I. INTRODUCTION

The Rushy Marsh Embayment System is a simple estuary located within the Town of Barnstable on Cape Cod, Massachusetts with a southern shore bounded by water from Nantucket Sound (Figure I-1). Rushy Marsh is situated on the coast between the larger estuarine systems of Popponesset Bay and Three Bays. The watershed to Rushy Marsh is fully within the Town of Barnstable, making Barnstable the sole municipal steward of this small estuary. Virtually all watershed freshwater and nutrients enter Rushy Marsh via groundwater seepage, as there are no significant surface inflows to this system. As a result, there is little opportunity for nitrogen removal during transport from watershed source to estuarine waters.

Rushy Marsh Pond is a simple estuary, with a single embayment and highly restricted tidal inlet. The open water area of ~15 acres, makes Rushy Marsh Pond a great salt pond, similar to Oyster Pond in Falmouth. The present configuration of the Rushy Marsh Estuary is relatively new in the coastal landscape, as the southern coast of Cape Cod in the vicinity of Rushy Marsh is a moderately dynamic region, where natural wave and tidal forces continue to reshape the shoreline (see Chapters II and V). All the while, Rushy Marsh was formed by the flooding of a kettle pond as a result of rising sea level following the last glaciation approximately 18,000 years BP. The growth of salt marsh deposits along the northeastern portion of its shore, further enclosed the system, thus its classification as a lagoonal type estuary. This system appears to have persisted until the 1890's. USGS maps from 1893 show Rushy Marsh as a fully tidal estuary with salt marsh along its eastern and northern shores. An island exists off shore, Gull Island, which disappeared in about 1896 (Coast & Harbor Institute and Robert L. Fultz Associates 2002). During the 1900's the tidal inlet became restricted due to sedimentation deposits and the formation of a barrier beach. During this period Popponesset Spit elongated, then breached, with the northern portion finally attaching to the shoreline just north of Rushy Marsh around 1960. This formed a cove to Nantucket Sound running the length of and parallel to Rushy Marsh Pond. Over the next two decades this cove was filled by overwash and today all that remains is a small pond in the barrier beach (Figure I-1). However, the process of barrier beach formation and then overwash resulted in a freshening of Rushy Marsh Pond, even with efforts to keep the system tidal (pipes, culverts). By the turn of the century, the system was a brackish salt pond.

While Rushy Marsh Pond presently has a relatively low nitrogen load from its watershed, due to its small size and proportionally large undeveloped areas, it is still significantly impaired by nitrogen enrichment and is clearly eutrophic. This apparent paradox results from its very low tidal exchange rate, resulting from barrier beach processes restricting the inlet to Nantucket Sound. The low rate of tidal exchange serves to greatly increase the nitrogen sensitivity of this system, such that lower nitrogen inputs cause eutrophic conditions. In recent years the inlet periodically became closed and the pond level rose (due to groundwater inflow) to exceed sea level in the adjacent sound. This also resulted in a further decline in salinity to <1 ppt. The Town of Barnstable (through Conservation Department) working with Friends of Rushy Marsh and Three Bays Preservation partially restored tidal exchange (temporary fix). However, the persistent restricted tidal exchange has caused significant ecological degradation of the Rushy Marsh System. Even with the low watershed nitrogen loading, the low rate of nitrogen removal through tidal flushing results in high nitrogen levels, large phytoplankton blooms and periodic anoxia of bottom waters. In addition, the freshening of the pond waters has resulted in a loss of salt marsh area and a significant expansion of the areal coverage by the common reed, *Phragmites*. It is clear that restoration of Rushy Marsh Pond will require addressing the tidal restriction as one of the principal components, especially as the system has historically operated as a tidal estuary and its proximity to Nantucket Sound prevents its management as a freshwater system due to periodic overwash of salt water (similar to Oyster Pond, Falmouth, see Howes et al., 2005).

Figure I-1. Study region for the Massachusetts Estuaries Project analysis of the Rushy Marsh Pond System. Tidal waters enter the Pond from Nantucket Sound. Freshwaters enter from the watershed primarily through direct groundwater discharge and direct precipitation. Note the small brackish pond in the barrier beach.

Although the nitrogen load to Rushy Marsh Pond is relatively low, nitrogen management should also be considered in the development of the restoration design. The Town of Barnstable has been among the fastest growing towns in the Commonwealth over the past two decades and does have a centralized wastewater treatment system located in Hyannis. However, the Rushy Marsh watershed is not connected to any municipal sewerage system, but relies on privately maintained septic systems for treatment and disposal of wastewater. As existing and probable increasing levels of nutrients impact Barnstable's coastal embayments, water quality degradation will accelerate, with further harm to invaluable environmental resources.

