I. INTRODUCTION

The Pleasant Bay embayment system is located within the Towns of Chatham, Harwich, Orleans, and Brewster on Cape Cod Massachusetts. The system has an eastern shore bounded by a narrow barrier beach, Nauset Spit, separating the Bay from the Atlantic Ocean, with which it exchanges tidal waters. The Pleasant Bay Estuary is the largest embayment on Cape Cod and is comprised of large open water areas (namely Little Pleasant Bay, Pleasant Bay and Chatham Harbor) as well as small tributary sub-embayments such as Meetinghouse Pond, Areys Pond, Lonnies Pond, Paw Wah Pond, Quanset Pond, Pochet, Round Cove, Muddy Creek, and the moderately sized Bassing Harbor sub-system (e.g. Crows Pond, Ryders Cove, and Bassing Harbor; Figure I-1). The watershed contributing nitrogen to the waters of the Pleasant Bay Estuary is distributed among the Towns of Orleans, Harwich, Brewster and Chatham. Restoration of degraded habitats within the estuary will depend upon the coordinated efforts of these municipalities and their citizens.

The present configuration of the Pleasant Bay embayment system results from a combination of glacially dominated geologic processes including the deposition of glacial outwash deposits and tidal flooding of drowned river valleys formed primarily by post-glacial rivers and enhancements to support human uses (e.g. tidal channel to Lonnies Pond). The major drowned-river valley components are found in The River with its associated tributaries. Pochet in its present configuration appears to be formed as a marsh behind the barrier beach. In the lower basin, Muddy Creek represents the major drowned river valley estuary. Overall, the Pleasant Bay System is a composite or complex estuary comprised of the aforementioned drowned river valley estuaries exchanging tidal waters with a large lagoonal estuary, represented by the large central basins and whose axis runs parallel to the shore line. The lagoon represents more than ¾ of the estuarine area and habitat and includes Little Pleasant Bay, Pleasant Bay and Chatham Harbor. The Pleasant Bay System is a relatively “young” estuary and coastal feature that required significant post glaciation sea-level rise and the formation of the barrier beach, occurring on the order of 2500-4000 years b.p.

Although erosional processes associated with post-glacial streams and rivers were fundamental to the formation of this system, at present streams are relatively small and discharge only a small portion of the aquifer recharge to the estuary. Small freshwater streams discharge to the uppermost reaches of the system such as Meetinghouse Pond, the Namequoit River, Areys Pond, and Lonnies Pond and in the lower Bay to Frost Fish Creek, Muddy Creek, Tar Kiln, and a small herring ladder to Ryders Cove from Stillwater Pond. Most freshwater from the watershed enters the Bay through direct groundwater seepage along the western shore.

As is typical of many other Cape Cod embayments (Nauset System, Popponesset Bay, Three Bays), Pleasant Bay is separated from the Atlantic Ocean by a barrier beach, which is heavily influenced by coastal storms and was recently breached forming the new tidal inlet. Within Pleasant Bay, the tide propagating through New Inlet and Chatham Harbor is significantly attenuated by the series of flood tidal shoals within the inlet throat. The mean tide range drops from just under 8 feet in the Atlantic Ocean to around 5 feet at the Chatham Fish Pier. Only minor attenuation occurs between the Fish Pier and Pleasant Bay; however, smaller sub-embayments separated from the main system by culverts exhibit significant additional tidal attenuation. Both Muddy Creek and Frost Fish Creek have mean tide ranges of less than 1 ft.

