II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

Nutrient additions to aquatic systems cause shifts in a series of biological processes that can result in impaired nutrient related habitat quality. Effects include: 1) excessive plankton and macrophyte growth (which leads to reduced water clarity), 2) organic matter enrichment of waters and sediments, with resulting increased rates of oxygen consumption and periodic depletion of dissolved oxygen, (especially in bottom waters), and 3) the limitation of the growth of desirable species such as eelgrass. Even without changes to water clarity and bottom water dissolved oxygen, the increased organic matter deposition to the sediments generally results in a decline in habitat quality for benthic infaunal communities (animals living in the sediments). This habitat change causes a shift in infaunal communities from high diversity deep burrowing forms (which include economically important species), to low diversity shallow dwelling organisms. This shift alone causes significant degradation of the resource and a loss of productivity to both the local shell fisherman and to the sport-fishery and offshore fin fishery, all of which are dependent upon these highly productive estuarine systems as a habitat and food resource during migration or during different life cycle phases. This process is generally termed "eutrophication" and in embayment systems, unlike in shallow lakes and ponds, it is not necessarily a part of the natural evolution of an estuarine system.

In most marine and estuarine systems, such as the Nantucket Harbor System, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. This approach has been formalized through the development of tools for predicting nitrogen loads from watersheds and the concentrations of water column nitrogen that may result. Additional development of the approach generated specific guidelines as to what is to be considered acceptable water column nitrogen concentrations to achieve desired water quality goals (e.g., see Cape Cod Commission 1991, 1998; Howes et al. 2002).

Most of these tools for predicting nitrogen loads and concentrations tend to be generic in nature, and overlook some of the specifics for any given water body. The present Massachusetts Estuaries Project (MEP) study focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for the specific conditions of each of the coastal embayments of southeastern Massachusetts, including the Nantucket Harbor System. As the MEP approach requires substantial amounts of site-specific data collection, part of the program is to review previous data collection and modeling efforts. These reviews are both for purposes of "data mining" and to gather additional information on an estuary's habitat quality or unique features.

Concern over the health of the Nantucket Island embayments has resulted in a number of studies relating to the nutrient related health of the Nantucket Harbor System over the past 2 decades. These investigations include both habitat assessments and studies relating to nitrogen loading, hydrodynamics and habitat health. While the majority of the previous studies did not provide a holistic view of the Nantucket Harbor System or its sub-basins (e.g. Polpis Harbor), they provide useful information to the present MEP effort.

Early studies of the Harbor System tend to focus on its geology. One detailed study by Lidz (1965) provides useful information on the geomorphology of the Harbor, and on its sediments. The sediment distribution within the Harbor basins is shown to be related to the

sorting of sediments by wave action and the generation of organic matter that falls into depositional areas. This study produced the first sediment map showing the distribution of high and low organic matter areas throughout the Harbor. This information is important relative to infaunal habitats and areas of high and low oxygen uptake and nitrogen regeneration.

Not surprising given the scallop fishery, there have been a number of studies to determine the distribution and temporal changes in eelgrass coverage within the Harbor basins. These efforts are summarized in Kelley (1989) and include mapping by Andrews in 1944 and Kelley in 1982 and 1989. These investigations show the trends in eelgrass distribution over the past half century. While some of the analysis is only semi-quantitative, due to the logistical constraints prior to modern GPS mapping tools, they are illustrative. Most importantly, is that the work by Kelley was specifically targeted at changes in eelgrass in specific locations and therefore is sufficiently robust for incorporation into the MEP analysis (see Chapter VII). Overall, it appears that eelgrass beds have been relatively stable over the past several decades. However, eelgrass once present in Polpis Harbor (East Basin) has been lost and the trend of gradual decline in the Head of Harbor beds appears to have been occurring in 1989.

As mentioned above, most of the studies on Nantucket Harbor did not provide a holistic view of the Harbor as a tidal embayment of Nantucket Sound, situated within its a watershed with specific nitrogen sources contributing to its waters. However, one report, the *Nantucket Harbor Study: A Quantitative Assessment of the Environmental Health of Nantucket Harbor for the Development of a Nutrient Management Plan, Final Report March 1997,* did provide a system-wide analysis. This investigation attempted to evaluate this estuary and its watershed within the larger regional system and to evaluate the potential for watershed nitrogen inputs (present and at build-out) to produce habitat declines within the receiving estuary. Similar to the MEP, the study did build on water quality monitoring data, conduct watershed delineation and land-use loading analysis; conduct surveys of infaunal animals, eelgrass beds and bottomwater oxygen levels; and evaluate hydrodynamics. Although this early effort did include some preliminary hydrodynamic analysis, the water quality modeling tools were not yet sufficient to conduct quantitative predictions of changes in Harbor waters associated with altering the watershed nitrogen loading rate. The present MEP analysis builds on this earlier effort and completes the quantitative water quality modeling and nitrogen management threshold determination using new approaches not available to the 1997 Harbor Study.