As the stakeholder to the Rushy Marsh Pond System, the Town of Barnstable and its citizens have been active in promoting restoration of this system. This local concern also led to the conduct of several studies (see Chapter II) to support restoration and the Town is presently willing to implement an appropriate plan. To this end, Friends of Rushy Marsh and Three Bays Preservation Inc. have been active in field data collection. One of the key projects undertaken by Three Bays Preservation was to establish, in 2002, a nitrogen related water quality monitoring program within Rushy Marsh Pond. The Three Bays/Rushy Marsh Water Quality Monitoring Program was provided technical assistance by the Coastal Systems Program at SMAST-UMD and over the past several years has been incorporated into Barnstable's Town-wide embayment monitoring program. This effort provides the quantitative watercolumn nitrogen data (2002-2005) required for the implementation of the MEP's Linked Watershed-Embayment Approach used in the present study.

Since the initial results of the Water Quality Monitoring Program and the coastal processes and land-use studies indicated that parts of the Rushy Marsh Estuary are currently impaired by nitrogen enrichment, the Town of Barnstable and Three Bays Preservation undertook additional site-specific data collection to support MEP's ecological assessment and modeling project. The effort was part of the Town's Wastewater Facilities Planning effort and was aimed at restoration of the estuarine resources. As a result of these efforts and to facilitate the development and implementation of restoration, it was appropriate to complete the evaluation of the Rushy Marsh salt pond system at this time.

The common focus of the Barnstable effort has been to gather site-specific data on the current nitrogen related water quality throughout the Rushy Marsh Pond System and determine its relationship to tidal flushing 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 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 develop and implement management alternatives needed by the Town of Barnstable for estuarine restoration/protection. 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, most notably within the Departments of Conservation and Public Works and from members of the local non-governmental organizations (NGO's), Three Bays Preservation and Friends of Rushy Marsh. The modeling tools developed as part of this program provide the quantitative information necessary for the Town of Barnstable to develop and evaluate the most cost effective management alternatives to restore this coastal resource.

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 and the food chain which they support. At higher levels, enhanced nitrogen 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 frequently related to changes in land-use as watersheds become more developed. The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the culture, economy, and tax base of Massachusetts's coastal communities.

The primary nutrient causing the increasing impairment of the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within Southeastern Massachusetts alone, almost all of the municipalities (as is the case with the Town of Barnstable) 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 (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 and municipalities 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 outline of an implementation plan. For this project, the DEP recognizes that there are likely to be multiple ways to achieve the desired goals, some of which are more cost effective than others and therefore, it is extremely important for each Town to further evaluate potential options suitable to their community. As such, DEP will likely be recommending that specific activities and timelines be further evaluated and developed by the Towns (sometimes jointly) through the Comprehensive Wastewater Management Planning process.

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). In these cases, the MEP (through SMAST) will produce a Technical Analysis and Report to support a bacterial TMDL for the system from which MA DEP develops the TMDL. The goal of the bacterial program is to provide information to guide targeted sampling for specific source identification and remediation.

In contrast to the bacterial program, the MEP nitrogen program also includes site-specific habitat assessments and watershed/embayment modeling approaches to develop and assess various nitrogen management alternatives for meeting selected nitrogen goals supportive of restoration/protection of embayment health.

The major MEP nitrogen management goals are to:

- provide technical analysis and supporting documentation to Towns as a basis for sound nutrient management decision making towards embayment restoration
- 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 municipal 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 approximately 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 facilitates the evaluation of nitrogen management alternatives relative to meeting water quality targets within a specific embayment. The Linked Watershed-Embayment Model also enables Towns to evaluate improvements in water quality relative to the associated cost. In addition, once a model is fully functional it can be "kept alive" and updated 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 both calibrated and 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:

- Watercolumn 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

Rushy Marsh Pond is a simple estuary, with a single embayment and highly restricted tidal inlet. The open water area of ~15 acres, makes Rushy Marsh Pond a great salt pond. The Rushy Marsh Estuarine System presently exchanges tidal water with Nantucket Sound through a 2' pipe running through the barrier beach in the general location of the historic natural inlet (see Chapter V). The present "inlet" was installed to lower pond levels and to restore tidal exchange that had virtually ceased in late 2002 or early 2003. As mentioned above, the severe tidal restriction of this system has resulted in nitrogen related habitat declines and shifts in wetland communities. For the MEP analysis, Rushy Marsh Pond is the principal estuarine basin in the modeling and thresholds analysis.

