

## I. INTRODUCTION

The Quashnet River Estuary, Hamblin Pond/Little River Estuary, and Jehu Pond/Great River Estuary are 3 major tributary sub-embayments to the Waquoit Bay System and are located along its eastern shore. These three sub-estuaries were prioritized for initial analysis by the DEP/SMASST Massachusetts Estuaries Project (MEP) to support on-going nitrogen management planning by the Town of Mashpee. These systems will be revisited and fully integrated into the entire Waquoit Bay System synthesis and modeling effort, at the point that baseline monitoring data and appropriate nitrogen loading and cycling data are available for the greater system.

The eastern Waquoit Bay sub-embayments (Quashnet River, Hamblin Pond/Little River, and Jehu Pond/Great River) are located within the Towns of Falmouth (north & west) and Mashpee (east), on Cape Cod Massachusetts. To the south is a barrier beach that separates the Waquoit Bay System from adjacent Nantucket Sound (Figure I-1). At present, each of the three sub-estuaries exchanges tidal waters with the main basin of Waquoit Bay, which receives tidal flows from Nantucket Sound. The main Bay has two main openings to Nantucket Sound waters, a historically open inlet in the main Bay and an ephemeral inlet that connects Eel Pond to Nantucket Sound. More recently, Hurricane Bob in 1991 created a third inlet immediately east of the Eel Pond entrance; however, this inlet has closed over the past few years.

The primary ecological threat to the eastern Waquoit Bay sub-embayment (Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River) resources is degradation resulting from continuing nutrient enrichment. Although the watershed and the Bay have some organic contamination and bacterial contamination issues, these do not appear to be having large system-wide impacts. Organic contamination has been associated with groundwater recharged in the upper watershed, within the Massachusetts Military Reservation (MMR). Plumes enter two of the major freshwater ponds, Ashumet Pond and Johns Pond, which eventually provide freshwater to the eastern sub-embayments of the Waquoit Bay System. The Ashumet Pond plume is mainly secondarily treated wastewater previously discharged to groundwater infiltration beds at the former MMR Wastewater Treatment Facility. The John's Pond plume stems from a relatively small input of organic contamination. However, it is unlikely that the organic contaminants associated with Johns Pond have any significant effect on Waquoit Bay, due to the passage through Johns Pond and the mode of transport (surface water flow). It is likely that some fraction of the nitrogen loading from the wastewater plume entering Ashumet Pond does contribute to the overall nitrogen loading to the Waquoit System. However, this potential load has decreased in recent years, due to MMR's reduction of land disposal of treated wastewater. Moreover, relative to the longer term, MMR has relocated its disposal beds to an area near the Cape Cod Canal and the disposal area from where the nutrient rich plume originated has been abandoned. Also, the nitrogen within this plume appears to be significantly attenuated by pond ecosystem function. In addition, the wastewater plume is primarily moving through the Ashumet Valley to Great and Green Ponds in Falmouth, rather than towards the Waquoit System. This nitrogen source was included in the present MEP analysis.

Bacterial contamination causes closures of shellfish harvest areas periodically within the Bay System. Overall, the Waquoit Bay System is relatively free of bacterial levels requiring management activities, with levels of indicator bacteria exceeding management thresholds only periodically in small areas, generally associated with the smaller tributary systems (Quashnet River, Hamblin Pond, Little River). However, the mouth of the Moonakis (Quashnet) River is



Figure I-1. Major components of the Waquoit Bay Estuarine System. The study region for the present Massachusetts Estuaries Project analysis is the 3 major sub-embayments within the eastern portion of the Waquoit Bay System (Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River). Tidal waters from Nantucket Sound enter the main Bay through a single inlet in the barrier beach and a smaller inlet to the Eel Pond sub-embayment. Freshwaters enter the estuary primarily through two major surface water discharges (Childs River to Eel Pond and Quashnet River), several smaller streams (e.g. Red Brook), and direct groundwater discharge.

