336



a. West Falmouth Harbor System Overall

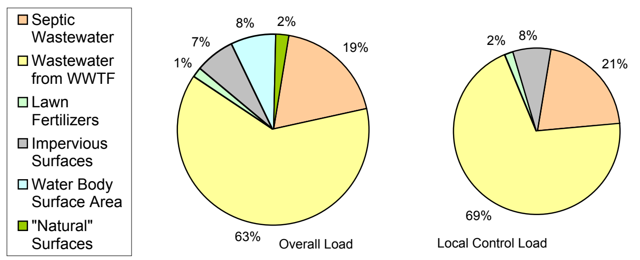


b. Mashapaquit Creek

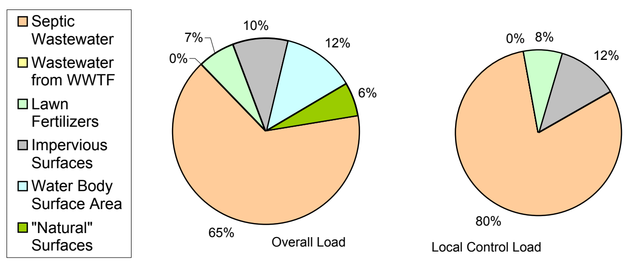


c. Snug Harbor

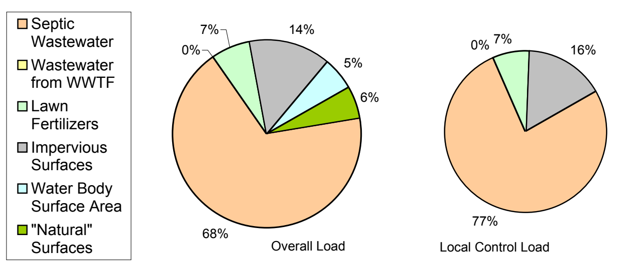
Figure IV-6 (a-c). Source-specific unattenuated nitrogen loads (by percent) to the (a) overall West Falmouth Harbor System watershed, (b) Mashapaquit Creek subwatershed, and (c) Snug Harbor subwatershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control (i.e., excludes atmospheric deposition to estuarine surface and natural areas).



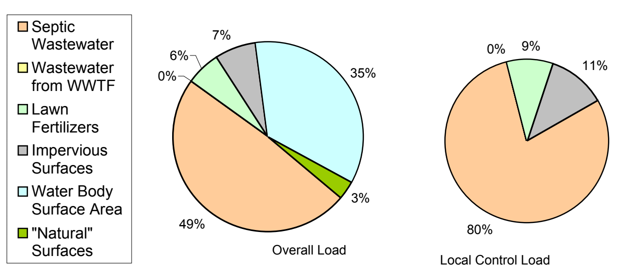
d. Inner Harbor



e. Harbor Head



f. Oyster Pond



g. Outer Harbor

Figure IV-6 (d-f). Source-specific unattenuated nitrogen loads (by percent) to the (d) Inner Harbor (South Basin) subwatershed, (e) Harbor Head subwatershed, (f) Oyster Pond subwatershed, and (g) Outer Harbor subwatershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control (i.e., excludes atmospheric deposition to estuarine surface and natural areas).

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development within the study area watershed. For the West Falmouth Harbor modeling, buildout of parcels were determined in consultation with the Town of Falmouth Planning Department. All municipal overlay districts (*e.g.*, water resource protection districts) and existing zoning were considered in the determination of minimum lot sizes. The buildout also includes an assumption that all industrial parcels in the Falmouth Industrial Park utilize Title 5 septic systems according to flow limits included in the development agreement for the park between the Cape Cod Commission and the Town of Falmouth. A nitrogen load for each parcel was determined for the existing development using the factors presented in Table IV-3 and discussed above. Parcels included in the buildout assessment for the West Falmouth Harbor watershed are shown in Figure IV-5. A summary of total potential additional nitrogen loading from build-out is presented as unattenuated and attenuated loads in Table IV-2. However, only the attenuated nitrogen loads were used for the water quality modeling, as the unattenuated rates of nitrogen loading would not permit model validation to conditions within embayment waters under any realistic physical conditions.

The buildout assessment also includes an upgrade in treatment levels and increase in flow at the Town WWTF according to the May 2001 decision of the Cape Cod Commission and the Department of Environmental Protection Groundwater Discharge Permit. The decision and permit limited discharge within the West Falmouth Harbor watershed to 1.0 MGD with a 3 ppm TN effluent concentration and required sewering of properties within the watershed west of Route 28. Since the ten year time of travel lines (see Figure III-1) roughly correspond to the location of Route 28, the buildout assessment assumed that all parcels within the less than 10 year lines were connected to the sewer and the wastewater is treated at the Town WWTF. The buildout assessment assumes 1.0 MGD of 3 ppm TN effluent discharge at the WWTF including connection of properties in the <10 year time of travel subwatersheds with flow divided among the spray irrigation and discharge basins according to the same assumption used in the existing conditions estimates. Due to the upgrade of the WWTF and the sewering of the parcels west of Rt. 28, the buildout nitrogen load to West Falmouth Harbor will be substantially less than the present nitrogen load. This watershed nitrogen management plan was develop specifically to address the nutrient related habitat decline of West Falmouth Harbor. The MEP Linked Watershed-Embayment Management Model's water quality module will be used to specifically assess the adequacy of this approach (Chapter VIII).

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 West Falmouth Harbor 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. 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 West Falmouth Harbor embayment system sub-watersheds, most of the freshwater flow and transported nitrogen enters the estuary directly in groundwater seepage. However, the sub-watershed to upper Mashapaquit Creek discharge to a small stream and then salt marsh. In the case of lower Mashapaquit Creek, groundwater and its associated nutrient load discharges directly to the salt marsh system. Although these sub-watersheds account for ~30% of the total watershed to the Harbor, they receive over 50% of the watershed nitrogen load. Upper and Lower Mashapaquit Creek as surface water systems present the opportunity for significant nitrogen attenuation.

Failure to determine or check 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 improvements in estuarine health if focused on the watershed region having unattenuated nitrogen transport (other factors being equal). In addition to attenuation by freshwater ponds (see Section IV.1.3, above), attenuation in surface water flows is also important. An example of the significance of surface water nitrogen attenuation relating to embayment nitrogen management was seen in the Agawam River, where >50% of nitrogen originating within the upper watershed was attenuated prior to discharge to the Wareham River Estuary (CDM 2001). 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). Similarly, the small tidal basin of Frost Fish Creek in the Town of Chatham showed ~20% nitrogen attenuation or watershed nitrogen load prior to discharge to Ryders Cove. In a large salt marsh system, Great Sippewissett Marsh, creek bottom denitrification was found to attenuate 72% of the nitrate entering from the watershed, nitrate being the predominant form of nitrogen entering the marsh from land-based sources. 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 attenuation of nitrogen entering upper Mashapaquit Creek were undertaken as part of the MEP approach, however this effort was interrupted approximately one month after inception. Mashapaquit Creek, upgradient of the Chase Road culvert, flows across private property and the MEP was asked by the property owner to remove the continuously recording stream gage that was placed in the creek to obtain a long term record of stream stage to be used as the basis for determining daily and annual flow. The MEP considered relocating the stream gage elsewhere, however, given the property lines a site was not available which would yield useful data. Given the unique circumstances impeding the gaging of this creek, the MEP had little choice other than to base its analysis on periodic point measurements of flow and nitrogen load obtained during a previous nutrient analysis undertaken by current members of the MEP Technical Team as it related to nutrient discharges from the Falmouth Wastewater Treatment Facility. These flow measurements were obtained in 1989 and 1990 and were enhanced with additional flow measurements made in 2003 by the MEP. A composite record was developed that contained at least one flow measurement in each of the twelve months of the composite year. The point flow measurement in a given month was assumed to be representative of flow for that month and as such was used to calculate a monthly flow. This was repeated for each of the twelve months for the composite year and as such an annual flow for Upper Mashapaquit Creek was calculated as the basis for loading calculations.

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 Upper Mashapaquit Creek at Chase Road provides a direct integrated measure of all of the processes presently attenuating nitrogen in the sub-watersheds upgradient from the flow measurement location. In order to check freshwater volume passing through the Chase Road culvert as determined by the watershed area and recharge rate method discussed in Section IV.1, flow was measured at the Chase Road site for 12 months of record (Figure IV-8). Additionally, in the months for which total nitrogen data was available, the MEP was able to check nitrogen attenuation previously determined in an earlier 1997-2000 study of the West Falmouth Harbor system. Total nitrogen concentrations were available during six of the 12 months of the composite year used in this evaluation. A monthly mean total nitrogen concentration was calculated based on the available total nitrogen data and the mean total nitrogen concentration was applied to each of the 12 months for which flow data existed thereby yielding an annual attenuated total nitrogen load at the Chase Road culvert.

Flow at the Chase Road culvert was determined from monthly measurements of velocity profiles in the channel. 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) in a given month. 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.

The annual flow record for the Mashapaquit Creek (Chase Road culvert) surface water flow was merged with the nutrient data set generated through the collection of water quality samples at the time the flow measurements were obtained to determine an estimate of nitrogen loading rates to the head of Lower Mashapaquit Creek salt marsh. Lower Mashapaquit Creek is comprised of the tidal creeks and vegetated salt marsh lying between Chase Road and the Nashawena Road bridge.

Nitrogen discharge from Mashapaquit Creek at Chase Road was calculated using the paired discharge and total nitrogen concentration data to determine the mass flux of nitrogen through the gaging site that reaches the head of the marsh system on a monthly basis. Water samples were collected (at low tide) in order to determine nutrient concentrations from which nutrient load was calculated. Salinity measurements indicated that all samples were freshwater (<0.1ppt). The nitrogen discharge data are expressed as nitrogen mass per unit time (kg/month) and can be summed in order to obtain annual nutrient load to the embayment system. 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 MEP to check the degree to which natural biological processes within the watershed, upgradient of the Chase Road site, attenuates nitrogen load prior to discharge to Lower Mashapaquit Creek marsh.

Figure IV-7. Location of Stream flow measurements (red circle) in the West Falmouth Harbor embayment system. Flow measurements obtained in Mashapaquit Creek at the Chase Road Culvert. Several studies of nitrogen transport from watershed source through Mashapaquit Creek prior to discharge to Snug Harbor support a removal rate of 40%.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge to Mashapaquit Creek Marsh

Unlike many stream systems across Cape Cod and southeastern Massachusetts, the freshwater portion of Mashapaquit Creek (Upper Mashapaquit Creek) does not drain a pond or have kettle ponds within its watershed. As a result, an integrated measure of natural nitrogen attenuation by biological processes associated with surface water transit is likely to be lower than many other streams on Cape Cod. Even though the freshwater portion of Mashapaquit

Creek is not associated with fresh ponds, it still supports enough direct groundwater flow to the stream channel to flow continuously throughout the year. As such, natural attenuation can occur as freshwaters flow through the freshwater wetlands and streambed associated with the creek. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to Mashapaquit Creek above the Chase Road culvert flow measurement site and the measured annual discharge of nitrogen at the same location, Figure IV-7.

At the Upper Mashapaquit Creek (Chase Road culvert) flow measurement location, a continuously recording vented calibrated water level gage was installed to yield the level of water in the freshwater portion of Mashapaquit Creek that carries the flows and associated nitrogen load to the head of Snug Harbor. At the request of the land-owner, the MEP removed the gage after 1 month and thereafter relied upon periodic point measurements of flow and nitrogen load (Section IV.2.1). The MEP assembled a composite year of flow measurements with which to calculate monthly and annual flow from Mashapaquit Creek. Measurements collected by the MEP Technical Staff in 2003 were enhanced by data obtained during a previous nutrient analysis undertaken by current members of the MEP Technical Team as it related to nutrient discharges from the Falmouth Wastewater Treatment Facility in 1997-1999. Flow measurements were obtained in every month of the composite year and some months had multiple flow measurements (same month but different years) which were averaged and assumed representative of flow for the month. Though this is clearly an estimate, yet in the absence of detailed stage records and stream specific rating curves, flow estimates are typically calculated in this manner. Naturally, the greater the number of flow measurements, the closer the estimate gets to being representative of flow in a stream during a given period of time. In order to obtain a daily flow, the MEP divided the calculated annual flow by 365 days. As Mashapaquit Creek up to the down gradient end of the Chase Road culvert is tidally influenced, flow measurements were made at the upgradient end of the culvert.

Stream flow (volumetric discharge) was measured at low tide using a Marsh-McBirney electromagnetic flow meter. Water samples were collected at the time flow measurements were made for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the estuarine portion of Mashapaquit Creek Marsh (Figure IV-8 and Table IV-5). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at the flow measurement site (Chase Road culvert).

The annual freshwater discharge from Upper Mashapaquit Creek as determined by the MEP based on flow measurements obtained during a composite year was 613,396 m^3 yr^{-1} (1680 m^3 day^{-1}). This flow was compared to the long-term average flows determined by the USGS modeling effort (685,143 m^3 yr^{-1}, 1877 m^3 day^{-1}). The measured freshwater discharge from Mashapaquit Creek at Chase Road as determined by the MEP was 90% of the long-term average modeled flows and as such the watershed and river datasets appear to be in balance.

Total nitrogen concentrations within the Upper Mashapaquit Creek discharge were relatively high, 0.654 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 1.10 kg/day and a measured total annual TN load of 401 kg/yr. From the measured nitrogen load discharged by the creek at the Chase Road culvert to the head of Mashapaquit Creek marsh and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of watershed derived nitrogen during transport through the stream and associated freshwater wetland. Based upon lower nitrogen load (401 kg yr^{-1}) discharged from the freshwater Upper Mashapaquit Creek compared to that added by the various land-uses to the associated watershed (770 kg yr^{-1}), the integrated attenuation in passage through the creek and freshwater wetlands is 48% (i.e. 48% of nitrogen input to the watershed upgradient of the Chase Road culvert does not reach the estuary). This level of attenuation is consistent with attenuation rates within the Quashnet River and lower than streams with significant kettle ponds within their watersheds. The directly measured nitrogen load from the creek was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI).

Table IV-5. Water flow and nitrogen discharges from Upper Mashapaquit Creek (above Chase Road culvert) discharging to Lower Mashapaquit Creek and the head of Snug Harbor. The "Stream" data is from the MEP stream flow measurement effort. Watershed data is based upon the MEP watershed modeling effort by USGS and CCC.

Stream Discharge Parameter	Stream Discharge (a) to Upper Mashapaquit Creek	Data Source
Total Days of Record	365[b]	(1)
Flow Characteristics		
Stream Average Discharge (m3/day)	1681	(1)
Contributing Area Average Discharge (m3/day)	1877	(2)
Discharge Stream 2002-03 vs. Long-term Discharge	10%	
Nitrogen Characteristics		
Stream Average Total N Concentration (mg N/L)	0.654	(1)
Total Nitrogen (TN) Average Stream Discharge (kg/day)	1.10	(1)
TN Average Contributing UN-attenuated Load (kg/day)	2.11	(2)
Attenuation of Nitrogen in Pond/Stream (%)	48%	(3)

(a) Measured flow and N load to to Upper Mashapaquit Creek (No Pond contributing areas).
(b) Composite year January to December.

(1) MEP flow measurement site data (Chase Road culvert).
(2) Calculated from MEP watershed delineations to Chase Road culvert.
and the annual recharge rate.
(3) Calculated from measured TN discharge from the creek vs. the unattenuated watershed load.

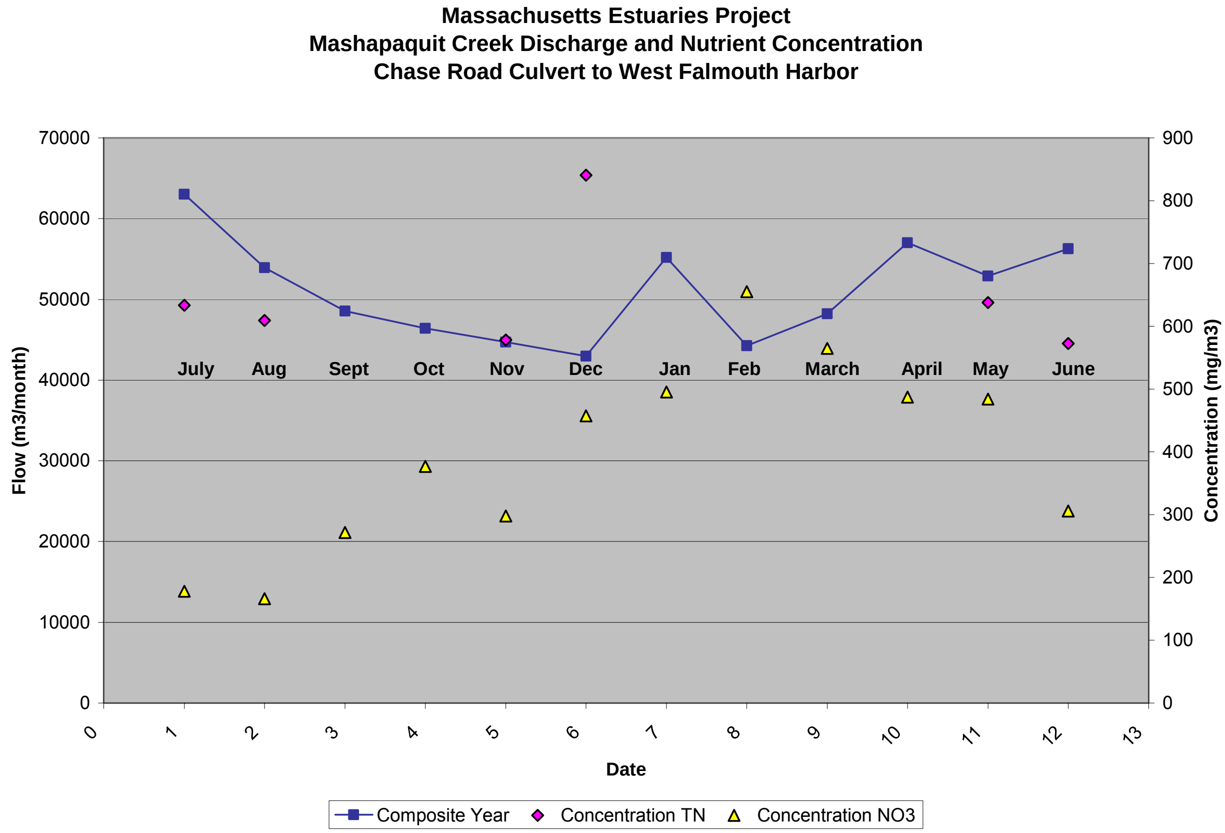


Figure IV-8. Upper Mashapaquit Creek discharge at the Chase Road culvert with composite year flow (solid blue line), nitrate (yellow triangles) and total nitrogen (pink diamonds) concentrations used for determination of annual volumetric discharge and nitrogen load from the upper watershed to the Mashapaquit Creek salt marsh at the head of Snug Harbor (Table IV-5).

Table IV-6. Summary of annual volumetric discharge and nitrogen load from Upper Mashapaquit Creek discharging to Lower Mashapaquit Creek salt marsh and the head of Snug Harbor based upon the data presented in Figure IV-8 and Table IV-5.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m^3/year)	ATTENUATED LOAD (Kg/year)	
			Nox	TN
Mashapaquit Creek (Freshwater)	Composite Year	613396	--	401
Mashapaquit Creek (Freshwater)	Based on Watershed Area and Recharge	685143	--	770

IV.2.3 Mashapaquit Creek Marsh: Attenuation of WWTF and Watershed Nitrogen Loads

Critical to the discussion of attenuation of watershed nitrogen loads to the West Falmouth Harbor system as a whole is the fact that the majority (62%) of the wastewater treatment facility nitrogen load to West Falmouth Harbor enters the Mashapaquit Creek marsh. Since salt marshes can remove significant watershed derived nitrogen through denitrification in creek bottoms, an accurate determination of the watershed nitrogen load which reaches the open waters of West Falmouth Harbor requires an accounting for attenuation during transit through Mashapaquit Creek. A detailed study of nitrogen attenuation by the Mashapaquit Creek marsh was conducted by the Coastal Systems Program-SMAST, 1997-2000.

The Falmouth Wastewater Treatment Facility (WWTF), is located approximately 1 km upgradient of West Falmouth Harbor, at an average elevation of about 30 m above sea level (Figure IV-9). The WWTF has been discharging secondarily treated wastewater to five sand infiltration beds (3480 m^2 each) since October 1986. Since June 1988, additional nitrogen removal was attempted through seasonal spray irrigation of five vegetated areas (forest/grassland). Three additional infiltration beds (5787 m^2 each) began receiving effluent in November 1995. Monitoring wells located at the WWTF indicate a depth to groundwater of ~25 to 30 m (see section IV.1).

Reduced nitrogen in the treated effluent is rapidly oxidized to nitrate as it travels through the unsaturated zone to the water table (Weiskel and Howes, 1994). The resultant nitrate-rich groundwater travels conservatively through the aquifer on its way to West Falmouth Harbor. Since a significant portion of the WWTF nutrient load is discharged to Mashapaquit Creek and is primarily as nitrate, it is readily removed by denitrification in the sediments of the salt marsh present there (Smith, 1999).

Mashapaquit Creek Marsh is a small (14 acre, 5.7 ha), mature salt marsh that fringes Mashapaquit Creek and exchanges with the adjacent waters of West Falmouth Harbor through a 6-m wide rectangular culvert under the Nashawena Street Bridge (Figure IV-9). The marsh exhibits nearly symmetrical semi-diurnal tides with an average range of 1.2 m and drains almost completely during spring low tides. Watershed inputs to the marsh are delivered almost exclusively via groundwater discharge, and ebbing creek waters freshen over the ebb interval, becoming nearly fresh during the two hour period preceding low tide. Freshwater enters the marsh-creek system directly through groundwater seepage and through three groundwater-fed surface flows—at the head of the marsh through a 0.6-m diameter concrete culvert under Chase Road and through two small tributary creeks.

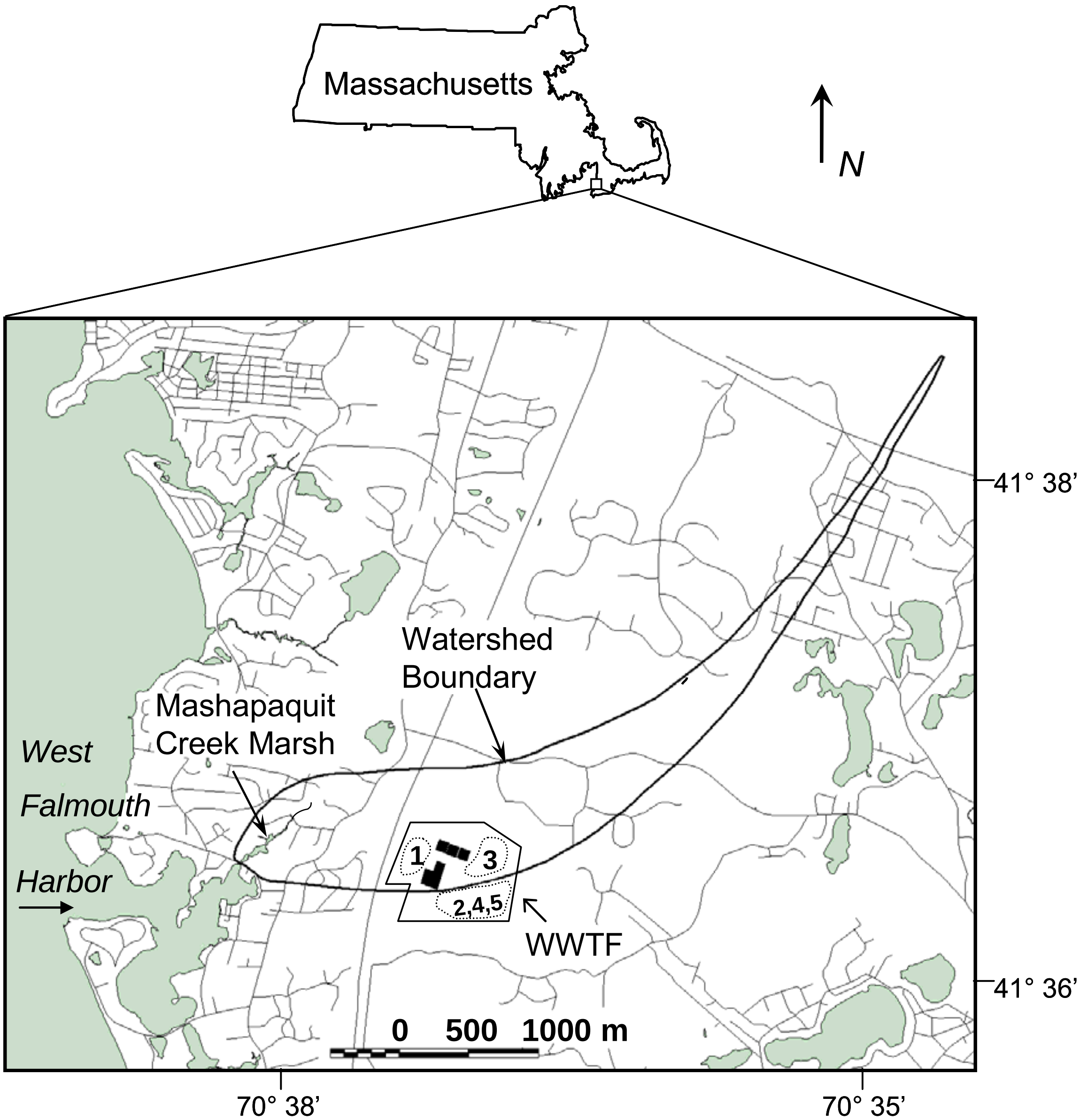


Figure IV-9: Location of West Falmouth Harbor and the Falmouth Wastewater Treatment Facility (WWTF). Heavy line represents the sub-watershed drained by Mashapaquit Creek Marsh, determined by the West Cape Model (Masterson et al., 1998). Solid blocks are WWTF infiltration beds; dotted areas 1-5 are spray irrigation areas (from Howes et al. 2000).

The marsh is typical of New England salt marshes, with the emergent marsh vegetated primarily by *Spartina patens* and with tall *S. alterniflora* present along the creek banks. The lower half of Mashapaquit Creek is characterized by depositional areas of intertidal mud flat, while the upper half has both sandy and muddy bottom sediment. Groundwater seepage face areas (consisting of 2m to 5m wide stretches of shoreline composed of sand, gravel and cobbles) are prevalent in the upper two-thirds of the marsh and are located mainly along the southern shoreline where the distance between the creek bank and the upland is small.

The primary goals of the SMAST study were to (a) quantify the proportion of the nitrogen plume from the Falmouth WWTF which was entering Mashapaquit Creek and (b) determine the amount of nitrogen loading from the surrounding watershed (inclusive of the WWTF plume) which was removed by the marsh, specifically by sediment denitrification.

The study conducted from 1997-2000, quantified nitrogen loads to Lower Mashapaquit Creek, discharges to Snug Harbor and nitrogen attenuation within the salt marsh based on 4 approaches: 1) classical land-use nitrogen modeling, 2) seasonal tidal exchange studies, 3) groundwater and surface water discharge measurements, and 4) detailed annual measurements of creek bottom denitrification using sediment incubations (see Smith 1999, Hamersley and Howes 2003). Additional evaluations of the wastewater plume, loading, mass transport and flow direction were conducted using monitoring data collected as part of the Town of Falmouth's NPDES Permit. These data were provided by the Town of Falmouth (R. Jack, R. White).

The watershed loading model calculated the 1998 N load from the WWTF to the marsh watershed from 1992 effluent discharge, based upon an average 6-year groundwater travel time predicted by the West Cape groundwater flow model (J. Masterson, pers. comm. 1999). Nitrogen loading to groundwater for 1992 was determined from flows (recorded daily) to individual infiltration beds and spray irrigation areas within the marsh watershed boundary and effluent dissolved inorganic nitrogen (DIN) concentration (measured monthly, Town of Falmouth).

Because watershed boundaries on Cape Cod are strongly influenced by changes in groundwater recharge (Millham and Howes 1994), and the WWTF discharge represents a large source of artificial recharge so close to the modeled watershed boundary (Figure IV-10), changes in the water table near the WWTF were evaluated to reduce uncertainty in nitrogen loading calculations. Water table mapping of the southern portion of the Mashapaquit Creek Marsh watershed indicated a static northern edge that agrees well with the West Cape modeled boundary but a southern border that shifts considerably (Figure IV-10). Spatially and temporally variable WWTF discharge of large volumes of treated effluent, especially to infiltration beds 1-5 and spray irrigation of areas 2, 4, and 5 evidently causes localized mounding of the water table and watershed boundary deflection to the north near the beds and to the south near the irrigation areas.

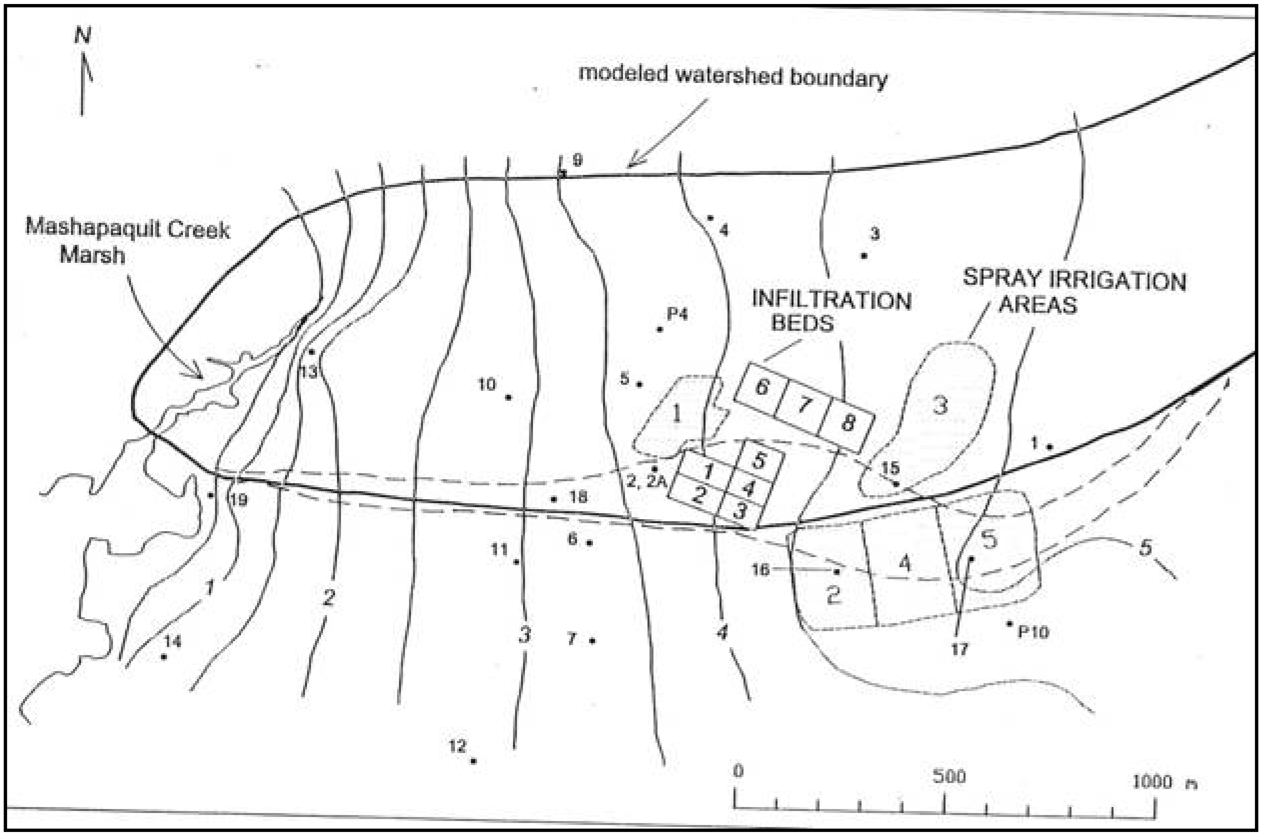


Figure IV-10: Detail of southern watershed boundary (heavy line) to Mashapaquit Creek Marsh, determined by West Cape regional groundwater flow model (1998). Average water table contours (gray lines, contour interval 0.5 m above mean sea level) shown for 1993, determined from monitoring well data (black circles). Discharge to the WWTF infiltration beds (numbered squares) and spray irrigation areas (shaded areas) creates mounding of the water table and causes excursion of the southern watershed boundary (dashed lines show maximum range of excursion). 1992 watershed loading (~1 yr vertical travel time to groundwater) from WWTF sources calculated as a % of 1992 annual load proportional to fraction of time the source (or portion thereof) is located within the boundary.

The watershed loading model indicated that the Falmouth WWTF (in 1992, the discharge year reaching the marsh in 1998) was the largest source of nitrogen in the marsh watershed, contributing 64% of nitrogen inputs, or 2793 kg N yr^{-1} . This contrasts with many non-urbanized coastal watersheds where the majority of fixed nitrogen is delivered to groundwater through a diffuse array of individual residential on-site septic systems. While most of the Mashapaquit Creek Marsh watershed has typical residential development, it is the import of wastewater from outside the watershed (via sewers) and discharge over about 10% of the watershed surface (the WWTF infiltration beds and spray irrigation areas) which creates a “point source” of nitrogen loading.