Rushy Marsh Pond is currently a brackish embayment with limited tidal exchange with adjacent Nantucket Sound. The basin consists of a drowned kettle pond and is relatively deep (>2m) compared to nearby typical drowned river valley estuaries (e.g. Green Pond, Falmouth, 1m). At present, the embayment is eutrophic and has periodic summer phytoplankton blooms and anoxia. MEP surveys found sediments consistent with eutrophication, i.e. very soft organic/sulfidic muds. The result is a system virtually devoid of benthic animals. The associated wetlands have also been altered as a result of the varying inlet and tidal exchange rates. Salt marsh is no longer found bordering the pond. Brackish wetland plants, principally Phragmites, now fringe the basin with freshwater marsh slightly inland in the northern region. The loss of salt marsh is likely the result of both the freshening of the system (periodically to <1ppt) and to the periodic rise in standing water (several feet), which would "drown" the salt marsh zone under severe tidal restriction or complete blockage.

As management alternatives are being developed and evaluated, it is important to note that the Rushy Marsh System is naturally a relatively dynamic system and has undergone significant alterations to its hydrologic and biological systems over the past 100 years. Within such dynamic systems, restoration alternatives need to be evaluated relative to the system's "maximum level of sustainable environmental health" in addition to traditional standards..

While the nutrient related health of the Rushy Marsh Estuary as it exists today is linked to changes wrought by natural processes and human activities, it is the physical structure of the system laid down by the retreat of the Laurentide Ice Sheet that still controls much of the Systems' tolerance to nutrient inputs. The physical structure, shape and depth of a coastal embayment plays a major role in its susceptibility to ecological impacts from nutrient loading. Physical structure (geomorphology), which includes embayment bathymetry, inlet configuration and saltwater reaches, when coupled with the tidal range of the adjacent open waters, determines the system's rate of flushing. System flushing rate is generally the primary factor for removing nutrients from active cycling within coastal bays and harbors like Rushy Marsh Pond. As a result maximizing system flushing is one of the standard approaches for controlling the nutrient related health of coastal embayments.

The present configuration of the Rushy Marsh Estuary is relatively new in the coastal landscape, as the southern coast of Cape Cod in the vicinity of Rushy Marsh is a moderately dynamic region, where natural wave and tidal forces continue to reshape the shoreline (see Chapters II and V). All the while, Rushy Marsh was formed by the flooding of a kettle pond as a result of rising sea level following the last glaciation, approximately 18,000 years BP. The growth of salt marsh deposits along the northeastern portion of its shore further enclosed the system resulting in the system's classification as a lagoonal type estuary. This system appears to have persisted until the 1890's. USGS maps from 1893 show Rushy Marsh as a fully tidal estuary with salt marsh along its eastern and northern shores. An island exists off shore, Gull Island, which disappeared in about 1896 (Gaines and Fultz 2005). During the 1900's the tidal inlet became restricted due to sedimentation deposits and the formation of a barrier beach. During this period Popponesset Spit elongated, then breached, with the northern portion finally attaching to the shoreline just north of Rushy Marsh around 1960. This formed a cove to