The beach and the inlet are very dynamic geomorphic features, due to the influence of littoral transport processes. The Pleasant Bay embayment system presently exchanges tidal water with the Atlantic Ocean through a single inlet to Chatham Harbor at the southern end of the overall Pleasant Bay system. While the formation of the Pleasant Bay system was dependent upon coastal processes which formed the barrier beach to form the lagoon, the estuary continues to be affected by these same coastal processes as they alter both the length of the spit and the location of the tidal inlet. The effect of these processes is no longer to significantly affect the geomorphology of the estuary and its basins, but to partially control the quality of the habitats within the estuary. Changes in hydrodynamics wrought by inlet dynamics is a key factor in determining the effects on watershed nitrogen loading on estuarine health (see Chapters V & IX). To the extent that the inlet becomes restricted or migrates south and tidal flushing is reduced, nitrogen loading impacts will be magnified over present conditions. Any long term habitat management plan for the Pleasant Bay System must recognize the importance of inlet dynamics and include options to maintain the present (or other suitable) hydrodynamic conditions (see Chapter IX).

Similar to the Nauset and Barnstable Harbor embayment systems, Pleasant Bay is a shallow coastal estuary dominated by salt marsh and tidal flats, as well as being located within a watershed that includes glacial outwash plain (Harwich Outwash Plain) and ice contact deposits (Nauset Height ice-contact deposits) consisting of material deposited after the retreat of the South Channel Lobe of the Laurentide Ice sheet ~15,000 years ago. In fact, Pleasant Bay is situated in the location of 2 sub-lobes of the South Channel lobe, from which these deposits were generated (Oldale, 1992). The material is highly permeable and varies in composition from well sorted medium sands to course pebble sands and gravels. As such, direct rainwater run-off is typically rather low for these coastal systems 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 Paw Wah Pond and Lonnies Pond). Pleasant Bay acts as a large mixing zone for terrestrial freshwater inflow and saline tidal flow from the Atlantic Ocean, however, the salinity characteristics of the embayment system varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with the Atlantic Ocean. Given the large tidal flows and volumetric exchange, there is presently only minor dilution of salinity throughout most of the estuary, with the exception of a few of the tidally restricted sub-embayments (e.g. upper Muddy Creek, upper Frost Fish Creek).

Pleasant Bay, along with its associated terminal sub-embayments, constitutes an important component of the natural and cultural resources of Cape Cod and the Towns of Orleans, Harwich, Chatham and Brewster (though Brewster occupies large parts of the upper watershed to portions of Pleasant Bay, it has relatively limited frontage on the Bay compared to the other Towns). As such the Towns of Orleans, Harwich, and Chatham have worked steadily over many years to have the Pleasant Bay embayment system designated in 1987 as an Area of Critical Environmental Concern (ACEC). In addition, a cooperative agreement was developed between the Towns enabling the development of a resource management plan for Pleasant Bay and in 1998 the Towns formed the Pleasant Bay Alliance to implement the recommendations of the resource management plan.

The primary ecological threat to Pleasant Bay 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 outer Cape embayment systems such as Nauset in the Town of Orleans, like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. The Towns of Orleans and Chatham have been among the fastest growing towns in the Commonwealth over the past two decades and do not have centralized wastewater treatment throughout all

Town areas. As existing and probable increasing levels of nutrients impact the coastal embayments of Orleans, Harwich and Chatham, water quality degradation will accelerate, with further harm to invaluable environmental resources.

The large shoreline and numerous terminal sub-embayments 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, the more enclosed basins within the upper reaches of the Bay, as well as terminal sub-embayments such as Quanset Pond, Paw Wah Pond, and Round Cove along the Pleasant Bay shoreline, are at risk of eutrophication from high nitrogen loads entering via direct groundwater seepage in addition to surface water inflows from adjacent sub-watersheds.

Figure I-1. Study region proximal to the Pleasant Bay embayment system for the Massachusetts Estuaries Project nitrogen thresholds analysis. Tidal waters enter the system through one inlet to the Atlantic Ocean. Freshwaters enter from the watershed primarily through 3 surface water discharges to Paw Wah Pond, Lonnies Pond and Tar Kiln Marsh, as well as direct groundwater discharge. The main basins forming most of the estuarine area are Little Pleasant Bay, Pleasant Bay and Chatham Harbor.