frequently closed to the harvest of shellfish due to bacterial contamination and the Department of Marine Fisheries area associated with Hamblin Pond (DSGA SC16.2) is classified “Prohibited”. This area is located at the northern end of Hamblin Pond near the entry of Red

Brook waters. In addition, a small area associated with the Little River Boatyard is classified “Conditionally Approved”, closed between May 1 and October 31, as a management precaution related to marina activities. But progress has been made in recent years to reduce bacterial contamination of Bay waters. In 1994, Waquoit Bay was designated a Federal No-Discharge Zone, which mandates that boaters must not discharge wastewaters anywhere within the Bay System. Smaller projects to reduce direct stormwater inflows have also been undertaken, for example improvements associated with the recently redesigned Meadow Neck Bridge over the mid-lower Quashnet River estuary.

In contrast to bacterial contamination, loading of the critical eutrophying nutrient, nitrogen, to the Bay waters has been greatly increased over the past few decades with further increases certain unless nitrogen management is implemented. The increasing rates of nitrogen loading to the Waquoit Bay Estuarine System, like almost all embayments in southeastern Massachusetts, have resulted from activities associated with a shift in watershed land-use from primarily pine/oak forest to residential development. The largest single nitrogen source associated with this shift is on-site septic disposal of domestic wastewater. The Towns of Mashpee and Falmouth have been among the fastest growing towns in the Commonwealth over the past two decades and do not have broad sewer service supported by centralized wastewater treatment; although two small facilities (Mashpee High School and Southport) operate within the watershed of one of the tributary embayments to eastern Waquoit Bay, the Quashnet River. Within the eastern Waquoit Bay sub-embayment watersheds, wastewater is returned to the aquifer almost entirely through individual on-site septic systems. As existing and probable increasing levels of nutrients impact Falmouth’s and Mashpee’s coastal embayments, water quality degradation will accelerate, with further declining health of their environmental resources.

The primary stakeholders for the three eastern tributary sub-embayments to the Waquoit Bay System are the Towns of Mashpee and Falmouth. These Towns have cooperative agreements relating to the resources of Waquoit Bay, for example shellfish resources are shared (cf. Town of Mashpee Shellfish Regulations 2004). Both communities are concerned about documented declines in System health. Initial concerns over habitat quality were followed by significant successful efforts of open space protection, most notably South Cape Beach, Washburn Island, and large portions of the Quashnet River watershed. These efforts both preserved habitat areas and reduced the amount of nitrogen likely to be added to Bay waters at watershed full development (build-out). However, these acquisitions do little to restore the nitrogen impaired waters of the Waquoit Bay System. Other notable management actions include designation as an Area of Critical Environmental Concern (ACEC) in 1979 and in 1988, admission into NOAA’s National Estuarine Research Reserve Program (WBNERR, 1996). At present, the Waquoit Bay National Estuarine Research Reserve is jointly managed by NOAA and the Massachusetts Department of Conservation Resources (DCR), formerly the Massachusetts Department of Environmental Management (DEM). It should be noted, however, that implementation of nitrogen management strategies for restoration of this system is still primarily a municipal issue, which will require the efforts of citizens and managers primarily within the Towns of Mashpee and Falmouth.

Concern over declining habitat quality within the Waquoit Bay System continues to this day. Periodic macroalgal blooms have caused significant public attention, most recently in the summer of 2003, when massive *Cladophora* accumulations were observed over a large expanse of the nearshore of the main Bay (drift algae). While this “event” was dramatic, it only underscored the extent of nutrient overloading, as macroalgal accumulations have been a serious concern for more than three decades in this system (Curley et al., 1971).