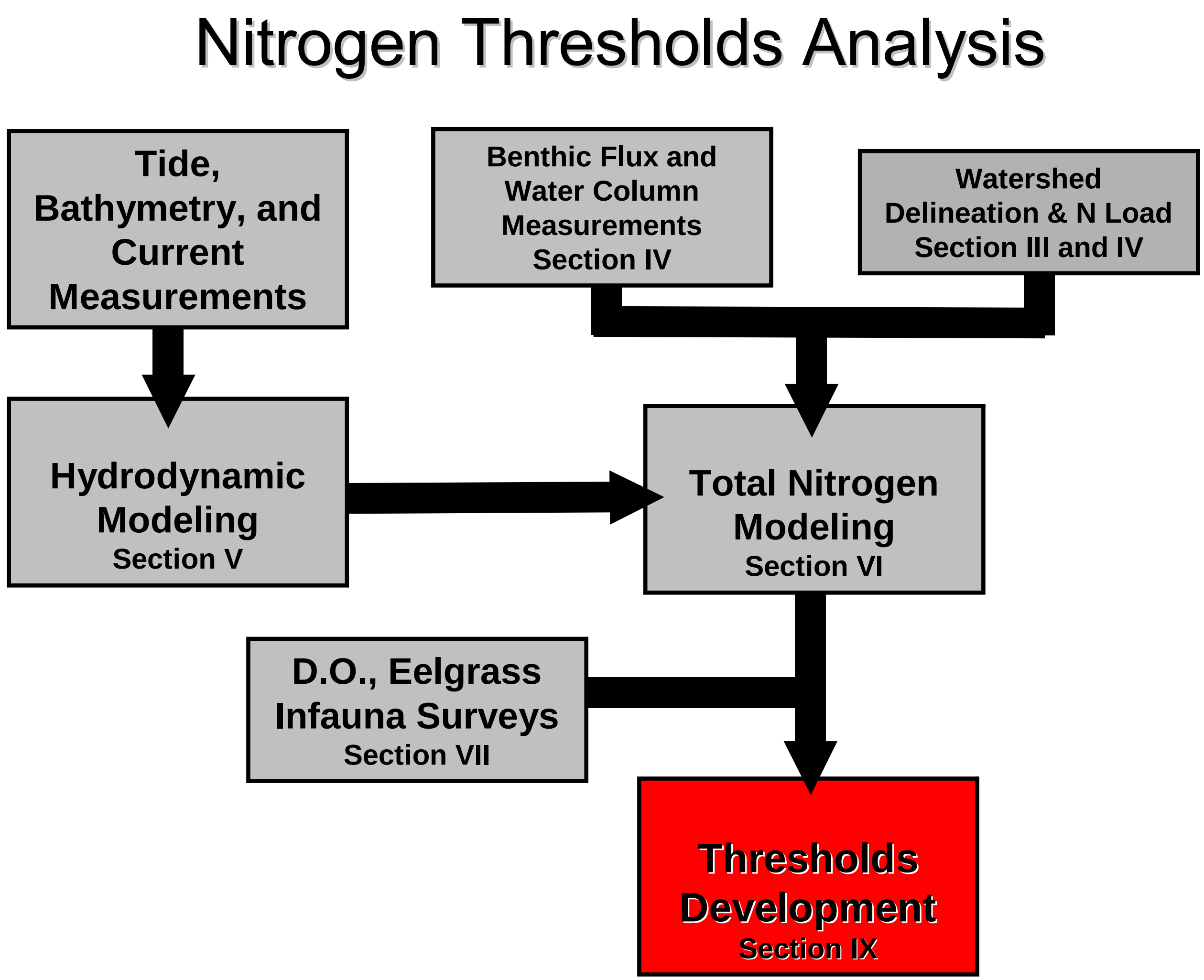

Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach

Nantucket Sound running the length of and parallel to Rushy Marsh Pond. Over the next two decades this cove was filled by overwash and today all that remains is a small pond in the barrier beach. However, the process of barrier beach formation and then overwash resulted in a freshening of Rushy Marsh Pond, even with efforts to keep the system tidal (pipes, culverts). By the turn of the century, the system was a brackish salt pond.

While Rushy Marsh Pond presently has a relatively low nitrogen load from its watershed, due to its small size and proportionally large undeveloped areas, it is still significantly impaired by nitrogen enrichment and is clearly eutrophic. This apparent paradox results from its very low tidal exchange rate, resulting from barrier beach processes restricting the inlet to Nantucket Sound. The low rate of tidal exchange serves to greatly increase the nitrogen sensitivity of this system, so that lower nitrogen inputs are needed to cause eutrophic conditions. In recent years the inlet periodically became closed and the pond level rose (due to groundwater inflow) to exceed sea level in the adjacent sound. This also resulted in a further decline in salinity to <1 ppt. The Town of Barnstable (through Conservation Department) working with Friends of Rushy Marsh and Three Bays Preservation partially restored tidal exchange (temporary fix). However, the persistent restricted tidal exchange has caused significant ecological degradation of the Rushy Marsh System. Even with the low watershed nitrogen loading, the low rate of nitrogen removal through tidal flushing results in high nitrogen levels, large phytoplankton blooms and periodic anoxia of bottom waters. In addition, the freshening of the pond waters has resulted in a loss of salt marsh area and a significant expansion of the areal coverage by the common reed, *Phragmites*. It is clear that restoration of Rushy Marsh Pond will require addressing the tidal restriction as one of the principal components, especially as the system has historically operated as a tidal estuary and its proximity to Nantucket Sound prevents its management as a freshwater system due to periodic overwash of salt water (similar to Oyster Pond, Falmouth, see Howes et al., 2005).

