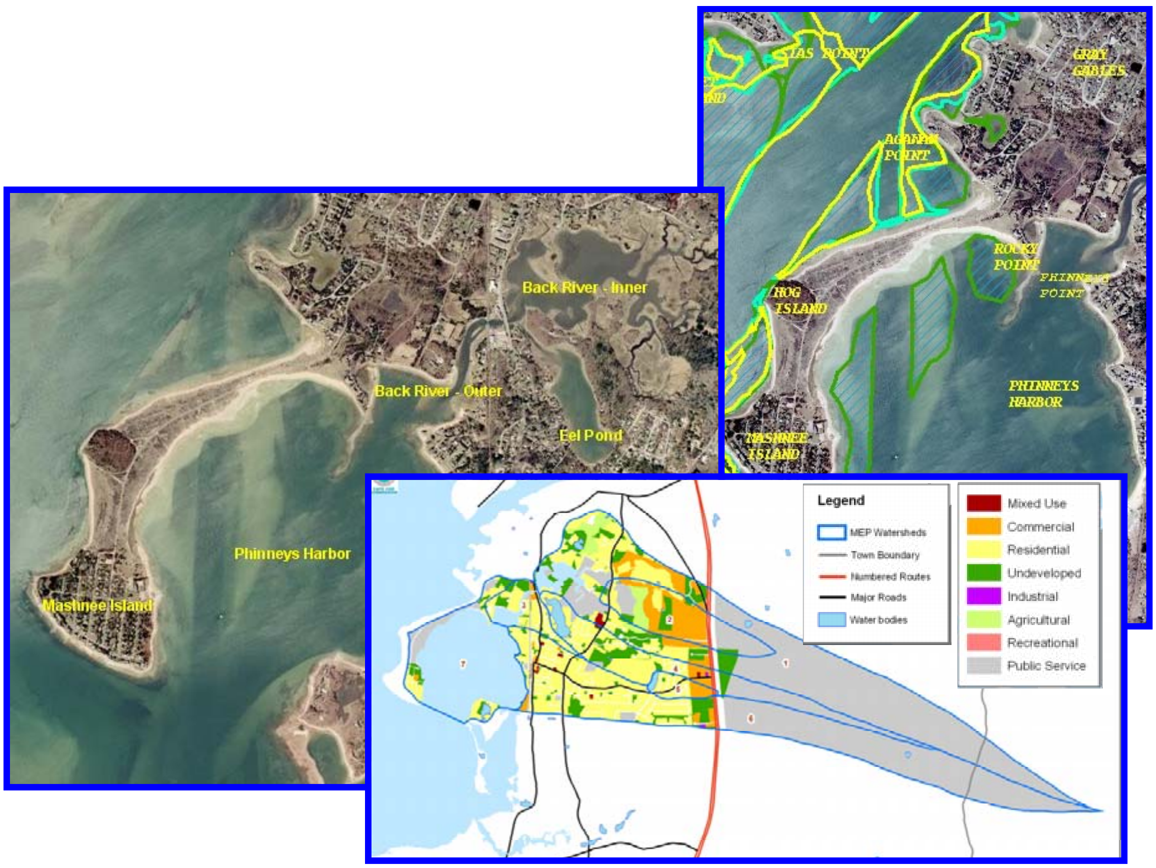
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Phinneys Harbor, Eel Pond and Back River System, Bourne, Massachusetts



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

FINAL REPORT – MAY 2006

Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Phinneys Harbor, Eel Pond and Back River System Bourne, Massachusetts

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Brian Howes
Roland Samimy
David Schlezinger

Trey Ruthven
John Ramsey

Ed Eichner

Contributors:

US Geological Survey
Don Walters and John Masterson

Applied Coastal Research and Engineering, Inc.
Elizabeth Hunt and Trey Ruthven

Massachusetts Department of Environmental Protection
Charles Costello and Brian Dudley (DEP project manager)

SMAST Coastal Systems Program
Jenifer Antosca, Michael Bartlett, Sara Sampieri and Elizabeth White

Cape Cod Commission
Xiaotong Wu

Massachusetts
Department of
Environmental
Protection

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Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Phinneys Harbor, Eel Pond and the Back River System Bourne, Massachusetts

Executive Summary

1. Background

This report presents the results generated from the implementation of the Massachusetts Estuaries Project's Linked Watershed-Embayment Approach to the Phinneys Harbor, Eel Pond and Back River embayment system, a coastal embayment within the Town of Bourne, Massachusetts. Analyses of the Phinneys Harbor, Eel Pond and Back River embayment system was performed to assist the Town with up-coming nitrogen management decisions associated with the Towns' current and future wastewater planning and management efforts, as well as wetland restoration, anadromous fish runs, shell fishery, open-space, and harbor maintenance programs. As part of the MEP approach, habitat assessment was conducted on the embayment based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. Nitrogen loading thresholds for use as goals for watershed nitrogen management are the major product of the MEP effort. In this way, the MEP offers a science-based management approach to support the Town of Bourne resource planning and decision-making process. The primary products of this effort are: (1) a current quantitative assessment of the nutrient related health of the Phinneys Harbor, Eel Pond and Back River embayment, (2) identification of all nitrogen sources (and their respective N loads) to embayment waters, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within embayment waters, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in embayment waters, and (5) a functional calibrated and validated Linked Watershed-Embayment modeling tool that can be readily used for evaluation of nitrogen management alternatives (to be developed by the Town) for the restoration of the Phinneys Harbor, Eel Pond and Back River embayment system.