Over the past two to three decades, both primary stakeholder communities (Falmouth and Mashpee) have examined potential management options for the Bay. At present both are undertaking Comprehensive Wastewater Facilities Planning, with an eye towards restoration of receiving marine waters. The Town of Mashpee is currently conducting planning for the watersheds of the eastern three sub-embayments and for the adjacent Popponesset Bay System. As part of this effort, the Town of Mashpee supported MEP data collection efforts and also supported the collection of the only nitrogen related water quality data available for these sub-embayments (and for the main Bay). The Mashpee Nutrient Monitoring Program will continue through summer 2004, since it is the only source of nitrogen baseline data for the whole of the Waquoit Bay System. Since it was becoming clear that nitrogen restoration of the Bay would likely require some traditional wastewater treatment approaches, the on-going ecological assessment and modeling project was combined with the Town of Mashpee's Wastewater Facilities Planning effort by the Mashpee Sewer Commission starting in 2000. Under the direction of the Mashpee Sewer Commission, the three eastern sub-embayments to Waquoit Bay were included in the first round prioritization of the Massachusetts Estuaries Project to provide state-of-the-art analysis and modeling. These data collection efforts by the Town of Mashpee were essential to the application of the MEP Linked Embayment-Watershed Approach to this estuarine system.

The present MEP effort builds upon the 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 each major sub-embayment. These critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning as well as nitrogen management alternatives development needed by the Towns of Mashpee and 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 numbers of Town staff and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns of Mashpee and Falmouth to develop and evaluate the most cost effective nitrogen management alternatives to restore these valuable coastal resources that 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. The nutrient sources 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 their assimilative capacity, the level where nutrients begin to cause declines in ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities. At higher levels, enhanced nutrient 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 a watershed becomes 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 Towns of Falmouth and Mashpee) are grappling with Comprehensive Wastewater Facilities 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 nitrogen management approach must directly link watershed and embayment nitrogen conditions. In addition any approach must be quantitative and directly support the evaluation of alternative management approaches, both from ecological and cost/benefit perspectives. This "Linked" Modeling approach must also be readily calibrated, validated, and implemented to support planning. Although it may be technically complex to implement, results must be understandable to the regulatory community, town officials, and the general public.

The Massachusetts Estuaries Project represents the next generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (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 scientific basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL must contain an implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

In appropriate estuaries, TMDLs for bacterial contamination are also being 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 assessment, synthesis, and

modeling approach will be used to evaluate 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 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.

***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 eastern Waquoit Bay sub-embayments (Quashnet River, Hamblin Pond/Little River, and Jehu Pond/Great River) are located within the Towns of Falmouth (north & west) and Mashpee (east), on Cape Cod Massachusetts. The southern shore is a barrier beach that separates the Waquoit Bay System from adjacent Nantucket Sound (Figure I-1). At present, each of the three sub-estuaries exchanges tidal waters with the main basin of Waquoit Bay, which receives tidal flows from Nantucket Sound. The main Bay has two main openings to Nantucket Sound, a historically open inlet in the main Bay and an ephemeral inlet that connects Eel Pond to Nantucket Sound. More recently, Hurricane Bob in 1991 created a third inlet immediately east of the Eel Pond entrance; however, this inlet has closed over the past few years.. The inlet to the main Bay has been fixed with jetties initially in 1918 (east) and 1937 (west), with subsequent lengthening and enhancements. This second inlet has been generally open over the past 50 years. The opening of the second inlet significantly increased the tidal range and flows within the Waquoit Bay System and caused important ecological shifts to its tidal wetlands and possibly other estuarine habitats (Orson and Howes, 1992). In recent years, Hurricane Bob (1991) opened a third inlet close to the second inlet to Eel Pond, helping to maintain the recent Waquoit Bay tidal range and circulation pattern. This important “natural” hydrodynamic shift coupled to anthropogenic alteration of the watershed support a recently highly altered estuarine habitat. Within the Quashnet River, Hamblin Pond, and Jehu Pond sub-embayments geomorphic and hydrologic alterations include the damming of the Quashnet (Moonakis) River to drive mills and alteration of riparian zone for cranberry agriculture, and creation of roadways altering circulation around Monomascocoy Island. However, the over-riding change affecting these sub-systems appears to have been the shift from pine/oak forest to farming to current residential land-uses, with its associated large increases in watershed nitrogen loading to the estuarine system.