In addition to contributing the largest single source of nitrogen to Mashapaquit Creek Marsh and to West Falmouth Harbor, the WWTF load has also increased throughout the 1990’s. The mass of WWTF nitrogen impacting groundwater within the Harbor watershed has nearly doubled between 1991-92 and 1996-98 (Figure IV-11). A peak load of 10,730 kg N discharged in 1997 was predicted to impact West Falmouth Harbor around 2004 based on the groundwater travel times predicted by the West Cape model. The 6-year lag time between discharge at the WWTF and entry to the Harbor systems is a critical part of the nitrogen issue for West Falmouth Harbor. This time lag means that even if the discharge ceased in 2000, nitrogen loading to the Harbor from the WWTF would continue to increase by ca. 50% over 1998 levels by the year 2004. Mashapaquit Creek would receive most of this increased N discharge. However, the nitrogen loading from the WWTF projected to discharge to Mashapaquit Creek has remained relatively constant from 1998 to 2004 at ~8000 kg N per year, although the 2004 WWTF discharge will not reach the estuary until ~2010. The result is that while nitrogen loads to Mashapaquit Creek from the WWTF increased sharply from 1992 to 2002, the loading from this source should be relatively constant until 2010 and then decline thereafter as a result of nitrogen removal prior to discharge within the newly upgraded WWTF. Note that the MEP modeling of existing conditions is based upon this 2002-2010 condition.

Uptake of watershed nitrogen by the Mashapaquit Creek Marsh during 1997-1999 was estimated as the difference between groundwater N (as nitrate) inputs and net NO_3^- loss from the marsh through tidal exchange. The results indicate that about 40% of the total watershed and WWTF nitrogen loading to the Mashapaquit Creek Marsh is removed, primarily by naturally occurring denitrifying bacteria living in the marsh creek bottom sediments.

Tidal exchange measurements were conducted on 8 dates in 1997-98 over either one or two complete tidal cycles, with flow, salinity and nutrients measured at least once every hour. Daily net nitrate outputs determined from the 8 tidal exchange measurements were converted to monthly outputs and integrated to determine an annual nitrate export from the marsh system to adjacent Snug Harbor waters. When the measured nitrogen export was compared to the rate of nitrogen input from the watershed nitrogen model or directly measured watershed nitrogen inputs (from stream and seepage measurements), it appears that 40%-50% of the nitrogen input from the watershed, is removed by the Lower Mashapaquit Creek System. (Smith 1999). These rates of attenuation were fully supported by direct measurements of nitrogen uptake and denitrification by the sediments of Lower Mashapaquit Creek conducted in 1999-2000 (Hamersley and Howes 2003). In this latter approach marsh nitrogen uptake was measured directly by “scaling up” point measurements of sediment denitrification for the whole marsh creek bottom area. Sediment denitrification was measured in laboratory core incubations, as the rate of sediment uptake of water column nitrate and dinitrogen release. Given that attenuation may diminish as nitrogen loading to the Creek increased, the lower attenuation rate (40%) was used in the MEP modeling of existing conditions. Note that attenuation of watershed nitrate by Great Sippewissett Marsh is ~70%. Also, 40% attenuation was used for modeling since attenuation varied seasonally, with highest rates during the warmer months, when the adjacent Harbor is most sensitive to nitrogen inputs. For these reasons, a nitrogen attenuation rate of 40% was deemed conservative for the MEP Linked Watershed-Embayment Modeling of West Falmouth Harbor.

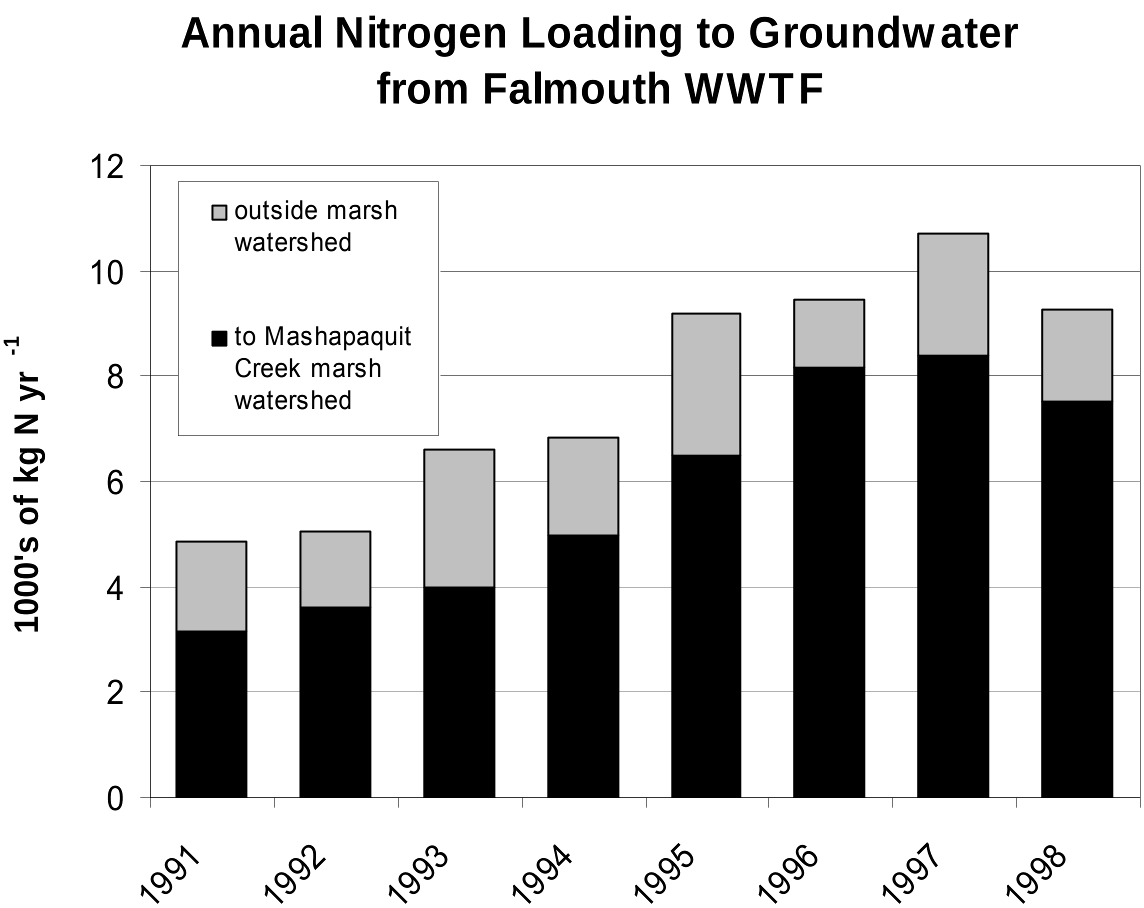


Figure IV-11. Yearly nitrogen discharge from the Falmouth WWTF to groundwater within the Mashapaquit Creek Marsh watershed (black) and outside of the marsh watershed (gray).

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 within each major basin area within the West Falmouth Harbor embayment system. The mass exchange of nitrogen between watercolumn and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

As stated in above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the West Falmouth Harbor embayment 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 watercolumn (once it entered), then predicting watercolumn 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 watercolumn for sufficient time to be flushed out to a downgradient larger waterbody (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 (e.g. Perch Pond in the Great Pond system). 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 watercolumn 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. In other systems the sediments are a net sink for nitrogen, during the summer, as a result of deposition of phytoplankton and denitrification. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. Failure to account for this the sediment nitrogen balance generally results in significant errors in determination of threshold nitrogen loadings. 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 West Falmouth Harbor system, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected from 14 sites in West Falmouth Harbor (Figure IV-12) in July 2002. 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 (see Figure IV-12) per incubation were as follows:

West Falmouth Harbor Benthic Nutrient Regeneration Cores

- Station WFH-1 1 core (Harbor Head)
- Station WFH-2 1 core (Harbor Head)
- Station WFH-3 1 core (West Falmouth Harbor South Basin)
- Station WFH-4 1 core (West Falmouth Harbor South Basin)
- Station WFH-5 1 core (West Falmouth Harbor South Basin)
- Station WFH-6 1 core (West Falmouth Harbor South Basin)
- Station WFH-7 1 core (Snug Harbor)
- Station WFH-8 1 core (Snug Harbor)
- Station WFH-9 1 core (Snug Harbor)
- Station WFH-10a/b 2 cores (Snug Harbor)
- Station WFH-11 1 core (West Falmouth Harbor North Basin)
- Station WFH-12 1 core (West Falmouth Harbor North Basin)
- Station WFH-13 1 core (Main Basin)
- Station WFH-14 1 core (Main Basin)
- Station WFH-15 1 core (Main Basin)

Sampling was distributed throughout the embayment system and the results for each site combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

Sediment-watercolumn exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1995) for nutrients and metabolism. Upon return to the field laboratory (private residence located nearby to West Falmouth Harbor) 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-12. West Falmouth Harbor embayment system sediment sampling sites (yellow symbols) for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-9 below.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

Watercolumn nitrogen levels are the balance of inputs from direct sources (land, rain etc), losses (denitrification, burial), regeneration (watercolumn and benthic), and uptake (e.g. photosynthesis). As stated above, during the warmer summer months the sediments of shallow embayments 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 watercolumn 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 watercolumn 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 watercolumn oxygen status. However, for the modeling of nitrogen within an embayment it is the relative balance of nitrogen input from watercolumn 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-13). However, in nitrogen enriched systems the sediments may serve as a net sink for nitrogen during summer, as well. Within the West Falmouth Harbor System, Mashapaquit Creek is a significant sink for nitrogen year-round, but higher in summer than in winter. This results from the continuous, high watershed nitrogen loading to this sub-system.

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 watercolumn 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 ammonium release, measured nitrate uptake or release, and estimate of particulate nitrogen input. Dissolved organic nitrogen fluxes were not used in this analysis, since they were highly variable and generally showed a net balance within the bounds of the method.

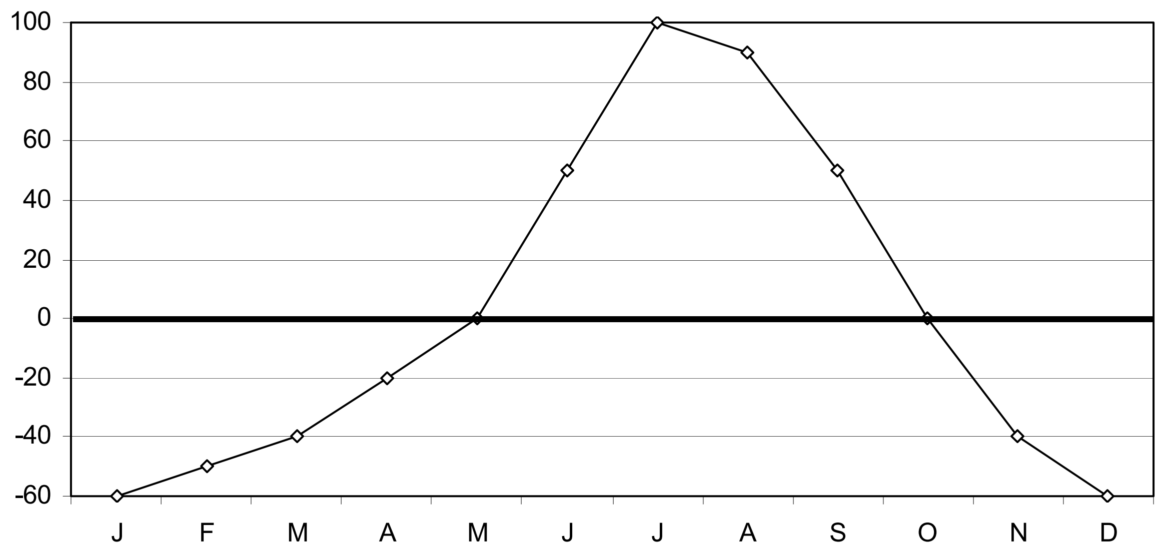


Figure IV-13. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Sediment sampling was conducted within the main basin of West Falmouth Harbor as well as throughout the tributary sub-embayments (Snug Harbor, South Basin, Outer/Mid Harbor) in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model (Figure IV-12). 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 and the average summer particulate carbon and nitrogen concentration within the overlying water. Two levels of settling were used. If the sediments were organic rich and a 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 a 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 that are net nitrogen sinks for the aquatic system. This approach was validated in other Cape Cod embayments (Town of Chatham, Town of Mashpee, Town of Barnstable, Town of Falmouth) by examining the relative fraction of the sediment carbon turnover (total sediment metabolism) that 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.

Net nitrogen release or uptake from the sediments within the West Falmouth Harbor embayment system for use in the water quality modeling effort (Chapter VI) are presented in Table IV-7. West Falmouth Harbor sediments showed a small net nitrogen uptake during summer. The rates of uptake reflect the level of nitrogen enrichment, with higher levels of uptake in the inner versus outer basins. While this nitrogen uptake serves to remove nitrogen from the embayment, the overall magnitude is relatively small and is insufficient to counter the daily watershed nitrogen loadings. The observed nitrogen cycling is also consistent with the lower velocity and more depositional inner basins and has been observed in a wide variety of similar embayment systems on Cape Cod.

Table IV-7. Rates of net nitrogen return from sediments to the overlying waters of the West Falmouth Harbor embayment 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.

	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			
Location	**Mean**	**S.E.**	**N**	**Sta**
West Falmouth Harbor Estuary				
Harbor Head	-10.8	0.3	2	1,2
South (Chappaquoit) Basin	-22.4	1.8	4	3,4,5,6
Snug Harbor	-30.8	0.9	3	7,8,9
Snug/South Basin	-24.1	1.2	2	10a,10b
Mid Basin	-10.9	1.5	3	11,12,13
Outer Basin	-11.6	0.6	2	14,15

Station numbers refer to Figure IV-12.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

West Falmouth Harbor, a coastal embayment connected to Buzzards Bay, is a significant marine resource within the Town of Falmouth. (Figure V-1). This estuary includes several sub-embayments that provide important recreational and environmental resources for the local community. In contrast to a majority of the coastal ponds and embayments throughout Cape Cod, water quality within West Falmouth Harbor has remained fairly high, until recently. The most important agent of change within the system has been the recent entry of nutrients (primarily nitrogen) discharged from the Town's Wastewater Treatment Facility (WWTF). The increased nutrient loading from the WWTF discharge, as well as from leaching septic systems and use of fertilizers has contributed to water quality degradation within the system.

Figure V-1. Map of West Falmouth Harbor (from United States Geological Survey topographic map).

Shallow coastal embayments are the initial recipients of freshwater flow and the nutrients they carry. The embayment's semi-enclosed structure increases the time that nutrients are retained in them before being flushed out to adjacent waters, and their shallow depths both decrease their ability to dilute nutrient (and pollutant) inputs and increases 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.

Estuarine water quality is dependent upon the nutrient and pollutant loading and the processes which 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 West Falmouth Harbor, the most important parameters are:

- Tide range
- Inlet configuration
- Estuary size, shape, and depth
- Longshore transport of sediment

The eastern shore of Buzzards Bay exhibits a moderate tide range, with a range of about 3.5 ft. Since the water elevation difference between Buzzards Bay and the Harbor is the primary driving force for tidal exchange, the local tide range provides a natural limit on the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) through the opening to West Falmouth Harbor is negligible, indicating a "well-flushed" system. The only significant constrictions in the system are (1) the culvert beneath Nashawena Street which connects Snug Harbor to Mashapaquit Creek and (2) the connection between Harbor Head and Oyster Pond. Based on the tidal characteristics alone, this might indicate that the West Falmouth Harbor system is "healthy"; however, land development in the watershed as well as effluent from the wastewater treatment plant provide substantial nutrient load to this system. Consequently, estuarine water quality may be more dependent on nitrogen loading than tidal characteristics for this system.

This section summarizes the development of a hydrodynamic model for West Falmouth Harbor. The calibrated model provides an understanding of water movement through the estuary. 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 provide the basis for an advanced water quality model (see Ramsey et al. (1995) for an example). This type of model will provide a tool for evaluating existing estuarine water quality, as well as determine the influence of various methods for improving overall estuarine health.

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 straight-forward extensions to the hydrodynamic modeling. For example, the spread of pollutants may be analyzed from tidal current information developed by the numerical models.

To calibrate the hydrodynamic model, field measurements of water elevations and bathymetry were required. Tide data was acquired within Buzzards Bay (two gauges were installed outside of the harbor mouth in open water), just inside the north jetty, upstream of the culvert in Mashapaquit Creek, at the Town Landing, both sides of the bridge on Chappaquoit Road and inside Oyster Pond. All eight (8) temperature-depth recorders (TDRs) were installed for a 30-day period to measure tidal variations through an entire neap-spring cycle. In this manner, attenuation of the tidal signal between Buzzards Bay and the various sub-embayments was evaluated accurately.

V.2 GEOMORPHIC AND ANTHROPOGENIC EFFECTS TO THE SYSTEM

Buzzards Bay generally runs northeast to southwest, bordered by the Massachusetts mainland to the west, Cape Cod to the east and northeast, and the Elizabeth Islands to the southeast. The bay was formed as a result of the most recent ice age and retreat of the glaciers (about 16,000 to 18,000 years ago). Along the eastern shore of the bay, these geologic processes created a number of shallow coastal embayments along the relatively irregular shoreline. Due to the proximity of the Falmouth Glacial Moraine in this region, the watersheds to many of these embayments (including West Falmouth Harbor) are relatively small; however the underlying geology make analyses of groundwater flow patterns complex.

Along with the geologic mechanisms that formed the shoreline and coastal embayments along the east side of Buzzards Bay, ongoing coastal processes also influence estuarine circulation and water quality. Although natural wave and tidal forces continue to reshape the shoreline, day-to-day conditions have limited impact on the shoreline migration and/or inlet stability. For typical wave conditions, longshore transport of sand is from south-to-north along the west coast of Falmouth, due primarily to the predominant local wind-driven waves (see Figure V-2 for a summary of long-term wind data). In contrast to the mild day-to-day conditions, infrequent hurricane events such as the hurricanes of 1938, 1944, and 1954, as well as Hurricane Bob in 1991, all caused significant overwash and transport of beach sediments. In addition, northeast storm events (causing elevated water levels and high wave events during the northwest winds typically following these storms) create a sediment transport reversal from typical conditions, where the longshore sediment transport is from north-to-south. The effect of this sediment transport reversal can often be seen by observing the sand impounded by the groins found along the shoreline, where typical summer conditions will impound sand along the south side of the groins and storm events during the winter will impound sand along the north side of the groins.

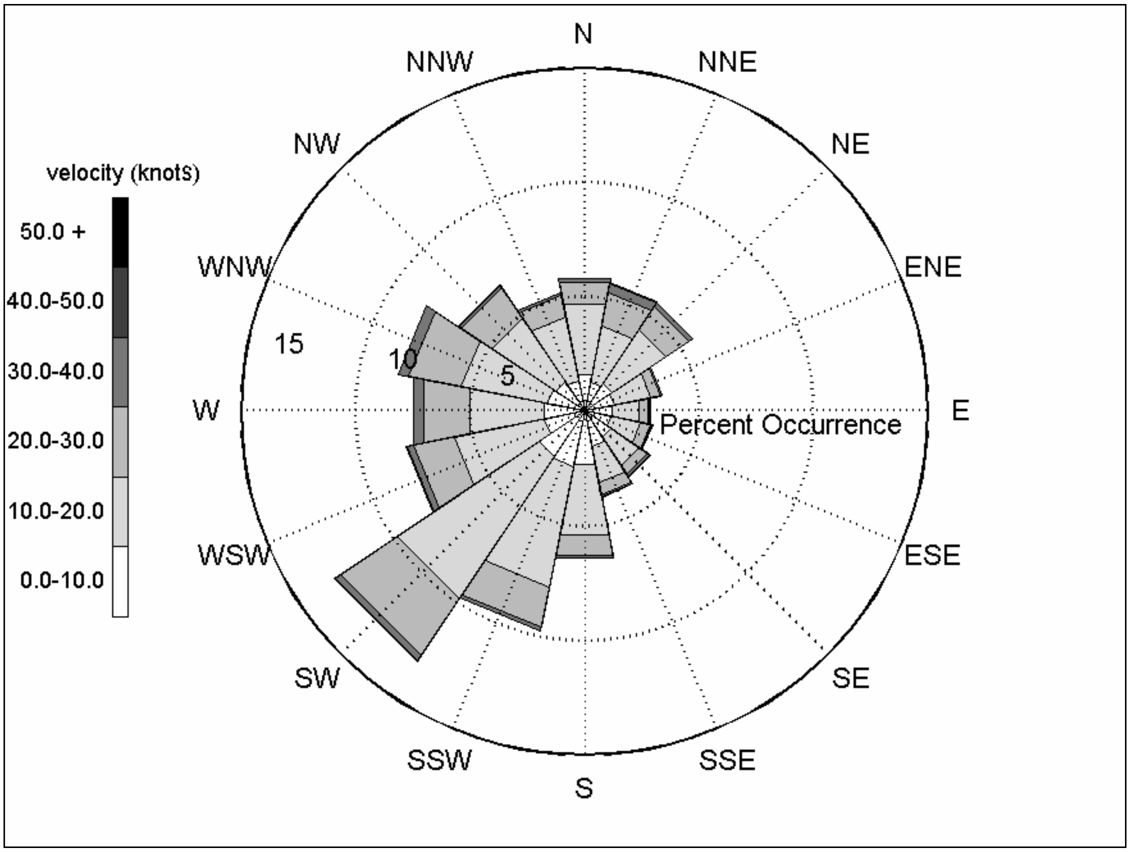


Figure V-2. Wind rose for the BUZM3 Station located near the southern entrance to Buzzards Bay. Wind data is for the time 20-year time period between 1985 and 2004.

For West Falmouth Harbor, inlet stability is of secondary concern, due to the relatively large entrance that resulted from the natural system geomorphology. In addition, the glacial nature of the regional shoreline has limited the sediment supply that potentially could create shoaling problems within the inlet throat. The 2001 aerial photograph shown in Figure V-3 illustrates the boulder strewn regions offshore of Chappaquoit and Little Islands, indicative of glacial deposits that are naturally erosion-resistant. These headland features stabilize the entrance of West Falmouth Harbor.

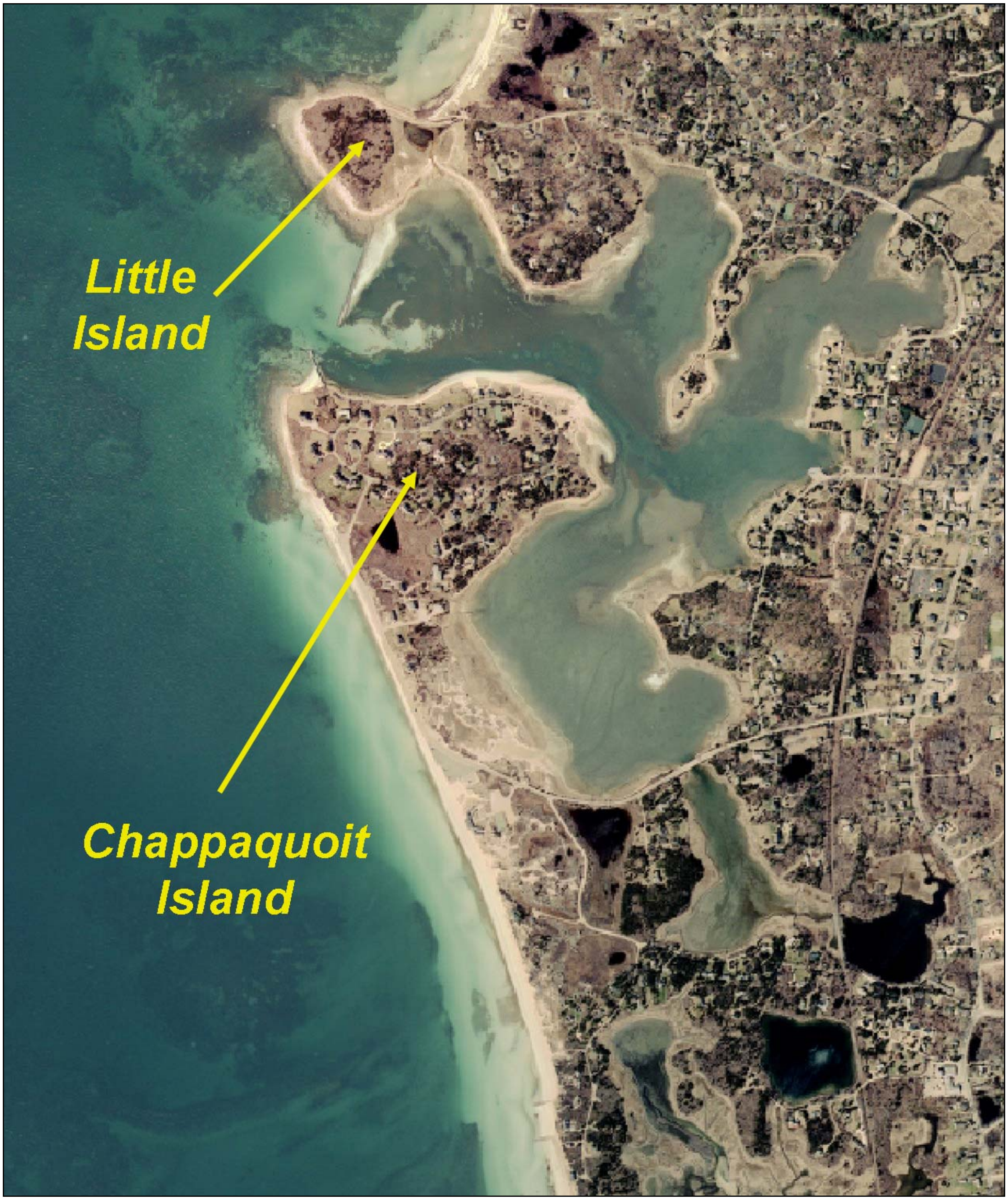


Figure V-3. 2001 aerial photograph illustrating Chappaquoit and Little Islands forming the entrance to West Falmouth Harbor.

In 1893, West Falmouth Harbor was called Hog Island Harbor (Figure V-4), and very little development existed along the waterfront. By 1941 (Figure V-5), however, roads had been developed out to Chappaquoit and Little Islands, with a small jetty constructed along the southern entrance channel to the harbor. Over the following decades, a second jetty was constructed at the southern end of Little Island to provide quiescent waters for boaters (as shown in Figures V-1 and V-3) and a vertical seawall was constructed along the seaward edge of Chappaquoit Road. This seawall has limited natural erosion and barrier beach overwash processes along Chappaquoit Beach, ultimately reducing the volume of available littoral sediment and causing a reduced beach width.

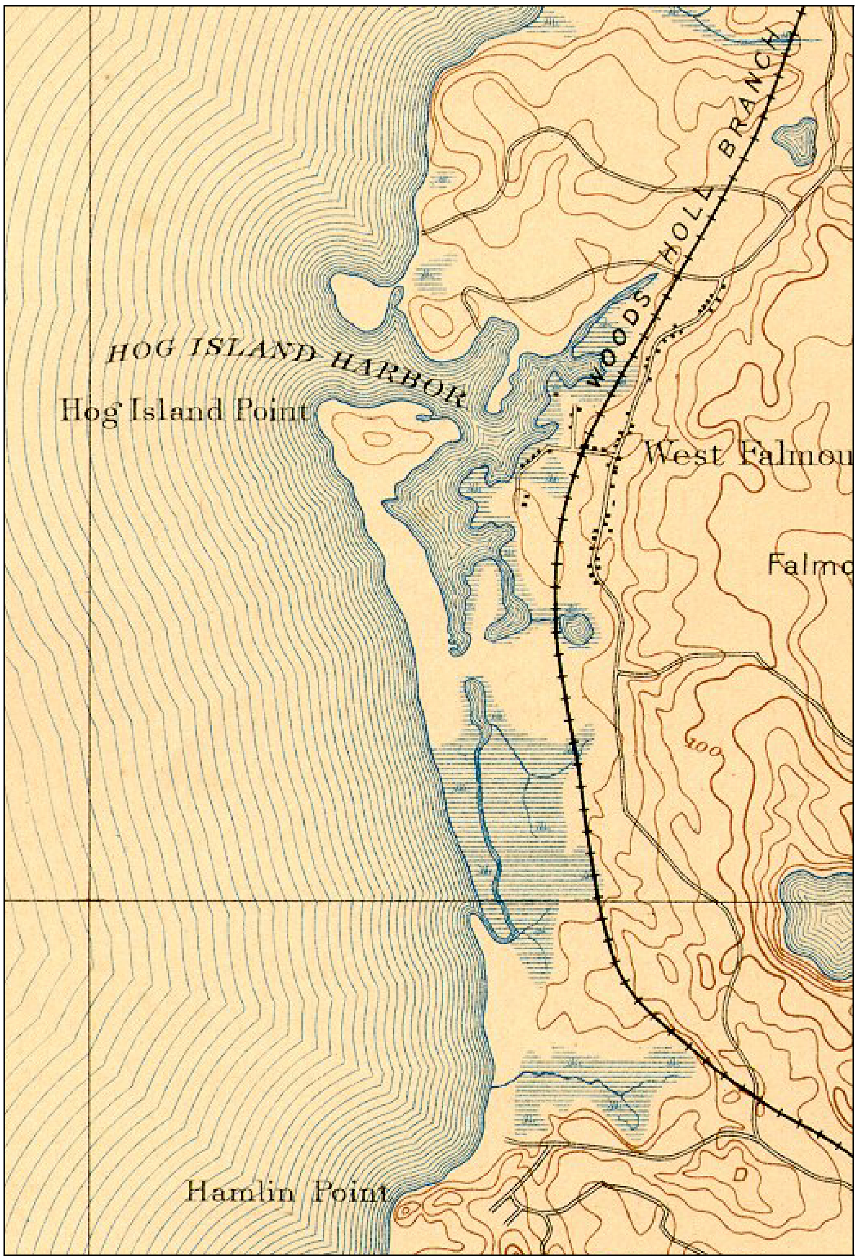


Figure V-4. A portion of the U.S.G.S. 1893 map showing West Falmouth Harbor. This map depicts the condition of this system prior to the installation of jetties.

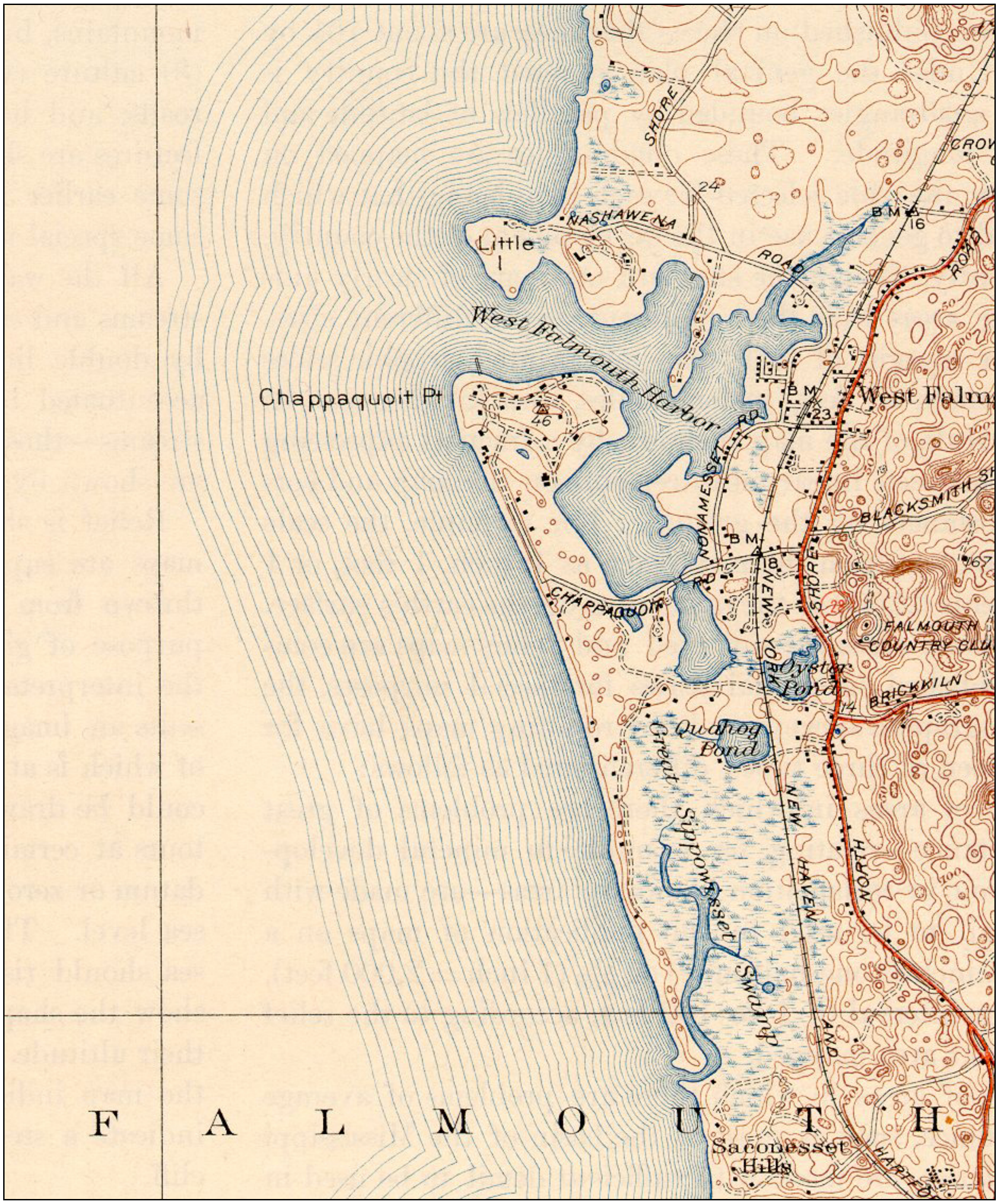


Figure V-5. A portion of the U.S.G.S. 1941 map showing West Falmouth Harbor. This map depicts the condition of this system following initial development of Chappaquoit and Little Islands.