Wastewater Planning: As increasing numbers of people occupy coastal watersheds, the associated coastal waters receive increasing pollutant loads. Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The elevated nutrients levels are primarily related to the land use impacts associated with the increasing population within the coastal zone over the past half-century.

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 our coastal embayments is nitrogen, with its primary sources being wastewater disposal, and nonpoint source runoff that carries nitrogen (e.g. fertilizers) from a range of other sources. Nitrogen 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 shallow nature and large shoreline area, are generally the first coastal systems to show the effect of nutrient pollution from terrestrial sources.

In particular, the Phinneys Harbor, Eel Pond and Back River embayment system within the Town of Bourne is at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater and surface water from the increasingly developed watershed to this coastal system. Eutrophication is a process that occurs naturally and gradually over a period of tens or hundreds of years. However, human-related (anthropogenic) sources of nitrogen may be introduced into ecosystems at an accelerated rate that cannot be easily absorbed, resulting in a phenomenon known as cultural eutrophication. In both marine and freshwater systems, cultural eutrophication results in degraded water quality, adverse impacts to ecosystems, and limits on the use of water resources.

The Town of Bourne has recognized the severity of the problem of eutrophication and the need for watershed nutrient management. To that end, the Town of Bourne and work groups have recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets is required for sound decision-making and alternatives analysis relative to watershed nutrient management for the protection and/or restoration of the Phinneys Harbor, Eel Pond and Back River system. The conduct of this multi-step process has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, which is a partnership effort between all MEP collaborators and the Town. The modeling tools developed as part of this program provide the quantitative information necessary for the Towns' nutrient management groups to predict the impacts on water quality from a variety of proposed management scenarios.

Nitrogen Loading Thresholds and Watershed Nitrogen Management: Realizing the need for scientifically defensible management tools has resulted in a focus on determining the aquatic system's assimilative capacity for nitrogen. The highest-level approach is to directly link the watershed nitrogen inputs with embayment hydrodynamics to produce water quality results that can be validated by water quality monitoring programs. This approach when linked to state-of-the-art habitat assessments yields accurate determination of the "allowable N concentration increase" or "threshold nitrogen concentration". These determined nitrogen concentrations are then directly relatable to the watershed nitrogen loading, which also accounts for the spatial distribution of the nitrogen sources, not just the total load. As such, changes in nitrogen load from differing parts of the embayment watershed can be evaluated relative to the degree to which those load changes drive embayment water column nitrogen concentrations toward the "threshold" for the embayment system. To increase certainty, the "Linked" Model is independently calibrated and validated for each embayment.

Massachusetts Estuaries Project Approach: 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 to communities throughout southeastern Massachusetts (the Linked Watershed-Embayment Management Model) for nutrient management in their coastal embayment systems. Ultimately, use of the Linked Watershed-Embayment Management Model tool by municipalities in the region results in effective screening of nitrogen reduction approaches and eventual restoration and protection of valuable coastal resources. The MEP provides technical guidance in support of policies on nitrogen loading to embayments, wastewater management decisions, and establishment of nitrogen Total Maximum Daily Loads (TMDLs). A TMDL represents the greatest amount of a pollutant that a waterbody can accept and still meet water quality standards for protecting public health and maintaining the designated beneficial uses of those waters for drinking, swimming, recreation and fishing. The MEP modeling approach assesses available options for meeting selected nitrogen goals that are protective of embayment health and achieve water quality standards.

The core of the Massachusetts Estuaries Project analytical method is the Linked Watershed-Embayment Management Modeling Approach, which links watershed inputs with embayment circulation and nitrogen characteristics.

The Linked Model builds on 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 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.

For a comprehensive description of the Linked Model, please refer to the *Full Report: Nitrogen Modeling to Support Watershed Management: Comparison of Approaches and Sensitivity Analysis*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm. A more basic discussion of the Linked Model is also provided in Appendix F of the *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm. The Linked Model suggests which management solutions will adequately protect or restore embayment water quality by enabling towns to test specific management scenarios and weigh the resulting water quality impact against the cost of that approach. In addition to the management scenarios modeled for this report, the Linked Model can be used to evaluate additional management scenarios and may be updated to reflect future changes in land-use within an embayment watershed or changing embayment characteristics. 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. Unlike many approaches, the Linked Model accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics and accommodates the spatial distribution of these processes. For an overview of several management scenarios that may be employed to restore embayment water quality, see *Massachusetts Estuaries Project Embayment Restoration Guidance for Implementation Strategies*, available for download at http://www.state.ma.us/dep/smerp/smerp.htm.

Application of MEP Approach: The Linked Model was applied to the Phinneys Harbor, Eel Pond and Back River embayment system by using site-specific data collected by the MEP and water quality data from the Coalition for Buzzards Bay Water Quality Monitoring Program (see Chapter 2). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Bourne Planning Department, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Phinneys Harbor, Eel Pond and Back River embayment system and the systems sub-embayments as appropriate (current and build-out loads are summarized in Table IV-3). Water quality within a sub-embayment is the integration of nitrogen loads with the site-specific estuarine circulation. Therefore, water quality modeling of this tidally influenced estuary included 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. Once the hydrodynamics of the system was quantified, transport of nitrogen was evaluated from tidal current information developed by the numerical models.