# Nitrogen Thresholds Analysis

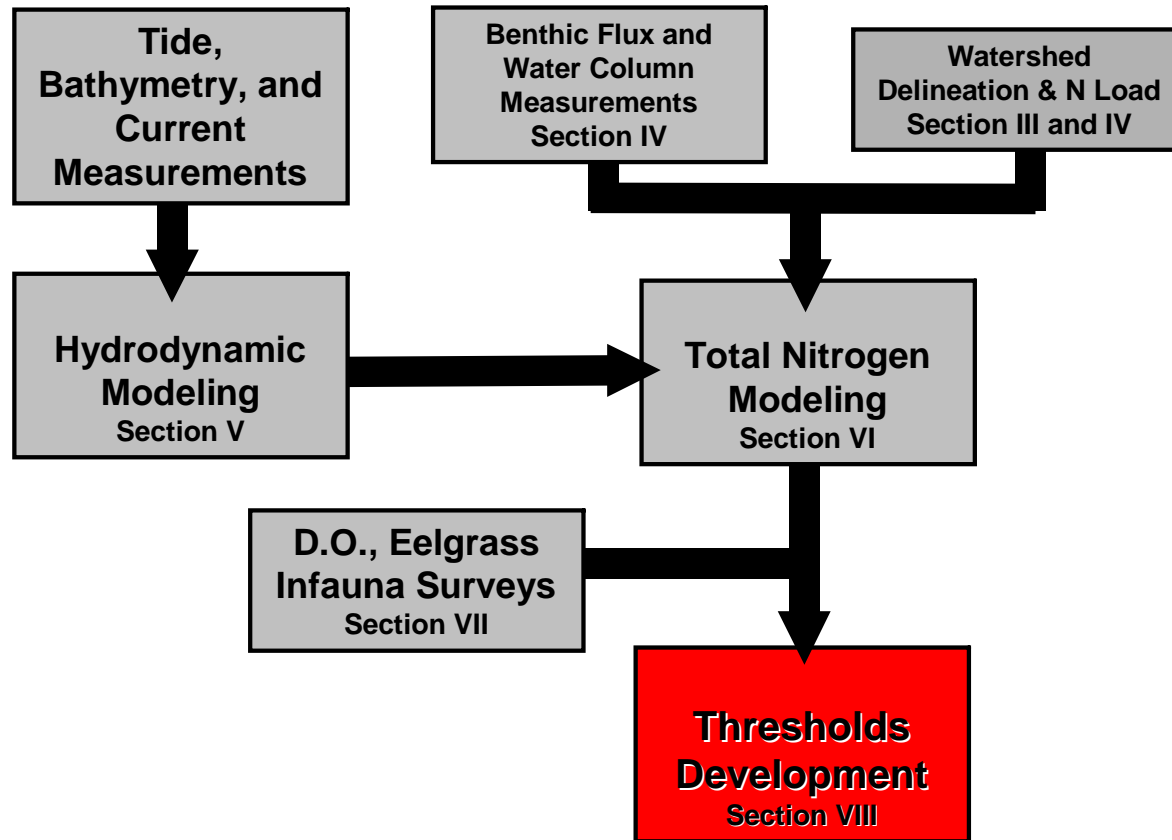


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

The Bay's watershed is distributed among the Towns of Falmouth and Mashpee, with a small portion of the upper-most region of the watershed located in Sandwich. The eastern sub-embayments are located in the Mashpee Pitted Outwash Plain that supports numerous kettle ponds (Oldale 1992). The Quashnet River Estuary is a drowned river valley estuary resulting from rising sea-level flooding the lower reaches of the Quashnet River. Hamblin and Jehu Pond appear to be drowned kettles currently exchanging tidal flows with Waquoit Bay through tidal rivers, Little River and Great River, respectively. Both the Hamblin Pond and Jehu Pond sub-systems support significant saltwater wetland resources.