The Nantucket Harbor Study grew out of an effort to address concerns over the potential for water quality degradation in Nantucket Harbor in the late 1980's. The Town of Nantucket Health Department and Marine Department, the Nantucket Land Council and the Woods Hole Oceanographic Institution joined in 1987 in an effort to assess existing conditions in the harbor and to define potential problem areas. The first step was to establish a baseline water quality program. The results of the baseline water quality study indicated that different areas within the Nantucket Harbor system were showing varying levels of environmental health (Howes and Goehringer 1989). Specifically the data indicated that the Harbor was showing high nutrient related water quality, but that there was discernable nitrogen enrichment in the Head of the Harbor and Polpis Harbor basins and a general decrease in nitrogen levels moving toward the tidal inlet. The 2 inner basins also had slightly higher chlorophyll values. The data also indicated that nitrogen was the nutrient controlling the productivity and habitat quality of Nantucket Harbor, like other estuaries in the region.

The Town of Nantucket Water Quality Monitoring Program has continued from 1988 to present (2005) and the focus continues to be to gather site-specific data on the nitrogen related water quality throughout all the embayments of the Island (including Nantucket Harbor) to track

water quality and habitat health. Additionally, as remediation plans for this and other various systems are implemented, the continued monitoring is planned to provide quantitative information to the Town relative to the efficacy of remediation efforts. The MEP effort builds upon the water quality monitoring program, and previous hydrodynamic and water quality analyses conducted by Applied Coastal Research and Engineering and SMAST, and includes high order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Nantucket Harbor embayment system and its major sub-embayment (Polpis Harbor).

The Town of Nantucket Water Quality Monitoring Program provided the quantitative water column nitrogen data (1988-2005) required for the implementation of the MEP's Linked Watershed-Embayment Approach. The MEP effort also builds upon previous watershed delineation and land-use analyses and the embayment water quality and eelgrass surveys. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Nantucket Harbor embayment system. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the Nantucket Harbor System and to avoiding additional cost to the Town of Nantucket. The MEP analysis has been completed with matching funds provided through MassDEP to the Technical Team.

Building on the water quality program and recognizing the importance of managing the biological resources of the Harbor as part of an overall ecosystem and the need to develop management strategies before significant environmental degradation occurs, the Nantucket Harbor Study began in 1991. The project was a unique collaboration between private citizens, scientists at the Woods Hole Oceanographic Institution, land management specialists and local governments. The goal of the effort was to integrate state-of-the-art coastal and watershed ecological approaches with land-use planning and the policy concerns and education objectives of Nantucket Islanders.

The overall goal of the program was to develop management and monitoring strategies based on quantitative data to provide the most cost effective yet ecologically sound approaches toward nutrient related water quality problems. The study was designed to encompass all of the major ecological processes dominating the water quality and productivity of the harbor, including nutrient conditions, high frequency oxygen monitoring, groundwater inputs, sediment nutrient regeneration, circulation, primary production, submerged macrophyte production, and infaunal populations. By measuring all of the dominant ecological parameters in concert, a detailed understanding of the functioning of the Harbor system and its nutrient assimilative capacity was developed thus enabling predictions as to the responses to increased or decreased nutrient loading. Specific project goals were to:

- assess the existing ecological status of the Harbor under current nutrient loading
- identify areas of high, moderate and low susceptibility to nutrient based degradation
- provide the necessary information for an overall harbor management strategy aimed at preserving ecological, fisheries and aesthetic resources.

Another fundamental goal of the Nantucket Harbor Study was to directly involve students in the research aspects of the project. At the time of the report submittal approximately twenty undergraduate and graduate students had been involved with Harbor studies. Nantucket High School students were also involved from the project's inception as student volunteers and through the Nantucket Harbor Study Environmental Internship. In addition, the Nantucket Harbor Study made Nantucket Harbor a regional center for environmental education through

continuing programs such as the Buzzards Bay RIM Project for teacher education and the Center for Talented Youth.