As shown in Figure V-6, hurricanes can have a significant impact on both the shoreline and the inlets. Due to the relatively quiescent wave and tide regime within this region, the impact of infrequent storms, primarily a result of storm surge, can be dramatic. According to historic flooding information (U.S. Army Corps of Engineers, 1939), the storm surge level in West Falmouth Harbor was approximately 14 feet above mean tide level during the peak of the 1938 Hurricane. Due to this elevated water level, the low-lying barrier beach that separated West Falmouth Harbor from Buzzards Bay was overtopped and portions of the village were flooded as well. These infrequent storms can reshape the shoreline in ways that would require many years or decades under the typical wave, wind, and tide regime of the Falmouth Buzzards Bay coast. During the twentieth century, the severe hurricanes influencing the Falmouth shoreline include the hurricanes of 1938, 1944, and 1954, as well as Hurricane Bob in 1991. Of these storms, the Hurricane of 1938 had the largest storm surge along the Buzzards Bay shore of Falmouth (U.S. Army Corps of Engineers, 1988).

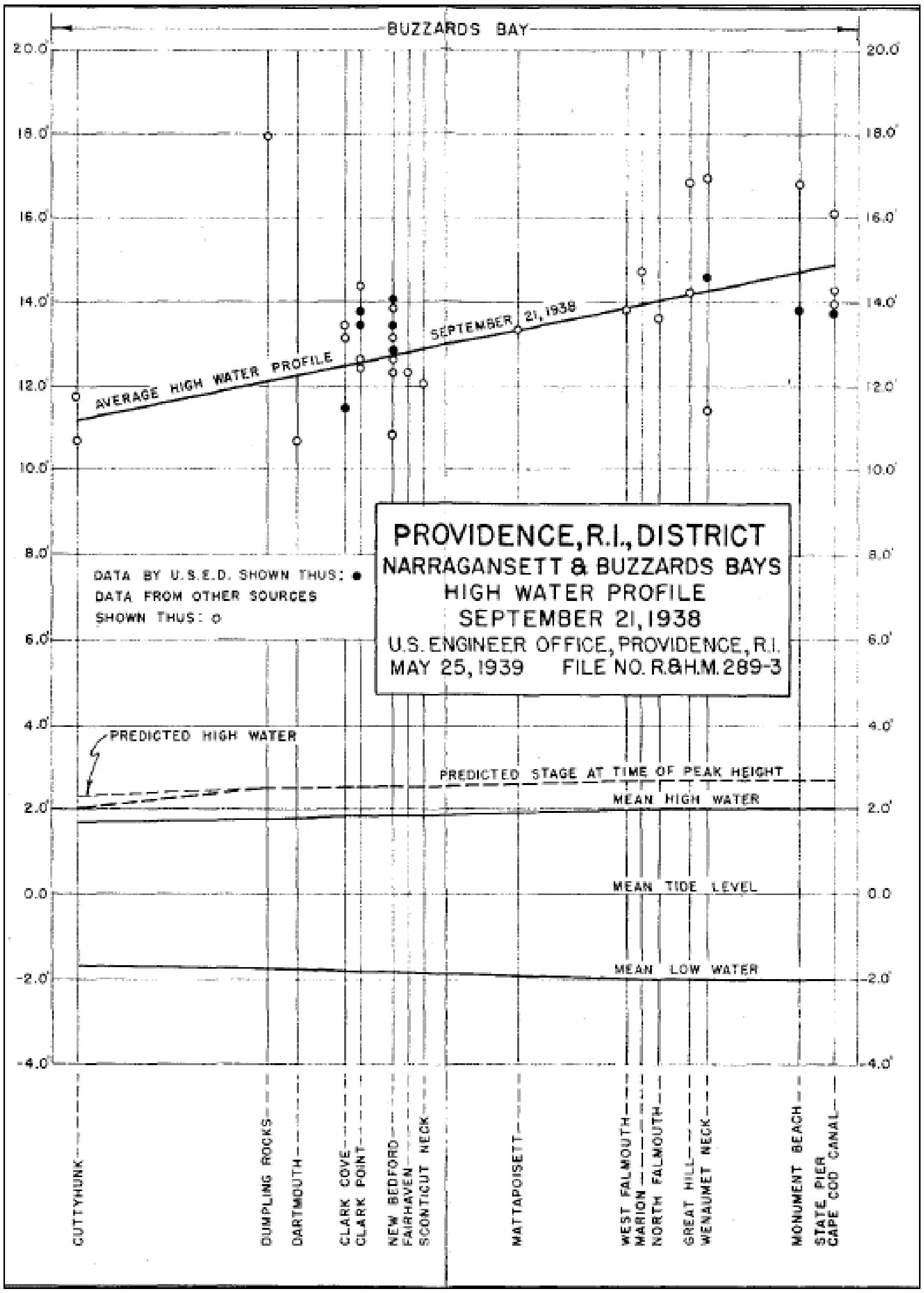


Figure V-6. Flood levels at various locations in Buzzards Bay resulting from the September 21, 1938 Hurricane (USACE, 1939).

As noted above, the geologic history and infrequent storms appear to be the dominant processes that govern water circulation within West Falmouth Harbor. Secondary processes include the average day-to-day littoral transport (causing shoaling) and anthropogenic modifications to the system, including jetty construction that channelized inlet flow, bridges and culverts that altered tidal exchange to various parts of the estuarine system, and coastal armoring that reduced the sediment supply to the inlet region. Future plans to nourish Chappaquoit Beach with approximately 100,000 cubic yards of beach compatible material may increase the sediment supply to the West Falmouth Harbor entrance. However, the natural rocky shoreline of Chappaquoit Island should reduce potential adverse impacts associated with this project.

V.3 FIELD DATA COLLECTION AND ANALYSIS

A requirement for the numerical model generation is precise descriptions of embayment geometry as well as hydrodynamic forcing processes. To this end, the bathymetry of the embayments and water elevation variations were measured. The bathymetry of the West Falmouth Harbor system was measured, including Mashapaquit Creek and Oyster Pond. The resulting depth measurements were used to create computational grids of each pond. In addition to the bathymetry surveys, tide gauges were installed in Buzzards Bat and at selected locations within each embayment to observe the rise and fall of water surfaces. These data were processed to provide input information required for the numerical model and, in addition, analyzed to provide insight into existing hydrodynamic conditions for each system.

V.3.1 Bathymetry

Bathymetry, or depth, the West Falmouth Harbor system was measured during a series of field surveys in early May, 2004. The surveys were completed using a small vessel equipped with a precision fathometer interfaced to a differential GPS receiver. The fathometer has 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 echosounder and GPS were logged to a laptop computer, which integrated the data to produce multiple data sets consisting of water depth as a function of geographic position (latitude/longitude).

These data files were merged with water surface elevation measurements to correct the measured depths to the NGVD 1929 vertical datum. Once corrected, the data were then merged into larger ‘xyz’ files containing x-y horizontal position (in Massachusetts State Plan 1927 coordinates) and vertical elevation of the bottom (z) relative to NGVD29. These xyz files were then input to mapping software to calculate depth contours for each Pond. Figure V-7 shows the depth contours of these grids for the whole system.

As Figure V-7 shows, the entire West Falmouth Harbor system is relatively shallow with the exception of Oyster Pond, where the depth exceeds 25 feet. The main channel and Mid - Harbor exhibit depths of 10-12 feet while a majority of the system shows water depths of 6 feet or less.

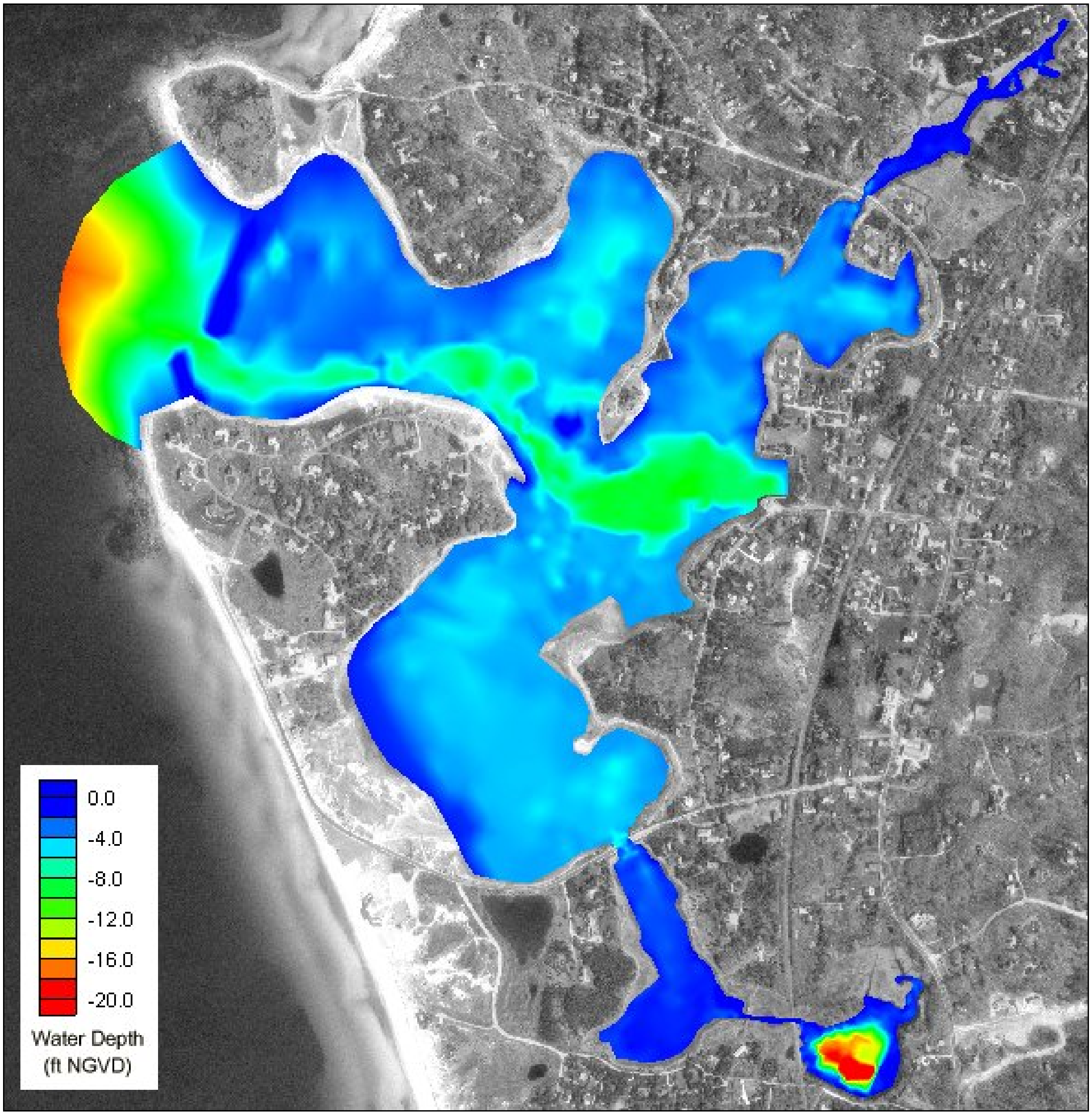


Figure V-7. Depth contour plot of the numerical grid for the hydrodynamic model. Depth values are relative to NGVD29.

V.3.2 Water Elevation Measurements and Analysis

Changes in water surface elevation were measured using internal recording tide gauges. These tide gauges were installed throughout the system to record changes in water pressure. These water surface variations can be due to tides, wind set-up, or other low-frequency oscillations of the sea. The tide gauges were installed in seven (7) locations throughout the study area (see Figure V-8) in late June, 2004 and removed in early August, 2004. Data records span at least 28 days, an adequate time period to resolve the primary tidal constituents. The actual location of the offshore gauge (Wfal-1) is outside of the picture so an approximate location is given.

The tide gauges used for the study consisted of Brancker TG-205, Coastal Leasing Microtide, and Global Water WL-14 instruments. Data sampling was set for 10-minute intervals, with each 10-minute observation resulting from an average of 16 1-second pressure measurements. Each of these instruments use strain gauge transducers to sense variations in pressure, with resolutions on the order of 1 cm head of water. Each gauge was calibrated prior to installation to assure accuracy. Each gauge returned 100% of the desired data.

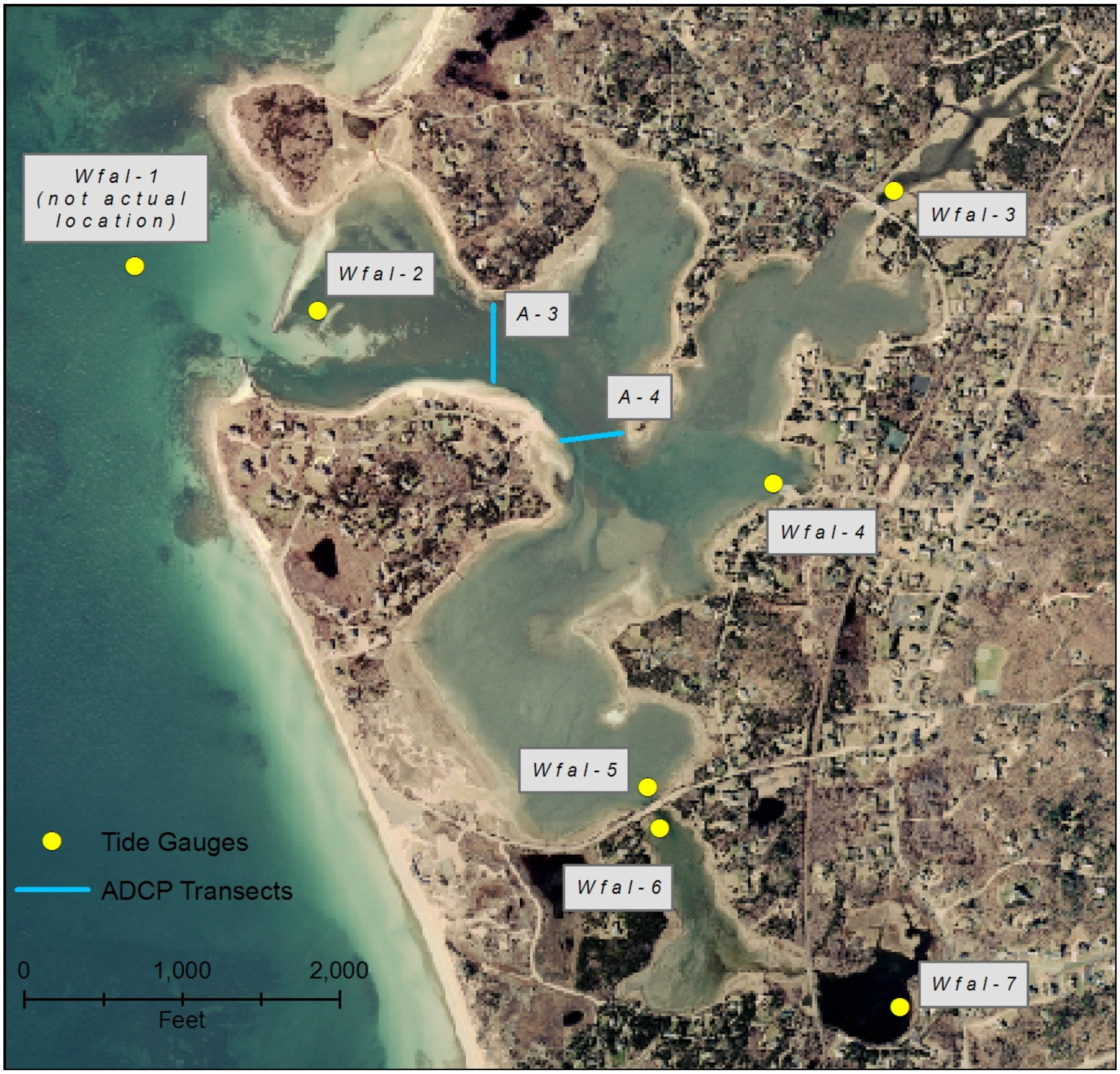


Figure V-8. Map of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. Gauges were deployed from late June to early August, 2004. Each yellow circle represents the approximate locations of the tide gauges. Each blue line shows the location of an ADCP survey.

Once the data were downloaded from each instrument, the water pressure readings were corrected for variations in atmospheric pressure. Hourly atmospheric pressure readings were obtained from the NOAA station in Buzzards Bay, interpolated to 10-minute intervals, and subtracted from the pressure readings, resulting in variations in water pressure above the instrument. Further, a (constant) water density value of 1025 kg/m^3 was applied to the readings to convert from pressure units (psi) to head units (for example, feet of water above the tide gauge). Several sensors had been surveyed into local benchmarks to provide vertical rectification of the water level; these survey values were used to adjust the water surface to a known vertical datum. The result from each gauge is a time series record representing the variations in water surface elevation relative to the NGVD 1929 vertical datum. Figure V-9 presents the time variation of water level in each of the ponds. Plots of all tide gauges are presented in Figure V-9.

To better quantify the changes to the tide from the inlet to inside the system, the standard tidal statistics were computed from the 30-day records. These statistics are presented in Table V-1. The tides in Buzzards Bay are semi-diurnal, meaning that there are typically two tide cycles (two highs and two lows) each day and there is usually a difference in elevation between the two high tides and between the two low tides. The Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels represent the average of the single highest or lowest water level recorded each day. The Mean High Water (MHW) and Mean Low Water (MLW) statistics represent the average of the two highest or two lowest elevations recorded each day. The Mean Tide Level (MTL) is simply the average of MHW and MLW.

For most NOAA tide stations, these statistics are computed using 19 years of tide data, which is the length of a tidal epoch. For this study, a significantly shorter time span of data was available; however, these values still provide a useful comparison of tidal dynamics within the system. From the computed statistics, it is apparent that there is little tide damping throughout the system (with the noted exception of Oyster Pond). Again, the absence of tide damping exhibited in West Falmouth Harbor indicates that it flushes efficiently.

A more thorough harmonic analysis was also performed on the time series data from each gauging station in an effort to separate the various component signals which make up the observed tide. The analysis helps reveal the relative contribution that diverse physical processes (i.e. tides, winds, etc.) have on water level variations within the estuary. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 tidal constituents, with periods between 4 hours and 2 weeks, result from this procedure. The observed tide is therefore the sum of an astronomical tide component and a residual atmospheric component. The astronomical tide in turn is the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-10.

Table V-2 presents the amplitudes of eight significant tidal constituents. The M_2, or the familiar twice-a-day lunar semi-diurnal, tide is the strongest contributor to the signal with an amplitude of 1.73 feet in Buzzards Bay. The range of the M_2 tide is twice the amplitude, or about 3.46 feet. The diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar), possess amplitudes of approximately 0.28 and 0.19 feet respectively and account for the semi-diurnal variance between high tides and low tides seen in Figure V-9. The N_2 tide, a lunar constituent with a semi-diurnal period, is the next largest tidal constituent and is roughly 3.5 time smaller then the main semi-diurnal constituent (M_2) with an amplitude of 0.48 feet. The M_4 tide, a higher frequency harmonic of the M_2 lunar tide, results from frictional dissipation of the M_2 tide in shallow water.

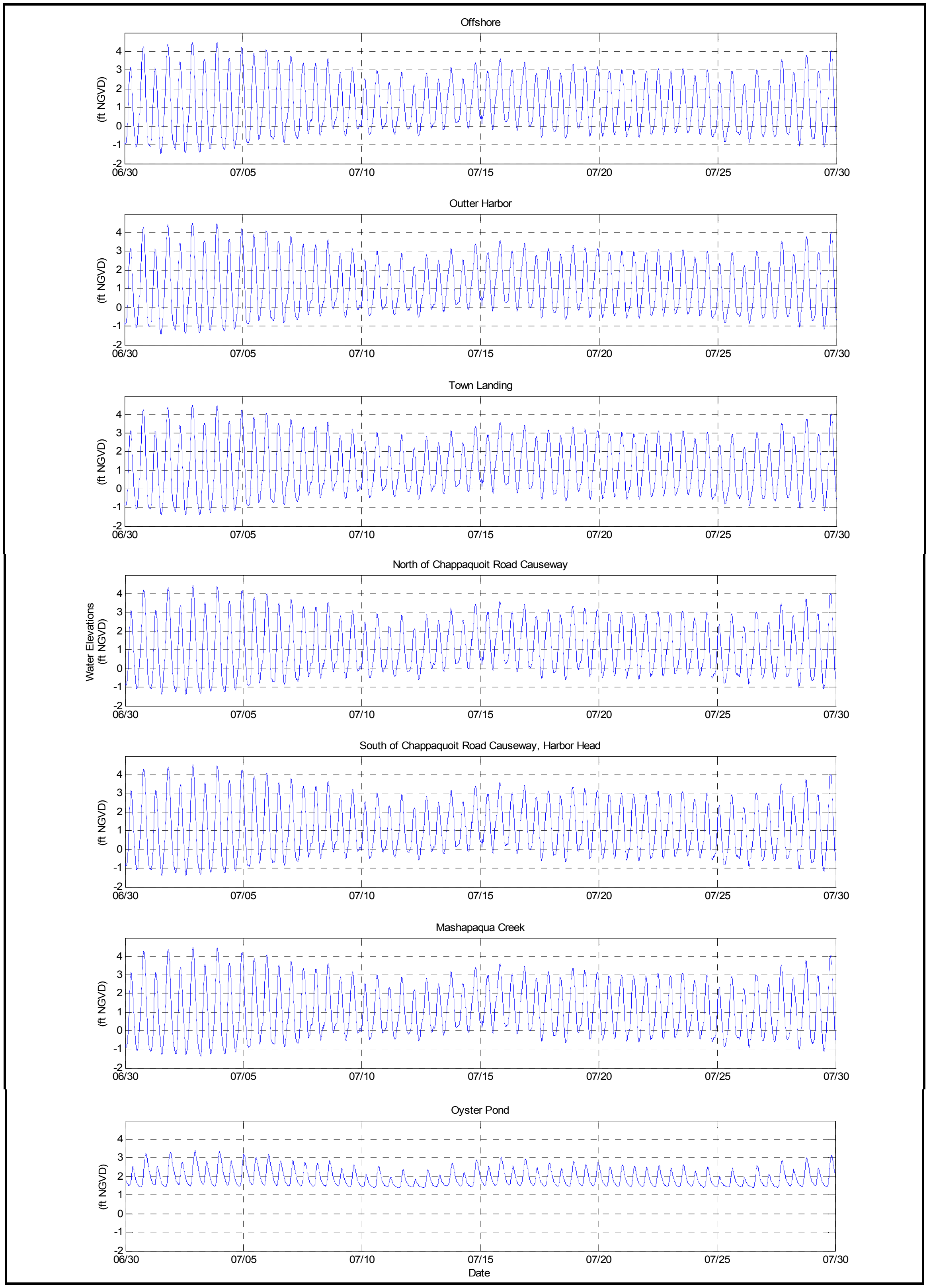


Figure V-9. Water elevation variations as measured at the seven locations within the West Falmouth Harbor System.

Table V-1. Tidal statistics computed from records collected in the West Falmouth Harbor system June 30 - July 30, 2004. Elevations are given in feet relative to NGVD 27.

	Buzzards Bay	Outer Harbor	Town Landing	North of Chappaquoit Rd Bridge	South of Chappaquoit Rd. Bridge, Harbor Head	Mashapaquit Creek	Oyster Pond
Highest Water Level	4.48	4.51	4.50	4.45	4.53	4.49	3.39
MHHW	3.50	3.51	3.50	3.47	3.51	3.50	2.85
MHW	3.21	3.21	3.21	3.19	3.22	3.21	2.63
MTL	1.32	1.32	1.32	1.32	1.32	1.32	2.05
MLW	-0.58	-0.58	-0.57	-0.55	-0.59	-0.58	1.47
MLLW	-0.69	-0.70	-0.69	-0.67	-0.70	-0.69	1.45
Lowest Water Level	-1.45	-1.39	-1.41	-1.39	-1.41	-1.37	1.39

Table V-2. Tidal Constituents, West Falmouth Harbor System June 30 - July 30, 2004.

AMPLITUDE (feet)								
	M2	M4	M6	S2	N2	K1	O1	Msf
Period (hours)	12.42	6.21	4.14	12	12.66	23.93	25.82	354.61
Buzzards Bay	1.73	0.28	0.03	0.27	0.48	0.28	0.19	0.14
Outer Harbor	1.73	0.28	0.03	0.27	0.48	0.29	0.19	0.14
Town Landing	1.73	0.26	0.04	0.27	0.48	0.30	0.19	0.14
North of Chappaquoit Road Bridge	1.70	0.26	0.04	0.26	0.47	0.28	0.19	0.15
South of Chappaquoit Road Bridge, Harbor Head	1.73	0.26	0.05	0.27	0.48	0.29	0.19	0.14
Mashapaquit Creek	1.72	0.26	0.05	0.26	0.47	0.29	0.19	0.15
Oyster Pond	0.49	0.15	0.04	0.09	0.11	0.12	0.14	0.18

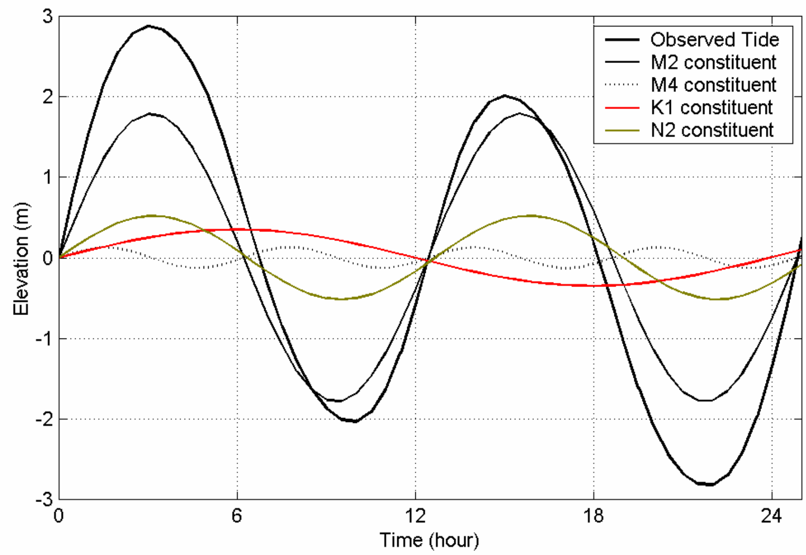


Figure V-10. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-3 presents the phase delay of the M_2 tide at all tide gauge locations inside the Harbor. The phase delay is minimal just inside the jetties and is only 7-8 minutes for all but the furthest reaches of the system. Mashapaquit creek lags behind the main basin by only a few minutes, suggesting that the culvert beneath Nashawena Street is well sized and working efficiently. The greatest delay occurs between the Buzzards Bay and Oyster Pond because the culvert connecting Oyster Pond to the system severely restricts flow in and out of the pond.

Table V-3. M_2 Phase Delay, West Falmouth Harbor.	
June 30th – July 30th 2004 (Delay in minutes relative to Buzzards Bay)	
Location	Delay (minutes)
Outer Harbor	2.2
Town Landing	7.3
North of Chappaquoit Rd Bridge	7.0
South of Chappaquoit Rd Bridge, Harbor Head	7.9
Mashapaquit Creek	11.2
Oyster Pond	125.0

The tide data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation, with the results being summarized in Table V-4 below. The water elevations measured in the field can be thought of as the combination of energy from both tidal and non-tidal processes. The tidal input is simply the sum of the energy contained in the constituents discussed above and is strictly due to astronomical forces. Non-tidal processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. In some estuaries, variations in water surface elevation can also be affected by freshwater discharge entering the water bodies, but this is not the case for the West Falmouth Harbor system.

Thus, subtracting the tidal information from the original elevation time series reveals 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-11 shows the comparison of the measured water elevations from Buzzards Bay along with the astronomical tide and the non-tidal residual signal.

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. The analysis also shows that tides are responsible for approximately 97% of the water level changes in West Falmouth Harbor. The remaining 3% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of Buzzards Bay and West Falmouth Harbor. The total energy content of the tide signal from each gauging station does not change significantly, nor does the relative contribution of tidal vs. non-tidal forces along the estuary basin. This is indication that tide attenuation across the inlet and through the system is negligible. Because the residual signal is uniform across the whole system, it can be inferred that the source of the non-tidal residual energy is generated offshore, with no additional non-tidal energy input within the system (e.g., from wind set-up of the pond surface). Oyster Pond is the noted exception. It was shown to have a significant reduction in amplitude relative to Harbor Head and this is again seen by a 2.5 time increase of non-tidal energy. The residual energy is a larger percentage of the total in Oyster Pond also because the total energy is smaller than most of the system.

Table V-4. Percentages of Tidal versus Non-Tidal Energy, West Falmouth Harbor.

	Total Variance	Total	Tidal	Non-tidal
Unit	(ft^2)	(%)	(%)	(%)
Buzzards Bay	1.85	100	97.6	2.4
Outer Harbor	1.85	100	97.6	2.4
Town Landing	1.85	100	97.6	2.4
North of Chappaquoit Road Causeway	1.79	100	97.2	2.8
South of Chappaquoit Road Causeway, Harbor Head	1.85	100	97.6	2.4
Mashapaquit Creek	1.83	100	97.4	2.6
Oyster Pond	0.19	100	93.6	6.4

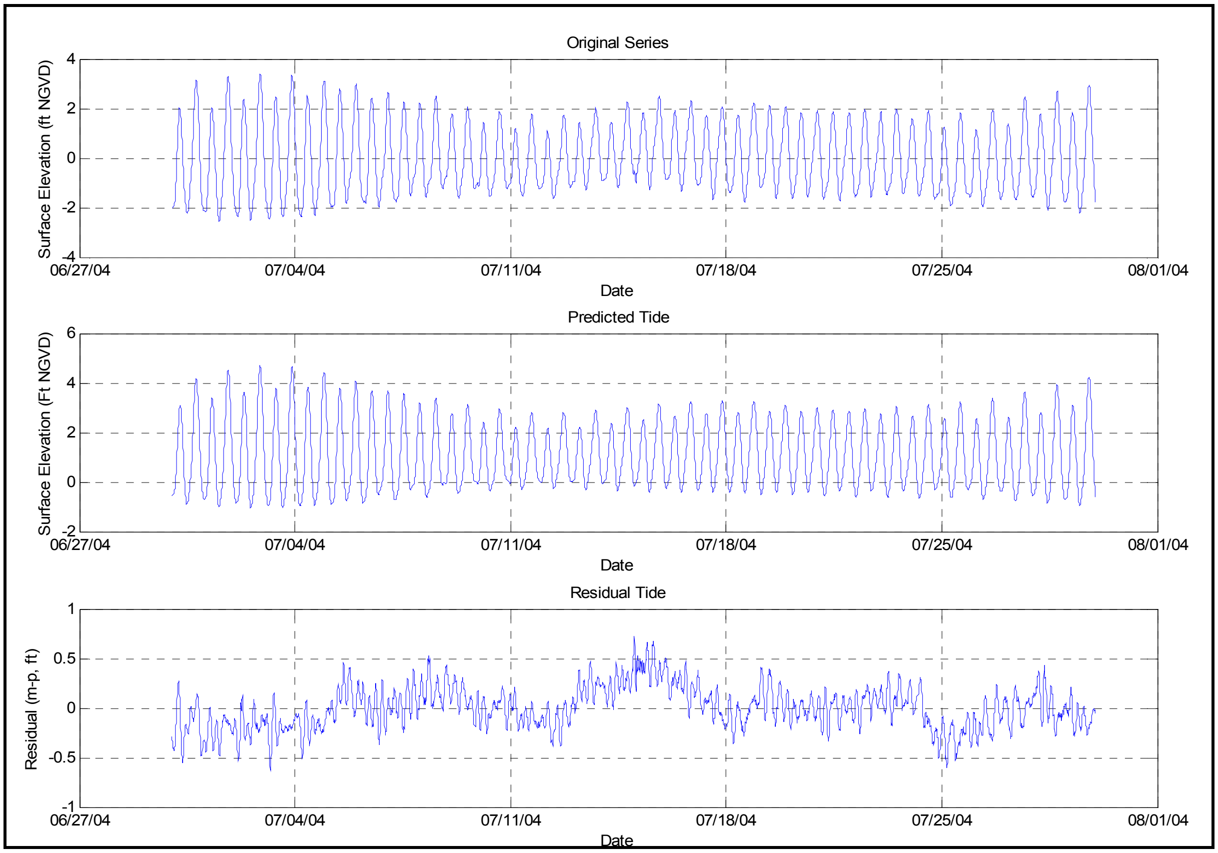


Figure V-11. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured in Buzzards Bay (Wfal-1).