As the primary stakeholders to the Pleasant Bay embayment system, the Towns of Orleans, Harwich and Chatham were among the first communities to become concerned over perceived degradation of embayment health. The Town of Orleans (via the Planning Office) and the Town of Chatham (via the Chatham Water Watchers / Water Quality Laboratory) and the Town of Harwich (via the Natural Resources Office) have long recognized the potential threat of nutrient over-enrichment of the Town's coastal embayments. As such, a comprehensive water quality monitoring program was developed as a coordinated effort among the three Towns as well as the Pleasant Bay Resource Management Alliance. Each Town as well as the Pleasant Bay Alliance became responsible for collection of water samples from specific monitoring stations situated throughout Pleasant Bay. These water quality programs coordinated in order to collect consistent comparable data system-wide, essential to the application of the MEP Linked Watershed-Embayment Management Modeling Approach.

The common focus of the water quality monitoring efforts undertaken by the Towns of Orleans, Chatham, Harwich and the Pleasant Bay Alliance has been to gather site-specific data on the current nitrogen related water quality throughout the Pleasant Bay system, such as Meetinghouse Pond, Pochet, Areys Pond, Quanset Pond etc., 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 combined water quality data sets from each of the above mentioned water quality monitoring programs in Pleasant Bay form a baseline from which to gauge long-term changes as watershed nitrogen management moves forward. The quality of these data allowed the MEP to prioritize the Pleasant Bay System for this next step in the Bay's restoration and management.

The MEP effort builds upon the efforts of the water quality monitoring programs, 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 Pleasant Bay embayment system, including all sub-embayments such as Bassing Harbor, Namequoit River and others.

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 Towns of Orleans, Harwich, Chatham and Brewster, for restoration of the impaired habitats within the Pleasant Bay System. 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 Towns to develop and evaluate the most cost effective nitrogen management alternatives to restore these valuable coastal resources 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. 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 watershed 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 Towns of Orleans, Harwich and Chatham) 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 next generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (MassDEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts.

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region's coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the municipalities and MassDEP with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system will serve as the basis for the development of Total Maximum Daily Loads (TMDLs). Development of TMDLs is required pursuant to Section 303(d) of the Federal Clean Water Act. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources, the allowable load to meet the state water quality standards and then allocate that load to all sources taking into consideration a margin of safety, seasonal variations, and several other factors. In addition, each TMDL outlines an implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

In appropriate estuaries, TMDLs for bacterial contamination will also be conducted in concert with the nutrient effort (particularly if there is a 303d listing). Within the Pleasant Bay System, the MEP has already completed the Technical Reports and MASSDEP the TMDLs related to bacterial contamination in Muddy Creek and Frost Fish Creek sub-embayments. 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 model available to address future regulatory needs.

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

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

The Linked Model has been applied for watershed nitrogen management in ca. 20 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 coastal embayment system of Pleasant Bay is the largest estuarine system on Cape Cod and is comprised of approximately 7,000 acres of barrier beaches and islands, salt marsh, tidal flats, as well as both fresh and saltwater ponds. The System contains more than 1000 acres of salt marsh, more than most other estuaries in southeastern Massachusetts. The system is situated on the eastern shore of Cape Cod with the main basins forming a lagoonal estuary oriented in a north – south manner with one large inlet at the southern end nearest Chatham Harbor lighthouse and tributary drowned river valley estuaries entering along the western shore of the lagoon. The inlet provides Atlantic Ocean source water to the overall Pleasant Bay system. The inlet can be significantly affected by longshore sand transport (north to south), where shoaling can impede hydrodynamic exchange at the mouth and, in the case of extreme events, close an existing inlet and open a new one, as was the case in 1987 when the barrier beach was breached and the New inlet opened up. The existing inlet to the Pleasant Bay system is a natural inlet and is not armored in any way. A navigational channel is maintained, however, shoals are abundant in the vicinity of the inlet and depths vary significantly. Depths throughout Pleasant Bay vary due to the tidal salt marsh characteristics of the system in combination with the open water areas that can be as deep as 10 to 14 feet. At low tide large areas of Pleasant Bay are exposed tidal flats with little to no water.

