I. INTRODUCTION

The Little Pond embayment system is located within the Town of Falmouth, on Cape Cod Massachusetts. The system has a southern shore bounded by water from Vineyard Sound (Figure I-1). The watershed for this great salt pond system is also distributed fully within the Town of Falmouth. The present configuration of the Little Pond embayment results from the drowning by rising sea level of valleys formed primarily via post-glacial erosion by groundwater fed rivers and streams. At present, Little Pond is a tidal embayment with a groundwater fed stream discharging to its headwaters. This situation is mirrored in almost all of the salt ponds on this stretch of the southern coast of Cape Cod. As is typical with other Falmouth embayments (Great, Green, and Bournes Pond) Little Pond is separated from Vineyard Sound by a barrier beach, which was naturally breached and is now artificially maintained by jetties. The beach and the opening to the embayment is a very dynamic geomorphic feature due to the influence of littoral transport processes. Over the past century the Little Pond inlet has experienced varying degrees of occlusion thereby affecting tidal exchange and circulation within the salt pond. By example, Bournes Pond became very restricted and finally completely isolated from Vineyard Sound waters in the late 1970’s/early 1980’s and was re-opened with a fixed inlet in mid 1980’s. Currently, the inlet to Little Pond is periodically dredged to maintain the small tidal channel into the pond.

Similar to the Great, Green and Bournes Pond embayment systems, Little Pond is a mesotrophic (moderately nutrient impacted) to eutrophic (nutrient-rich) shallow coastal salt pond. The embayment is located within a glacial outwash plain, the Mashpee Pitted Plain, consisting of material deposited after the retreat of the Cape Cod Lobe of the Laurentide Ice sheet ~18,000 years ago. The outwash material is highly permeable and varies in composition from well sorted medium sands to course pebble sands and gravels extending down to about 17 m below mean sea level (Millham and Howes, 1993). As such, direct rainwater run-off is typically rather low for these finger ponds and therefore, most freshwater inflow to these estuarine systems is via groundwater discharge or groundwater fed surface water flow (e.g. stream to the head of Little Pond, Coonamessett River to Great Pond, Backus River to Green Pond etc.). Little Pond acts as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Vineyard sound, however, the salinity characteristics of the salt pond varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with Vineyard Sound.

Little Pond, along with the other salt pond embayments along the south coast of Falmouth, constitutes an important component of the Town’s natural and cultural resources. In addition, the large length to width ratio (8:1) greatly increases the potential for direct discharges from homes situated on the shore and decreases the travel time of groundwater from the watershed recharge areas to bay regions of discharge. The nature of enclosed embayments in populous regions brings two opposing elements to bear: as protected marine shoreline they are popular regions for boating, recreation, and land development; as 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, Little Pond as well as the Great, Green and Bournes Pond embayment systems along the Falmouth shoreline are at risk of eutrophication from high nitrogen loads in the groundwater and runoff from their watersheds.

Figure I-1. Study region proximal to the Little Pond embayment system for the Massachusetts Estuaries Project nutrient analysis. Tidal waters enter the salt pond through one inlet to Vineyard Sound. Freshwaters enter from the watershed primarily through 1 surface water discharge (stream to the head of Little Pond) and direct groundwater discharge.

The primary ecological threat to Little Pond resources is degradation resulting from nutrient enrichment. Loading of the critical eutrophying nutrient, nitrogen, to the embayment waters has been greatly increased over the past few decades with further increases certain unless nitrogen management is implemented. The nitrogen loading to this and other Falmouth salt ponds, like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. The Town of Falmouth has been among the fastest growing towns in the Commonwealth over the past two decades and does not have centralized wastewater treatment throughout the entire Town. At present Little Pond is beyond its ability to tolerate additional nitrogen inputs. It is presently showing habitat degradation consistent with nitrogen overloading. Although the Little Pond watershed is approaching build-out, nitrogen related degradation will likely increase slightly with further water quality degradation, unless nitrogen management is initiated. Fortunately, as Little Pond nitrogen loads are near their build-out rates, management options can be clearly defined and implemented with a high degree of certainty for restoration.

To this end, as the primary stakeholder to the Little Pond 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 a nutrient enriched wastewater plume generated by the Falmouth Wastewater Treatment Facility.

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, though 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. Lastly, the PondWatch Program has grown into being a repository of environmental data on Falmouth’s coastal ponds. The database includes basic water quality monitoring data in addition to special project data on watershed nutrient loading and watershed delineation, circulation characteristics of the ponds, wetland delineations and plant and animal distributions.