A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the Phinneys Harbor, Eel Pond and Back River embayment system. 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 model was 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 while nitrogen entering Bourne's coastal embayment was quantified by direct measurement of stream nutrient concentrations and freshwater flow, predominantly groundwater, in streams discharging directly to the embayment. Boundary nutrient concentrations in Buzzards Bay source waters were taken from water quality monitoring data. Measurements of current salinity distributions throughout the estuarine waters of the Phinneys Harbor, Eel Pond and Back River embayment system was used to calibrate the water quality model, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic model was calibrated and validated independently using water elevations measured in time series throughout the embayments.

MEP Nitrogen Thresholds Analysis: The threshold nitrogen level for an embayment represents the average water column concentration of nitrogen that will support the habitat quality being sought. The water column nitrogen level is ultimately controlled by the watershed nitrogen load and the nitrogen concentration in the inflowing tidal waters (boundary condition). The water column nitrogen concentration is modified by the extent of sediment regeneration. Threshold nitrogen levels for the embayment systems in this study were developed to restore or maintain SA waters or high habitat quality. High habitat quality was defined as supportive of eelgrass and infaunal communities. Dissolved oxygen and chlorophyll a were also considered in the assessment.

The nitrogen thresholds developed in Section VIII-2 of this report were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Phinneys Harbor, Eel Pond and Back River system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel station (Phinneys Harbor, PH-4) chosen for Phinneys Harbor, Eel Pond and Back River. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented in the report represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation in this report of load reductions aims to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

The Massachusetts Estuaries Project's thresholds analysis, as presented in this technical report, provides the site-specific nitrogen reduction guidelines for nitrogen management of the Phinneys Harbor, Eel Pond and Back River embayment system in the Town of Bourne. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to the embayment. The MEP analysis has initially focused upon nitrogen loads from on-site septic systems as a test of the potential for achieving the level of total nitrogen reduction for restoration of the embayment system.

2. Problem Assessment (Current Conditions)

The Phinneys Harbor System is a complex estuary composed of 3 component basins: a large embayment (Phinneys Harbor), a small drowned kettle pond (Eel Pond) and a tidal salt marsh (Back River). Each of these 3 basins has different natural sensitivities to nitrogen enrichment and organic matter loading. Evaluation of habitat quality must consider the natural structure of each system and the types of eelgrass habitat and infaunal communities that they naturally support. A habitat assessment was conducted throughout Phinneys Harbor, Eel Pond and Back River based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements, and benthic community structure. At present, the Phinneys Harbor System is showing variations in nitrogen enrichment among its 3 principal component basins. The inner basins of Eel Pond and Back River are clearly nitrogen enriched over Phinneys Harbor and Phinneys Harbor is clearly enriched over the adjacent Buzzards Bay waters. The evaluation of habitat quality within each of these 3 basins was based upon the level of nitrogen enrichment, resultant oxygen depletion and chlorophyll enhancement, eelgrass and infaunal indicators. Moreover, the evaluation of habitat quality was made relative to the ecology of each specific basin. The results indicate a system currently supportive of healthy infaunal habitat for the salt marsh basin of Back River, the kettle basin of Eel Pond and the outer basin of Phinneys Harbor. However, the Phinneys Harbor basin must be classified as impaired as a result of its virtual total loss of eelgrass habitat over the past 10-15 years.

Overall, the oxygen levels within the 3 major sub-basins to the Phinneys Harbor System are not showing significant impairment when their physical structure and natural biogeochemical cycling is considered. Similar to other embayments in southeastern Massachusetts, the Back River and Eel Pond portions of the Phinneys Harbor system evaluated in this assessment showed high frequency variation, apparently related to diurnal and sometimes tidal influences. The dissolved oxygen records indicate that Eel Pond is nitrogen enriched, but the oxygen depletion was generally to the 4-5 mg/L level, consistent with the chlorophyll average of 11.8 ug/L. Similarly, the Back River also showed oxygen depletion consistent with its function as a salt marsh. Both inner basins showed greater nitrogen enrichment and subsequent oxygen depletions and chlorophyll levels than for the outer basin of Phinneys Harbor. However, the cause of these conditions appears to stem primarily from the naturally organic enriched nature of salt marshes (Back River) and the structure of the drowned kettle pond, Eel Pond (2-3 m deep). At present nitrogen enrichment to Eel Pond appears related to its nature as a depositional basin, as removal of anthropogenic nitrogen inputs in the Linked Watershed-Embayment Model did little to lower watercolumn nitrogen levels (Chapter VI, VIII). Given the relatively low watershed nitrogen loading (Chapter IV) and the minor change in predicted nitrogen levels with removal of anthropogenic sources (modeled, Chapters VI, VIII), it appears that this is predominantly "natural" condition and is consistent with the absence of eelgrass in the 1951 survey (Section VII.3) and relatively healthy infaunal habitat (Section VII.4).

The Phinneys Harbor Estuary is moderately deep compared to others along the south shore of Cape Cod and even nearby West Falmouth Harbor. However, water depths are well within the range for eelgrass growth in Massachusetts, given suitable conditions of light penetration. The eelgrass surveys reviewed for this threshold analysis indicated that eelgrass habitat within this estuary is limited to the Phinneys Harbor basin as there is no evidence that eelgrass has colonized either Eel Pond or Back River. At present there is virtually no eelgrass habitat within the Phinneys Harbor System at a tidally averaged total nitrogen level for the Harbor basin of 0.36 mg N/L, higher than the 0.35 threshold for eelgrass in nearby West Falmouth Harbor, with even higher total nitrogen levels in the inner nearshore areas. The temporal surveys indicate that eelgrass habitat loss in Phinneys Harbor is a relatively recent phenomenon. The decline of eelgrass beds appears to have occurred primarily between 1985 and 1995 and continued to 2001. The current absence of eelgrass throughout Phinneys Harbor is consistent with the depth of the basin and the chlorophyll levels of 5-10 ug/L as measured by the BayWatcher Program (Howes et al. 1998). The timing of the eelgrass habitat loss is also consistent with changes in land-use within the watershed. In addition, the spatial pattern of bed loss is consistent with the typical pattern of habitat decline related to increasing nitrogen loading from a watershed. Based on the available data (1951, 1985) it appears that the total area of impaired eelgrass habitat within the Phinneys Harbor basins is approximately 70-80 acres. Although Phinneys Harbor presently supports healthy infaunal habitat (tolerant of higher levels of enrichment), it appears to have become sufficiently nutrient enriched to impair its eelgrass habitat.