Similar to the Nauset embayment system just to the north of Pleasant Bay, Pleasant Bay exchanges tidal water with the Atlantic Ocean through a single natural inlet crossing the barrier beach that separates this estuarine system from the ocean. The inlet to Pleasant Bay has not been stabilized with riprap and is greatly influenced by shifting sands. The inlet to Pleasant Bay has gone through significant transformations over the last century as a result of intense coastal processes (refer to Chapter V on hydrodynamics). Most recently, Nauset Spit was breached during a northeast storm that occurred on January 2, 1987 thus forming what is commonly referred to as New Inlet. The tidal exchange of waters from Pleasant Bay with the Atlantic Ocean water is driven by a moderate tidal difference between the estuary and the ocean of approximately 5 ft (Chapter V).

For the MEP analysis, the Pleasant Bay system was analyzed in totality with all the associated sub-embayments contributing to the estuarine dynamics of the overall system. This required the integration of previous MEP modeling efforts undertaken for the Town of Chatham specific to the Muddy Creek system, Frost Fish Creek, Ryders Cove, Crows Pond and Bassing Harbor. It was not reasonable to model the Pleasant Bay system without reconsidering the role that the Chatham sub-embayments play relative to the Pleasant Bay nutrient regime and vice versa. The Pleasant Bay estuarine system was partitioned into four general embayment groups: 1) the upper tributary estuaries of The River and Pochet, 2) the coves and drowned kettles along the western shore, 3) the mid and lower tributary estuaries of Bassing Harbor and Muddy Creek, and 4) the main lagoonal basins of Little Pleasant Bay, Pleasant Bay and Chatham Harbor (see Figure I-1). Similar to other embayment systems throughout the MEP study area (e.g. Nauset system, Popponesset Bay, Three Bays) Pleasant Bay is an estuary with focused freshwater input at the headwaters and tidal exchange of marine waters from the Atlantic Ocean (tide range of approximately 5 ft) at its southern inlet. Though the system does receive freshwater discharges to a limited number of terminal sub-embayments, these stream discharges are relatively small and groundwater seepage is the predominant pathway for freshwater recharge from the watershed to enter the estuary. The high rate of tidal exchange and the entry of freshwater all along the western shore (perpendicular to the long axis of the estuary) combine to minimize the salinity gradients in the open basins.

Overall, the Pleasant Bay system is a shallow mesotrophic, moderately nutrient impacted, (with some eutrophic sub-embayments) coastal embayment system on the eastern coast of Cape Cod. The estuary is situated on the southern margin of the Harwich Outwash Plain and Nauset Ice Contact deposits are the primary sediments in the study area. Pleasant Bay is a true composite estuary with a large lagoon formed behind the barrier beach and smaller tributary drowned river valley estuaries entering perpendicular to the lagoon. The System acts as the mixing zone of terrestrial freshwater inflow and saline tidal waters from the Atlantic Ocean. Salinity in the system ranges from approximately 32 ppt at the New inlet to generally not less than 28 ppt in the headwaters of its sub-embayments.

The beach and the inlet are very dynamic geomorphic features, due to the influence of littoral transport processes. The Pleasant Bay embayment system presently exchanges tidal water with the Atlantic Ocean through a single inlet to Chatham Harbor at the southern end of the overall Pleasant Bay system. The tide is the main driver of circulation throughout the Pleasant Bay System and tidal forcing for the system is generated from the Atlantic Ocean. The Atlantic Ocean, adjacent the Nauset Spit barrier beach separating the Pleasant Bay embayment system from the ocean, exhibits a moderate tide range, with a mean range of about 5 ft at the southern inlet of the system. Since the water elevation difference between the Atlantic Ocean and Pleasant Bay 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).