The common focus of the Falmouth PondWatch Program effort has been to gather site-specific data on the current nitrogen related water quality throughout Falmouth's coastal embayments (e.g. Little Pond, Great, Green, and Bournes Pond embayment systems) and determine the relationship between observed water quality and watershed nitrogen loads. This multi-year effort has provided the baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. The PondWatch Program in Little Pond developed a data set that elucidated the long-term trend of declining water quality and its relation to watershed based nutrient loading. The MEP effort builds upon the Falmouth water quality monitoring program, and previous hydrodynamic and water quality analyses, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Little Pond embayment system, including any major sub-embayments, of which there are none for the Little Pond system. This is unlike the adjacent Great Pond system which has Perch Pond as a sub-embayment connected to the main bay of Great Pond

Falmouth's Planning Office continues to enhance its tools for gauging future nutrient effects from changing land-uses. The GIS database used in the present MEP evaluation is part of that continuing effort. Unfortunately, PondWatch monitoring has documented that most regions within the Town's coastal ponds, including Little Pond, are currently showing water quality declines and are beyond the limits set by the By-law. Based on the wealth of information obtained over the many years of study of these coastal ponds, in addition to the nutrient analyses undertaken as a precursor to the Massachusetts Estuaries Project, the Little Pond 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 the Towns' on-going data collection and modeling effort, minimal additional municipal funds were required for MEP tasks.

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 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 these valuable coastal resource which are currently being degraded by nitrogen overloading.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. 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 declining 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 use.

Similar to nutrients, bacterial contamination is related to changes in land-use as watershed become more developed. Regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to 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 ca. 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.