The infaunal study indicated an overall system supporting generally healthy infaunal habitat relative to the ecosystem types represented. Evaluation of infaunal habitat quality considered the natural structure of each system relative to the type of infaunal communities that they support. Overall, Phinneys Harbor basin is presently supporting a healthy infaunal habitat. Six of the eleven sites supported infaunal communities of 20-25 species and ~250 or more individuals. Diversity and eveness were excellent, generally >2.5 and >0.65, respectively. The 5 locations sampled with lower species and population counts were generally within present or historic deep channels (PNH 2,3,4,10) with one station located in an area of gravels (PNH 9). The community was dominated by mollusks and crustaceans (40 species total) with polychaetes comprising 44% or 31 of the total species observed. Deep burrowing forms were common.

Eel Pond and Back River also showed healthy to moderately healthy infaunal habitat relative to the ecosystem type. The Back River marshes support healthy infaunal habitat, with ~10 species per sample, but high numbers of individuals (500-1500), with high diversity and Eveness (H'= 2.1 – 2.7; E >0.66). The population was dominated by *Gemma* (a small bivalve), and polychaetes (Hesonids and Capitellids). The presence of the organic enrichment indicator, *Capitella capitata* (16% of individuals) reflects the natural organic enrichment of these systems.

In contrast to Back River, Eel Pond is a drowned kettle pond which is sensitive to nitrogen enrichment that can result in organic matter accumulation and oxygen depletion (Section VII.2). Consistent with its generally good oxygen condition, Eel Pond is presently supportive of a healthy to moderately healthy infaunal habitat. Both the species numbers (11-17) and numbers of individuals (650-1900) indicate a productive benthic animal community dominated by hesonids (carnivorous polychaetes) and Gemma (small bivalve), which small polychaetes also being important (*Streblospio, Capitella, Carezziella*). The diversity and eveness indices were indicative of a healthy environment being 2.2-3.1 and 0.64-0.84, respectively. Mollusks and crustaceans accounted for 34% of the species and deeper burrowing forms were observed.

The overall results indicate a system generally supportive of diverse and healthy communities appropriate to each of the 3 component basin types. The infaunal habitat quality within each of the 3 basins of the Phinneys Harbor System is fully consistent with the oxygen and chlorophyll measurements, temporal trend in eelgrass (i.e. only recent loss from outer basin) and relatively low tidally averaged total nitrogen concentration for each basin, ranging from 0.45 mg N/L in Eel Pond, 0.42 mg N/L in Back River to 0.36 in Phinneys Harbor (basin average). These levels compare well to the levels supportive of healthy infauna found in West Falmouth Harbor (main basin) of 0.38 mg N/L and in enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg N/L were found to be supportive of healthy infaunal habitat.

3. Conclusions of the Analysis

The threshold nitrogen level for an embayment represents the average watercolumn concentration of nitrogen that will support the habitat quality being sought. The watercolumn nitrogen level is ultimately controlled by the integration of the watershed nitrogen load, the nitrogen concentration in the inflowing tidal waters (boundary condition) and dilution and flushing via tidal flows. The water column nitrogen concentration is modified by the extent of sediment regeneration and by direct atmospheric deposition.

Threshold nitrogen levels for each of the sub-embayment systems in this study were developed to restore or maintain SA waters or high habitat quality. In these systems, high habitat quality was defined as supportive of eelgrass and diverse benthic benthos animal communities. Dissolved oxygen and chlorophyll *a* were also considered in the assessment.

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Town of Bourne Phinneys Harbor, Eel Pond and Back River embayment system was comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 70%-90% of the controllable watershed nitrogen load to the embayment was from wastewater.

A major finding of the MEP clearly indicates that a single total nitrogen threshold can not be applied to Massachusetts' estuaries, based upon the results of the Great, Green and Bournes Pond Systems, Popponesset Bay System, the Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay and the Pleasant Bay and Nantucket Sound embayments associated with the Town of Chatham. This is almost certainly going to be true for the other embayments within the MEP area, as well.

The threshold nitrogen levels for the Phinneys Harbor, Eel Pond and Back River embayment system in Bourne were determined as follows:

Phinneys Harbor, Eel Pond and Back River Threshold Nitrogen Concentrations

- The Phinneys Harbor System is presently supportive of infaunal habitat throughout its 3 main basins, but is clearly impaired by nitrogen enrichment in the largest component basin of Phinneys Harbor. Given the documented importance of eelgrass habitat to this outer basin and the virtual loss of all 88 acres of eelgrass that it historically supported, eelgrass restoration in this basin was set as the primary nitrogen management goal for the overall System. Based upon the eelgrass habitat restoration objective and the distribution of total nitrogen within the Harbor basin, most appropriate sentinel station is PH-4, as lowering TN levels at this station will also result in even lower levels at the other stations in the outer basin.

