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.

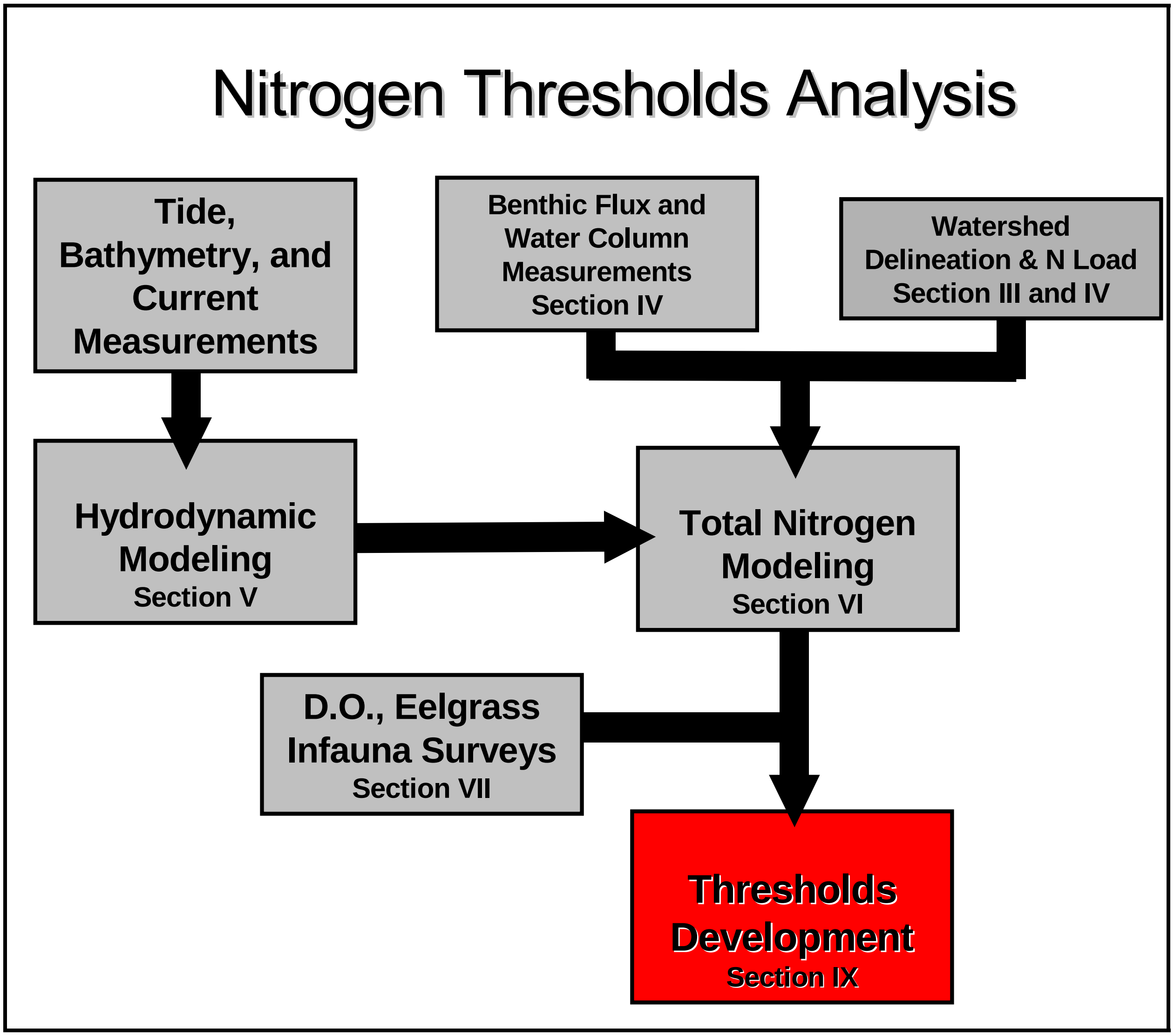

Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

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).