The results from Table V-4 indicate that hydrodynamic circulation throughout West Falmouth Harbor is dependent primarily upon tidal processes. However the small residual component of the non-tidal energy is still included in the hydrodynamic modeling effort described below. This is because the measured water level elevations from Buzzards Bay were used to force the model so that both the tidal and non-tidal energy are inherently included in the model.

V.4. HYDRODYNAMIC MODELING

This study of West Falmouth Harbor 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, 1990a). 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-2V for numerous flushing studies on Cape Cod, including Popponesset Bay, Stage Harbor and the Pleasant Bay estuary.

V.4.1 Model Theory

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by Brigham Young University through a package called the

Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report primarily were generated within the SMS modeling package.

RMA-2 is a finite element model designed for simulating one- and two-dimensional depth-averaged hydrodynamic systems. The dependent variables are velocity and water depth, and the equations solved are the depth-averaged Navier Stokes equations. Reynolds assumptions are incorporated as an eddy viscosity effect to represent turbulent energy losses. Other terms in the governing equations permit friction losses (approximated either by a Chezy or Manning formulation), Coriolis effects, and surface wind stresses. All the coefficients associated with these terms may vary from element to element. The model utilizes quadrilaterals and triangles to represent the 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 it is unconditionally stable. Once the equations are solved, corrections to the initial estimate of velocity and water elevation are employed, and the equations are re-solved until the convergence criteria is met.

V.4.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

The finite element grid was generated within the shoreline as determined by aerial photos. A time-varying water surface elevation boundary condition (measured tide) was specified just offshore of the harbor entrance based on the tide gauge data collected in Buzzards Bay. There were no freshwater recharge boundary conditions included in this model. Once the grid and boundary condition were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through numerous (15+) model calibration simulations for the system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.4.2.1 Grid Generation

The grid generation process was simplified by the use of the SMS package. The aerial photos and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary. Figure V-12 illustrates the finite element grid covering the entire West Falmouth Harbor system. The entire mesh consists of two-dimensional (depth-averaged) elements.

The finite element grid provided the detail necessary to evaluate accurately the variation in hydrodynamic properties of each estuary. Fine resolution was required to simulate the channel constrictions which can significantly impact the estuarine hydrodynamics. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the field survey.

Grid resolution was governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability present. Relatively fine grid resolution was employed where complex flow patterns were expected. For example, smaller node spacing in the vicinity of the inlet and main channel was chosen to provide a more detailed analysis in these regions of rapidly varying flow. Similarly, small spacing was needed to accurately reproduce flow through the channels and culverts leading to Mashapaquit Creek and Oyster Pond. More widely spaced nodes were defined for Harbor Head and the northern reaches of the main harbor, where flow patterns did not change dramatically.

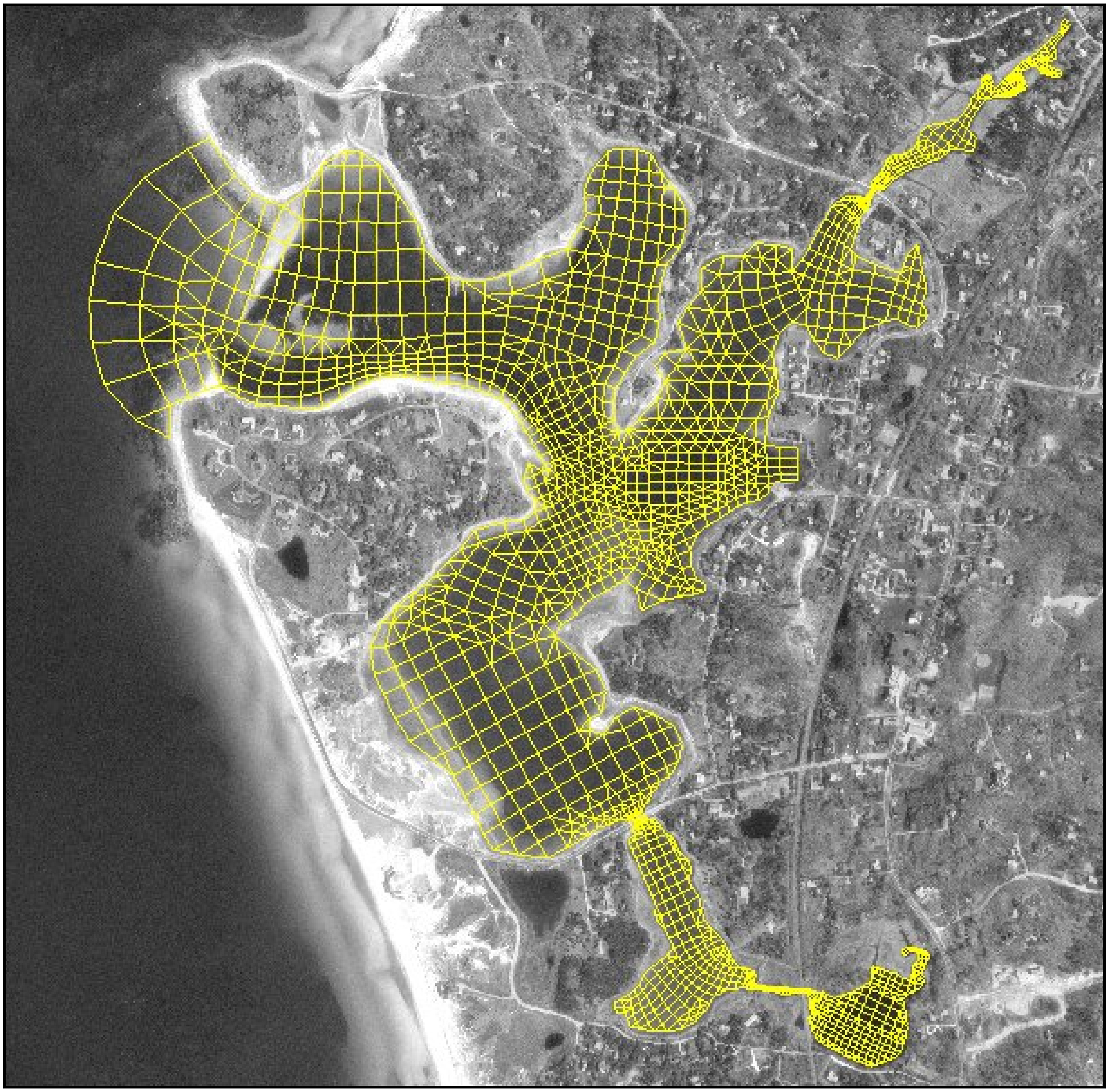


Figure V-12. Plot of numerical grid (yellow) used for hydrodynamic modeling of West Falmouth Harbor.

Once the grid is constructed, the system is broken down into regions with each region given its own material type. The material types contain information primarily about element roughness and eddy viscosity which are used to calibrate the model as discussed in Section

V.4.2.3 below. By dividing the system into regions and assigning each its own material type, the model can be more easily calibrated, with unique attributes assigned for each embayment, creek or culvert. Figure V-13 shows the finite element grid again, with the different material types now color coded. In total there were 10 material types used. There are two very small areas which are not discernable in the figure. These are used to model the creek leading to Oyster Pond and the culvert beneath Nashawena Street leading into Mashapaquit Creek.

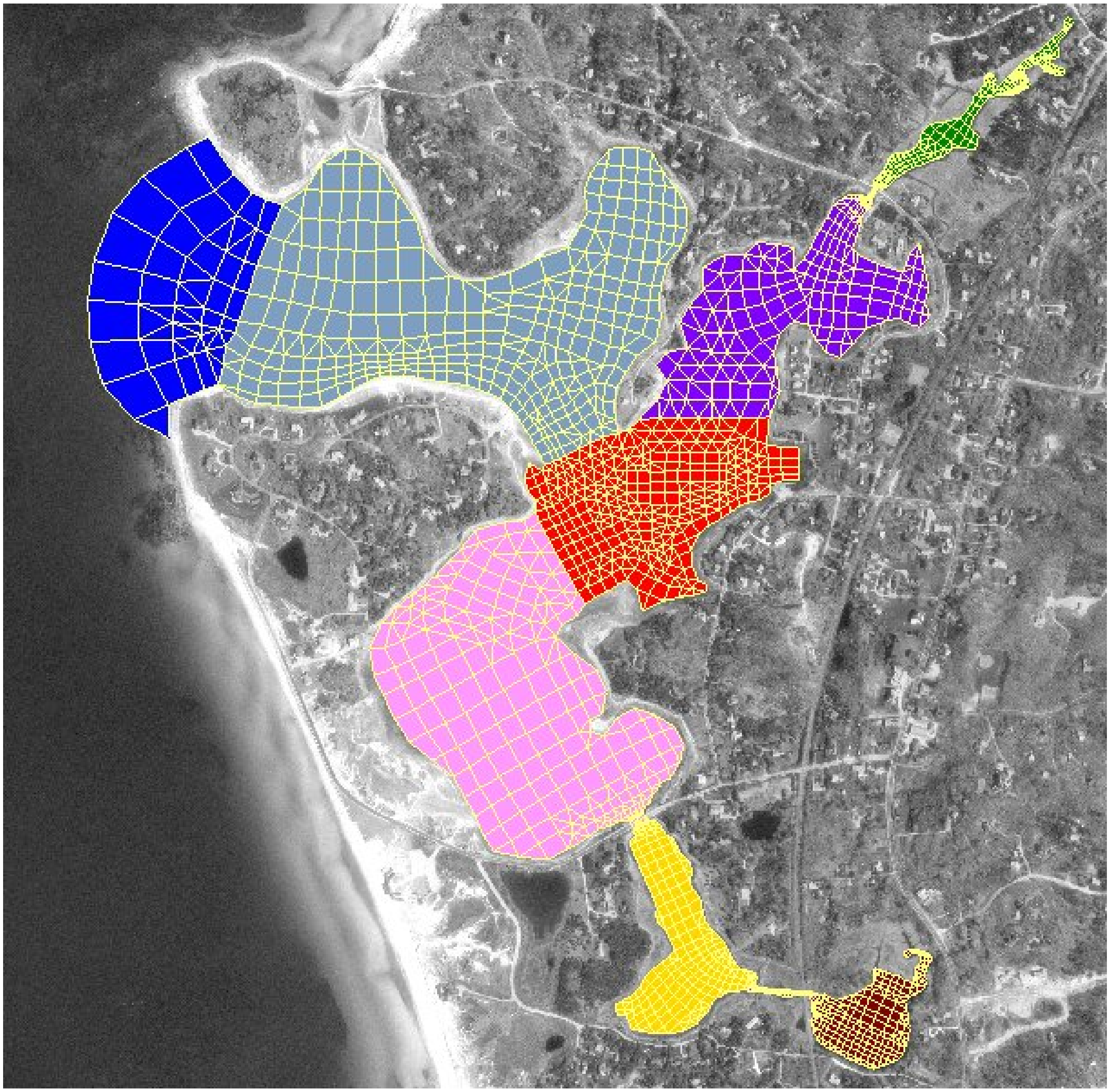


Figure V-13. Plot of numerical grid (yellow) used for hydrodynamic modeling of West Falmouth Harbor. Each different colored region represents a unique material type.

V.4.2.2 Boundary Condition Specification

Two types of boundary conditions were employed for the RMA-2 model: 1) "slip" boundaries and 2) tidal elevation boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. A tidal boundary condition was specified seaward of the inlet. The water elevations measured from Buzzards Bay provided the required data. Dynamic (time-varying) model simulations specified a new water surface elevation at the offshore boundary every 10 minutes.

V.4.2.3 Calibration

After developing the finite element grids, and specifying boundary conditions, the model was calibrated. Calibration ensured the model predicted accurately what was observed in nature during the field measurement program. Numerous model simulations were required (15+) to fine tune the model and complete the calibration. The calibrated model not only provides the basis for the flushing analysis, but is also a diagnostic tool that could be used to evaluate future changes proposed for the system (e.g. the effects of changing the culvert sizing into Oyster Pond).

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. A seven-day period was modeled to calibrate the model based on dominant tidal constituents discussed in Section V.3.2. The seven-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions.

The calibration was performed for a seven-day period beginning 0:00 EST on July 19, 2004. This representative time period was selected because it included the range of tidal conditions typical in the estuary during the 30-day deployment period. To provide average tidal forcing conditions to the predictive water quality model, a time period was chosen that had minimal atmospheric pressure and/or wind effects. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire seven-day simulation. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events (e.g. surge or wind setup occurring during a storm). 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.4.2.3.1 Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient. Initially, Manning's friction coefficient between 0.02 and 0.04 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).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning’s coefficients were matched to bottom type. For example, lower friction coefficients were specified for the smooth sandy channels in the entrance channel, versus the silty bottom of the shallow regions of Harbor Head, which provided greater flow resistance. Final model calibration runs incorporated various values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were selected based on the Civil

Engineering Reference Manual (Lindeburg, 1992) and values required to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-5.

V.4.2.3.2 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 more swift, such as inlets and bridge constrictions. According to King (1990a), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). The model for West Falmouth Harbor was relatively insensitive to turbulent exchange coefficients because there are no regions of strong turbulent flow. Primarily, this can be attributed to the moderate tide range and absence of strong changes in bathymetry throughout the system. Final calibrated eddy viscosities are shown in Table V-5.

Table V-5. Manning's Roughness and Eddy Viscosity coefficients used in simulations of modeled embayments. These delineations correspond to the material types shown in Figure V-13.

System Embayment	Bottom Friction	Eddy Viscosity
Harbor Entrance	0.03	20
Outer Harbor	0.03	20
Mid-Harbor	0.05	20
Snug Harbor	0.1	100
Nashawena Street Culvert	Varies by depth	200
Mashapaquit Creek	Varies by depth	100
Chappaquoit Basin	0.1	20
Harbor Head	0.1	20
Creek to Oyster Pond	Varies by depth	100
Oyster Pond	0.03	50

V.4.2.3.3 Marsh Porosity Processes

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 vary 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. It is also useful to help ensure the stability of the model.

V.4.2.3.4 Comparison of Modeled Tides and Measured Tide Data

A best-fit of model predictions for the first TDR deployment was achieved using the values for friction and turbulent eddy viscosity listed above. Figures V-14 through V-15 illustrate a two tidal cycle sub-section of the seven-day calibration simulation. Modeled (solid line) and measured (each data point plotted as a x) tides are illustrated for each of the measurement locations within the harbor basin. The 7th field location (Wfal-1) is offshore and was used as the boundary condition to drive the model. Only two tidal cycles are illustrated to focus on the details of the tide curve. Figures V-14 through V-15 confirm visual agreement between modeled and measured tides throughout the system.

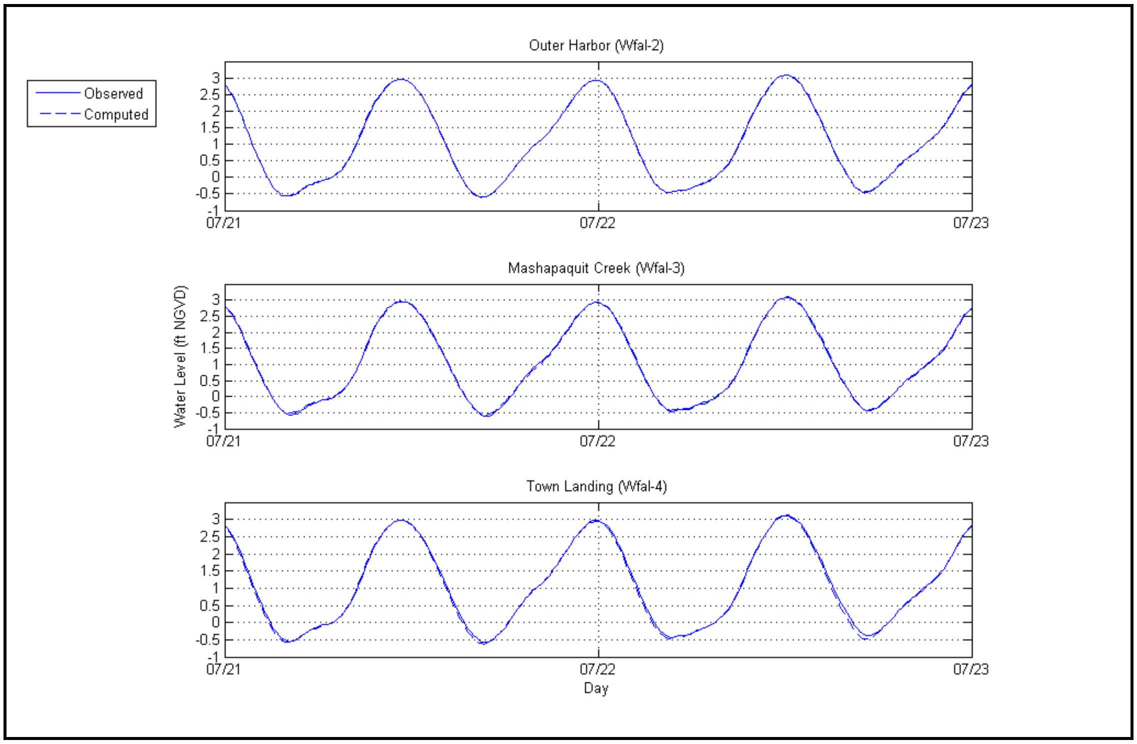


Figure V-14. Observed versus computed water level elevations for the Outer Harbor (Wfal-2), Mashapaquit Creek (Wfal-3) and the Town Landing (Wfal-4).

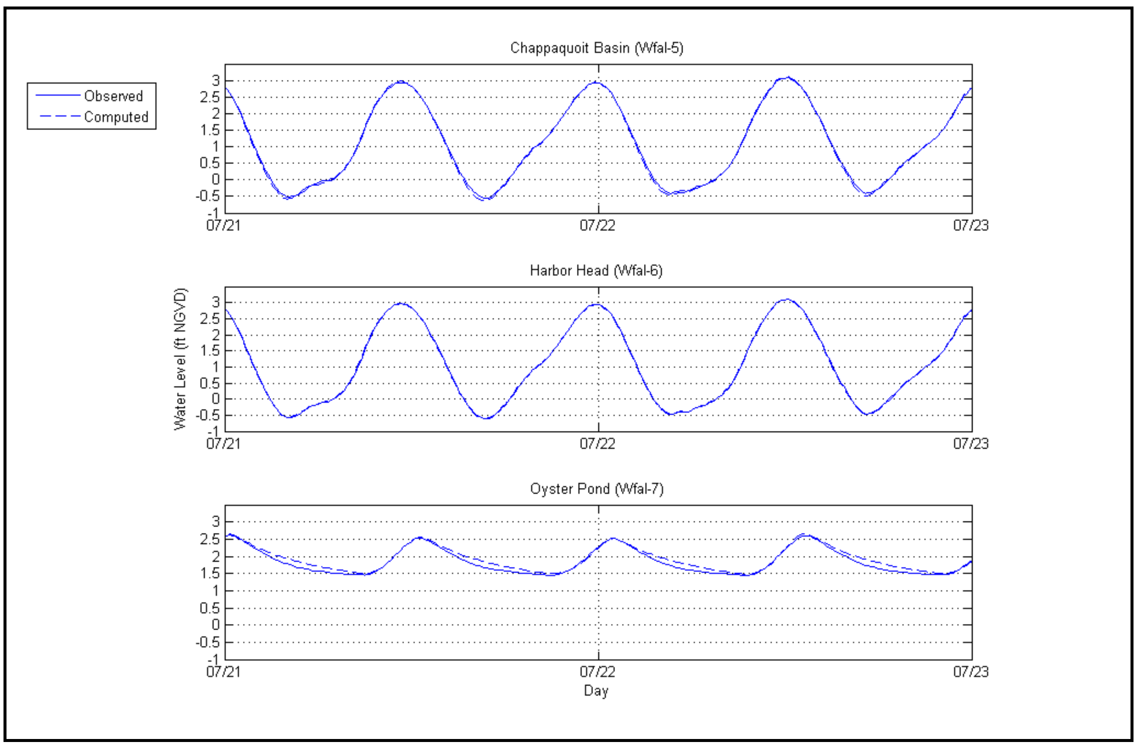


Figure V-15. Observed versus computed water level elevations for Chappaquoit Basin (Wfal-5), Harbor Head (Wfal-6) and Oyster Pond (Wfal-7).

Although visual calibration revealed the modeled tidal hydrodynamics were reasonable, tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in Buzzards Bay. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1, M_2, M_4, and M_6. Measured tidal constituent heights (H) and time lags (ϕ_{lag}) are shown in Table V-6. The specific values of the constituents for the calibration period differ from those in Table V-2 because constituents were computed for only the seven-day section of the thirty-days represented in Table V-2. Table V-6 compares tidal constituent height and time lag for modeled and measured tides at each of the 6 locations inside the system. Time lag represents the time required for a constituent to propagate from Buzzards Bay to each location.

The constituent calibration revealed excellent agreement between modeled and measured tides. Errors associated with tidal constituent height were on the order of 0.1 ft, which was only slightly larger than the accuracy of the tide gauges (0.032 ft). Time lag errors were typically less than the time increment resolved by the model (0.17 hours or 10 minutes), indicating good agreement between the model and data. Since tidal amplitude and phase attenuation was relatively minor, with the exception of Oyster Pond constituent calibration required that the M_2 constituent propagate into the Ponds with minimal resistance. The tide attenuation at Oyster Pond primarily results from the narrow culvert. The hydrodynamic model was able to predict accurately the effect of this constriction on flow properties.

The hydrodynamic model's ability to predict propagation of the secondary non-linear constituents through the estuary is important for understanding the attenuation of the tidal signal and the impact this has on estuarine circulation. Of primary interest is the M_4 constituent, which can be used to determine the flood dominance (sediment trapping characteristics) of an estuarine system. Proper prediction of M_4 provides confidence in the model's accuracy, since this indicates that the model is capable of simulating the tidal wave form and size. Similar to the model predictions for M_2, comparison of the information from Table V-6 indicates that the modeled phase of M_4 falls within approximately one time step of the observed value.

Table V-6. Tidal constituents for measured water level data and calibrated model output

Location	Constituent Amplitude (ft)				Phase (deg)	
Model calibration run						
Location	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Outer Harbor	1.64	0.28	0.04	0.13	358.3	34.4
Mashapaquit Creek	1.62	0.26	0.06	0.12	358	32.4
Town Landing	1.64	0.27	0.05	0.13	6.0	36.6
Chappaquoit Basin	1.64	0.26	0.05	0.13	3.8	37.2
Harbor Head	1.64	0.26	0.05	0.13	5.0	37.3
Oyster Pond	0.42	0.15	0.05	0.04	100.9	58.0
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Outer Harbor	1.64	0.28	0.04	0.13	357.1	33.5
Mashapaquit Creek	1.64	0.26	0.05	0.13	2.7	35.7
Town Landing	1.64	0.26	0.05	0.16	2.1	35.1
Chappaquoit Basin	1.60	0.25	0.05	0.13	1.6	35.6
Harbor Head	1.64	0.26	0.05	0.13	2.7	35.7
Oyster Pond	0.45	0.16	0.05	0.03	120.9	57.4
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Outer Harbor	0.00	0.00	0.00	0.00	1.2	0.9
Mashapaquit Creek	-0.02	0.00	0.01	-0.01	-4.7	-3.3
Town Landing	0.00	0.01	0.00	-0.03	3.9	1.5
Chappaquoit Basin	0.04	0.01	0.00	0.00	2.2	1.6
Harbor Head	0.00	0.00	0.00	0.00	2.3	1.6
Oyster Pond	-0.03	-0.01	0.00	0.01	-20.0	0.6

V.4.2.4 Model Verification Using Horizontal ADCP Measurements

The calibration procedure used in the development of the finite-element models required a match between measured and modeled tides. To verify the performance of the West Falmouth Harbor model, computed flow rates were compared to flow rates measure using an ADCP. The ADCP data survey efforts are described in Chapter III and the survey locations are shown in Figure V-8 above. For model verification, the model was run for a 3 day period ending with the end of the run corresponding to the day of the actual ADCP survey, July 28, 2004. Model flow rates were computed in RMA-2V at continuity lines (channel cross-sections) that correspond to the actual ADCP transects followed in each survey.

Comparisons of the measured and modeled volume flow rates in the West Falmouth system are shown in Figures V-16 and V-17. For each figure, the top plot shows the flow comparison, and the lower plot shows the time series of tide elevation for the same period. Each ADCP point (blue circles shown on the plots) is a summation of flow measured along the ADCP transect.

Data comparisons at both ADCP transect show good agreement with the model predictions. The calibrated model accurately describes the discharge magnitude at both locations. In general the model results record slightly larger values than the ADCP measurements. This is primarily due to the fact that the ADCP survey excludes flow from the extreme edges of the transect due to depth limitations from the survey boat itself. The R^2 correlation coefficient between data and model results are 0.91 for transect A-3 (figure V-16 below) and 0.93 for transect A-4 (figure V-17 below).

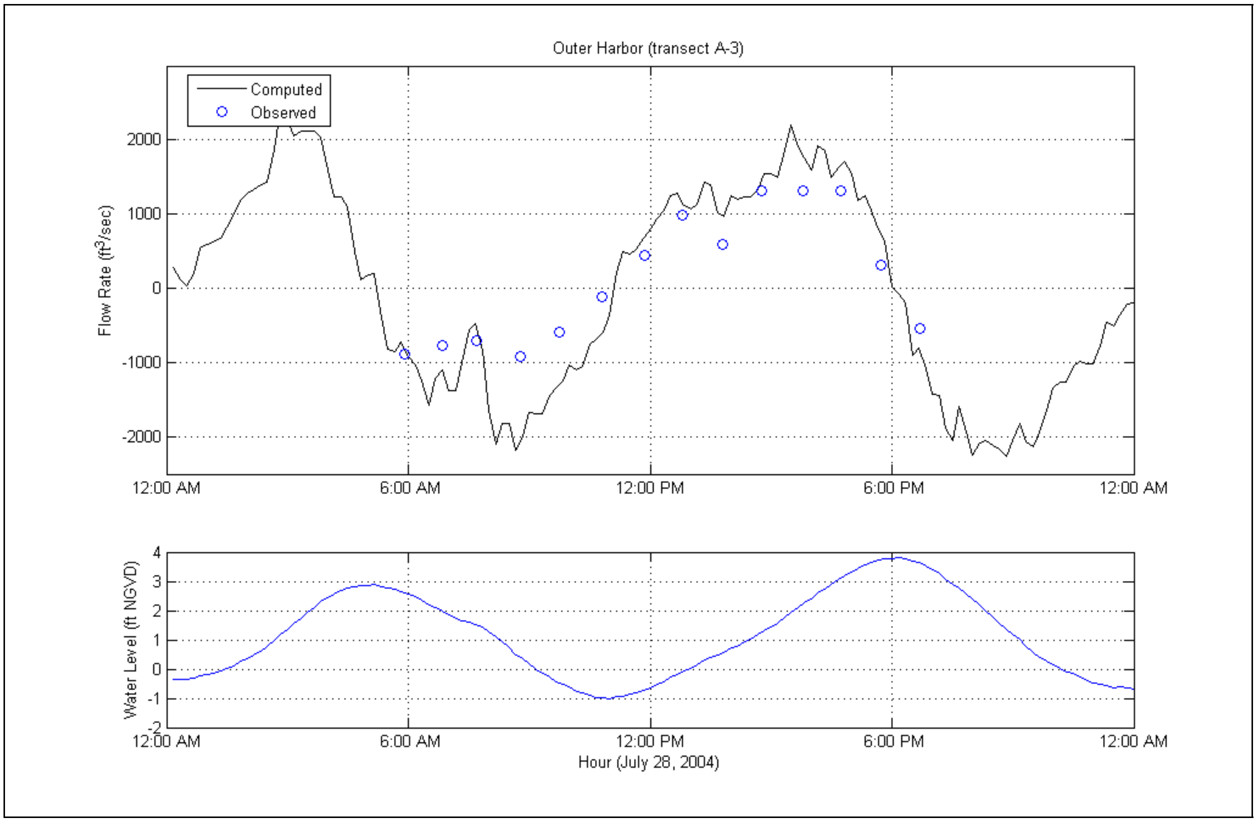


Figure V-16. Flow rate measurements collected on June 28 at transect A-3. The top plot shows measured and modeled flow rates while the bottom plot shows the offshore tide for the same time period.

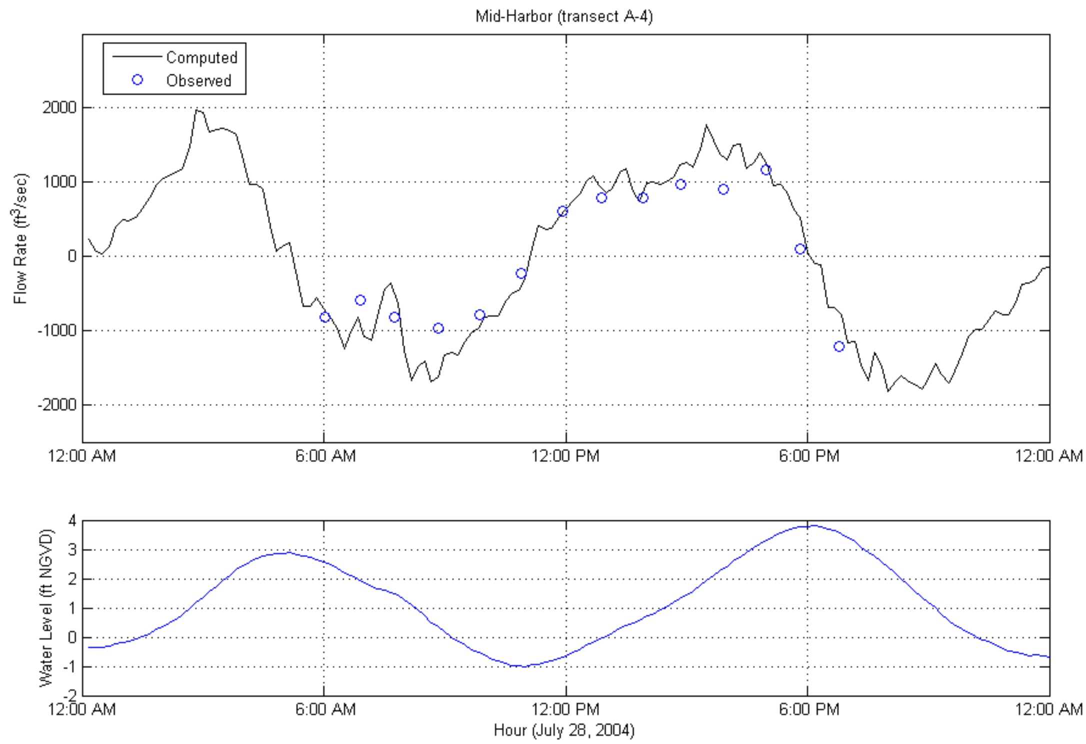


Figure V-17. Flow rate measurements collected on June 28 at transect A-4. The top plot shows measured and modeled flow rates while the bottom plot shows the offshore tide for the same time period.

V.4.2.5 Model Circulation Characteristics

Tides in West Falmouth Harbor affect sediment transport, pollutant dispersion, and water circulation. The calibrated hydrodynamic model provided an unparalleled tool to evaluate details of tidal circulation in the system. For example, field measurements of current flow within a system, using either single-point current meters or Lagrangian drifters, are intrinsically limited. Single point measurements are limited to small regions of the flow, and cannot account for spatial variations in the current throughout a region. Lagrangian drifters (drogues) follow the spatial track of the flow, but are limited to a single 'snapshot' of time at each location and do not resolve temporal variations in the flow. Numerical models offer both spatial and temporal coverage of circulation patterns that reveal the essence of the hydrodynamic behavior. Such insight is invaluable in evaluating tidal characteristics.

The tidal analysis revealed that West Falmouth Harbor exhibits flood-dominant characteristics (Aubrey and Speer, 1985). The slightly stronger flood tide currents of short-duration, and corresponding weaker ebb flows over a longer duration are the characteristics of flood-dominant estuaries. Typically, flood-dominance is an indicator of an estuary's tendency to trap and accumulate sediment. A simplified explanation of this complex phenomenon is that stronger flood currents have the energy to drag suspended sediment into the system, whereas weaker ebb flows do not have sufficient energy to suspend and flush these sediments. A majority of the sediment most likely settles after flood tides and is not re-suspended on the ebb.

The primary sediment source to West Falmouth Harbor is the predominant south-to-north littoral drift along Falmouth's Buzzards Bay coast. Since the estuary is flood-dominant, sand entering the inlet will continue to cause shoaling within the inlet throat and in the channel region immediately east of the entrance. The relatively small volume of littoral sediments available makes shoaling a secondary concern and does not have a major impact on the overall ability of the estuary to exchange water with Buzzards Bay.