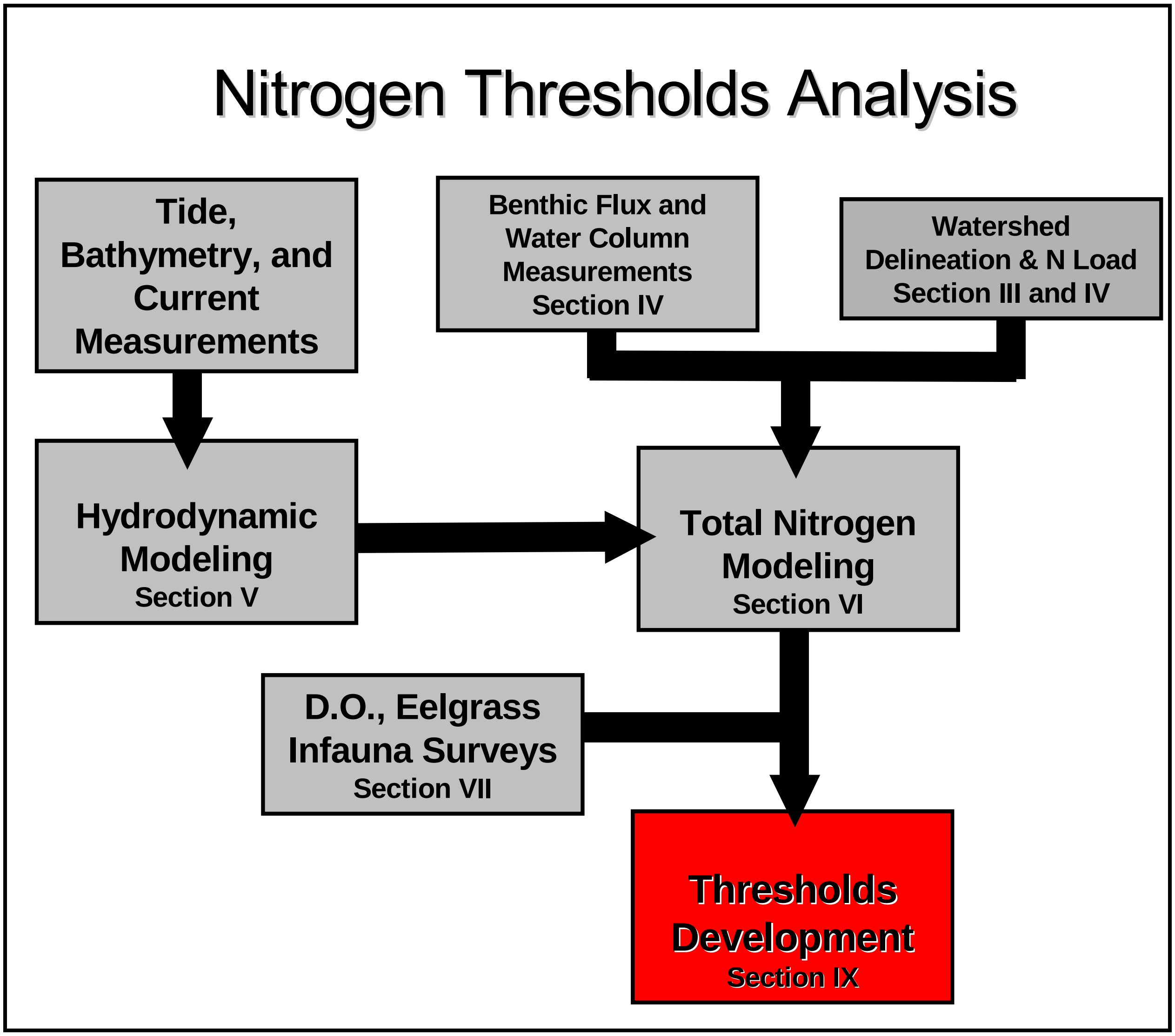

Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

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 coastal salt ponds of Falmouth, including Little Pond, are oriented north-south, and open to Vineyard Sound via inlets. The configuration of the Little Pond and adjacent embayments results from the drowning by rising sea level of valleys formed primarily by post-glacial erosion by groundwater fed rivers and streams. At present, Little Pond is a tidal embayment with a groundwater fed stream discharging to its headwaters. This situation is mirrored in almost all of the salt ponds on this stretch of the southern coast of Cape Cod. As is typical with other Falmouth embayments (Great, Green, and Bournes Pond) Little Pond is separated from Vineyard Sound by a barrier beach, which was naturally breached and is now artificially maintained by jetties. The beach and the opening to the embayment is a very dynamic geomorphic feature due to the influence of littoral transport processes. Over the past century the Little Pond inlet has experienced varying degrees of occlusion thereby affecting tidal exchange and circulation within the salt pond. By example, Bournes Pond became very restricted and finally completely isolated from Vineyard Sound waters in the late 1970's/early 1980's and was re-opened with a fixed inlet in mid 1980's. Currently, the inlet to Little Pond is periodically dredged to maintain the small tidal channel into the pond.

Similar to the Great, Green and Bournes Pond embayment systems, Little Pond is a shallow coastal salt pond located within a glacial outwash plain, the Mashpee Pitted Plain, consisting of material deposited after the retreat of the Cape Cod Lobe of the Laurentide Ice sheet ~18,000 years ago. The outwash material is highly permeable and varies in composition from well sorted medium sands to course pebble sands and gravels extending down to about 17 m below mean sea level (Millham and Howes, 1993). Depth to bedrock is approximately 75 m below sea level (O'Hara & Oldale 1987). The permeable nature of the upper outwash results in low rates of direct rainwater run-off and most freshwater inflow to these estuarine systems is via groundwater discharge or groundwater fed surface water flow (e.g. stream to the head of Little Pond, Coonamessett River to Great Pond, Backus River to Green Pond etc.). Little Pond acts as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Vineyard sound, however, the salinity characteristics of the salt pond varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with Vineyard Sound.

The Little Pond Estuary is a relatively recent ecological system. After the formation of the valley which holds the present Little Pond about 18,000 years B.P. until 4,500-3,000 years B.P., sea level was too low to support tidal exchange. Only over the past 4,500-3,000 has "Little Pond" existed as an estuarine system. After the initial entry of tidal waters to the valley, coastal processes formed the barrier beach and restricted inlet. As sea level has risen, the estuary has migrated inland to its present location.

The habitat quality of Little Pond is linked to the level of tidal flushing through its inlet to Vineyard Sound. Although the salt pond embayment systems of Falmouth bounding Vineyard Sound exhibit slightly different hydrologic characteristics (river dominated versus tidally dominated), the tidal forcing for these systems is generated from Vineyard Sound. Vineyard Sound, adjacent the barrier beach separating the Little Pond embayment system from the ocean, exhibits a moderate to low tide range, with a mean range of about 0.5 m at the southern inlet of the pond. Since the water elevation difference between Vineyard Sound and Little Pond 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 affected significantly by longshore sand transport (west to east), where shoaling can impede hydrodynamic exchange. The inlet is presently armored with jetties and the channel armored with riprap and features a significant scour channel between these structures. Little Pond is long and narrow, with length-to-breadth ratio of approximately 8-to-1. Little Pond, for example, is nearly 1400 meters in length with a width of approximately 170 meters. Depths within the deeper scour channel at the inlet are approximately 2 meters, with the upper (northern) reaches of the Pond frequently less than 1 meter deep.