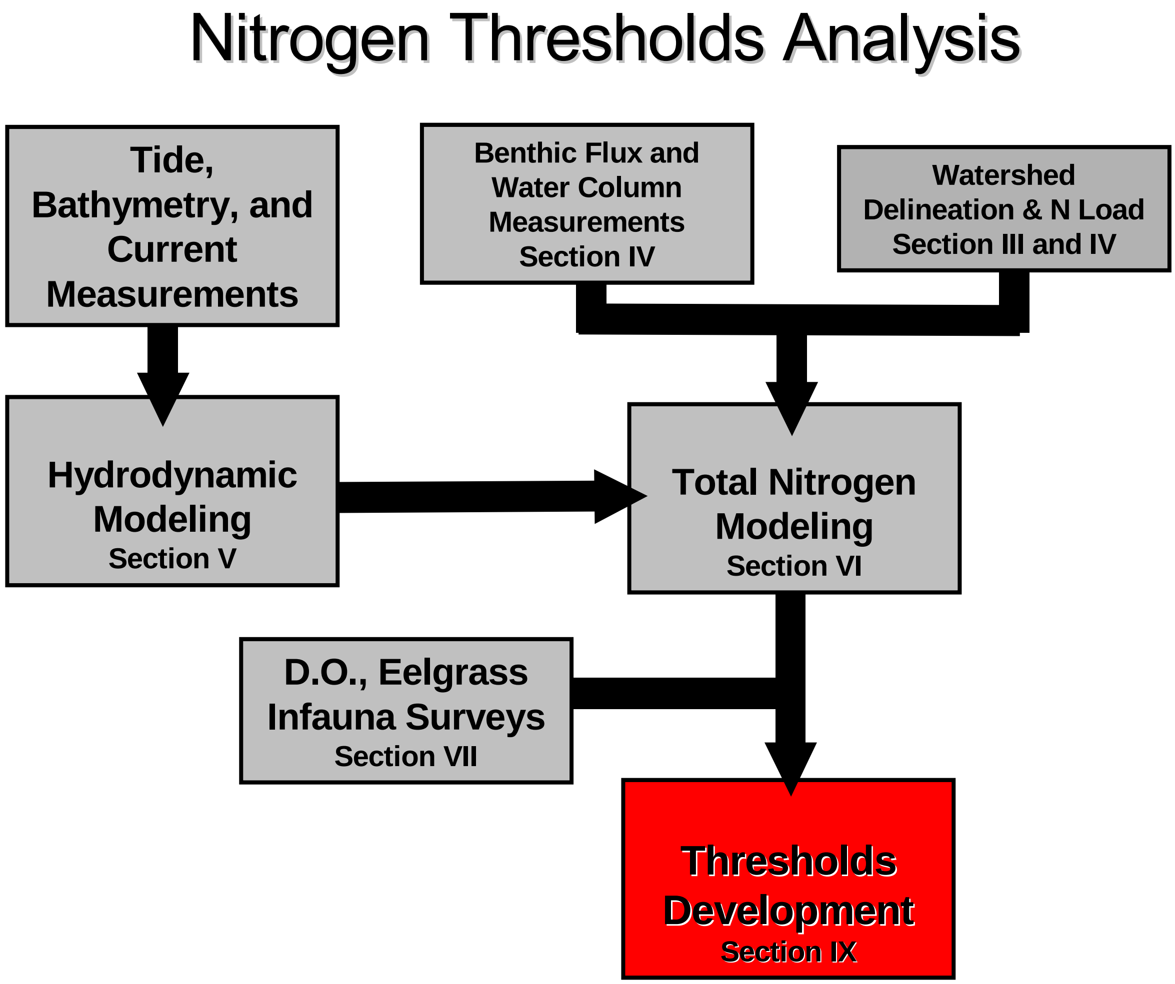

Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

As management alternatives are being developed and evaluated, it is important to note that nitrogen loading and tidal exchange within each sub-embayment is the primary factor controlling habitat health in that sub-basin. The quality of the inflowing waters from Pleasant Bay is the other, although a slightly less critical controlling factor. In addition the nitrogen loading to each sub-embayment affects the health of the receiving main basin of the System. Most of the nitrogen entering the lagoonal component, first passes through a sub-embayment. The result is that the restoration of nitrogen impaired sub-embayments to the Pleasant Bay System require both "local" or contributing area specific nitrogen management, as well as management of nitrogen levels within the watershed of the larger "regional" main basins.

Unlike many smaller estuarine systems, the main nutrient gradients are found in the sub-embayments rather than in the larger lagoon, which accounts for about ¾ of the estuarine areas. For example, there is a large steep gradient in nitrogen from the mouth of Muddy Creek to its headwaters which is many time the gradient found from Chatham Harbor inlet to the upper reach of Little Pleasant Bay. It is in these small tributary estuaries that the greatest nitrogen related impairment of habitat quality is found within the Pleasant Bay 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 Pleasant Bay 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 Pleasant Bay system follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

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

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

Protection and restoration of coastal embayments from nitrogen overloading has resulted in a focus on determining the assimilative capacity of these aquatic systems for nitrogen. While this effort is ongoing (e.g. USEPA TMDL studies), southeastern Massachusetts has been the site of intensive efforts in this area (Eichner et al., 1998, Costa et al., 1992 and in press, Ramsey et al., 1995, Howes and Taylor, 1990, 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 Pleasant Bay system monitored by the Chatham, Orleans, and Pleasant Bay Alliance Water Quality Monitoring Programs 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 smaller sub-embayments to Pleasant Bay (Meetinghouse Pond, Lonnies Pond, Areys Pond, The River, Muddy Creek, Round Cove, Quanset Pond, Paw Wah Pond, Ryders Cove in the Bassing Harbor sub-system) are near or beyond their ability to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated throughout the upper portions of the system and eelgrass