V.5. FLUSHING CHARACTERISTICS

Since freshwater inflow is negligible in comparison to the tidal exchange through each inlet, the primary mechanism controlling estuarine water quality within West Falmouth Harbor is tidal circulation. A rising tide in Buzzards Bay creates a slope in water surface from the bay into the estuary. Consequently, water flows into (floods) the estuary. Similarly, the estuary drains into the bay on an ebbing tide. This exchange of water between the estuary and bay is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of the 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. Embayment mean volumes and average tidal prisms are shown in Table V-7.

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. For example, the **system residence time** is the average time required for water to migrate from Mashapaquit Creek to Buzzards Bay, where the **local residence time** is the average time required for water to migrate from Mashapaquit Creek to Snug Harbor. 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).

Table V-7. Embayment mean volumes and average tidal prism during simulation period.		
Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
West Falmouth Harbor (total)	39,738,000	26,824,000
Mashapaquit Creek	279,000	468,000
Snug Harbor	4,705,000	4,116,000
Oyster Pond	2,440,000	252,000
Harbor Head	3,512,000	1,627,000
Chappaquoit Basin	13,510,000	8,947,000

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. This is a valid approach in this case, since it assumes the bay has relatively higher quality water relative to the estuary.

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 pollutant/nutrient dispersion. The water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the West Falmouth Harbor system.

Residence times reflect the lack of tidal damping through the harbor mouth as well as the bathymetry found in West Falmouth Harbor and each sub-embayment. Since tidal waters flow freely into the harbor, the volume of water exchanged during a tidal cycle can be approximated by the surface area of the embayment multiplied by the tide range. For systems with little tidal damping, the bathymetry tends to control residence times, where shallow sub-embayments will exhibit lower residence times than deeper sub-embayments. This is most clearly illustrated by Oyster Pond, which is the deepest sub-embayment within the system. This “kettle hole” is connected to Harbor Head by a shallow channel and small culvert. The tidal exchange through the culvert is severely restricted. This restriction, along with the deep water depths (approaching 30 ft in the southeast portion of the pond) cause the percentage of total volume exchanged with Harbor Head to be relatively low compared to other sub-embayments within the system.

The relatively long residence time for some sub-embayments (e.g. Mashapaquit Creek) revealed the inadequacy of using system residence time alone to evaluate water quality. By definition, smaller sub-embayments have longer residence times; therefore, residence times may be misleading for small, remote parts of the estuary. Instead, it is useful to compute a local residence time for each sub-embayment. A local residence time represents the time required for a water parcel to leave the particular sub-embayment. For instance, the local residence time for Mashapaquit Creek represents the time required for a water parcel to be flushed from the

Creek into Snug Harbor. Local residence times are computed as the volume of the sub-embayment divided by the tidal prism of that sub-embayment, and units are converted to days. Table V-8 lists local residence times for several areas within West Falmouth Harbor. The basins utilized for residence time calculations are shown in Figure V-18.

Local residence times in Table V-8 are significantly lower than residence times based on the volume of the entire estuary. For example, flow entering Snug Harbor on an average tidal cycle flushes through the entrance to West Falmouth Harbor in 5 days, but flushes into the main harbor areas in only 0.6 days (just longer than one tidal cycle). Generally, a local residence time is only useful where the adjacent embayment has high water quality. For West Falmouth Harbor, the receiving waters (the outer and mid- harbor areas) that exchange tidal flow with the various sub-embayments, show signs of ecological stress. This is indicative of poor water quality. Therefore, system residence times may be more appropriate for future planning scenarios.

Table V-8. Computed System and Local residence times for embayments in the system.

Embayment	System Residence Time (days)	Local Residence Time (days)
West Falmouth Harbor (total)	0.8	0.8
Mashapaquit Creek	43.9	0.3
Snug Harbor	5	0.6
Oyster Pond	81.6	5.0
Harbor Head	12.6	1.1
Chappaquoit Basin	2.3	0.8

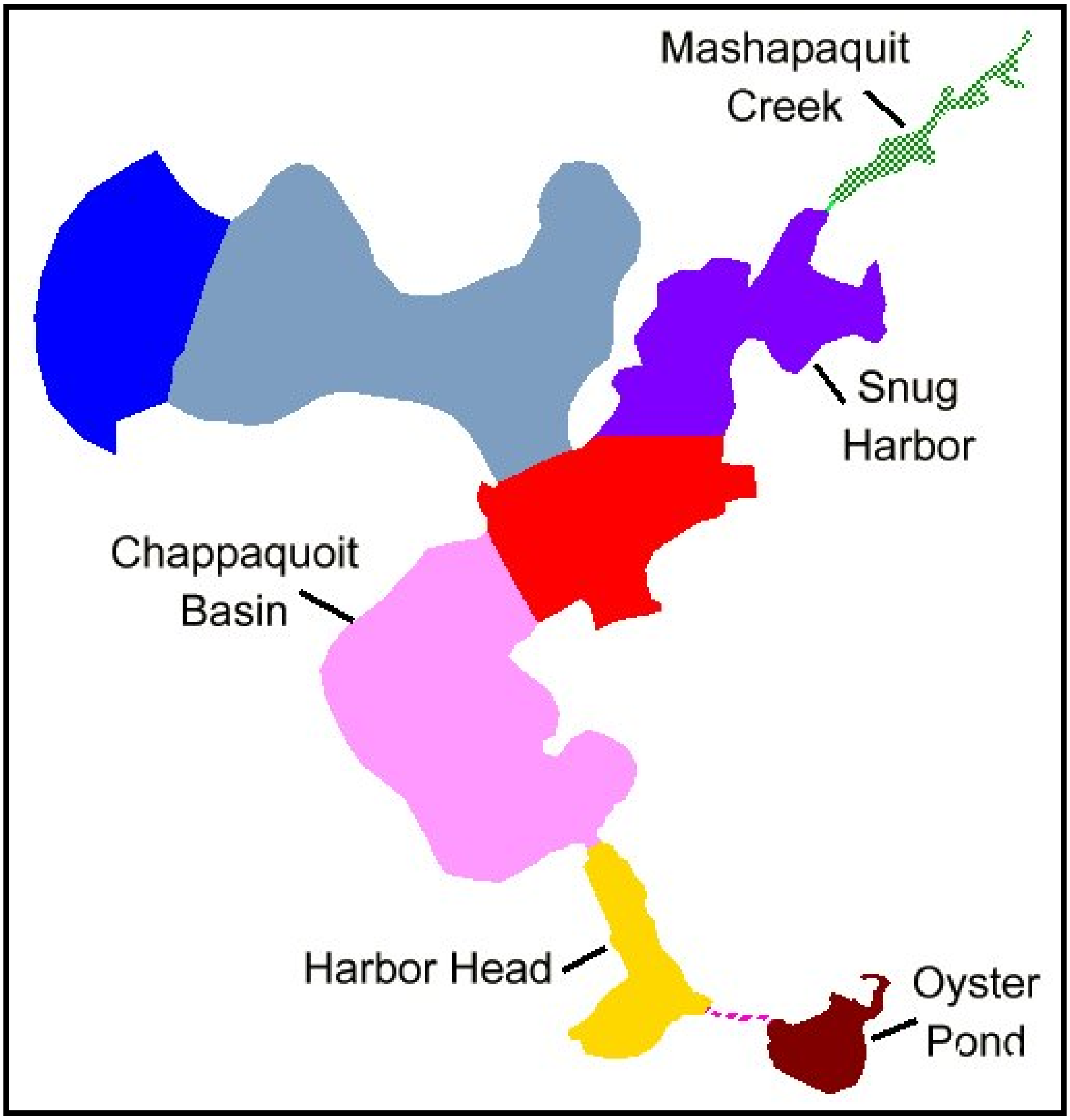


Figure V-18. Basins used to compute residence times for the system.

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 West Falmouth Harbor system. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayments

Extensive field measurements and hydrodynamic modeling of the 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 West Falmouth Harbor system. Files of node locations and node connectivity for the RMA-2V model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic output for the water quality model calibration was a the 7 day period beginning July 19, 2004 0000 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 had reached a dynamic "steady state", and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the 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 West Falmouth Harbor 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. Typically, ten years of data (collected between 1995 and 2004) were available for stations monitored by SMAST.

Table VI-1. Measured data and modeled Nitrogen concentrations for the West Falmouth Harbor estuarine system used in the model calibration plots of Figures VI-2 and VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data represented in this table were collected in the summers of 1995 through 2004, except the Buzzards Bay station, which are from the summer of 1991.

Sub-Embayment	monitoring station	data mean	s.d. all data	N	model min	model max	model average
Mashapaquit Cr., Nashawena Rd.	PWF1	0.742	0.288	71	0.459	0.853	0.627
Harbor Head, Chappaquoit Rd.	PWF2	0.482	0.144	68	0.411	0.468	0.437
Chappaquoit Basin	PWF3	0.415	0.194	69	0.355	0.409	0.382
Inner West Falmouth Harbor	PWF4	0.389	0.114	75	0.340	0.404	0.370
Snug Harbor	PWF5	0.444	0.122	73	0.411	0.526	0.464
Outer West Falmouth Harbor	PWF6	0.343	0.083	67	0.305	0.356	0.327
Outer West Falmouth Harbor	PWF7	0.346	0.115	69	0.296	0.353	0.312
Oyster Pond	PWF8	0.506	0.137	184	0.528	0.543	0.534
Buzzards Bay	Sta13-10	0.296	0.023	4	-	-	-

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 West Falmouth Harbor estuarine system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of West Falmouth Harbor. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod embayments, including systems other systems in 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 Cape Cod Commission watershed loading analysis (based on the USGS watersheds), as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements were utilized as model boundaries and as calibration data. Hydrodynamic model output (discussed in Section V) provided the remaining information (tides, currents, and bathymetry) needed to parameterize the water quality model of the West Falmouth Harbor system.

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

VI.2.1 Model Formulation

The formulation of the model is for two-dimensional depth-averaged systems in which concentration in the vertical direction is assumed uniform. The depth-averaged assumption is justified since vertical mixing by wind and tidal processes prevent significant stratification in the modeled 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 West Falmouth Harbor system.

VI.2.2 Water Quality Model Setup

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

Based on measured surface water flow rates from SMAST and groundwater recharge rates from the USGS, the hydrodynamic model was set-up to include the latest estimates of flows from Mashapaquit Creek (0.69 ft^3/sec).

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 5 tidal-day (125 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the West Falmouth Harbor model.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, 3) summer benthic regeneration, and 4) the point source input developed from measurements of the freshwater portions of Mashapaquit Creek. 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 Snug Harbor 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 West Falmouth Harbor system are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each 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 all areas of West Falmouth Harbor, the benthic flux is relatively low or negative indicating a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in the Buzzards Bay region offshore West Falmouth Harbor was set at 0.296 mg/L, based on SMAST data collected in the summer of 1991.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Outer West Falmouth Harbor	1.690	0.921	-3.086
Inner West Falmouth Harbor	10.386	0.866	-6.091
Harbor Head	1.085	0.153	-0.478
Oyster Pond	1.359	0.079	0.000
Snug Harbor	9.570	0.455	-3.699
Mashapaquit Creek	17.649	0.019	0.000

VI.2.4 Model Calibration

Calibration of the total nitrogen model of West Falmouth Harbor 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 of the south shore of Cape Cod 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.

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

Embayment Division	E m^2/sec
West Falmouth Harbor Inlet	5.0
Outer West Falmouth Harbor	5.0
Inner West Falmouth Harbor	5.0
Lower Snug Harbor	5.0
Upper Snug Harbor	4.5
Nashawena Rd. Culvert	5.0
Mashapaquit Creek (estuarine)	5.0
Mashapaquit Creek (fresh)	1.0
Chappaquoit Basin	1.0
Harbor Head	3.0
Oyster Pond Creek	5.0
Oyster Pond	5.0

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 SMAST monitoring stations.

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

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

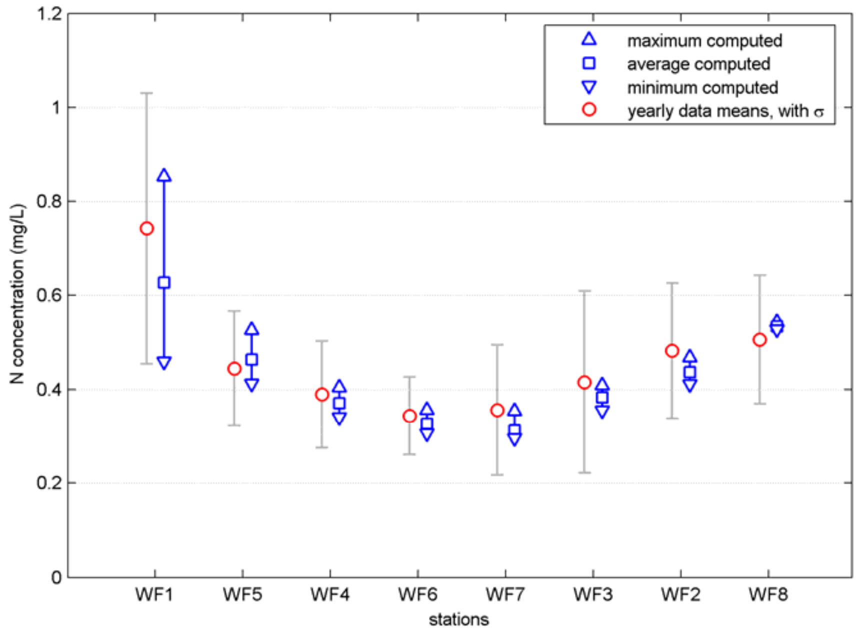


Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in the West Falmouth Harbor system. Station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the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

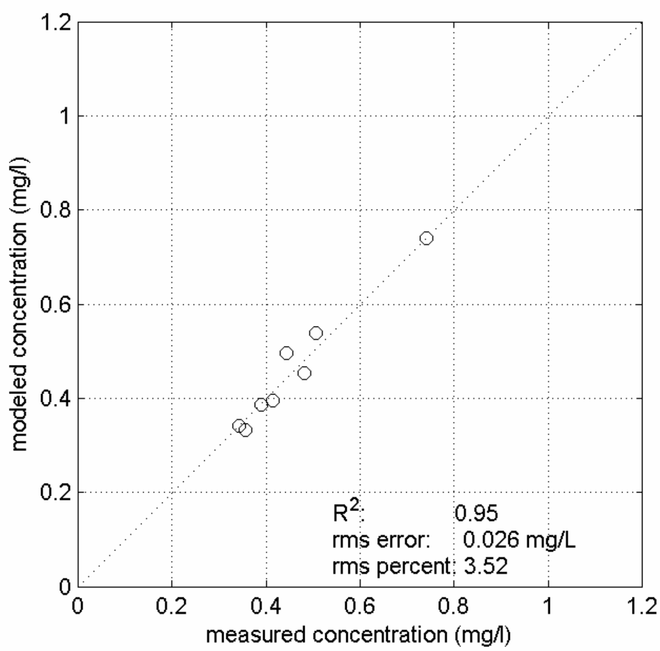


Figure VI-3. Model total nitrogen calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for the model are also presented.

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 5-tidal-day model simulation output period.

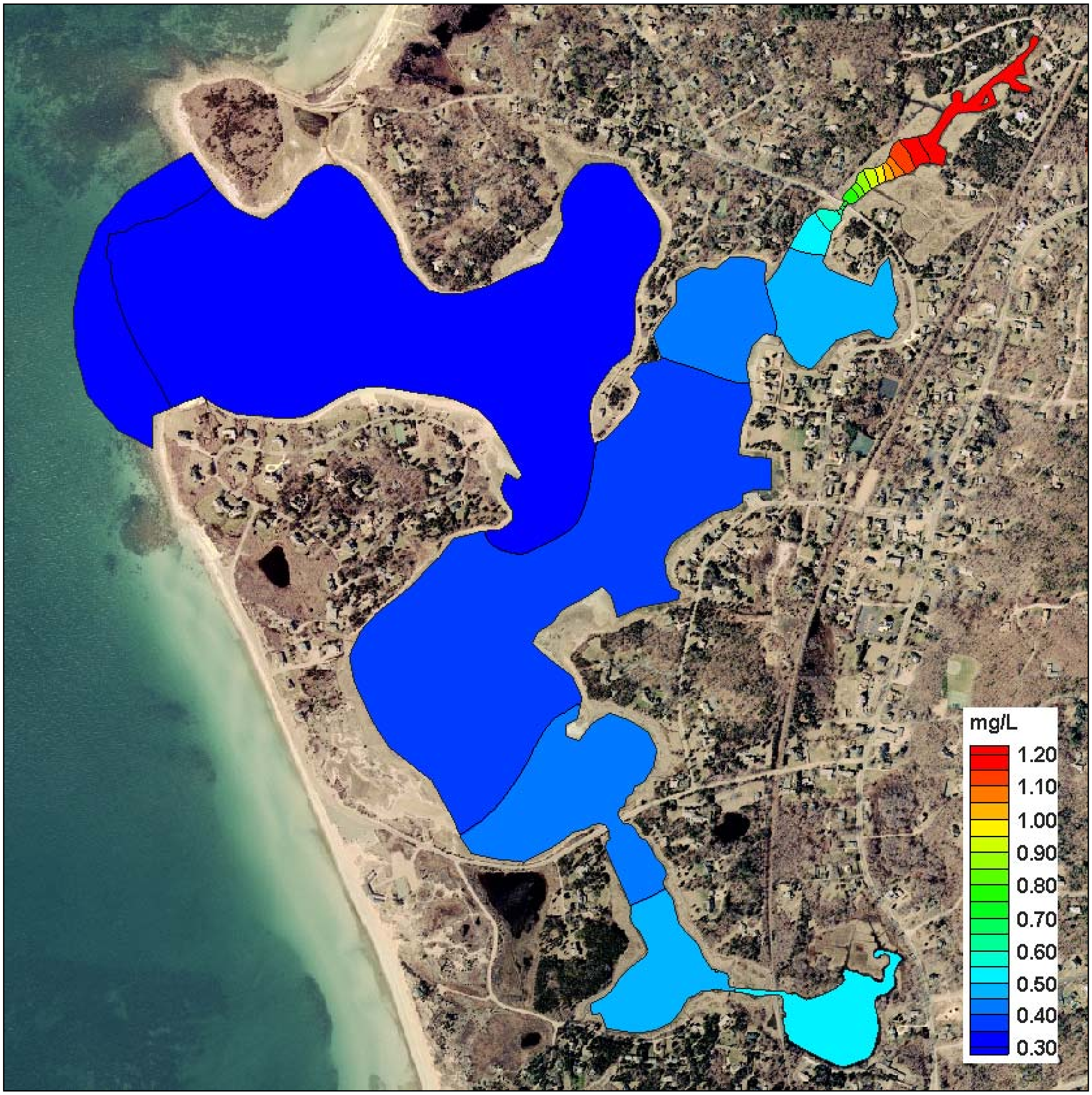


Figure VI-4. Contour plot of average total nitrogen concentrations from results of the present conditions loading scenario, for the West Falmouth Harbor system.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the West Falmouth Harbor system using salinity data collected at the same stations as the nitrogen data. The only required inputs into the RMA4 salinity model of each system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, at the freshwater stream discharges, and groundwater inputs. The open boundary salinity was set at 30.0 ppt. For surface water steams and groundwater inputs salinities were set at 0 ppt. Surface water stream flow rates for the streams were the same as those used for the total nitrogen model, as presented earlier in this section. Groundwater inputs used for each model were 1.83 ft^3/sec (4,474 m^3/day) for Mashapaquit Creek, 0.91 ft^3/sec (2,233 m^3/day) for Snug Harbor, 1.30 ft^3/sec (3,181 m^3/day) for the inner harbor basin, 0.42 ft^3/sec (1027 m^3/day) for the Harbor Head, 0.51 ft^3/sec (1,247 m^3/day) for Oyster Pond, and 0.30 ft^3/sec (722 m^3/day) for the outer harbor basin. Groundwater flows were distributed evenly in the model through the use of several 1-D element input points positioned along each model's land boundary.

Comparisons of modeled and measured salinities are presented in Figures VI-5 and VI-6, with contour plots of model output shown in Figure VI-7. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients throughout the West Falmouth Harbor estuary system. The rms error of the three models is less than 0.7 ppt, and correlation coefficient between the model and measured salinity data is 0.88. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical system.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the West Falmouth Harbor, two standard water quality modeling scenarios were run: a "build-out" scenario based on potential development (described in more detail in Section IV) and a "no anthropogenic load" or "no load" scenario assuming only atmospheric deposition on the watershed and sub-embayment, as well as a natural forest within each watershed. Comparisons of the alternate watershed loading analyses are shown in Table VI-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.

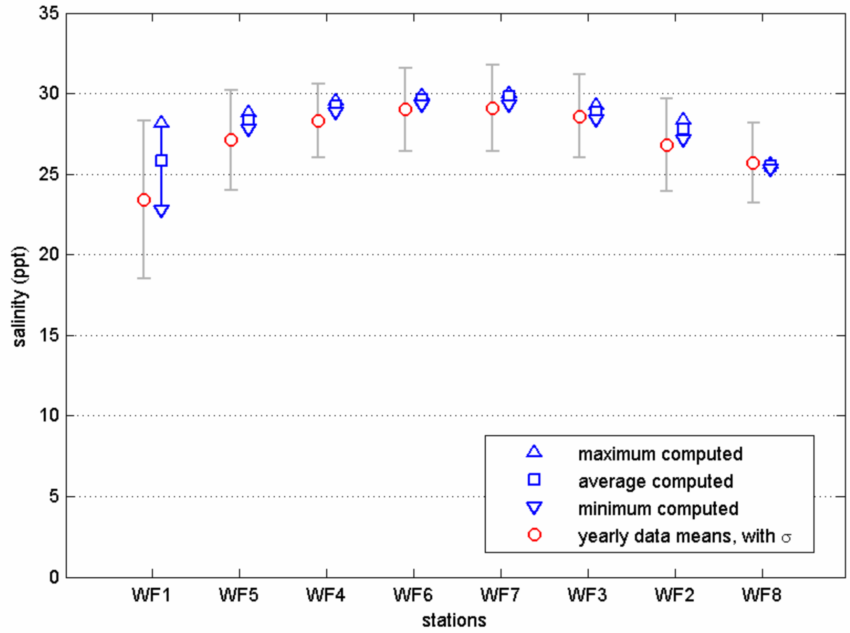


Figure VI-5. Comparison of measured and calibrated model output at stations in West Falmouth Harbor. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along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

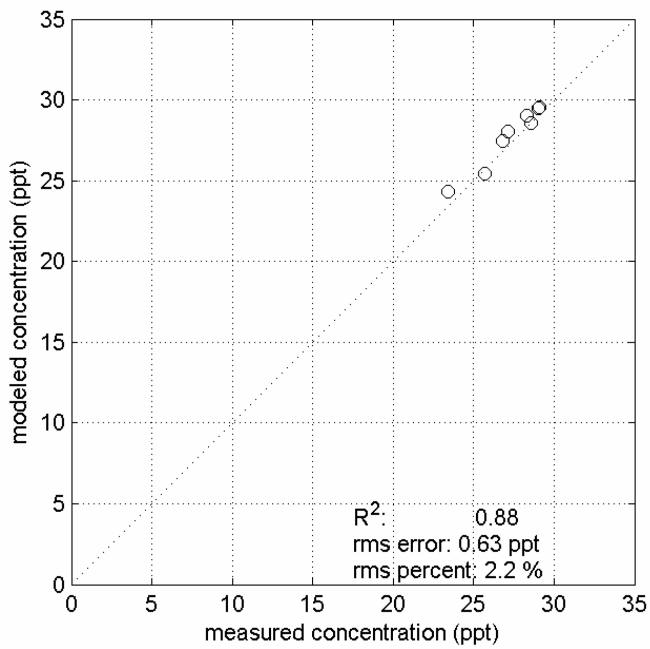


Figure VI-6. Model salinity target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

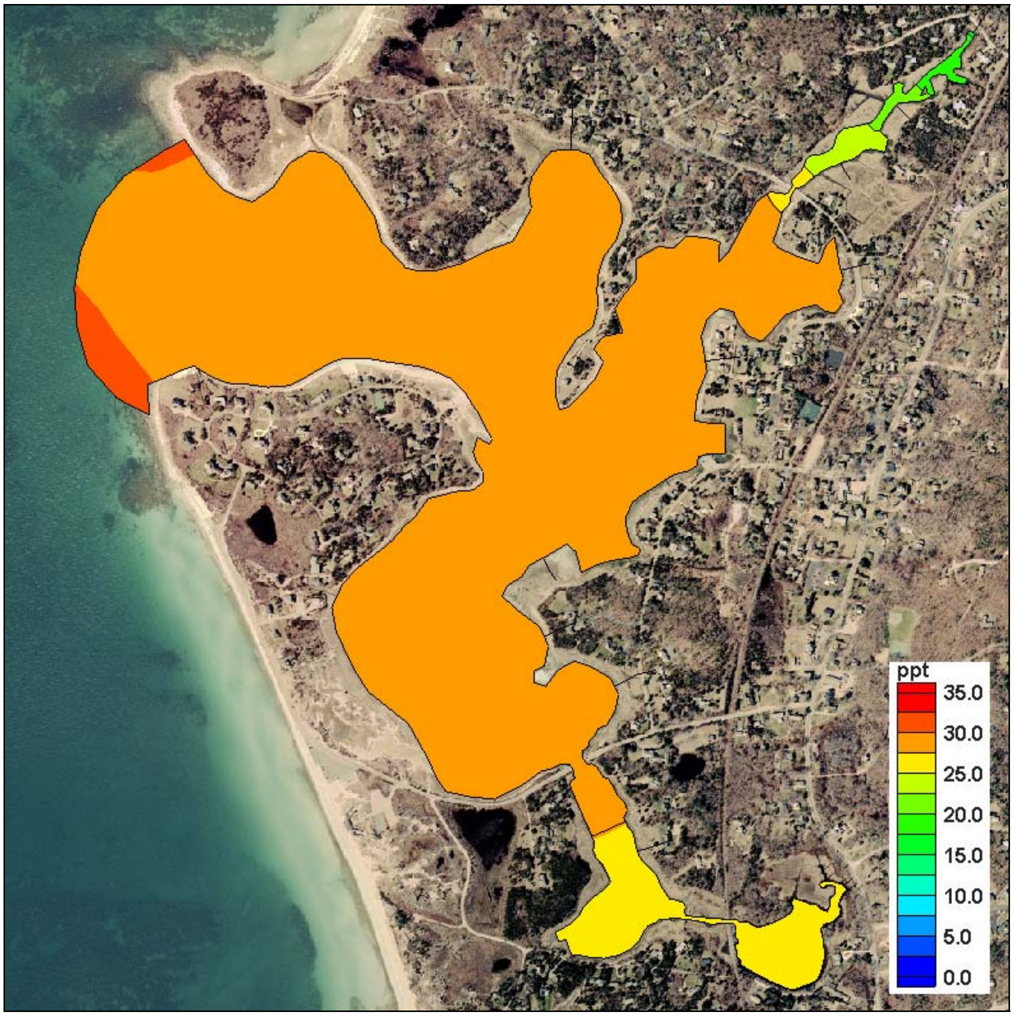


Figure VI-7. Contour Plot of modeled salinity (ppt) in the West Falmouth Harbor system.

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

sub-embayment	present load (kg/day)	build out (kg/day)	build-out % change	no load (kg/day)	no load % change
Outer West Falmouth Harbor	1.690	1.359	-19.6%	1.274	-24.6%
Inner West Falmouth Harbor	10.386	5.301	-49.0%	2.085	-79.9%
Harbor Head	1.085	0.592	-45.5%	0.811	-25.3%
Oyster Pond	1.359	0.718	-47.2%	0.984	-27.6%
Snug Harbor	9.570	3.715	-61.2%	1.912	-80.0%
Mashapaquit Creek	17.649	6.844	-61.2%	0.822	-95.3%

VI.2.6.1 Build-Out

In general, for build-out loading, the loading to the West Falmouth Harbor watershed decreases compared to present condition. This is because the build-out scenario for West

Falmouth Harbor includes improvements to the WWFT and also sewering of the Harbor watershed, both of which contribute to the reduction in the nitrogen load to the system. The build-out scenario indicates that there would be less between a 45% to 50% decrease in watershed nitrogen load to the Inner Harbor, Harbor Head and Oyster Pond. For both Snug Harbor and Mashapaquit Creek, the load reduction for build-out would be more than 61%. For the Outer Harbor region, which already receives a relatively low nitrogen load, the reduction in load for build-out is only 25%. For the no load scenarios, almost all of the load entering the watershed is removed; therefore, the load is generally lower than existing conditions by as much as 95%.

For the build-out scenario, a breakdown of the total nitrogen load entering each sub-embayment is shown in Table VI-5. The benthic flux for the build-out scenarios is assumed to vary proportional to the watershed load, where an increase in watershed load will result in an increase in benthic flux (i.e., a positive change in the absolute value of the flux), and *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-5. **Build-out** sub-embayment and surface water loads used for total nitrogen modeling of the West Falmouth Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Outer West Falmouth Harbor	1.359	0.921	-2.895
Inner West Falmouth Harbor	5.301	0.866	-4.949
Harbor Head	0.592	0.153	-0.372
Oyster Pond	0.718	0.079	0.000
Snug Harbor	3.715	0.455	-2.892
Mashapaquit Creek	6.844	0.019	0.000

Following development of the nitrogen loading estimates for the build-out scenario, the water quality models of each system were 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. Total N concentrations decreased the most in the upper portions of the system, with the largest change at a station in Snug Harbor (-24% at PWF5), with the least change occurring in outer West Falmouth Harbor (-3.6% at PWF7) near the system's inlet to Buzzards Bay. Again, it bares repeating that the nitrogen concentrations in the build-out scenario decrease compared to present loading conditions because in this loading scenario there is a smaller nitrogen load to the Harbor. This is because the Harbor watershed is extensively sewered and also because the WWTF discharges less nitrogen in this scenario. Color contours of model output for the build-out scenario are present in Figure VI-8. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-4, which allows direct comparison of nitrogen concentrations between loading scenarios.

An important result of the build-out scenario model run is that this loading condition will meet the threshold requirements for habitat restoration in the harbor. The threshold requirements are discussed more thoroughly in Section VIII.

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

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Mashapaquit Cr., Nashawena Rd.	PWF1	0.627	0.412	-34.3%
Harbor Head, Chappaquoit Rd.	PWF2	0.437	0.353	-19.1%
Chappaquoit Basin	PWF3	0.382	0.326	-14.8%
Inner West Falmouth Harbor	PWF4	0.370	0.320	-13.5%
Snug Harbor	**PWF5**	**0.464**	**0.353**	**-24.0%**
Outer West Falmouth Harbor	PWF6	0.327	0.306	-6.5%
Outer West Falmouth Harbor	PWF7	0.312	0.301	-3.6%
Oyster Pond	PWF8	0.534	0.407	-23.8%

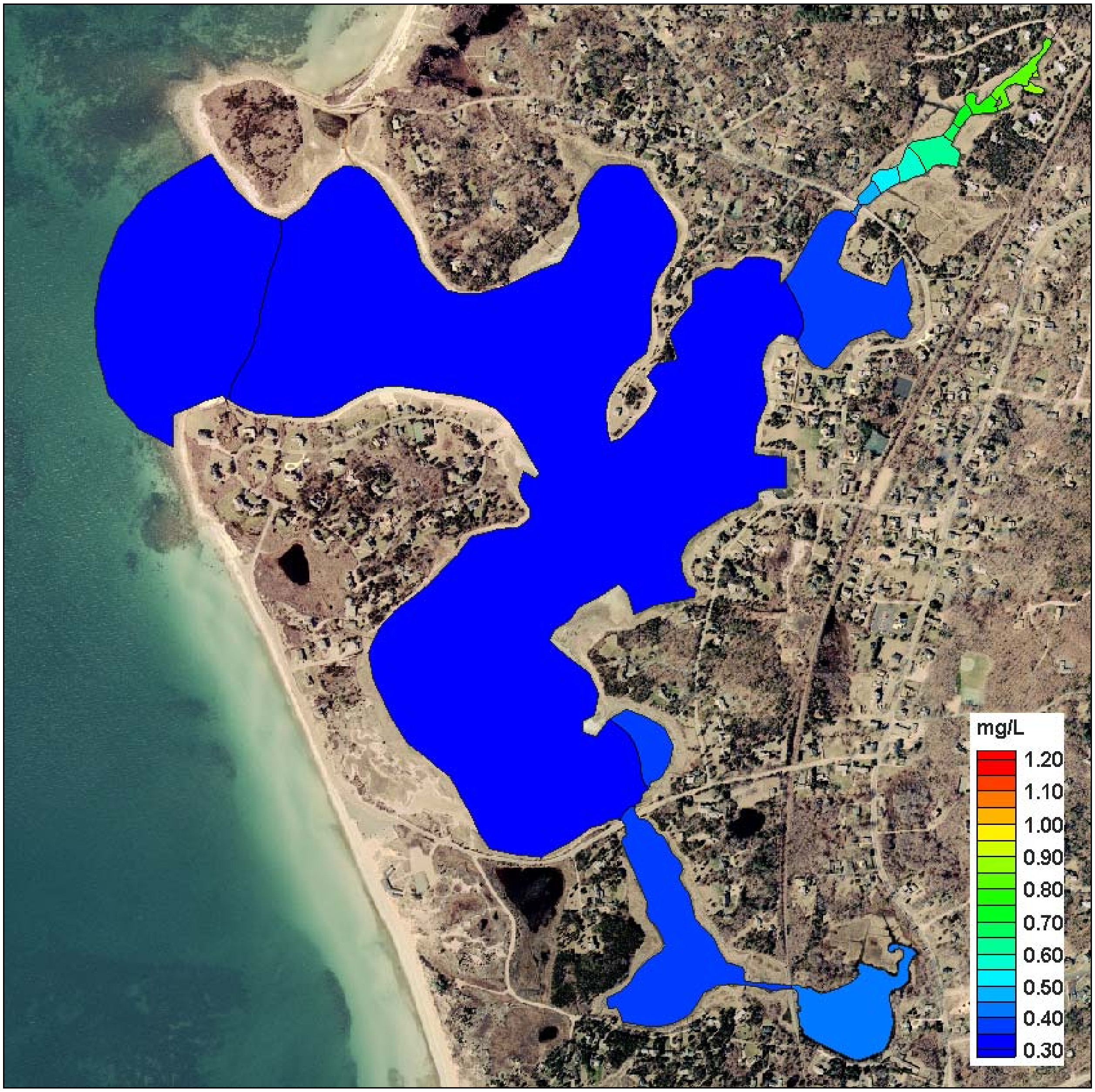


Figure VI-8. Contour plot of modeled total nitrogen concentrations (mg/L) in the West Falmouth Harbor system, for projected build-out loading conditions.