The present Little Pond inlet was not formed naturally, but relocated as a result of road construction (See Section V). The inlet was located to the east of its present location in maps from 1846, 1880 and 1893. Between 1880 and 1893 a road was constructed along the length of the barrier beach to the inlet, but there is no evidence of jetties in this region at that time. By 1936 the road on the barrier had been extended fully across to the Maravista Peninsula, probably in the 1920's, but tidal exchange was maintained. However, Millham (1993) reconstructing recent changes to Little Pond, indicated that after the roadway extension, tidal flushing was restricted. He stated that "Anecdotal evidence of the fresh or brackish water conditions in the pond before 1964 were offered by several local individuals who fished (trout and perch) and trapped the pond prior to 1964. The reports give some details of the control of the pond level by the old culvert, which was apparently set at a level to prevent the entrance of seawater during most high tides. However, during spring tides and under wind forcing conditions, salt water from Nantucket Sound did flow into the pond inlet". In 1964 the Town of Falmouth placed dual culverts and jetties in the present location and pond tidal exchange was enhanced (Millham 1993). These structures were again replaced in February 1995 to repair damage from Hurricanes and to provide more consistent tidal exchange, at which time the inlet cross-section was altered to be wider to allow greater water exchange with Vineyard Sound under open channel conditions (from Sound to Pond). The tidal exchange of waters from Little Pond with Vineyard Sound water is driven by a relatively small tidal difference between the pond and the sound (<0.5m). It appears that in recent times that Little Pond ecological systems have varied significantly as a result of varying tidal exchange due to inlet changes.

At present, sedimentation of the "channel" between Vineyard Sound and the lower basin of Little Pond, as well as in the culvert, is resulting in less than maximum tidal exchange. Tidal damping (reduction in tidal amplitude) through an embayment can range from negligible indicating "well-flushed" conditions or show tidal attenuation caused by constricted channels and marsh plains indicating a "restrictive" system, where tidal flow and the associated flushing are inhibited. MEP tidal data indicate significant tidal damping through the Little Pond inlet. Due to significant tidal damping through the overall Little Pond System, enhancements in system flushing times may be realized if future modifications to the inlet are considered as a part of nutrient management.

Little Pond is a shallow mesotrophic (moderately nutrient impacted) to eutrophic (nutrient-rich) coastal pond on the southern coast of Falmouth. For the MEP analysis, the Little Pond system was analyzed individually as a stand-alone system. Similar to other salt ponds in Falmouth (e.g. Great/Perch Pond, Green Pond, and Bournes Pond) Little Pond is an estuary with focused freshwater input at the headwaters and tidal exchange of marine waters from Vineyard Sound (tide range of approximately 0.5 m) at its southern inlet. The Little Pond Estuarine System was partitioned into two regions: an 1) upper narrow portion, considered the head of the estuary, which receive discharge from the headwater stream and 2) a lower portion that includes the main basin and the tidal inlet (see Figure I-3). Little Pond is a true estuary, acting as the mixing zone of terrestrial freshwater inflow and saline tidal waters from Vineyard Sound. Salinity in the pond ranges from approximately 30 ppt at the Vineyard Sound inlet to less than 10 ppt at the northern end.

Figure I-3. Partitioning of the Little Pond embayment system relative to basin boundary volumes.

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

Nitrogen loading to the Little Pond embayment system was determined relative to the upper and lower portions of the estuary as depicted in Figure I-3. The watershed to Little Pond is fully within the Town of Falmouth. Based upon land-use and the watershed being fully with in Falmouth, it appears that nitrogen management for Pond restoration may likely be more rapidly developed and implemented than otherwise. As management alternatives are being developed and evaluated, it is important to note that strong gradients define the nutrient characteristics of each pond and as such the associated habitat impacts. There is a strong gradient in nitrogen level and health in Little Pond, with highest nitrogen and lowest environmental health in the headwaters of the system and lowest nitrogen and greatest health near the inlet to Vineyard Sound. The upper reach of Little Pond is presently showing poor water quality and "Eutrophic" conditions. Eelgrass is absent from this region and periodic fish kills have been reported, resulting from oxygen depletion.

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

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

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

Protection and restoration of coastal embayments from nitrogen overloading has resulted in a focus on determining the assimilative capacity of these aquatic systems for nitrogen. While this effort is ongoing (e.g. USEPA TMDL studies), southeastern Massachusetts has been the site of intensive efforts in this area (Eichner et al., 1998, Costa et al., 1992 and in press, Ramsey et al., 1995, Howes and Taylor, 1990, and the Falmouth Coastal Overlay Bylaw). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the “allowable N concentration increase” or “threshold nitrogen concentration” used in previous studies had a significant uncertainty due to the need for direct linkage of watershed and embayment models and site-specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout the Little Pond 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 Little Pond is near or beyond its ability to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated throughout the system and only sparse eelgrass has been observed for over a decade in the lower basin of Little Pond. 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 increased nitrogen loading to the system and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within Little Pond 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 embayment into a “pristine” system.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” for water quality modeling of the Little Pond 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 Little Pond. 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 Falmouth's salt ponds 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 Vineyard Sound source waters and throughout the Little Pond 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 Little Pond 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 Vineyard Sound (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 Little Pond system. Finally, analyses of the Little Pond 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).