is showing a downward trend. The result is that nitrogen management of the primary sub-embayments tributary to the main basins of Pleasant Bay 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 the Pleasant Bay system could potentially occur without anthropogenic 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 Pleasant Bay 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 Pleasant Bay and all of its component sub-embayments. 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 Monomoy model for sub-watershed areas designated by MEP. Almost all nitrogen entering the Pleasant Bay system is transported by freshwater, predominantly groundwater. Concentrations of total nitrogen and salinity of Atlantic Ocean source waters and throughout the Pleasant Bay system was taken from the water quality monitoring programs run by the Towns of Orleans and Chatham as well as the Pleasant Bay Alliance (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 Pleasant Bay System for the Towns of Chatham, Harwich, Orleans and Brewster. A review of existing studies related to habitat health or nutrient related water quality is provided in Chapter II with a more detailed review of prior hydrodynamic investigations in Chapter V. The development of the watershed delineations and associated detailed land use analysis for watershed based nitrogen loading to the coastal system is described in Chapters III and IV. In addition, nitrogen input parameters to the water quality model are described. Since nitrogen recycling associated with the 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 (Chapter 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 station data on the flooding tide just inside the inlet to the Pleasant Bay system (Chapter 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 Chapter IV. Results of hydrodynamic modeling of embayment circulation are discussed in Chapter 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 Chapter 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 and the results of a benthic analysis (Chapter VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment in Chapter 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 Pleasant Bay system. Finally, analyses of the Pleasant Bay system was relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of dredging options to improve nitrogen related water quality. In the case of the Pleasant Bay System, this included an evaluation of potential habitat quality shifts that might occur should the present inlet shift causing a lower rate of tidal exchange or a different offshore source water (i.e. Chatham Roads rather than the Atlantic Ocean) The results of the nitrogen modeling for each scenario have been presented (Chapter IX).