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.

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

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Outer West Falmouth Harbor	0.271	0.921	-2.786
Inner West Falmouth Harbor	1.027	0.866	-4.214
Harbor Head	0.197	0.153	-0.306
Oyster Pond	0.290	0.079	0.000
Snug Harbor	0.901	0.455	-2.367
Mashapaquit Creek	0.822	0.019	0.000

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Again, total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was significant as shown in Table VI-8, with reductions greater than 37% (at PWH5) occurring the upper portions of the system. Results for each system are shown pictorially in Figure VI-9.

Table VI-8. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the West Falmouth Harbor system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The sentinel threshold station is in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no load (mg/L)	% change
Mashapaquit Cr., Nashawena Rd.	PWF1	0.627	0.294	-53.0%
Harbor Head, Chappaquoit Rd.	PWF2	0.437	0.295	-32.6%
Chappaquoit Basin	PWF3	0.382	0.288	-24.7%
Inner West Falmouth Harbor	PWF4	0.370	0.291	-21.5%
Snug Harbor	**PWF5**	**0.464**	0.290	-37.4%
Outer West Falmouth Harbor	PWF6	0.327	0.292	-10.7%
Outer West Falmouth Harbor	PWF7	0.312	0.294	-5.9%
Oyster Pond	PWF8	0.534	0.319	-40.2%

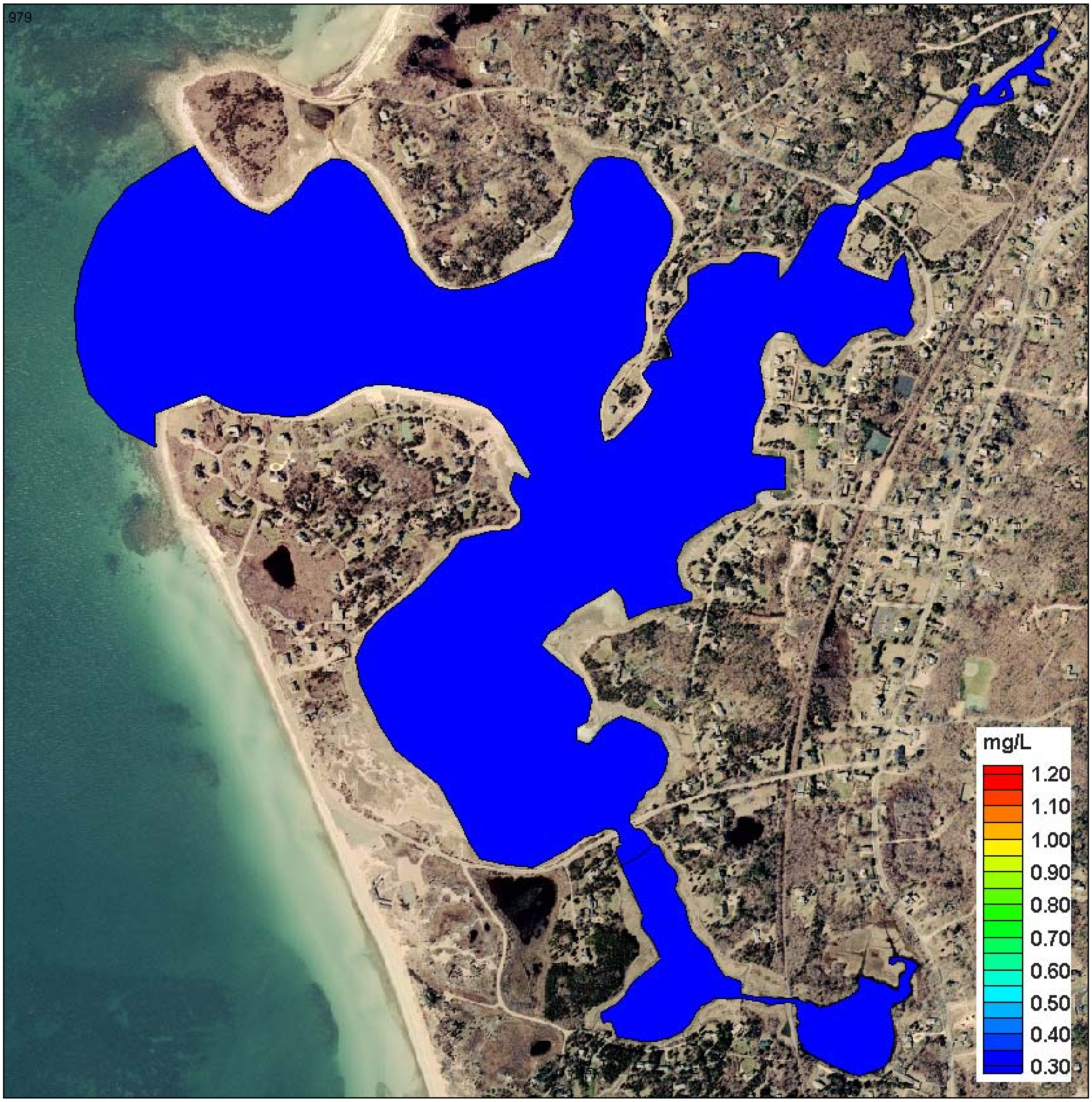


Figure VI-9. Contour plot of modeled total nitrogen concentrations (mg/L) in West Falmouth Harbor, for no anthropogenic loading conditions.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters as well as the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the West Falmouth Harbor embayment system in the Town of Falmouth, Cape Cod, MA, our assessment is based upon data from the water quality monitoring database and surveys of eelgrass distribution (1951, 1979, 1995, 1999, 2001), benthic animal communities (Fall 2003), sediment characteristics, and dissolved oxygen records obtained during the summer of 2005. These data form the basis of an assessment of this system's present health. When the habitat assessment is coupled with a full water quality synthesis and projection of future conditions based upon the water quality modeling effort, complete nitrogen threshold development for these systems can be supported in a rigorous scientific manner (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 to evaluate the ecological health of embayment systems. The best biological indicators are those species which are non-mobile and which persist over relatively long periods, assuming 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, thereby 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 three dissolved oxygen sensors within the inner regions of the West Falmouth Harbor embayment (Outer/Mid Basin, South Basin, Snug Harbor) to record the frequency and duration of low oxygen conditions during the critical summer period.

The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the West Falmouth Harbor system has been conducted by a variety of groups over the past 25 years. Eelgrass distribution within the Harbor was first determined by J. Costa (Buzzards Bay Project) in 1979. Field surveys (1995, 2001) and review of historic records (1951) have been conducted for the MEP by the DEP Eelgrass Mapping Program (C. Costello). Finally, Coastal Systems Program (SMAST) scientists conducted field mapping in 1999 to support analysis relative to the upgrade of the West Falmouth WWTF. Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the West Falmouth Harbor system, temporal changes in eelgrass distribution provides a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet or lower nitrogen loading from WWTF upgrade) in nutrient enrichment.

In areas that do not support eelgrass beds (e.g. Harbor Head, Oyster Pond), 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 present in each sample. 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 West Falmouth Harbor system are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality. It is through the MEP and TMDL processes that management actions are developed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the West Falmouth Harbor 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 West Falmouth Harbor embayment system was collected during the summer of 2005.

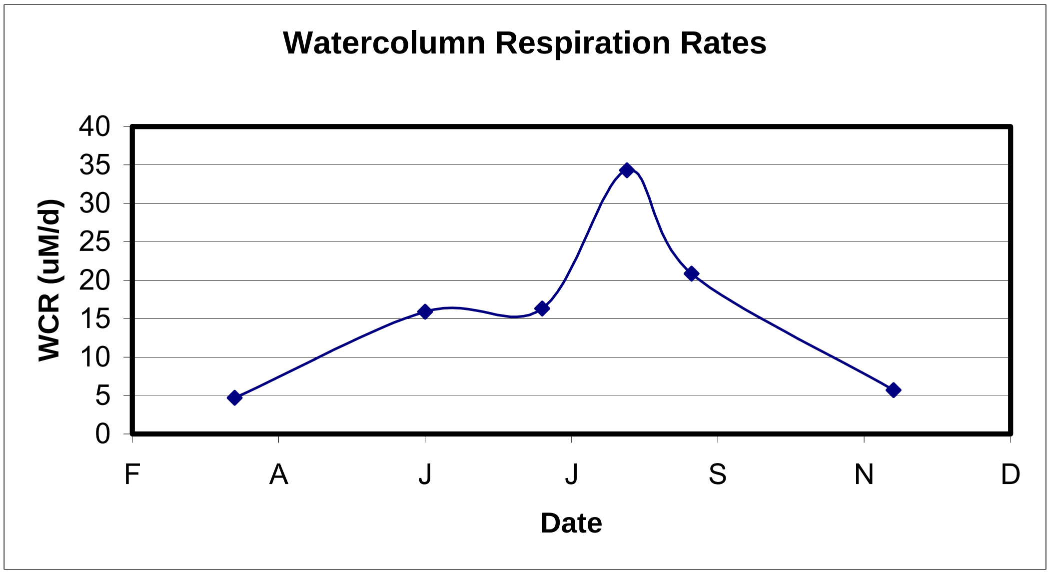


Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Summer dissolved oxygen depletion within the inner basins of West Falmouth Harbor appear to have become more frequent and more severe over the past 10 years. Monitoring by Falmouth PondWatch from 1992 to 2004 indicates that in the early 1990's oxygen depletions were less frequent than over the past several years (Figure VII-2). This temporal pattern is consistent with the 2 fold increase in nitrogen loading to the estuary that occurred during this interval, primarily as a result of the treated effluent plume from the WWTF. The plume first impinged on the Harbor in the 1992-1994 time frame, with the loading increasing until ~2002, due to loading at the WWTF. However, as nitrogen loading diminishes to 1992 levels, as the watershed nitrogen management plan associated with the WWFT upgrade is implemented, oxygen conditions should improve significantly to better than 1992 conditions. This should also result in improved habitat health for animal and eelgrass communities within the Harbor.

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

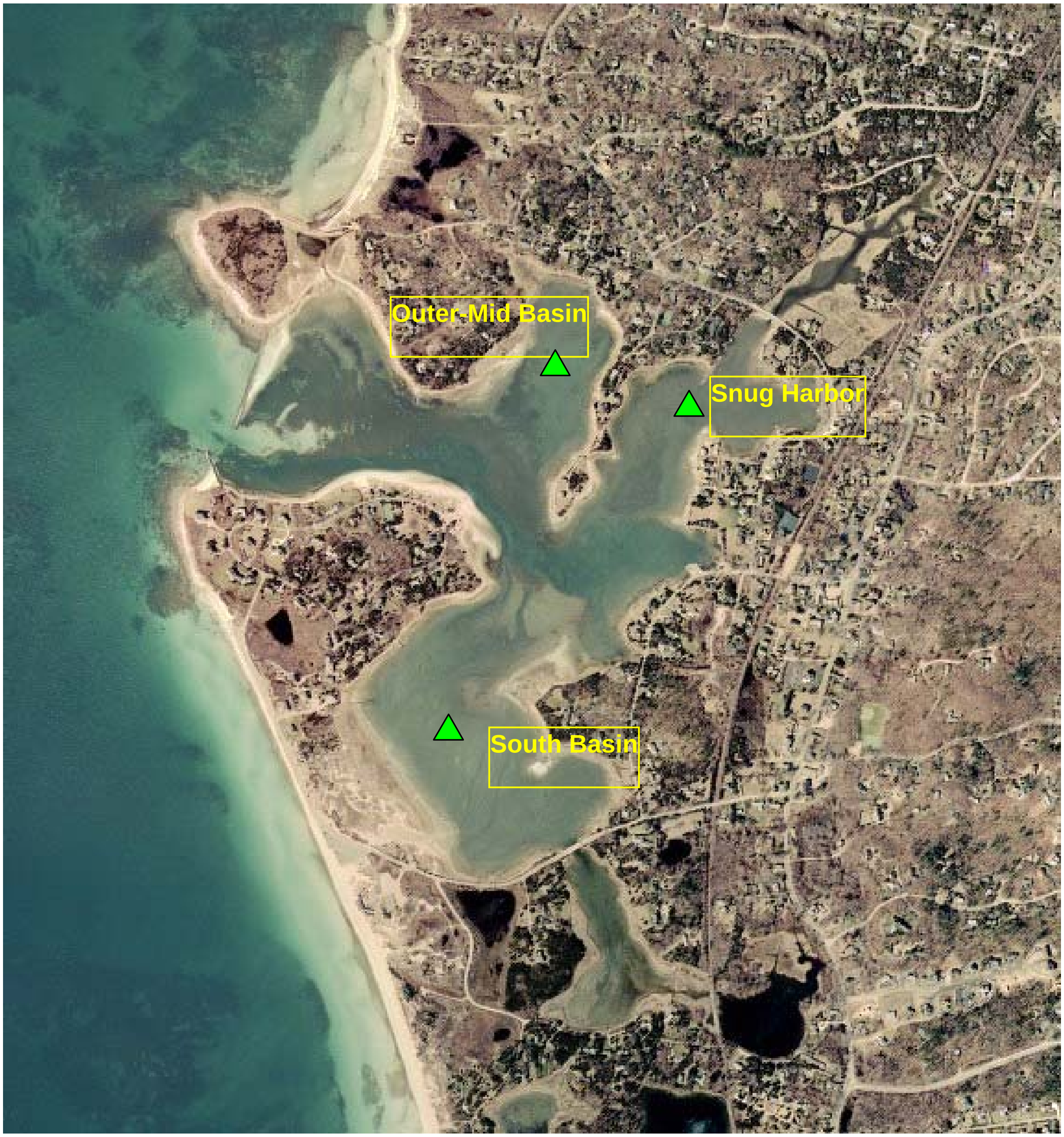


Figure VII-2. Dissolved Oxygen within the inner harbor basins of West Falmouth Harbor. Samples were collected at mid-ebb tide in July and August 1992-2004 (Goehringer and Howes unpublished data). Aerial Photograph of the West Falmouth Harbor system in Falmouth showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2005. Note that the Outer/Mid site is also referred to as the North site in Figures VII-3 to VII-8.

There was a clear pattern of oxygen depletion and elevated chlorophyll levels associated with nitrogen enrichment of the Snug Harbor Basin. Snug Harbor Basin is relatively enclosed and is the immediate recipient of the majority of the watershed nitrogen load. It showed both the highest chlorophyll levels (50% higher than the other basins) and greatest levels of oxygen decline. Oxygen depletion in Snug Harbor to levels below 5 mg/L was more than twice as frequent as at the Outer/Mid site, with the South Basin not showing declines to this level. The pattern of nutrient enrichment was also seen in the chlorophyll data with the inner basins supporting higher phytoplankton levels and periodic bloom compared to the outer basin (Snug Harbor>South Basin>Outer/Mid Basin). However, physical factors appear to be mediating oxygen levels in the other basins (South and Outer/Mid). South basin showed the highest oxygen levels, with levels only briefly dropping below 6 mg/L (Figures VII-3 to VII-8). The Outer/Mid basin appears to be influenced by organic matter (primarily macroalgae) transported from the inner Harbor. The result is periodic oxygen declines under generally low water column chlorophyll conditions.

Dissolved oxygen and chlorophyll a records were examined both for temporal trends and to determine the percent of the deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). 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.

West Falmouth Harbor has been designated high quality or SA waters by the Commonwealth. Unfortunately, each of the three basins showed periodic oxygen decline below 6 mg/L, the State standard for SA waters. Furthermore, Snug Harbor showed frequent depletions to 4 mg/L and below, while the Outer/Mid basin showed similar, but less frequent depletions. The oxygen data in Snug Harbor 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 Snug Harbor also 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 West Falmouth Harbor system are nutrient enriched.

The level of oxygen depletion and chlorophyll levels within Snug Harbor were indicative of organic matter enrichment and stressful conditions for benthic animal communities. The outer/mid basin supported only moderate chlorophyll levels and moderate oxygen depletions, while the South Basin showed generally good oxygen levels and moderate chlorophyll levels. Overall, based only on the oxygen and chlorophyll data habitat quality of Snug Harbor appears to be significantly nutrient impaired, with the outer/mid basin showing moderate to significant impairment and South Basin only moderate impairment. However, it is anticipated that the outer/mid basin will improve as organic matter enrichment from the inner harbor basins decreases with decreased watershed nitrogen loading.

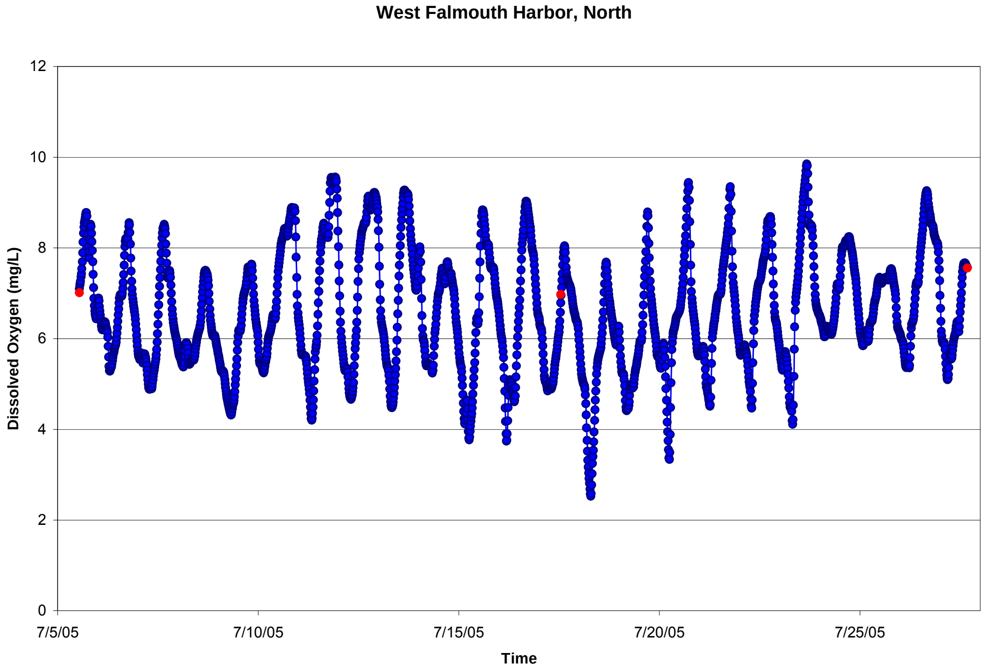


Figure VII-3. Bottom water record of dissolved oxygen at the West Falmouth North station, Summer 2005. Calibration samples represented as red dots. Note that "West Falmouth North" is the inner cove bounded by Old Field Point within the outer harbor region.

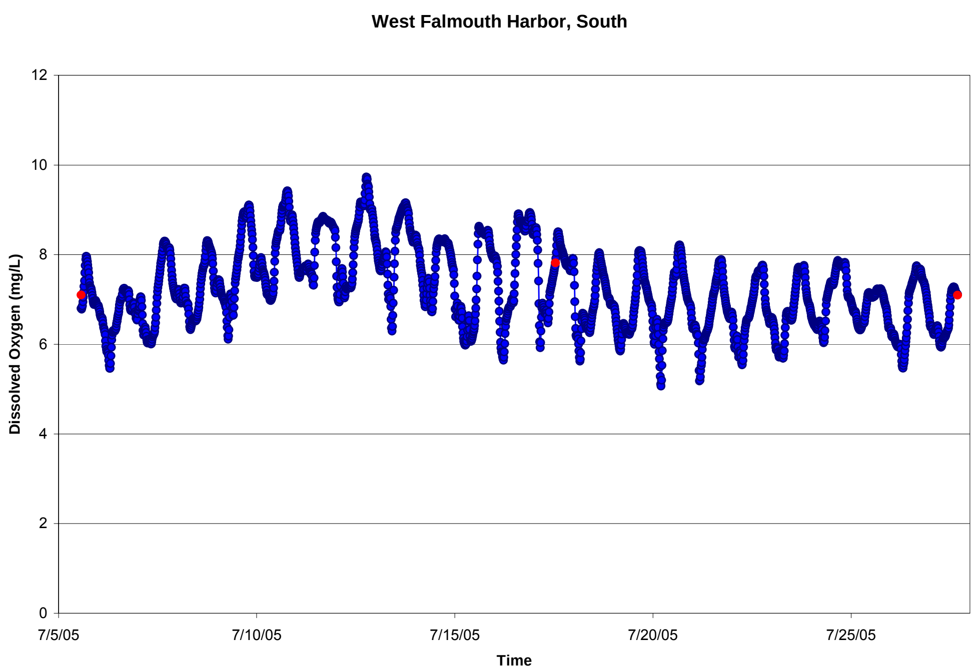


Figure VII-4. Bottom water record of dissolved oxygen in West Falmouth South station, Summer 2005. Calibration samples represented as red dots.

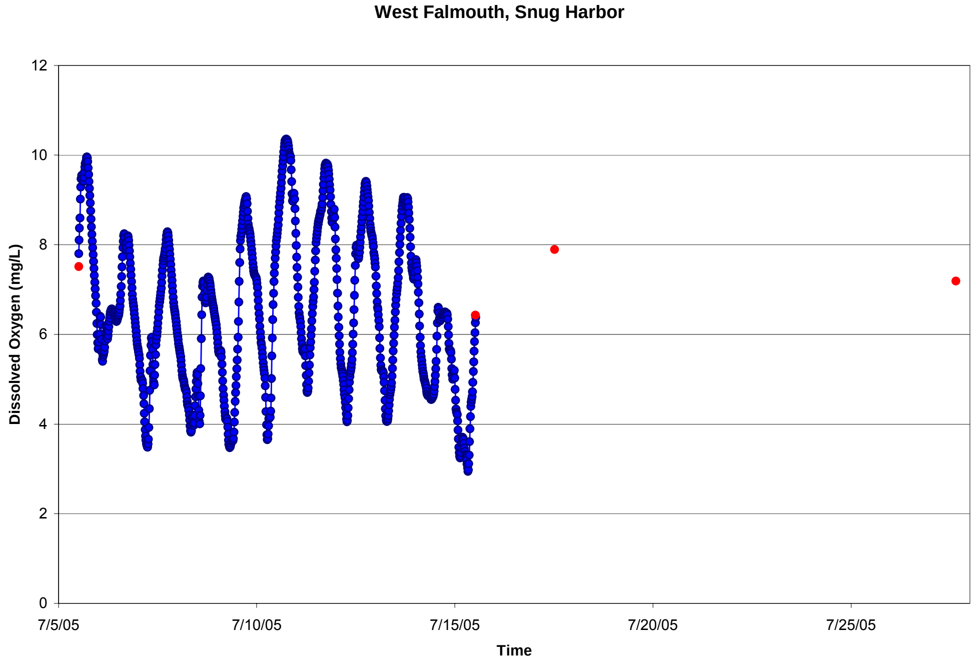


Figure VII-5. Bottom water record of dissolved oxygen in Snug Harbor station, Summer 2005. Calibration samples represented as red dots.

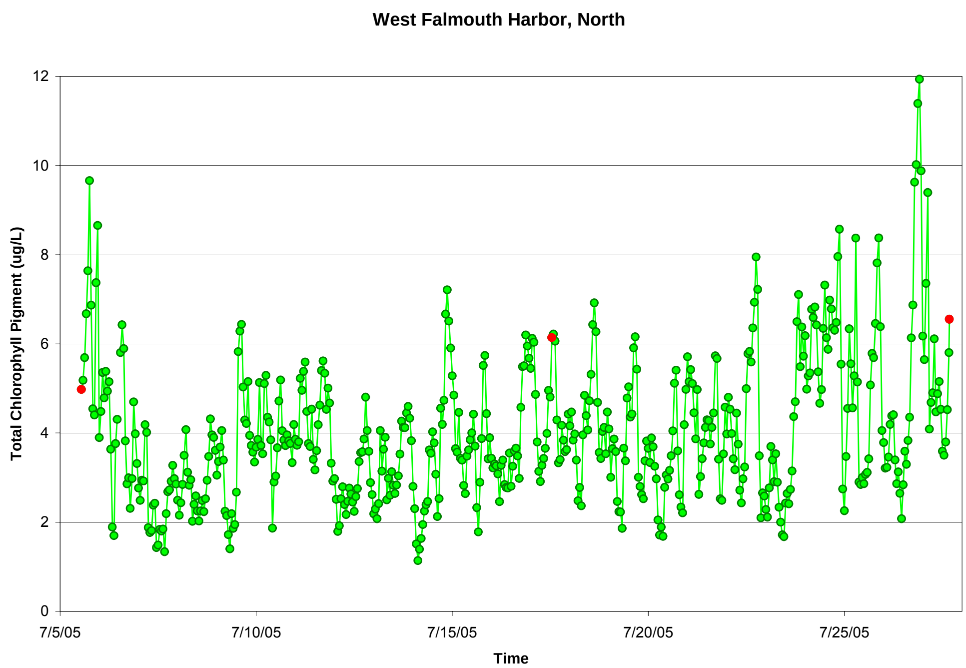


Figure VII-6. Bottom water record of Chlorophyll-*a* at the West Falmouth North station, Summer 2005. Calibration samples represented as red dots. Note that "West Falmouth North" is the inner cove bounded by Old Field Point within the outer harbor region.

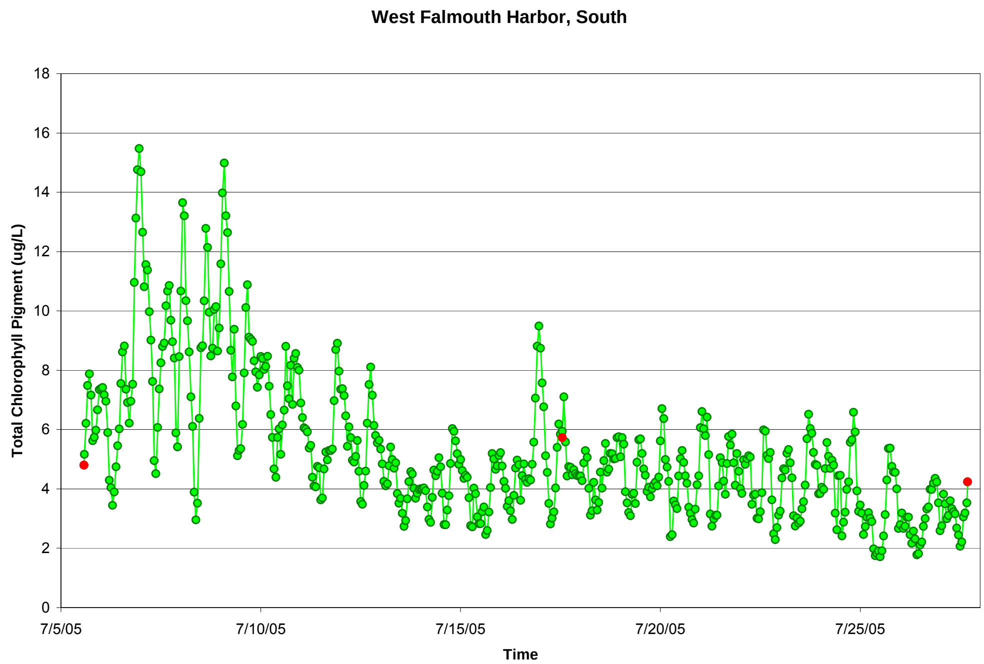


Figure VII-7. Bottom water record of Chlorophyll-*a* in the West Falmouth South station, Summer 2005. Calibration samples represented as red dots.

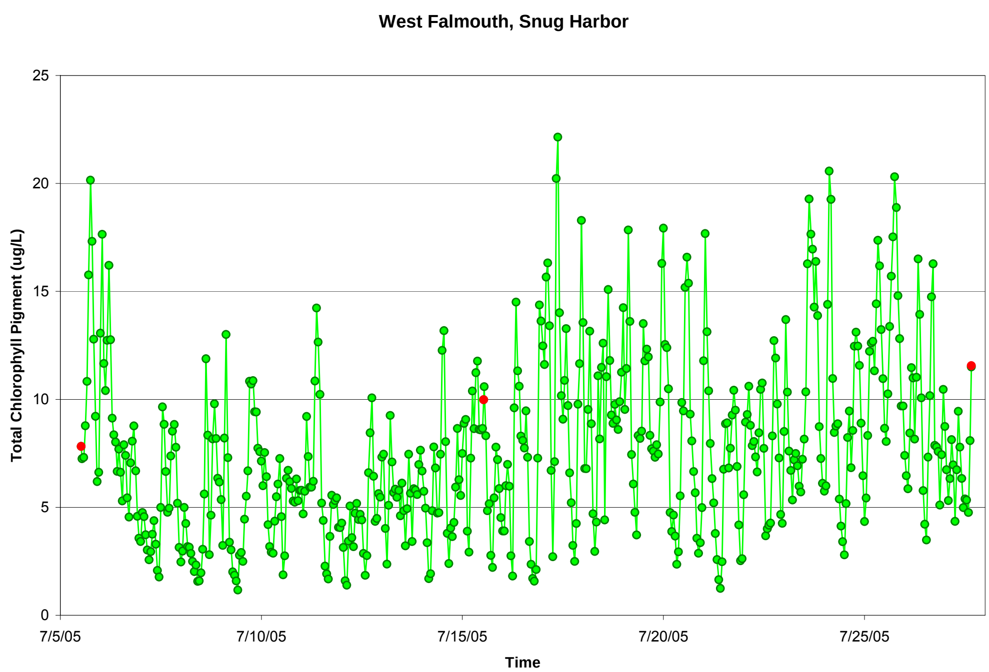


Figure VII-8. Bottom water record of Chlorophyll-*a* in the Snug Harbor station, Summer 2005. Calibration samples represented as red dots

Table VII-1. Duration of deployment time of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels. Note that "West Falmouth North" is the inner cove bounded by Old Field Point within the outer harbor region.

Mooring Location	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
West Falmouth, Snug Harbor	**7/5/2005**	**7/27/2005**	**10.03**	**4.24**	**2.34**	**0.71**	**0.02**
			Mean	0.35	0.20	0.12	0.02
			Min	0.03	0.01	0.01	0.02
			Max	0.67	0.46	0.31	0.02
			S.D.	0.21	0.14	0.11	NA
West Falmouth, North	**7/5/2005**	**7/27/2005**	**22.14**	**8.09**	**2.35**	**0.35**	**0.07**
			Mean	0.35	0.15	0.09	0.07
			Min	0.04	0.06	0.04	0.07
			Max	0.57	0.31	0.19	0.07
			S.D.	0.15	0.08	0.07	NA
West Falmouth, South	**7/5/2005**	**7/27/2005**	**22.11**	**1.31**	**0.00**	**0.00**	**0.00**
			Mean	0.09	NA	NA	NA
			Min	0.01	0.00	0.00	0.00
			Max	0.22	0.00	0.00	0.00
			S.D.	0.06	NA	NA	NA

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. Note that "West Falmouth North" is the inner cove bounded by Old Field Point within the outer harbor region.