- The threshold level to restore eelgrass within the outer basin of Phinneys Harbor was set at 0.35 mg N/L based upon the detailed quantitative analysis of nearby West Falmouth Harbor where both temporal nitrogen and eelgrass distribution trends could be assessed as well as comparative analysis of total nitrogen levels within healthy eelgrass beds. This threshold TN level is supported by site-specific factors from the Phinneys Harbor basin:

(a) at present there is virtually no eelgrass habitat within the Phinneys Harbor System at a tidally averaged TN level for the Harbor basin of 0.36 mgN/L;

(b) the present absence of eelgrass is at a tidally averaged TN level for the sentinel station of 0.37 mgN/L;

(c) the outer basin has only recently lost its eelgrass habitat and still supports healthy infaunal habitat, suggesting that it is only slightly over its nitrogen threshold level;

- The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location within the Phinneys Harbor System was determined to be 0.35 mg TN L^{-1}. This nitrogen level is lower than found for other complex systems such as Stage Harbor (0.38 N/L^{-1}) and analysis of nitrogen levels within the eelgrass bed in Waquoit Bay, near the inlet (measured TN of 0.395 mg N L^{-1}, tidally corrected <0.38 mg N L^{-1}), and (3) a similar analysis in Bournes Pond. The sentinel station under present loading conditions supports a tidally corrected average concentration of 0.37 mg TN L^{-1}, so a watershed nitrogen management will be required for restoration of the estuarine habitats within this system. It must be stressed that the nitrogen threshold for the Phinneys Harbor Estuary is at the sentinel location. A secondary criteria for infauna (discussed in Chapter VIII) should be met when the threshold is met at the sentinel station used for setting the nitrogen threshold for the Phinneys Harbor basin and serve as a “check”. .

It is important to note that the analysis of future nitrogen loading to the Phinneys Harbor, Eel Pond and Back River estuarine system focuses upon additional shifts in land-use from forest/grasslands to residential and commercial development. However, the MEP analysis indicates that significant increases in nitrogen loading can occur under present land-uses, due to shifts in occupancy, shifts from seasonal to year-round usage and increasing use of fertilizers (presently less than half of the parcels use lawn fertilizers). Therefore, watershed-estuarine nitrogen management must include management approaches to prevent increased nitrogen loading from both shifts in land-uses (new sources) and from loading increases of current land-uses. The overarching conclusion of the MEP analysis of the Phinneys Harbor, Eel Pond and Back River estuarine system is that restoration will necessitate a reduction in the present (2005) nitrogen inputs and management options to negate additional future nitrogen inputs.

Table ES-1. Existing total and sub-embayment nitrogen loads to the estuarine waters of the Phinneys Harbor and Back River estuary systems, observed nitrogen concentrations, and sentinel system threshold nitrogen concentrations.

Sub-embayments	Natural Background Watershed Load [1] (kg/day)	Present Land Use Load [2] (kg/day)	Present Septic System Load (kg/day)	Present WWTF Load [3] (kg/day)	Present Watershed Load [4] (kg/day)	Direct Atmospheric Deposition [5] (kg/day)	Present Net Benthic Flux (kg/day)	Present Total Load [6] (kg/day)	Observed TN Conc. [7] (mg/L)	Threshold TN Conc. (mg/L)
BACK RIVER SYSTEM										
Phinneys Harbor	1.252	2.143	12.608	0.00	14.751	5.186	15.525	35.462	0.53-0.28	--
Back River	1.406	4.477	5.186	0.00	9.663	0.929	1.538	12.131	--	--
Eel Pond	0.411	0.644	4.244	0.00	4.888	0.246	-0.709	4.425	0.64-0.30	--
Back River System Total	**3.07**	**7.264**	**22.038**	**0.00**	**29.302**	**6.361**	**16.354**	**52.017**	**0.64-0.28**	**0.350**[8]

1 assumes entire watershed is forested (i.e., no anthropogenic sources)
2 composed of non-wastewater loads, e.g. fertilizer and runoff and natural surfaces and atmospheric deposition to lakes
3 existing wastewater treatment facility discharges to groundwater
4 composed of combined natural background, fertilizer, runoff, and septic system loadings
5 atmospheric deposition to embayment surface only
6 composed of natural background, fertilizer, runoff, septic system atmospheric deposition and benthic flux loadings
7 average of 1992 – 2005 data, ranges show the upper to lower regions (highest-lowest) of an sub-embayment. Individual yearly means and standard deviations in Table VI-1.
8 Threshold for sentinel site located in Phinney's Harbor at water quality station PH4.

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Ashumet Valley embayment systems (Great, Green and Bournes Ponds), Towns of Falmouth, Massachusetts.						
Sub-embayments	Present Watershed Load [1] (kg/day)	Target Threshold Watershed Load [2] (kg/day)	Direct Atmospheric Deposition (kg/day)	Benthic Flux Net [3] (kg/day)	TMDL [4] (kg/day)	Percent watershed reductions needed to achieve threshold load levels
BACK RIVER SYSTEM						
Phinneys Harbor	14.751	4.694	5.186	12.165	22.045	-68.2%
Back River	9.663	9.663	0.929	1.538	12.131	0.00%
Eel Pond	4.888	4.888	0.246	-0.709	4.425	0.00%
Back River System Total	**29.302**	**19.245**	**6.361**	**12.994**	**38.601**	**-68.2%**

(1) Composed of combined natural background, fertilizer, runoff, and septic system loadings.
(2) Target threshold watershed load is the load from the watershed needed to meet the embayment threshold concentration identified in Table ES-1.
(3) Projected future flux (present rates reduced approximately proportional to watershed load reductions).
(4) Sum of target threshold watershed load, atmospheric deposition load, and benthic flux load.