The Nantucket Harbor Study focused on specific aspects of ecological function including but not limited to hydrology, benthic infaunal communities, nutrient cycling, oxygen status and habitat quality. A freshwater hydrologic balance of the Nantucket Harbor system was developed in part to evaluate the volume of tidal exchanges within each of the Harbor basins and as a central component of the Harbor nitrogen balance. Freshwater enters the waters of Nantucket Harbor as rainfall and as groundwater and surface water inflows. Freshwater inputs can directly affect Harbor habitat quality through salinity stratification (freshwater floating on more saline water). Periodic stratification of Harbor waters increases the potential for nutrient-related water quality problems, especially oxygen depletion, by preventing the mixing of oxygen rich surface waters with bottom waters where oxygen consumption is high. Regions of potential stratification were determined from the location and volume of freshwater input and actual stratification measurements from detailed water column profiling throughout the year. Direct measures indicated that while salinity stratification did occur in a portion of the Harbor sub-basins, stratification was infrequent, generally occurring during the warmer months when potential impact was greatest. Under levels of nitrogen inputs at the time of the study, water column stratification was not sufficient to produce frequent low oxygen events. Measurements of the distribution and volume of freshwater within the Harbor sub-basins relative to the rates of freshwater inflows were also used as a method for determining water exchange between the Harbor and Nantucket Sound. This freshwater approach to evaluation of Harbor flushing rate provides an independent validation of numerically modeled circulation.

Each pathway of freshwater entry also transports nitrogen to the Harbor from both natural and anthropogenic sources. Groundwater and surface water flows are the mechanisms by which nitrogen from the upland watershed of the Harbor reach Harbor waters. Both were quantified and each is dominated by different upland nitrogen sources. Groundwater nitrogen loading was primarily the result of on-site wastewater disposal (septic systems), infiltration of lawn fertilizers and rapid infiltration associated with runoff from impermeable surfaces. Surface water nitrogen loads comprised of discharging groundwater (with its N load), surface runoff containing fertilizers and runoff from impermeable surfaces (roads and roofs) tended to contribute less nitrogen, overall than other inputs. Transport from the watershed is one of the major sources of nitrogen to the Harbor and represent the primary inputs that can be regulated. While most of the inflow volume and nitrogen is via the groundwater pathway, surface water inputs were locally important.

In addition to characterization of the hydrology associated with Nantucket Harbor, a characterization of the benthic animal community of the Harbor was also undertaken. Infaunal communities were assessed seasonally within each Harbor basin to provide a direct assessment of current habitat quality and as a validation of nitrogen assimilative capacity. The study undertook a detailed examination of the infaunal communities and nutrient cycling within the Harbor with direct benefits to the Massachusetts Estuaries Project.

The Nantucket Harbor Study determined present (1990's) levels of nutrients, plant production and oxygen levels to assess present water and habitat quality of each of the Harbor basins. As presented in the study, ecological management of Nantucket Harbor required the quantitative assessment of nutrient loading from all sources relative to the rates of removal through tidal flushing, denitrification and sediment burial. Nutrient impacts were determined primarily by the location and total mass of nutrient inputs. The primary nutrient controlling the health of the Nantucket Harbor ecosystem was found to be nitrogen. Nitrogen was found to

enter the harbor primarily from the surrounding watershed, the atmosphere and in tidal exchanges with Nantucket Sound. Nitrogen recycled within the Harbor through biological activities in the watercolumn and sediments was also measured. As such, a quantitative nitrogen balance for each of the sub-basins of the Harbor was constructed in order to determine the role of anthropogenic versus natural nitrogen sources and to identify the key pathways of nitrogen input and output from the system. The nitrogen balance was integrated with assessments of habitat quality throughout the Harbor systems to determine the ability of each Harbor system to absorb nitrogen inputs without concomitant degradation (assimilative capacity) and to provide a basis for prediction of potential changes due to increasing or decreasing nitrogen loads.

At the time of the study, Nantucket Harbor systems were found to be supporting relatively high water quality. However, nutrient levels within the Harbor were found to be higher than adjacent Nantucket Sound waters. The elevated nutrient levels within the moderately well flushed Harbor were found to be the result of both the concentration of nutrient inputs from the surrounding watershed and the seasonal storage and release of nutrients by Harbor sediments. Nutrient enrichment of the Harbor system was supported by the 2-3 fold higher rates of plant production within the watercolumn and oxygen uptake by sediments in comparison to the adjacent "pristine" habitat of Nantucket Sound. At the time of the study, oxygen levels in the deep holes in the 2 major sub-basins (Quaise and Head of the Harbor) indicated that these basins were close to their assimilative capacity for nitrogen, with periodic moderate oxygen declines.

Based on the work undertaken during this initial in-depth investigation into the function of Nantucket Harbor, specific recommendations were developed as follows:

1) From a purely nutrient related water quality view, land acquisition to protect harbor water quality should focus on larger tracts of less expensive, non-harbor front properties, especially in the Wauwinet Watershed. Economically (purchase costs + tax base) it is generally most cost-effective to purchase inland tracts.

2) Wastewater:
   a) Residential wastewater should be discharged to the sewerage system (as possible), which exports nutrients from the harbor watershed.
   b) Denitrifying septic systems may be encouraged but, except possibly in the Polpis Harbor sub-watershed, the positive impact would likely be small.

3) For both coliform and nutrient issues, direct discharge of stormwater to the harbor should cease.