The tidal reach of the Quashnet River Estuary is located within the Town of Falmouth while much of the freshwater region of the Quashnet River and its watershed is found in the Town of Mashpee. The river is one of the two major surface water inflows to the Waquoit Bay System and originates in John's Pond. Hamblin Pond is divided between the Towns of Falmouth and Mashpee, while Jehu Pond is entirely situated within the Town of Mashpee. The Waquoit Bay system is composed of a main bay with multiple associated sub-embayments (Quashnet River, Hamblin Pond, Jehu Pond, Eel Pond, Childs River). These sub-embayments constitute important components of the region's natural and cultural resources. In addition, the large number of sub-embayments greatly increases the System's shoreline 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, the Waquoit Bay system and its sub-embayments along the Falmouth and Mashpee shores are at risk of eutrophication from high nitrogen loads in the groundwater and runoff from their watersheds. As will be presented in this report, numerous lines of evidence indicate that much of the Waquoit Bay System and the three sub-systems that this MEP Report focuses upon (Quashnet River, Hamblin Pond, Jehu Pond) are currently beyond their nitrogen loading threshold and are currently showing various levels of nitrogen related habitat decline.

Within the eastern Waquoit Bay System, the tidal portions of the major sub-estuaries (Quashnet River, Hamblin Pond/Little River, Jehu Pond/Great River, and Sage Lot Pond) show clear estuarine characteristics, with extensive salt marsh area, tidal flats and large salinity fluctuations. In contrast, the open water portion of eastern Waquoit Bay shows more typical characteristics of open water areas, having only fringing salt marshes, relatively stable salinity gradients and a large basin volume relative to tidal prism. The tidal forcing for these sub-systems is generated from Nantucket Sound. Nantucket Sound adjacent the inlets in South Cape Beach and the southern shore of Washburn Island, exhibits a moderate to low tide range, with a mean range of about 2.5 ft. Since the water elevation difference between Nantucket Sound and Waquoit Bay is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed into and out of the Bay System during a tidal cycle (note the tide range off Stage Harbor Chatham is ~4.5 ft, Wellfleet Harbor is ~10 ft).

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. Tidal data indicate only minimal tidal damping through Waquoit Bay inlet. It appears that the tidal inlet is operating efficiently, possibly due to the active inlet maintenance program. Similarly, within the eastern Waquoit Bay System, the tide generally propagates through the three focal sub-embayments with little attenuation, consistent with relatively unrestricted tidal exchanges.

Given the present hydrodynamic characteristics (well flushed) of the Waquoit Bay System, it appears that estuarine habitat quality is more dependent on nutrient loading to bay waters than tidal characteristics within the component sub-embayments. Due to the relatively well flushed conditions observed in the three sub-embayment systems that are the focus of this investigation, habitat degradation is therefore mostly a result of the exceedingly high nutrient loads currently being documented in these systems, not tidal damping.

Nitrogen loading to the eastern Waquoit Bay System was determined relative to the major eastern shore sub-embayments: Quashnet River, Hamblin Pond/Little River, and Jehu Pond/Great River (Sage Lot Pond is also included). The watershed for this estuarine system contains approximately 10,250 acres, the predominant land use based on area being public service/government, including the Massachusetts Military Reservation and protected open space along the Quashnet River. Public service occupies 54% of the total watershed area to eastern Waquoit Bay (see Figure IV-2). In contrast, while single-family residences occupy approximately 15% of the total watershed area to eastern Waquoit Bay, this land use class represents 61% of all the parcels. Commercial properties are fairly limited within the watershed, with two small clusters located on Route 28 and Route 151.