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The Massachusetts Estuaries Project Technical Team would like to acknowledge the contributions of the many individuals who have worked tirelessly for the restoration and protection of the critical coastal resources of the Phinneys Harbor – Eel Pond – Back River System. Without these stewards and their efforts, this project would not have been possible.

First and foremost is the significant time and effort in data collection and discussion spent by members and volunteers of the Coalition for Buzzards Bay BayWatchers Water Quality Monitoring Program, particularly Tony Williams, its Coordinator. These individuals gave of their time to collect nutrient samples from this system over many years and without this information, the present analysis would not have been possible. Also of special note is the support of the Town of Bourne Local Water Pollution Task Force, members of which have given their time and helped with logistical support and to focus attention on Harbor restoration. In addition, over the past several years, the Town of Bourne Department of Engineering and Planning have worked tirelessly with SMAST Coastal Systems Staff, engineers from Applied Coastal Research and Engineering, and the Cape Cod Commission towards the development of a restoration and management strategy for this system. These Town Departments along with the Department of Natural Resources have also provided important support to the present MEP effort, specifically in terms of field support.

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I. INTRODUCTION

The Phinneys Harbor Estuarine System (inclusive of Eel Pond, Back River and Phinneys Harbor) is located within the Town of Bourne, on Cape Cod Massachusetts. The system has a western shore bounded by water from Buzzards Bay (Figure I-1). The watershed for this embayment system is also distributed almost entirely within the Town of Bourne with the exception of the very uppermost portions of the watershed which extends inland into the Massachusetts Military Reservation (MMR) within the Town of Sandwich. The Phinneys Harbor System is one of the Town of Bourne's significant marine resources. At a time when many other coastal ponds and bays tributary to Buzzards Bay have been degraded, water quality in Phinneys Harbor has generally remained moderately high with eelgrass beds observed in the early 1990's. However, the tributary sub-embayments to Phinneys Harbor (Eel Pond and Back River) have shown indications of nutrient enrichment, although this may be a natural consequence of the large salt marsh area associated with the estuarine reach of the Back River (Coalition for Buzzards Bay, 1999). Significant in maintaining the water quality within this system is the flushing rate and tidal exchange with the high quality waters of Buzzards Bay.

The Phinneys Harbor System is a moderately complex estuary comprised of 3 principal basins covering 536 acres: a flooded kettle pond, Eel Pond; a wetland dominated portion, Back River; and an artificial large outer basin, Phinneys Harbor (Figure I-1). The present mouth of the Back River (between Rocky Point and Phinneys Point) was the historic seaward terminus of the functional estuarine system until the 1930's, when the causeway to Hog Island and Mashnee Island was constructed. It is this causeway that extended the estuary, by semi-enclosing a basin, now Phinneys Harbor (see Chapter V). In addition, the southern boundary of Phinneys Harbor has also become more enclosed with a causeway to Toby Island. Although Phinneys Harbor now functions as an "artificial" sub-embayment to Buzzards Bay, it previously had supported estuarine habitats as a coastal basin along the shore of the central Buzzards Bay Estuary. Therefore, ecological changes resulting from the enclosure are more associated with nutrient enrichment of a semi-enclosed basin receiving upland inputs than a major change in environmental forcing functions (e.g. estuarine/brackish, tidal/non-tidal, etc).

The Phinneys Harbor basin as it is known today is only about a half century old. The existing peninsula that connects Hog Island and Mashnee Island to the mainland was constructed to gain ready access to the Islands from Agawam Point to support summer residences. The Harbor was originally open water bounded by Agawam Point to the north and Toby Island to the south. The inlet between Rocky Point and Phinneys Point provided shallow access to Back River and Eel Pond from what was historically open water Buzzards Bay. Prior to the formation of Phinneys Harbor, coastal processes associated with the spit (Rocky Point) are likely to have periodically restricted tidal flow to Back River/Eel Pond. At present, neither the inlet to Phinneys Harbor nor to Back River are fixed by jetties. However, the channel into the Back River marshes is currently structured by the western Railroad Bridge, constructed in the late 1800's. The adjacent bridge to the east for Shore Road was constructed more recently with a wider span than the railroad bridge.

Figure I-1 Phinneys Harbor (inclusive of Eel Pond and Back River) study region for the Massachusetts Estuaries Project nutrient analysis. Tidal waters enter the estuarine system through one inlet to Buzzards Bay. Freshwaters enter from the watershed primarily through 1 surface water discharge (stream from Mill Pond to Back River upgradient of County Road) and direct groundwater discharge.