Mooring Location	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
West Falmouth, Snug Harbor	**7/5/2005**	**7/27/2005**	**22.15**	**15.75**	**5.29**	**1.38**	**0.21**	**0.00**
Mean Chl Value = 7.64 ug/L			Mean	0.34	0.13	0.08	0.05	N/A
			Min	0.04	0.04	0.04	0.04	0.00
			Max	1.46	0.38	0.17	0.08	0.00
			S.D.	0.32	0.09	0.04	0.02	N/A
West Falmouth, North	**7/5/2005**	**7/27/2005**	**22.14**	**5.13**	**0.13**	**0.00**	**0.00**	**0.00**
Mean Chl Value = 4.01 ug/L			Mean	0.14	0.13	N/A	N/A	N/A
			Min	0.04	0.13	0.00	0.00	0.00
			Max	0.50	0.13	0.00	0.00	0.00
			S.D.	0.12	N/A	N/A	N/A	N/A
West Falmouth, South	**7/5/2005**	**7/27/2005**	**22.11**	**9.54**	**1.21**	**0.04**	**0.00**	**0.00**
Mean Chl Value = 5.28 ug/L			Mean	0.29	0.17	0.04	N/A	N/A
			Min	0.04	0.08	0.04	0.00	0.00
			Max	1.88	0.38	0.04	0.00	0.00
			S.D.	0.38	0.11	N/A	N/A	N/A

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys (1995, 2001) and analysis of historical data (1951) was conducted for the West Falmouth Harbor system by the DEP Eelgrass Mapping Program as part of the MEP Technical Team. These data were supported by other surveys in 1979 (J. Costa, Buzzards Bay Project) and 1999 (Howes et al. 2000). The historical analysis was based upon available high resolution aerial photos from 1951, from which the eelgrass distribution prior to any substantial development of the watershed was determined. The 1951 data were only anecdotally validated, while the 1979, 1995, 1996-97 and 2001 maps were field validated. The 1979 mapping when nitrogen loading to the Harbor was ~1/3 of present day was consistent with the 1951 photo interpretation. The primary use of the data is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1979 to 1995 to 1999 to 2001 (Figure VII-9 toVII-12). The 1995 to 2001 surveys were completed during the time in which watershed nitrogen loading significantly increased to its present level due to the WWTF effluent plume reaching the Harbor. This temporal information can be used to determine the stability of the eelgrass community.

At present, eelgrass is present within both the inner and outer basins of the West Falmouth Harbor system. Based on the 2001 eelgrass survey conducted by the DEP Eelgrass Mapping Program the remaining eelgrass appears to be limited to an area just upgradient of the West Falmouth Harbor inlet as well as within Snug Harbor. However, the 1999 mapping and recent observations by MEP Technical Staff found that the Snug Harbor eelgrass is extremely sparse and exists in patches with <5% cover. In contrast the eelgrass in the outer Harbor basins is generally found in beds and the largest bed behind the northern jetty is dense and healthy. Observations of the outer/mid cove area adjacent Old Field Point (within the outer Harbor) does not support eelgrass beds in the inland most portion, although eelgrass is present in sparse patches not noted in the 2001 survey. However, the general presence or absence of eelgrass noted in the 2001 map was confirmed by the multiple MEP staff conducting the infaunal and sediment sampling and the mooring studies. The current decline of eelgrass beds relative to historical distributions is expected given the high chlorophyll a and low dissolved oxygen levels, as well as water column nitrogen concentrations within this system resulting from the watershed nitrogen loading to Mashapaquit creek and direct discharge to Snug Harbor.

In contrast to recent surveys, it appears that a substantial area of the overall West Falmouth Harbor system supported eelgrass beds in 1951 and 1979. The 1979 survey, which was field validated, showed similar coverage to the 1951 analysis. Similarly, the field survey of 1999 shows similar coverage to the 1995 and 2001 analyses. This agreement indicates that eelgrass loss within West Falmouth Harbor has been relatively rapid, occurring over a period of less than 20 years. During this period, nitrogen loading to the Harbor increased from rates ~1/3 of present to the current condition. The pattern of the bed loss is consistent with other embayments where eelgrass loss has occurred as a result of eutrophication (i.e. loss begins in inner basins and expands toward the inlet). In addition, the present eelgrass distribution within West Falmouth Harbor is consistent with the pattern of nitrogen related habitat quality currently observed within the system. It appears that as the West Falmouth Harbor system became nutrient enriched, that the inner basins could no longer support eelgrass beds. However, it is likely that if nitrogen loading were to decrease, eelgrass could first be restored in the lower portion of the main basin. With further reductions, eelgrass distribution could be restored to the 1951 pattern.

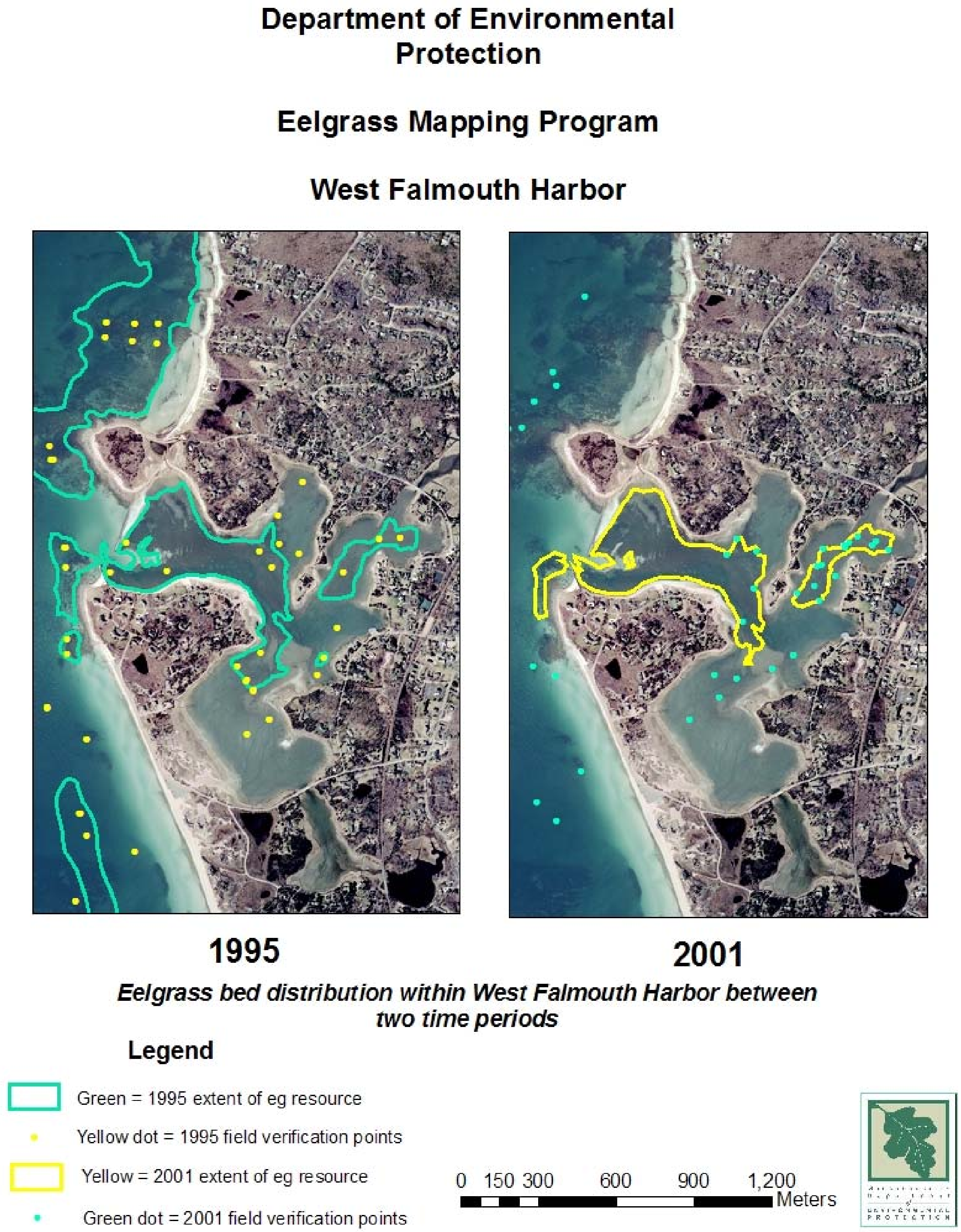


Figure VII-9. Eelgrass bed distribution within the West Falmouth Harbor System. The 1995 coverage is depicted by the green outline inside of which circumscribes the eelgrass beds. The yellow (2001) areas were mapped by DEP. All data was provided by the DEP Eelgrass Mapping Program.

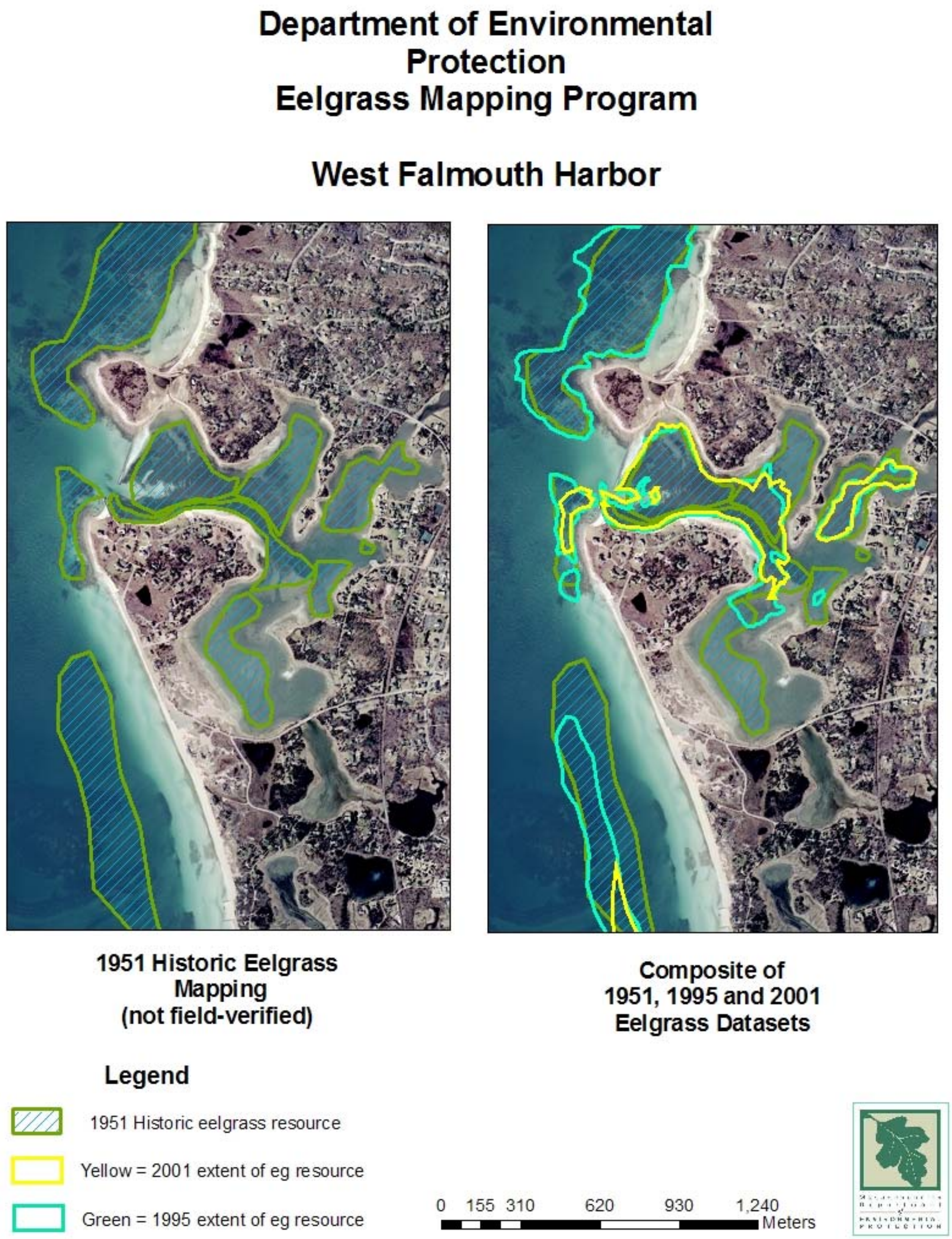


Figure VII-10. Eelgrass bed distribution within the West Falmouth Harbor System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were mapped by DEP. All data was provided by the DEP Eelgrass Mapping Program.

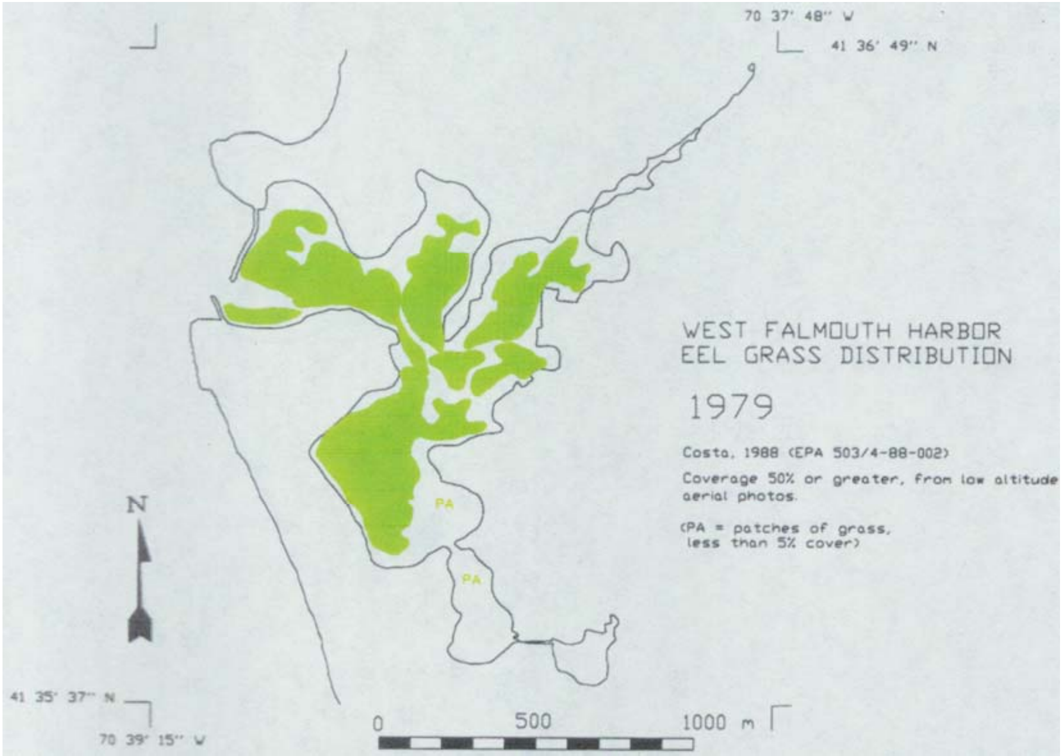


Figure VII-11. Eelgrass bed distribution within the West Falmouth Harbor System. The 1979 coverage is depicted by the dark green area that describes the eelgrass beds.

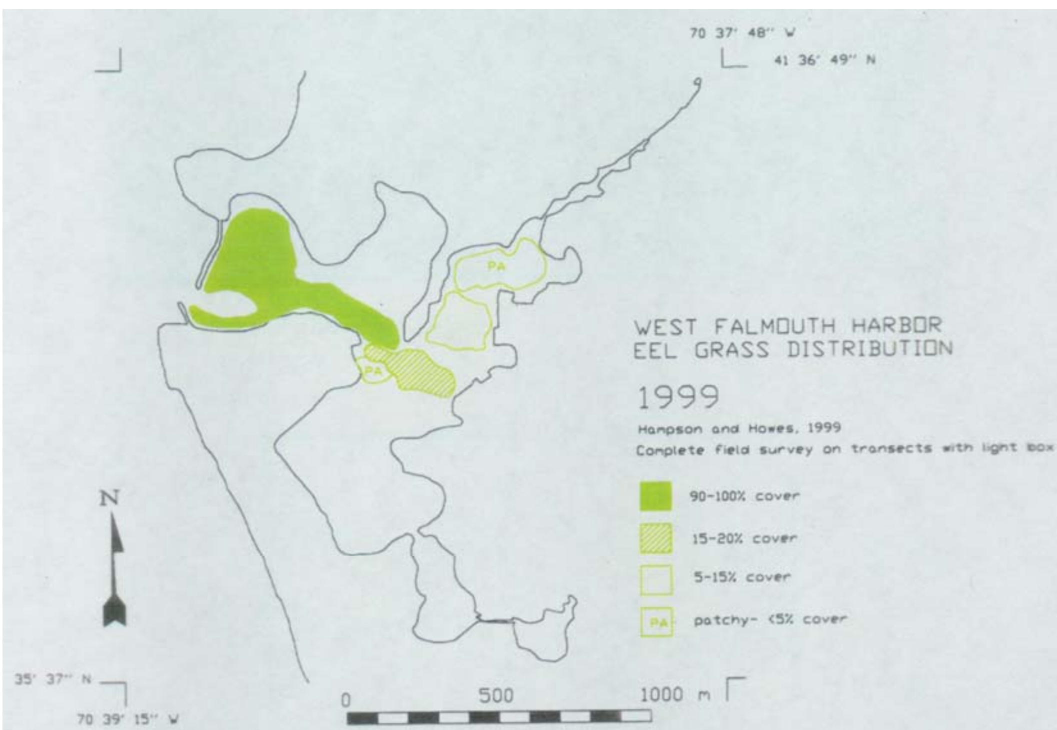


Figure VII-12. Eelgrass bed distribution within the West Falmouth Harbor System. The 1999 coverage is depicted by the dark green area that describes the eelgrass beds.

It is significant that eelgrass was detected in the upper regions of the West Falmouth Harbor system (e.g. Snug Harbor and South Basin) in the 1951 and 1979 data. It appears that these areas are capable of supporting this type of habitat if nutrient conditions are also supportive.

In systems like West Falmouth Harbor, the general pattern is for highest nitrogen levels to be found within the innermost basins, with concentrations declining moving toward the tidal inlet. This pattern is also observed in nutrient related habitat quality parameters, like phytoplankton, turbidity, oxygen depletion, etc. The consequence is that eelgrass bed decline typically follows a pattern of loss in the innermost basins (and sometimes also from the deeper waters of other basins) first. The temporal pattern is a “retreat” of beds toward the region of the tidal inlet.

Other factors which influence eelgrass bed loss in embayments may also be at play in the West Falmouth Harbor 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 changes in mooring numbers did not coincide with eelgrass loss. Similarly, pier construction and boating pressure may be adding additional stress in nutrient enriched areas, but do not seem to be the overarching factor. It is not possible at this time to determine the potential effect of shellfishing on eelgrass bed distribution, although eelgrass was lost from non-shellfishing areas within the Harbor. However, there is one non-eutrophication process that is likely to have caused the loss of some eelgrass beds within the Harbor system. Eelgrass beds within South Basin across from Chappaquoit Beach were overwashed with sand during Hurricane Bob in 1991. While this may explain a portion of bed loss from this one basin, it would not have affected the lower half of the bed area, which was still partially present in 1995 and virtually gone today.

Based on the available data, it is possible to utilize the 1951 (supported by the 1979 data) coverage data as an indication that eelgrass beds might be recovered. It appears that West Falmouth Harbor is capable of supporting 84 acres of eelgrass beds. Based upon the presence/absence data from 1995 and 2001, it appears that on the order of 33 acres have been lost to date, which should be restored if nitrogen management alternatives were implemented (Table VII-3). However, as indicated above, the 1995 and 2001 maps show the presence of eelgrass, not the density. Since the eelgrass in Snug Harbor is very sparse (<5% coverage) it is not functioning as an eelgrass bed. The result of nitrogen management will be to restore the functionality of this habitat. Therefore, the 33 acres under-estimates the “true” effect which will be to restore over 40 acres to “functional” eelgrass bed status within the system (33 acres of denuded bottom and >7 acres of sparse eelgrass). Note that restoration of eelgrass habitat within the Harbor’s main basins will necessarily result in restoration of other resources such as Harbor Head and Mashapaquit Creek.

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 West Falmouth Harbor Embayment System within the Town of Falmouth over the past half century (C. Costello). Note that the 1995 and 2001 coverages include areas with very sparse eelgrass as well as functional eelgrass beds.

Embayment	1951 (acres)	1995 (acres)	2001 (acres)	% Difference (1951 to 2001)
West Falmouth Harbor	83.66	56.62	50.35	40%

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted along 5 transects with multiple locations being sampled along a transect throughout the West Falmouth Harbor system (Figure VII-13). In some cases multiple assays were conducted. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The 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 West Falmouth Harbor system is clearly impaired by nutrient overloading. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

Analysis of the evenness and diversity of the benthic animal communities was also used to support the density data and the natural history information. The evenness statistic can range from 0-1 (one being most even), while the diversity index does not have a theoretical upper limit. The highest quality habitat areas, as shown by the oxygen and chlorophyll records and eelgrass coverage, have the highest diversity (generally >3) and evenness (~0.7). The converse is also true, with poorest habitat quality found where diversity is <1 and evenness is <0.4.

Assessing the overall quality of the benthic infaunal habitat within the basins of West Falmouth Harbor is based upon the types of species present, the numbers of individuals and species, and the diversity and eveness indices. It must be kept in mind that large numbers of stress indicator species does not indicate a healthy environment, while moderate numbers of species indicative of low organic matter loading generally does indicate habitat health. In addition, an eveness score of near 1 needs to be evaluated relative to the numbers of individuals. As seen in Oyster Pond, the eveness score was 0.98, but there were virtually no animals in the samples (see below). The MEP evaluation balances these issues to derive the level of habitat health for each basin. These evaluations are then coupled with 4 other parameters for the integrated assessment (see Chapter VIII). The infaunal assessment has generally been found to be consistent with the water quality, macroalgae, and eelgrass assessments, as should be the case when dealing with an ecosystem altering stress like nitrogen enrichment.

Figure VII-13. Aerial photograph of the West Falmouth Harbor system showing location of benthic infaunal sampling stations (red symbol).

The Infaunal study indicated that most of the Harbor basins have nutrient related impairment of benthic habitat, although it appears that near the inlet habitat quality remains high. However, the level of impairment varied greatly and was consistent with the observed gradients in water quality parameters and eelgrass habitat discussed above. Within the main Harbor, Snug Harbor was found to support patchy habitat dominated by stress indicator (opportunistic) species, like *Capitella*. Harbor Head was very similar to Snug Harbor in numbers of individuals and species and dominance by stress indicator species. Although the South Basin showed similar numbers of individuals and species to Snug Harbor and Harbor Head, it was dominated by species indicative of lower organic enrichment with deeper burrowers and mollusks. However, the moderate number of species (11) present in South Basin still indicates a moderately impaired community when compared to healthy embayments where >20 species is typical (Table VII-4). The Outer Harbor sites generally supported higher numbers of individuals and species than the inner Harbor sites. Even so, the Outer Harbor basins had patches of stress indicator species and lower numbers of species that are indicative of a healthy habitat. The drown kettle pond, Oyster Pond, was not found to support benthic infaunal habitat throughout most of the basin. At all 3 sampling sites, less than 10 individuals per sample were found. The primary cause of this apparently severely degraded habitat is that the Pond is deep (>8 m) with a very shallow tidal channel. In addition, Oyster Pond has fringing salt marsh which contributes detritus to its sediments. As a result of its structure, Oyster Pond stratifies and periodically goes hypoxic. Attempts to restore this habitat will have to address the natural structural issues of this salt pond.

The overall results indicate a system capable of supporting diverse healthy communities in the region nearest the tidal inlet, with inner basins supporting infaunal habitat that is significantly impaired (Snug Harbor, Harbor Head) to moderately impaired (South Basin) under present nitrogen loading conditions. Consistent with the gradients in habitat quality shown by the water quality and eelgrass parameters (above), the outer basins show higher quality infaunal habitat than the inner basins. Oyster Pond presently does not support infaunal habitat throughout most of its basin.

Table VII-4. Benthic infaunal community data for the West Falmouth Harbor 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). Values are averages of grab samples a-c.

Location	ID	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)	Infaunal Indicators
Snug Harbor							
Upper	a,b,c,d,e	13	258	11	2.55	0.68	SI[1]
South Basin							
Mid	a,b,c,d,e	11	241	9	2.07	0.61	MI
Harbor Head							
Mid	a,b,c	11	405	9	2.44	0.70	SI[1]
Oyster Pond							
Mid	a,b,c	2	3	n/a	1.63	0.98	SI[1]
Outer Harbor (Old Field Point to Inlet)							
Mid-Upper	11a,b	21	495	10	2.09	0.48	MI/SI[1]
Mid-Lower	12a,b	14	1314	11	2.97	0.80	H/MI
Channel	13a,b	10	951	6	1.86	0.58	H/MI

1 Capitellids or Spionids dominant

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

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll-a. Additional information on temporal changes within each sub-embayment and its associated watershed nitrogen load further strengthen the analysis. These data were collected to support threshold development for the West Falmouth Harbor System by the MEP Team and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels obtained from the water quality baseline established by the Falmouth PondWatch and BayWatcher Water Quality Monitoring Program.. At present, West Falmouth Harbor, is showing a strong gradient in habitat quality from severely degraded (Oyster Pond) to significantly impaired (Snug Harbor, Harbor Head) transitioning to less impaired (South Basin) to moderately impaired (Outer/Mid Basin) to healthy (basin nearest inlet). The Snug Harbor shows significant impairment based upon all 3 parameters (eelgrass, infauna, D.O.), while the outer/mid basin was moderately impaired in spite of its proximity to the tidal inlet and high quality waters of Buzzards Bay. 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).

Eelgrass: The West Falmouth Harbor Estuary is moderately deep compared to others along the south shore of Cape Cod from Falmouth to Barnstable (Chapter V). However, water depths are well within the range for eelgrass growth in Massachusetts, given suitable conditions of light penetration.

There has been a clear and ecologically significant alteration of eelgrass distribution within West Falmouth Harbor within the past 15 years. The first available quantitative mapping of eelgrass is for 1979 (Costa, 1988). This study documented eelgrass throughout the Harbor, with beds in the outer basins, South Basin and Snug Harbor. The 1979 distribution is similar to the 1951 historic analysis by DEP and is supported by a qualitative mapping effort conducted in 1985, as part of a food preference study on geese (Buchsbaum, 1985). While this latter study is only approximate, it clearly shows eelgrass within both South Basin and Snug Harbor, as in the 1979 and 1951 map (Chapter VII). This is important as it helps to constrain the timing of eelgrass loss in these basins. The later maps (1995, 1999, 2001) show generally similar distributions, but very different from the pre-1985 eelgrass distributions. Detailed mapping and validation by MA DEP in 1995 (Costello, 1999) indicated that eelgrass had been lost from the inner basins over the previous decade and that decline continued through the 2001 survey. The level of decline is even more significant than recorded by DEP in that the SMAST field survey of 1999 recorded both presence/absence of eelgrass and density of plants. This survey confirmed the DEP coverages, but indicated that Snug Harbor no longer supported functional eelgrass beds, but rather very sparse eelgrass in the outer region that ranged from small patches to 5%-15% coverage and in the inner region <5% coverage.

Analysis of the mapping data is consistent with a real change in eelgrass coverage. Comparison of inner versus outer Harbor areas indicates only a small decline in eelgrass area in the outer Harbor region from 1979 to 1999 (and 1995, 2001 data). This indicates that although three different groups conducted sampling, consistent results could be achieved. In contrast, the inner areas appear to have lost there functional eelgrass habitat, with only sparse coverages remaining in a small fraction of the area that historically supported eelgrass.

The large reduction in eelgrass distribution within West Falmouth Harbor represents a significant decline in habitat quality and a major shift in ecological structure. Analysis of the distribution maps indicates the following changes:

- major loss (ca. 2/3) of eelgrass from inner basin areas (South Basin and Snug Harbor), between 1985-1996,
- only sparse coverage remains within the colonized areas of the inner basins in 1999,
- decreasing coverage within the inner portions of the outer Harbor from 1979-1999, particularly from outer/mid basin (Field Cove) in the outer Harbor between 1985-1996.

This pattern of loss of eelgrass coverage from the inner-most Harbor regions and gradually expanding toward the tidal inlet is symptomatic of nutrient enrichment. In the absence of other system-wide disturbances which would have been noted by the PondWatch and BayWatcher Monitoring Programs, it is reasonable to conclude that the shift in Harbor health that occurred between 1985-1996 was associated with the entry of the Falmouth WWTF nitrogen plume into the Snug Harbor/Mashapaquit Creek area circa 1994).

The presence of remaining sparse eelgrass within the inner harbor is consistent with the relatively recent (more than 2 fold) increase in nitrogen loading. That nitrogen from the watershed and particularly the WWTF plume is affecting the Harbor is also supported by the observation of dense concentrations of macroalgae, *Ulva lactuca*, in Snug Harbor adjacent the inlet to Mashapaquit Creek. In the outer portion of Snug Harbor, eelgrass is still visible, but covered with invading algae. Eelgrass was almost totally absent in the inner portions of Snug Harbor and in its place the bottom was dominated by invading *Ulva* and other macroalgae.

It should be noted that the loss of eelgrass from the inner reaches of South Basin may have also been partially associated with overwash associated with Hurricane Bob in 1991. Evidence of overwash was found in cores from that basin collected by MEP. However, the subsequent loss of eelgrass from the outer reach of South Basin clearly follows the pattern of nutrient enrichment effects.

The pattern of eelgrass loss is fully consistent with the pattern of nitrogen levels throughout the Harbor and with the dissolved oxygen and chlorophyll data. As discussed below, infaunal communities also reflect a pattern of stress correlated with nitrogen levels. Tidally averaged TN is 0.46 mg/L in Snug Harbor declining to 0.38 in South Basin, with the Outer Harbor being significantly lower 0.31-0.33 mg/L. This nitrogen gradient is clearly seen in the gradient in oxygen depletion and infaunal habitat health, as well as in the eelgrass distribution data.

The surveys indicate that both the inner and outer Harbor basins are capable of supporting eelgrass when the watershed nitrogen loading rates are at the 1979-1985 levels. The current absence of functional eelgrass beds within the inner basins and the fact that these areas supported eelgrass in the recent past classifies the Snug Harbor and South Basin eelgrass habitat as “significantly impaired”. The presence of significant eelgrass beds within the mid/outer basin (Field Cove) coupled with recent declines in the uppermost portion classifies this basin’s eelgrass habitat as “moderately impaired”, while the outermost basin nearest the inlet still supports healthy eelgrass beds and garners a “healthy” classification. There is no evidence that the small tributaries to the main estuary (Mashapaquit Creek, Harbor Head and

Oyster Pond) have supported eelgrass and therefore restoration of eelgrass habitat in these basins is not a management goal (although infaunal habitat should be, see below).

Nitrogen management of this system is likely to restore eelgrass beds to the coverage of 84 acres observed in 1951 (Table VII-3). As noted above, this will restore on the order of 40 acres of eelgrass beds as the inner basin eelgrass distribution noted in Table VII-3 includes sparse coverages (<5%). Note that restoration of this habitat will necessarily result in restoration of other resources throughout the West Falmouth Harbor System Eelgrass recovery following nitrogen management would likely follow the pattern of beds first being re-established in the marginal areas in the lower basins and move to the deeper regions and the margins of the upper subembayments. Based upon the above analysis, eelgrass habitat was a primary nitrogen management goal for the West Falmouth Harbor System and was the focus of the management alternatives analysis (Chapter 9).

Water Quality: The dissolved oxygen records, based upon both continuous measurement and grab samples indicate that Snug Harbor, South Basin and outer/mid Harbor are currently under periodic oxygen stress during summer, consistent with nitrogen enrichment (Figure VII-2, Table VII-1). The deep salt pond, Oyster Pond, is periodically hypoxic/anoxic. However, within the main Harbor, the Snug Harbor sub-embayment clearly showed the highest level of oxygen stress. That the cause is nitrogen enrichment is supported by parallel observations of chlorophyll a (Table VII-2) and total nitrogen levels (Snug Harbor>South Basin>Outer Harbor). Oxygen conditions and chlorophyll a levels generally improved with decreasing distance to the tidal inlet. The results of the summer oxygen and chlorophyll a studies are consistent with the pattern of eelgrass loss within the West Falmouth Harbor System and the pattern of infaunal communities, where opportunistic species dominate the more nitrogen enriched basins. These observations are consistent with a classification of the inner basins of Snug Harbor and Oyster Pond as significantly impaired and severely degraded, respectively, and in South Basin and the outer/mid Harbor as moderately impaired.

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 Three Bays System are currently listed under this Classification as SA.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate nutrient enriched waters and impaired habitat quality, particularly in Snug Harbor. The oxygen data throughout the estuary is consistent with elevated 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 each estuary have the largest daily oxygen excursion, with daily excursions in excess of >4 mg L-1 common. This 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). This was periodically seen in Snug Harbor and the mid/outer Harbor. The oxygen and chlorophyll data also shows a gradient of impairment with high levels in the inner sub-embayments (Oyster Pond, Snug Harbor) and better conditions in the lower basins (Outer Harbor). The primary cause of the severely degraded habitat in Oyster Pond is that the Pond is deep (>8 m) with a very shallow tidal channel. In addition it has fringing salt marsh which contributes detritus to its sediments. The physical structure of Oyster Pond results in it stratifying and periodically becoming hypoxic. Attempts to restore this habitat will have to address the natural structural issues of this salt pond. Overall, there was clear oxygen depletion at all mooring sites within the main Harbor basins indicating that additional nitrogen loading will cause further habitat decline at all sites.

Infaunal Communities: The Infauna Study indicated that most of the Harbor habitat is presently impaired by nitrogen enrichment (Table VII-4). The gradient in habitat impairment followed the gradient in tidally averaged total nitrogen levels, eelgrass loss and oxygen depletion and chlorophyll levels. Assessing the overall quality of the benthic infaunal habitat within the basins of West Falmouth Harbor was based upon the types of species present, the numbers of individuals and species and the diversity and evenness indices. It must be kept in mind that large numbers of stress indicator species does not indicate a healthy environment, while moderate numbers of species indicative of low organic matter loading generally does indicate habitat health.