4) Harbor pump-out facilities should continue to be supported and the non-discharge zone enforced.

5) Reduction of lawn fertilizer usage presents a cost-effective mechanism to significantly reduce terrestrial nitrogen inputs to the Harbor when compared to wastewater treatment options (#2).

6) Need to determine the role of eelgrass deposition in the oxygen depletion of Quaise and Wauwinet Basins. Approaches to scallop fishing which minimize "mowing" of eelgrass beds should be investigated. An evaluation of the feasibility of limiting the period for dredging of scallops within the Harbor to November - January should be

performed. Only a small fraction (ca. 12%) of the total annual catch occurs in February and March.

7) Runoff from impermeable surfaces (rooftops and driveways) should be discharged to vegetated surfaces where possible (not to subsurface rapid infiltration where groundwater will be contaminated).

8) Circulation within the harbor subsystem, particularly Polpis Harbor and Wauwinet, must be maintained.

The Nantucket Harbor Study results and data were reviewed by the MEP Technical Team and found to be of sufficient quality for incorporation (as appropriate) in the MEP analysis of the Nantucket Harbor System. This resulted in the ability of the MEP to conduct its Linked Watershed-Embayment Management Modeling Approach at no additional cost to the taxpayers of the Town of Nantucket.

In parallel with these efforts was the development of a Nantucket and Madaket Harbor Action Plan (1993), which was coordinated by the Nantucket Harbor Planning Advisory Committee under the direction of the Board of Selectman and Massachusetts Coastal Zone Management. Development of the 1993 Harbor Management Plan was the culmination of a five year community effort with the specific mission of 1) examining the current condition of Nantucket's Harbors (including Madaket Harbor) and associated water fronts and 2) to develop a comprehensive plan to include recommendations on policies and actions. Implementation of recommended policies and actions by the Town of Nantucket and County Boards were envisioned to preserve the multiple yet inter-related uses of the harbors of the Island into the future. The goals of this effort continue to present.

The MEP Technical Team identified additional recent studies related to Nantucket Harbor's habitat quality. These efforts are also summarized in the Nantucket Harbor Watershed Work Group Report (2003). BUMP conducted a watershed nitrogen loading analysis to Nantucket Harbor (2000) as part of a larger contract to Applied Science Associates (ASA) for nutrient modeling. The study did not look at the Harbor itself. The BUMP study used the Waquoit Bay watershed approach which attempts to track nitrogen from all sources through all of the biological conversions and finally to the bay. Atmospheric deposition and nitrogen recycling within the Harbor were not part of this effort or as stated by the Work Group, "Because the BUMP Study is a watershed model, and deals only with applications of N from land within the watershed, atmospheric contribution in that report are strictly limited to those contributions on land." As opposed to their proper interpretation of the Harbor Study loading data, "deposition of N on the surface waters of the Harbor is... the greatest contributor of N to the Harbor of any source." The Harbor Study and the BUMP study tended to agree as to the most important sources of nitrogen within the watershed, but the BUMP study suggested very high rates of nitrogen removal during transport to the Harbor waters, which were not validated. This model was evaluated with other models in a MassDEP and USEPA effort and found to generally underestimate watershed nitrogen loads compared to the other management models employed in southeastern Massachusetts (Howes et al. 2001). The ASA Harbor Nutrient Model was also assessed by the Work Group, "to be of limited worth, due to technical difficulties in running the model. The analyses of various structural solutions led the Work Group to conclude that such solutions may not provide the water benefits that it had hoped for. The "solution" of developing a permanent breach in the barrier beach at the Head of the Harbor raises more questions than it answers at the present time and requires further study if it is to be seriously considered." Information from these efforts has been incorporated into the present effort, as appropriate.

Consistent with its holistic evaluation of the Harbor within its watershed, the Nantucket Harbor Study has been used for planning related to Nantucket Harbor, since 1997 and provided a scientific basis for the Nantucket Harbor Watershed, created by the Town to focus planning for Harbor protection in 1999. The purpose of the "Nantucket Harbor Watershed" is stated in Chapter 99 of the Nantucket Code. "It is in the public interest to delineate the boundaries of he Nantucket Harbor Watershed, thus providing a frame of reference for diverse, multi-jurisdictional strategies and activities....In the future, these activities might include structural improvements (i.e. dredging or other activities to enhance water circulation, extension of sanitary sewers to mitigate septic nutrient loading and the development of planning contingencies....It is also important that educational strategies, devised to inform the public of ways to preserve Harbor water quality , have a defined watershed as a frame of reference". Clearly, the Town of Nantucket was forward thinking toward the protection of its Harbor resources and cognizant that without planning those resources could be lost. It is the MEP Technical Team's hope that the present MEP Technical Report will contribute to the multi-decadal effort of protecting Nantucket Harbor's resources.