By far the greatest changes to the Rushy Marsh Pond watershed have also occurred during the last 100 years. The most obvious change has been the dramatic shift in land-use to residential housing during the last half of the 1900's. With this shift and the advent of fertilized lawns, has come an increase in the amount of nitrogen, which enters the estuary during a period where its sensitivity has increased due to reductions in tidal exchange rates. The previous large shifts in land-use, primarily from forest to agriculture did not have the same resultant enhancement in nitrogen loading, as agriculture generally recycled nitrogen (as opposed to commercial fertilizers) and the population was <10% of today.

The MEP analysis focused on determining the extent to which the environmental health of the Rushy Marsh System will be enhanced by restoration of tidal exchange with the high quality waters of Nantucket Sound, relative to the potential need to manage watershed nutrient loading. The goal of the MEP and the local stakeholders is to restore the estuarine habitats within Rushy Marsh to meet the high level of quality designated by the State Water Quality Standards for the benefit of both present and future generations.

I.3 NUTRIENT 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 Rushy Marsh 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 1996, 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 Rushy Marsh Estuary presently follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

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

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

Protection and restoration of coastal embayments from nitrogen overloading has resulted in a focus on determining the assimilative capacity of these aquatic systems for nitrogen. While this effort is ongoing (e.g. USEPA TMDL studies), southeastern Massachusetts has been the site of intensive efforts in this area (Eichner et al., 1998, Costa et al., 1992 and in press, Ramsey et al., 1995, Howes and Taylor, 1990, and the Falmouth Coastal Overlay Bylaw). While each approach may be different, they all focus on changes in nitrogen loading from watershed to embayment, and aim at projecting the level of increase in nitrogen concentration within the receiving waters. Each approach depends upon estimates of circulation within the embayment; however, few directly link the watershed and hydrodynamic models, and virtually none include internal recycling of nitrogen (as was done in the present effort). However, determination of the “allowable N concentration increase” or “threshold nitrogen concentration” used in previous studies had a significant uncertainty due to the need for direct linkage of watershed and embayment models and site-specific data. In the present effort we have integrated site-specific data on nitrogen levels and the gradient in N concentration throughout the Rushy Marsh System monitored by the Town of Barnstable/Three Bays Preservation Water Quality Monitoring Program, with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) utilized to “tune” general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, Rushy Marsh Pond is presently beyond its ability to assimilate additional nutrients without impacting their ecological health. This is in significant part due to the very restricted tidal exchange with Nantucket Sound waters. Nitrogen levels are elevated, eelgrass beds have not been observed within Rushy Marsh Pond for the past half century and there are large summer phytoplankton blooms and periodic anoxia of bottom waters. The result is that nitrogen management of the Rushy Marsh Pond system 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 systems and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within the Rushy Marsh System 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. In addition, to the impairment of Rushy Marsh Pond's sub-tidal habitats, there has been a loss of emergent salt marsh from the system stemming from the restricted tidal exchange in recent years. Restriction of the tidal inlet has resulted in freshening of the estuarine waters (sometimes to <1ppt) and an increase in both the mean tide level and during closures, the high water level. At present, the wetlands associated with Rushy Marsh are dominated by fresh and brackish water plants, with large areas of the common reed, *Phragmites*. It appears that the tidal restriction is affecting both the subtidal and intertidal resources, albeit through different mechanisms.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important "boundary conditions" (e.g. watershed derived and offshore nutrient inputs) for water quality modeling of the Rushy Marsh System; however, a thorough understanding of hydrodynamics 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 Rushy Marsh Pond under a variety of nitrogen input (loading) and hydrodynamic conditions. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations (both actual and projected under various inlet configurations) was employed. Once the hydrodynamic properties of the 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 the Rushy Marsh System is transported by freshwater, almost entirely through groundwater. Concentrations of total nitrogen and salinity of Nantucket Sound source waters and throughout Rushy Marsh Pond were taken from the Water Quality Monitoring Program (a coordinated effort between the Town of Barnstable, Three Bays Preservation and the Coastal Systems Program at SMAST). Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of the Systems (2002-2005) 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 Rushy Marsh System for the Town of Barnstable. 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 for restoration of the Estuary in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined Bay threshold for restoration. This latter assessment represents only one of many solutions and is produced to assist the Town in developing a variety of alternative restoration options for this system. Finally, analyses of the Rushy Marsh System were relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of various inlet options to improve nitrogen related water quality (and wetland communities). The results of the nitrogen modeling for each scenario have been presented (Section IX).