The watershed to Phinneys Harbor is somewhat geologically complex, being composed primarily of Buzzards Bay Plain glacial deposits near the coast, glacial moraine deposits, the Buzzards Bay Glacial Moraine (inland) and Mashpee Outwash Plain deposits in the uppermost regions of the watershed. These formations consist of material deposited after the retreat of the Cape Cod Lobe of the Laurentide Ice sheet ~18,000 years ago. The material is highly permeable and as such, direct rainwater run-off is typically rather low for this type of coastal system. Therefore, most freshwater inflow to the estuarine system is via groundwater discharge or groundwater fed surface water flow. At present, Phinneys Harbor is a tidal embayment with a small groundwater fed stream originating in shallow Mill Pond (upgradient of County Road) and discharging to the headwaters of the Back River sub-estuary. Almost all of the 85 acres of salt marsh in the Phinneys Harbor System is held within the Back River estuarine reach. The other inner tributary sub-embayment, Eel Pond, is a very different functional unit than the wetland dominated Back River. Eel Pond is a drowned kettle pond which is connected to Back River through a narrow tidal channel. Eel Pond receives relatively low amounts of freshwater inflow (Chapter III) and maintains a salinity greater than 27 ppt compared to ~29 ppt within the outer Harbor. However, it appears Eel Pond may infrequently stratify due to its geomorphology, thus increasing its sensitivity to nitrogen enrichment. Phinneys Harbor acts as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Buzzards Bay, however, the salinity characteristics of the system varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with Buzzards Bay. Overall, the small freshwater contributing area and large tide range result in a relatively high salinity (>27ppt) throughout much of the Phinneys Harbor System.

Similar to other embayments on Cape Cod Phinneys Harbor is a mesotrophic (moderately nutrient impacted) shallow coastal estuarine system. However, eelgrass beds within Phinneys Harbor have historically filled most of the seabed in the northwestern quadrant of the open water portions of the Harbor as can be determined from photo-interpretation of 1951 aerial photographs of the Harbor (MASSDEP Eelgrass Mapping Program, Section VII.3). Eelgrass beds within the southern portion of Phinneys Harbor off Monument Beach have been documented circa. 1980 (Costa 1988). This historical distribution may result from the fine sand and muds within the protected area formed by the Mashnee Island Causeway versus the coarse sand, rock and cobble of the higher energy region adjacent Monument Beach. However, DMF surveys in the early 1990's noted eelgrass decline in the northern portion of the basin, which was documented by the MASSDEP surveys in 1995 and 2001 (Chapter VII). The presence of eelgrass is particularly important to the use of Phinneys Harbor as fish and shellfish habitat. Currently eelgrass beds have retreated to small fringing patches located in the outer areas in the vicinity of Mashnee Island and Toby Island. The Phinneys Harbor System represents an important shellfish resource to the Town of Bourne, primarily for quahogs. However, shellfishing activities are seasonally suspended by the Massachusetts Division of Marine Fisheries as a result of bacterial contamination from watershed run-off and other potential sources. Selectively open DMF segments located in the Phinneys Harbor system include BB:47.1 (Back River mouth, open Nov 1 – April 15), BB:47.2 (Back River and Eel Pond, conditionally closed Jan 20, 2006, exclusive of BB:47.3 of Back River in the vicinity of the boatyard), BB:46.1 (portion of Monument Beach open Nov 1-May 30) and BB:46.3 (portion of Mashnee Island shoreline open Dec 1 – April 30, primarily due to waterfowl). The DMF designated shellfish growing area BB:46.0 (main open water portion of Phinneys Harbor) approved for shellfishing year round. The shellfish closures and documented eelgrass loss has raised public concern over the estuarine resources within this system in recent years. The Town of Bourne has specifically targeted stormwater remediation within the watershed (DPW).

Phinneys Harbor is important for recreational boating and supports approximately 400 moorings. Additionally, the Town of Bourne owns and operates a public marina in the Inner Harbor near the causeway connecting the mainland to Tobys Island. The municipal marina has both a Town Dock, which consists of a pier with floats, and a public boat ramp. Boat fueling activities at the Town Dock are available as is electricity. Pump-out facilities for boat waste are provided by the Town of Bourne. The Monument Beach Marina facilities, off Shore Road, include a dock with 61 slips, a gasoline pump, 35 town moorings, private bathrooms & showers, public bathrooms and a public snack bar. Adjacent to the Marina are a public beach, a permitted parking area associated with the public boat ramp.

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, Phinneys Harbor, specifically the Eel Pond and Back River portions of the overall system, as well as other embayment systems on Cape Cod, is at risk of eutrophication from high nitrogen loads in the groundwater and runoff from their watersheds.

The primary ecological threat to Phinneys Harbor 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 Phinneys Harbor and other Bourne embayments (Red Brook Harbor, Pocasset River, Megansett Harbor, Squeteague), like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. The Town of Bourne has been among the fastest growing towns in the Commonwealth over the past two decades. The Town does not have centralized wastewater treatment and there is presently no WWTF servicing the Phinneys Harbor System watershed. These unsewered areas contribute significantly to the nitrogen loading of Phinneys Harbor System, both through transport in direct groundwater discharges to estuarine waters and through surface water flow to the estuarine reach of the Back River.

The Harbor's watershed includes a variety of nutrient sources, among them the runoff from roads and lawns, as well as effluent from a growing number of residential septic systems. One of the potential sources of nitrogen of public concern has been the Town Landfill which is partially within the upper portion of the Harbor watershed. The MEP Technical Team working with the Town Departments and Landfill staff conducted an investigation to determine the coastal discharge location of nitrogen enriched groundwater, primarily from the historic septage disposal lagoons. The investigation used watershed delineation modeling (Chapter III), groundwater modeling using particle tracking and analysis of the monitoring well network associated with the Landfill site. The analysis indicated that the Landfill is contributing negligible nitrogen to the Phinneys Harbor System and that the flow path for nitrogen enriched groundwater from the historic septage lagoons is to the Cape Cod Canal, between the Railroad and Bournes Bridges (Chapter IV).