The Infaunal study indicated that most of the Harbor basins have nutrient related impairment of benthic habitat, although it appears that near the inlet habitat quality remains high. However, the level of impairment varied greatly between sub-embayments. Within the main Harbor, Snug Harbor was found to support patchy habitat dominated by stress indicator (opportunistic) species such as *Capitella*. Harbor Head was very similar to Snug Harbor in numbers of individuals and species and dominance by stress indicator species. The infaunal habitat in these basins appears to be “significantly impaired” by organic matter enrichment stemming from nitrogen overloading. In contrast, South Basin was not dominated by opportunistic species but by species indicative of lower organic enrichment with deeper burrowers and mollusks, although the numbers of individuals and species were similar to Snug Harbor and Harbor Head. This indicates a less stressed habitat. However, South Basin’s moderate number of species (11) indicates a “moderately impaired” community when compared to healthy embayments where >20 species is typical (Table VII-4). Similar to the gradient found in the other health indicators, the Outer Harbor sites showed less stress overall than the inner basins. The outer basins generally supported almost double the numbers of individuals and more species that the inner Harbor sites. However, the Outer Harbor basins had patches of stress indicator species and lower numbers of species that would be indicative of a fully healthy habitat. Overall, the outer harbor appears to range from Healthy conditions to moderately impaired conditions when moving from the inlet toward the inner Harbor. The drown kettle pond, Oyster Pond, was not found to support benthic infaunal habitat throughout most of the basin. At all 3 sampling sites, less than 10 individuals per sample were found. This system clearly is supporting “severely degraded” infaunal habitat, although some portion of the poor conditions results from the physical structure of this drown kettle pond.

Overall, the pattern of infaunal community quality is consistent with the pattern of oxygen depletion and chlorophyll a during summer and eelgrass habitat quality. Almost all sites showed some level of degradation, either in number of individuals, diversity or the presence of stress indicator species. Lowering nitrogen inputs to this system should allow a relatively rapid recovery of communities in the mid/outer Harbor and South Basins, with higher levels of nitrogen management required to restore benthic habitat to Snug Harbor and Harbor Head. Creation of Oyster Pond infaunal habitat (there is no viable bottom habitat at present) may not be possible by nitrogen management alone and would need to focus on the physical and biological processes controlling stratification and seasonal hypoxia. It appears that implementation of watershed nitrogen management to reduce loading to the Harbor should restore infaunal habitat first throughout the outer harbor and then South Basin followed by Snug Harbor and Harbor Head. It is anticipated that habitat restoration will be relatively rapid following a reduction in nitrogen load.

Table VIII-1. Summary of Nutrient Related Habitat Health within the West Falmouth Harbor Estuary on the Buzzards Bay coast of Falmouth, MA., based upon assessment data presented in Chapter VII.

Health Indicator	West Falmouth Harbor Estuary						
	Mashap Creek Marsh	Snug Harbor	South Basin	Harbor Head	Oyster Pond	Outer Harbor	
						Mid	Outer
Dissolved Oxygen	--	SI	MI[3]	--	SD[1]	MI/SI[2]	--
Chlorophyll	--	SI/MI	MI	--	--	H	--
Macroalgae	SI	SD[4]	--	--	MI	MI[5]	H
Eelgrass	--[8]	SI	SI	--[8]	--[8]	MI	H
Infaunal Animals	--	SI[9]	MI	SI[9]	SD[7]	MI	H/MI
Overall:	**SI**	**SI**	**MI/SI**	**SI**	**SI/SD**	**MI**	**H**

1 – periodic oxygen depletions to <2 mg/L and frequently <4 mg/L, grab data only
2 – infrequent oxygen depletions to 3-4 mg/L, periodic 4-5 mg/L., generally >5 mg/L.
3 – generally >5 mg/L..
4 – high macroalgal accumulations during summer
5 – moderate macroalgal accumulations or patches on bottom.
6 – modest numbers of individuals dominated by stress indicator species.
7 – absence of infaunal community (<15 individuals/grab).
8 – no evidence this basin is supportive of eelgrass.
9 – infaunal community dominated by opportunistic 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 second to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality. The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined, the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved.

Determination of the critical nitrogen threshold for maintaining high quality habitat within West Falmouth Harbor 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 in other approaches.

Given the importance of eelgrass to the habitat quality of West Falmouth Harbor, a target nitrogen concentration within the inner Harbor waters supportive of eelgrass habitat will provide for a high level of overall habitat health. Selection of the sentinel station in Snug Harbor will support restoration of the various sub-basins (except possibly Oyster Pond). Snug Harbor is presently the most nitrogen enriched of the West Falmouth Harbor sub-embayments (Snug Harbor, South Basin, Harbor Head, Outer Basins). Consequently, Snug Harbor is showing the highest level of habitat impairment of these basins. Restoration of the Snug Harbor basin to be supportive of eelgrass beds will necessarily result in lower nutrient concentrations in the outer, better flushed basins and the South Basin such that eelgrass habitat will be supportable.

At present, the healthy eelgrass beds within the Outer Harbor are at tidally averaged total nitrogen levels of 0.33-0.31 mg N/L. Total nitrogen levels in the upper and lower reach of Snug Harbor where sparse eelgrass is still found are 0.46 (<5% cover) and 0.37 (5-15% cover and patches), respectively. South Basin does not currently have eelgrass and has a tidally averaged total nitrogen level of 0.38 mg N/L. Note that the background total nitrogen in the inflowing Buzzards Bay waters is 0.296 mg N L^{-1}. The average measured mid-ebb tide total nitrogen level in the outer harbor, which currently supports eelgrass beds is 0.345 mg N L^{-1}, which compares well with the 0.353-0.356 mg N L^{-1} ebb tidal maximum from the MEP water quality module (Chapter VI). In addition, measured mid-ebb tide total nitrogen levels in the inner basins in 1992-93, when eelgrass habitat was still presumably relatively healthy (pre-WWTF plume discharge to Harbor) were 0.34-0.36 mgN/L^{-1}. These data argue for a tidally averaged total nitrogen level <0.37 N/L^{-}1 and mid-ebb concentration <0.36 mg N/L^{-1} to support high quality eelgrass habitat. Given all of the above data the tidally averaged total nitrogen threshold at the sentinel station in Snug Harbor was set at 0.35 mg N L^{-1}. This threshold is also consistent with previous analyses of this system (Eichner et al. 1998, Howes et al. 2000), targeted at restoration of high quality estuarine habitats throughout the West Falmouth Harbor System. A nitrogen threshold greater than 0.35 mg N L^{-1} is likely to result in some loss of eelgrass habitat. It should be noted that this is a best estimate of the upper boundary of nitrogen. It should be emphasized that eelgrass coverage declined in Old Field Cove at total nitrogen levels less than 0.35 mg N L^{-1}, although this may have resulted from macroalgal transport from the inner harbor interfering with eelgrass survival. However, a threshold of 0.35 N/L^{-1} for Snug Harbor, would ensure that most of the other regions of the Harbor would have lower average total nitrogen concentrations, and commensurate levels of environmental health.

Although a single sentinel station (Snug Harbor) was selected, secondary criteria relating to infaunal habitat must be achieved at other locations (e.g. Harbor Head). The secondary criteria serve only as checks to make sure that the targets are achieved when the nitrogen threshold at the sentinel station has been reached. The historical analysis did not indicate that Harbor Head is supportive of eelgrass habitat and therefore eelgrass was not used to evaluate habitat health. In these cases, as discussed previously, the MEP focuses on maintenance of a high quality infaunal habitat as the restoration objective. At present, the infaunal habitat within the Harbor Head basin is significantly impaired. The present tidally averaged total nitrogen level is 0.44 N/L^{-1} and the measured mid-ebb average is 0.48 N/L^{-1}. This contrasts with South Basin which shows only a modest level of impairment to infaunal habitat at 0.38 N/L^{-1}. The secondary criteria relating to Harbor Head infaunal habitat would then require tidally averaged total nitrogen level between 0.35 and 0.38 N/L^{-1} when the nitrogen level at the sentinel station is achieved.

The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location within the West Falmouth Harbor System was determined to be 0.35 mg TN L^{-1}. This nitrogen level is lower than found for other complex systems such as Stage Harbor (0.38 N/L^{-1}) and analysis of nitrogen levels within the eelgrass bed in Waquoit Bay, near the inlet (measured TN of 0.395 mg N L^{-1}, tidally corrected <0.38 mg N L^{-1}), and (3) a similar analysis in Bournes Pond. The sentinel station under present loading conditions supports a tidally corrected average concentration of 0.46 mg TN L^{-1}, therefore a watershed nitrogen management will be required for restoration of the estuarine habitats within this system.

It must be stressed that the nitrogen threshold for the West Falmouth Harbor System is at the sentinel location. The secondary criteria should be met when the threshold is met at the sentinel station used for setting the nitrogen threshold and serves as a “check” on the threshold established for the system. The nitrogen loads associated with the threshold concentration at the sentinel location are discussed in Section VIII.3, below.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the West Falmouth Harbor 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 West Falmouth Harbor. 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. However, the recent upgrade to the WWTF allowed streamlining of the target nitrogen loads to West Falmouth Harbor, since this upgrade significantly reduced the total nitrogen entering the estuarine system.

The initial development of nitrogen load reductions needed to meet the threshold concentration of 0.35 mg/l in Snug Harbor was based on the Town of Falmouth moving forward with sewer upgrades in West Falmouth. In addition, full build-out of the watershed was assumed, since this only generates a small increase in overall nitrogen load, much of which will be sent to the WWTF. Table VIII-2 shows the septic load reductions modeled for this scenario. These nitrogen load reductions are a result of (a) the recently upgraded WWTF and (b) development of the currently planned sewer system in the West Falmouth Harbor watershed. In general, the greatest reduction in septic load is from the upper parts of the estuarine system including Oyster Pond, Harbor Head, Snug Harbor, and Mashapaquit Creek.

Tables VIII-3, VIII-4, and VIII-5 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 61% of the septic load from Harbor Head sub-watershed results in a 45% reduction in total nitrogen load. For Mashapaquit Creek, septic load reduction of 45% resulted in total attenuated watershed load reduction of over 61%. The reason that the total load reduction in Mashapaquit Creek is actually larger than the reduction in septic load is due to the WWTF. Since the majority of the existing nitrogen load entering Mashapaquit Creek is from the WWTF, the recent upgrade will cause a large-scale reduction in nitrogen entering the estuary at this location. Table VIII-4 illustrates the significant reduction in total nitrogen load resulting from the WWTF upgrade, even considering the additional load associated with build-out.

Table VIII-5 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-5, 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.

Model results for the build-out scenario with the upgraded WWTF achieve the target TN concentrations at the sentinel station, as shown in Table VIII-6 and Figure VIII-1. To achieve the threshold nitrogen concentrations at the sentinel station, a reduction in TN concentration of greater than 20% is required for Snug Harbor, with TN reduction levels decreasing toward the inlet. The maximum reduction in TN levels occurs in Mashapaquit Creek, where TN levels drop more than 30%. The basis for the watershed nitrogen removal strategy utilized to achieve the embayment thresholds has merit, since it follows the existing WWTF upgrade and sewer construction plan developed by the Town of Falmouth.

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

sub-embayment	present septic load (kg/day)	threshold septic load (kg/day)	threshold septic load % change
Outer West Falmouth Harbor	1.274	0.942	-26.0%
Inner West Falmouth Harbor	2.085	1.901	-8.8%
Harbor Head	0.811	0.318	-60.8%
Oyster Pond	0.984	0.342	-65.2%
Snug Harbor	1.912	0.589	-69.2%
Mashapaquit Creek	2.975	1.650	-44.5%

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

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Outer West Falmouth Harbor	1.690	1.359	-19.6%
Inner West Falmouth Harbor	10.386	5.301	-49.0%
Harbor Head	1.085	0.592	-45.5%
Oyster Pond	1.359	0.718	-47.2%
Snug Harbor	9.570	3.715	-61.2%
Mashapaquit Creek	17.649	6.844	-61.2%

Table VIII-4. Comparison of Falmouth WWTF loads to West Falmouth Harbor for present and build-out.		
watershed	Present WWTF load kg/day	Buildout WWTF load kg/day
Inner West Falmouth Harbor	7.118	2.216
Snug Harbor	6.584	2.052
Mashapaquit Creek	13.731	4.251
Total	27.432	8.519

Table VIII-5. Threshold sub-embayment loads used for total nitrogen modeling of the West Falmouth Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux			
sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Outer West Falmouth Harbor	1.359	0.921	-2.895
Inner West Falmouth Harbor	5.301	0.866	-4.949
Harbor Head	0.592	0.153	-0.372
Oyster Pond	0.718	0.079	0.000
Snug Harbor	3.715	0.455	-2.892
Mashapaquit Creek	6.844	0.019	0.000

Table VIII-6. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the West Falmouth Harbor system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The threshold station is shown in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Mashapaquit Cr., Nashawena Rd.	PWF1	0.627	0.412	-34.3%
Harbor Head, Chappaquoit Rd.	PWF2	0.437	0.353	-19.1%
Chappaquoit Basin	PWF3	0.382	0.326	-14.8%
Inner West Falmouth Harbor	PWF4	0.370	0.320	-13.5%
Snug Harbor	**PWF5**	**0.464**	**0.353**	**-24.0%**
Outer West Falmouth Harbor	PWF6	0.327	0.306	-6.5%
Outer West Falmouth Harbor	PWF7	0.312	0.301	-3.6%
Oyster Pond	PWF8	0.534	0.407	-23.8%

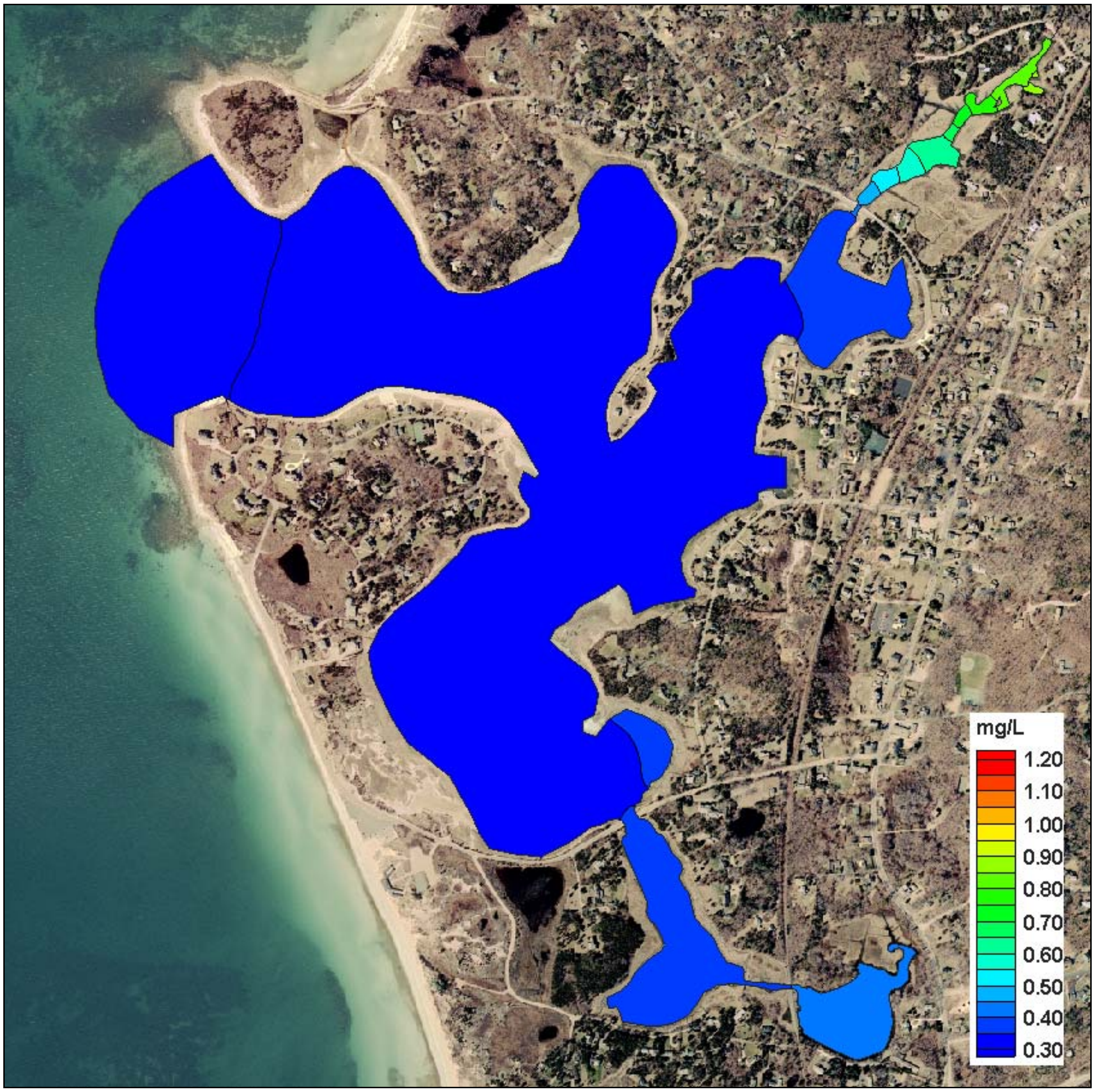


Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the West Falmouth Harbor system, for threshold conditions (0.35 mg/L in Snug Harbor).

IX. ALTERNATIVES TO IMPROVE TIDAL FLUSHING AND WATER QUALITY

IX.1 PRESENT LOADING WITH WWTF LOAD REMOVED

Due to the significant impact associated with nitrogen load generated by the WWTF, an alternative was developed to assess West Falmouth Harbor under existing development, excluding input from the WWTF. As shown in Table IX-1, this alternative has no effect on the groundwater derived nitrogen to Outer West Falmouth Harbor, Harbor Head, or Oyster Pond. However, the nitrogen plume affects the remaining sub-embayments, with the largest impact on Mashapaquit Creek which has approximately 77% of its nitrogen load derived from the WWTF. To properly model this scenario, benthic flux loads were also modified to account for the relatively large reduction in upland nitrogen load. The loads utilized to model the scenario are shown in Table IX-2.

Table IX-1. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer, and the WWTF) used for modeling of present loading scenarios of the West Falmouth Harbor system, with and without the WWTF load. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Outer West Falmouth Harbor	1.690	1.690	0.0%
Inner West Falmouth Harbor	10.386	3.268	-68.5%
Harbor Head	1.085	1.085	0.0%
Oyster Pond	1.359	1.359	0.0%
Snug Harbor	9.570	2.986	-68.8%
Mashapaquit Creek	17.649	3.986	-77.4%

Table IX-2. Sub-embayment loads used for total nitrogen modeling of the West Falmouth Harbor system for present loading scenario with WWTF load removed, 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)
Outer West Falmouth Harbor	1.690	0.921	-2.868
Inner West Falmouth Harbor	3.268	0.866	-4.731
Harbor Head	1.085	0.153	-0.354
Oyster Pond	1.364	0.079	0.000
Snug Harbor	2.986	0.455	-2.744
Mashapaquit Creek	3.986	0.019	0.000

Total nitrogen modeling results for existing conditions without the WWTF indicate that the West Falmouth Harbor system would meet the nitrogen threshold target within Snug Harbor

(Table IX-3 and Figure IX-1). In addition, significant reductions in nitrogen concentration are achieved in all of the landward sub-embayments (e.g. Oyster Pond and Mashapaquit Creek). Nitrogen concentration reductions range from approximately 4% in Outer West Falmouth Harbor to over 40% in Mashapaquit Creek (the waterbody that receives the greatest load from the WWTF). Overall, this scenario indicates that the West Falmouth Harbor system would be considered a healthy estuarine system under current development, if the WWTF had not been constructed.

Table IX-3. Comparison of model average total N concentrations from present loading scenarios (with and without the WWTF load), with percent change, for the West Falmouth Harbor system. The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Mashapaquit Cr., Nashawena Rd.	PWF1	0.627	0.362	-42.3%
Harbor Head, Chappaquoit Rd.	PWF2	0.437	0.361	-17.4%
Chappaquoit Basin	PWF3	0.382	0.321	-16.1%
Inner West Falmouth Harbor	PWF4	0.370	0.311	-16.0%
Snug Harbor	**PWF5**	**0.464**	**0.329**	**-29.0%**
Outer West Falmouth Harbor	PWF6	0.327	0.302	-7.5%
Outer West Falmouth Harbor	PWF7	0.312	0.299	-4.2%
Oyster Pond	PWF8	0.534	0.460	-14.0%

IX.2 ALTERNATE BUILD-OUT WITH NO SEWERING OF WEST FALMOUTH HARBOR WATERSHED

As described in Section VIII, the recent upgrade of the WWTF will result in a significant reduction in nitrogen load to West Falmouth Harbor. At the present time, the Town of Falmouth plans to sewer part of the West Falmouth Harbor watershed to ensure that nitrogen concentrations within the harbor allow the system return to the high quality habitat of the recent past. Based on the results of the alternative described in Section IX.1, it may not be necessary to sewer a significant portion of West Falmouth Harbor's watershed to ensure protection of this resource from nitrogen overload. Therefore, an alternative was assessed that considered build-out of the remaining parcels in the watershed, with the future anticipated loading from the upgraded WWTF and no sewer construction within the watershed to West Falmouth Harbor. Again, since the major contributor of nitrogen load to the harbor is the WWTF, prior to the recent upgrade, this alternative assesses whether the WWTF upgrade alone can improve water quality within the estuary to a level that meets the threshold, regardless of future build-out within the watershed.

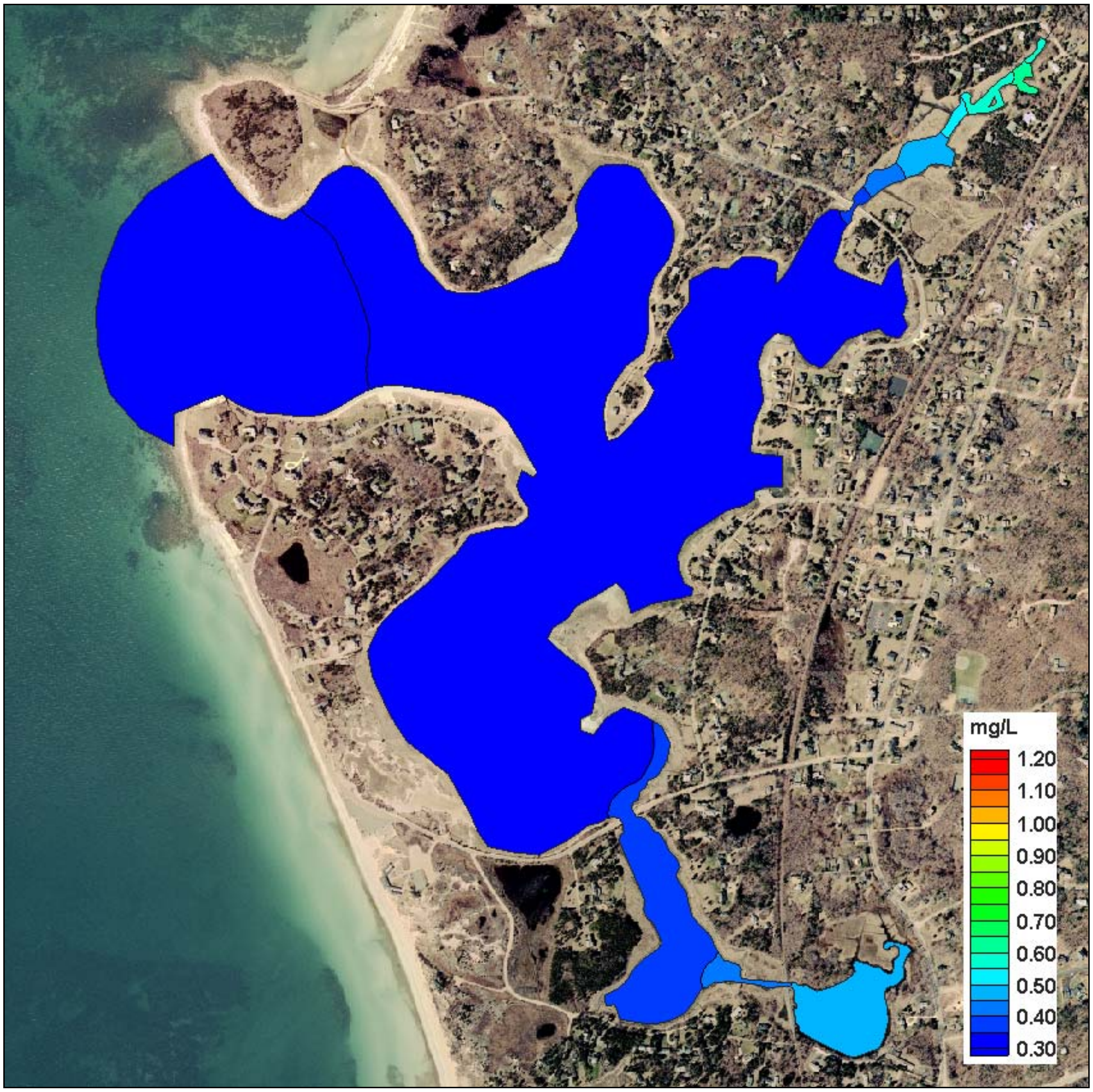


Figure IX-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the West Falmouth Harbor system, for present loading conditions and WWTF loads removed from the system watershed.

Table IX-4 shows the change in septic nitrogen loads from present day conditions associated with full build-out conditions. At first glance, the increases associated with build-out appear large relative to existing septic loads; however, these loads are relatively small when compared to the nitrogen loads generated by the WWTF prior to the 2005 upgrade. Table IX-5 illustrates the overall change to watershed loads resulting from this alternative, where significant reductions are realized in the up-gradient or landward sub-embayments of the system. The primary reason for the reductions in total watershed loads results from the WWTF upgrade. Based on the assumptions developed for this alternative, Table IX-6 presents the various components of nitrogen loading for the West Falmouth Harbor system.

Table IX-4. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and buildout loading scenario with no sewering of the West Falmouth Harbor watershed. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.

sub-embayment	present septic load (kg/day)	scenario septic load (kg/day)	threshold septic load % change
Outer West Falmouth Harbor	1.274	2.216	74.0%
Inner West Falmouth Harbor	2.085	3.334	59.9%
Harbor Head	0.811	1.060	30.7%
Oyster Pond	0.984	1.093	11.1%
Snug Harbor	1.912	2.397	25.4%
Mashapaquit Creek	2.975	3.272	10.0%

Table IX-5. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer, and the WWTF) used for modeling of present and buildout loading scenario with no sewering of the West Falmouth Harbor watershed. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Outer West Falmouth Harbor	1.690	2.633	55.8%
Inner West Falmouth Harbor	10.386	6.734	-35.2%
Harbor Head	1.085	1.334	23.0%
Oyster Pond	1.359	1.468	8.1%
Snug Harbor	9.570	5.523	-42.3%
Mashapaquit Creek	17.649	8.466	-52.0%

Table IX-6. Sub-embayment loads used for total nitrogen modeling of the West Falmouth Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux, for buildout loading scenario with no sewering of the West Falmouth Harbor watershed.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Outer West Falmouth Harbor	2.633	0.921	-2.950
Inner West Falmouth Harbor	6.734	0.866	-5.329
Harbor Head	1.334	0.153	-0.407
Oyster Pond	1.468	0.079	0.000
Snug Harbor	5.523	0.455	-3.147
Mashapaquit Creek	8.466	0.019	0.000

The water quality model for the alternative incorporating the upgraded WWTF, with no sewering within the West Falmouth Harbor watershed and build-out of existing parcels in the watershed, yielded the results shown in Table IX-7 and Figure IX-2. As described in Section VIII, the nitrogen concentration threshold within Snug Harbor was established at 0.35 mg/l. The results of the selected alternative indicate a modeled nitrogen concentration of approximately 0.38 mg/l, which does not meet the threshold level established by the MEP for full restoration of this estuarine system. While the scope of the modeling scenarios developed for this report was not intended to be exhaustive, model results indicate that the Town of Falmouth can meet their nitrogen loading targets at build-out by following the proposed sewering plan of the West Falmouth Harbor watershed, as described in Section VIII. If no sewers are constructed in the watershed and all parcels are developed, the total nitrogen levels in the estuarine system will exceed the threshold value selected for Snug Harbor.

Table IX-7. Comparison of model average total N concentrations from present loading and for buildout loading scenario with no sewering of the West Falmouth Harbor watershed, with percent change, for the West Falmouth Harbor system. The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Mashapaquit Cr., Nashawena Rd.	PWF1	0.627	0.453	-28.8%
Harbor Head, Chappaquoit Rd.	PWF2	0.437	0.402	-8.1%
Chappaquoit Basin	PWF3	0.382	0.349	-8.7%
Inner West Falmouth Harbor	PWF4	0.370	0.334	-9.7%
Snug Harbor	**PWF5**	**0.464**	**0.378**	**-18.6**%
Outer West Falmouth Harbor	PWF6	0.327	0.313	-4.2%
Outer West Falmouth Harbor	PWF7	0.312	0.305	-2.4%
Oyster Pond	PWF8	0.534	0.509	-4.8%

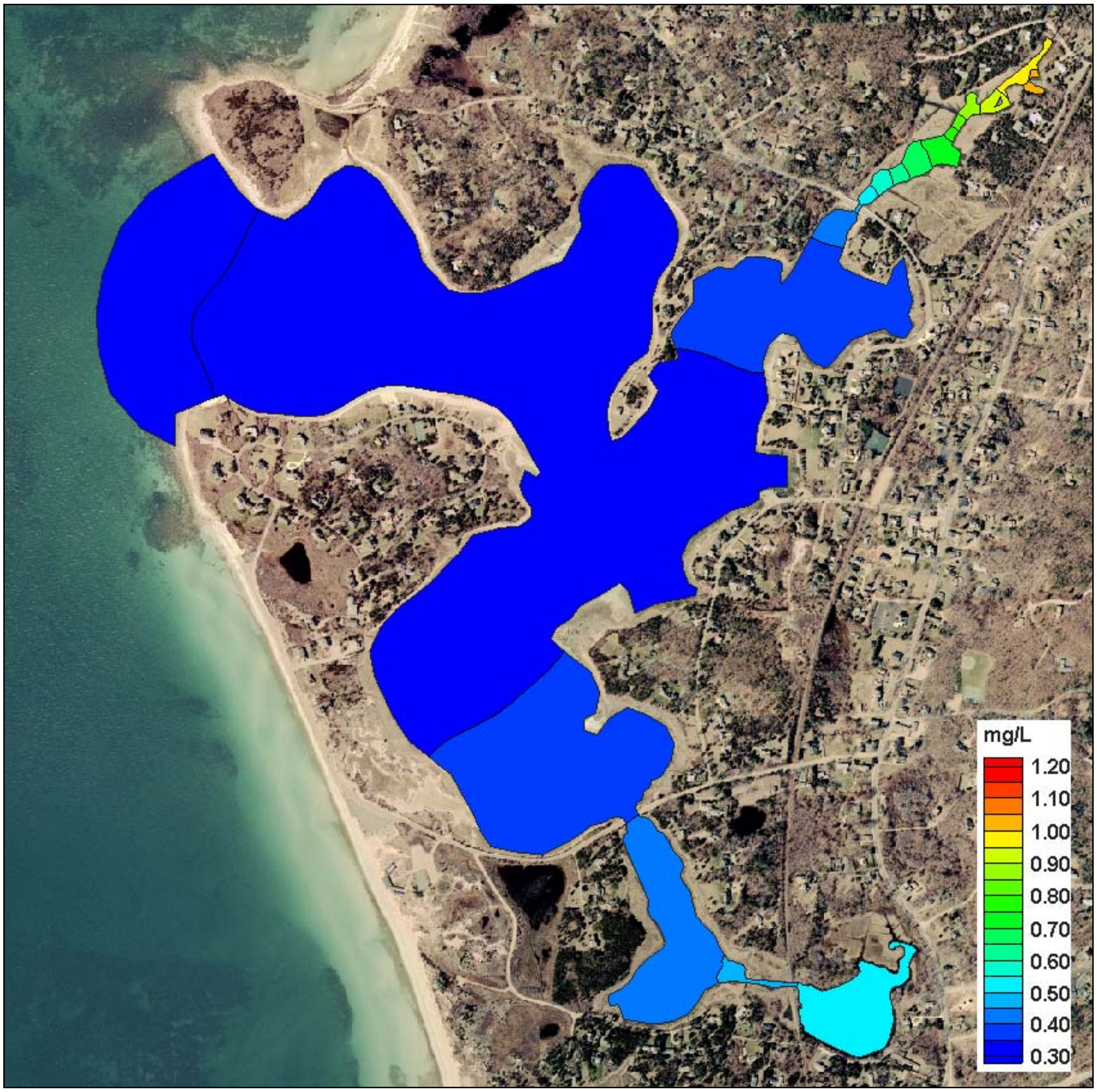


Figure IX-2. Contour plot of modeled total nitrogen concentrations (mg/L) in the West Falmouth Harbor system, for buildout loading conditions with no sewering of the West Falmouth Harbor watershed.

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