Relative to the Waquoit Bay System's eastern sub-embayments, residential land-uses primarily in the southern portion of Falmouth and in the Mashpee region create the major nutrient load. Approximately one half of the nitrogen load from single-family dwellings enters the Quashnet River sub-embayment, with almost all of the remainder entering the tidal reaches of Hamblin Pond and Jehu Pond Estuaries. The Sage Lot Pond watershed contains almost no residential development and is primarily a salt marsh with a central shallow pond.

As management alternatives are being developed and evaluated, it is important to note that eastern Waquoit Bay is presently a relatively dynamic and significantly man-altered estuarine system.

### **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 Waquoit Bay System, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer minerals (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 Waquoit Bay 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, nutrient related water quality degradation occurs. Continuing increases in nitrogen inputs beyond this threshold level result in further declines in habitat quality. 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 is done in the MEP effort). 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 total nitrogen concentration throughout each of the 3 eastern sub-embayment to the Waquoit Bay System monitored by the Mashpee Water Quality Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals). The integration of site specific nitrogen data with site specific habitat quality data allows the MEP 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 reaches within the eastern Waquoit Bay sub-embayment systems (including Waquoit Bay) are near or beyond their ability to assimilate additional nutrients without impacting their ecological health. Nitrogen levels are elevated throughout the System and a marked reduction in eelgrass coverage has been observed in the Hamblin Pond and Jehu Pond sub-estuaries (Short and Burdick, 1996). Eelgrass has not been observed in the Quashnet River sub-embayment, instead high levels of macroalgae have been documented (Curley et al., 1971, Valiela et al., 1992). The result is that nitrogen management for each of the three sub-embayments to the Waquoit Bay System covered in this MEP Report must focus on restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed "eutrophication" and when the nutrient loading is primarily from human activities, it is specified as "cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to the systems and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within Waquoit Bay's sub-embayments 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 eastern Waquoit Bay sub-embayment systems; however, a thorough understanding of estuarine circulation is required to accurately determine nitrogen concentrations within each system. Therefore, water quality modeling of tidally influenced estuaries must include a thorough evaluation of the hydrodynamics of the estuarine system. Estuarine hydrodynamics control a variety of coastal processes including tidal flushing, pollutant dispersion, tidal currents, sedimentation, erosion, and water levels. Numerical models provide a cost-effective method for evaluating tidal hydrodynamics since they require limited data collection and may be utilized to numerically assess a range of management alternatives. Once the hydrodynamics of an estuary system are understood, computations regarding the related coastal processes become relatively straightforward extensions to the hydrodynamic modeling. The spread of pollutants may be analyzed from tidal current information developed by the numerical models.

The MEP water quality evaluation examined the potential impacts of nitrogen loading into the eastern Waquoit Bay System, focusing on the tributary sub-embayments of Quashnet River, Hamblin Pond/Little Pond, Jehu Pond/Great River, and Sage Lot Pond. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for each of the systems. Once the hydrodynamic properties of each estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations by USGS using a modification of the West Cape model for sub-watershed areas designated by MEP. Almost all nitrogen entering east Waquoit Bay is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Nantucket Sound source waters and throughout the Waquoit Bay System were taken from the Mashpee Water Quality Monitoring Program (supported by the Town of Mashpee in association with the Coastal Systems Program at SMAST). Measurements of nitrogen and salinity distributions throughout estuarine waters of the System were used to calibrate and validate the water quality model (under existing loading conditions).

## **I.5 REPORT DESCRIPTION**

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the east Waquoit Bay sub-embayment system for the Towns of Falmouth and Mashpee. 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 Nantucket 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 the component sub-embayments was performed that included a review of existing water quality information and the results of a benthic analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed (Section VIII) for restoration of the sub-embayments to east Waquoit Bay. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined sub-embayments threshold for restoration. This latter assessment represents only one of many solutions and is produced to assist the Town(s) in developing a variety of alternative nitrogen management options for this system.