Of the watershed derived nitrogen load discharging to the Phinneys Harbor Estuarine System, about half is discharged to the Eel Pond and Back River sub-embayments, with the other half discharging through direct groundwater seepage to the Phinneys Harbor Basin directly. The greatest level of development and residential load is situated in the nearshore regions of the system. Estimates of nitrogen loading to the Harbor from the watershed have been previously conducted by SMAST scientists, the Cape Cod Commission and the Buzzards Bay Project. The bulk of the present nitrogen loading is from residential housing and light commercial areas, associated sources (roads, driveways, etc.), and the Brookside golf course located within the system watershed. Nitrogen loading from the upper portions of the watershed are very small, as approximately two-thirds of the upper watershed area is composed of forested lands of which nearly 40 percent is within the Massachusetts Military Reservation. Of the available developable land within the watershed nearly two-thirds of that developable land has already been utilized resulting in a watershed that is approaching build-out conditions with residential inputs accounting for the large fraction of nitrogen load to adjacent waters.

At present, Phinneys Harbor (specifically the Eel Pond and Back River tributary sub-embayments to Phinneys Harbor) appear to be beyond their ability to tolerate additional nitrogen inputs. Phinneys Harbor and possibly Eel Pond are presently showing habitat degradation consistent with nitrogen overloading. The Back River estuarine reach is currently functioning primarily as a salt marsh system and as such has a high tolerance for nitrogen inputs and has no signs of degradation. Although the Phinneys Harbor watershed is approaching build-out, nitrogen related degradation will likely increase with further water quality degradation, unless nitrogen management is initiated. Phinneys Harbor nitrogen loads can increase by 34% as build-out is reached, however, as management options are clearly defined and implemented a high degree of certainty for restoration can be attained so long as potential future sources of load are appropriately factored into the nutrient analysis for the watershed and the harbor.

The Town of Bourne, as the primary stakeholder to the Phinneys Harbor embayment system, has been concerned over the resource quality of this significant coastal resource. The community has worked to implement controls on direct stormwater discharges and the Town of Bourne Task Force on Local Pollution has focused on this and other Town embayments for protection and restoration. In addition, the Town of Bourne has supported the Coalition for Buzzards Bay's Water Quality Monitoring Program which has been collecting data on nitrogen related water quality within the Phinneys Harbor System since 1992. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of Bourne's embayments and harbors. The BayWatchers is a citizen-based water quality monitoring program run by the Coalition for Buzzards Bay (T. Williams, Project Coordination) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD.

The common focus of the Coalition for Buzzards Bay BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay and determine the relationship between observed water quality and habitat health. This multi-year effort was initiated in 1992, with significant support from the Buzzards Bay Project. The BayWatcher Water Quality Monitoring Program in Phinneys Harbor developed a data set that elucidated the long-term water quality of this system. Additionally, as remediation plans for various systems are implemented, the continued monitoring will help satisfy monitoring requirements by State regulatory agencies and provide quantitative information to the Town relative to the efficacy of remediation efforts. The MEP effort builds upon the Coalition for Buzzards Bay 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 Phinneys Harbor embayment system, and its major sub-embayments (Back River and Eel Pond).

In conjunction with other Town efforts, the Town of Bourne's Planning Office continues to enhance its tools for gauging future nutrient effects from changing land-uses. The GIS database used in the present MEP evaluation is part of that continuing effort. Based on the wealth of information obtained over the many years of study of the Phinneys Harbor System, particularly as relates to the Town Landfill, the Eel Pond and Back River portions of the Phinneys Harbor embayment system were included in the first round prioritization of the Massachusetts Estuaries Project to provide state-of-the-art analysis and modeling. This effort was undertaken as a partnership with the Town Department and Landfill staff. In the interest of maximizing efficiency and rigor of the nutrient analysis for Eel Pond and Back River, it was decided to add Phinneys Harbor in order to complete the overall analysis, even though Phinneys Harbor entered the Massachusetts Estuaries Project in Round 4 of embayment prioritizations. Additionally, given that the MEP was able to fully integrate the Towns' on-going data collection and modeling efforts, minimal additional municipal funds were required for MEP tasks.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning and nitrogen management alternatives development needed by the Town of Bourne. While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large number of Town staff and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for the Town Bourne to develop and evaluate the most cost effective nitrogen management alternatives to restore the Town's valuable coastal resources 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 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 Bourne) are grappling with Comprehensive

Wastewater Planning and/or environmental management issues related to the declining health of their estuaries.

Municipalities are seeking guidance on the assessment of nitrogen sensitive embayments, as well as available options for meeting nitrogen goals and approaches for restoring impaired systems. Many of the communities have encountered problems with “first generation” watershed based approaches, which do not incorporate estuarine processes. The appropriate method must be quantitative and directly link watershed and embayment nitrogen conditions. This “Linked” Modeling approach must also be readily calibrated, validated, and implemented to support planning. Although it may be technically complex to implement, results must be understandable to the regulatory community, town officials, and the general public.

The Massachusetts Estuaries Project represents the newest generation of watershed based nitrogen management approaches. The Massachusetts Department of Environmental Protection (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 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 must contain an implementation plan. That plan must identify, among other things, the required activities to achieve the allowable load to meet the allowable loading target, the time line for those activities to take place, and reasonable assurances that the actions will be taken.

In appropriate estuaries, TMDLs for bacterial contamination will also be conducted in concert with the nutrient effort (particularly if there is a 303d listing). However, the goal of the bacterial program is to provide information to guide targeted sampling for specific source identification and remediation. As part of the overall effort, the evaluation and modeling approach will be used to assess available options for meeting selected nitrogen goals, protective of embayment health.

The major Project goals are to:

- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment 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

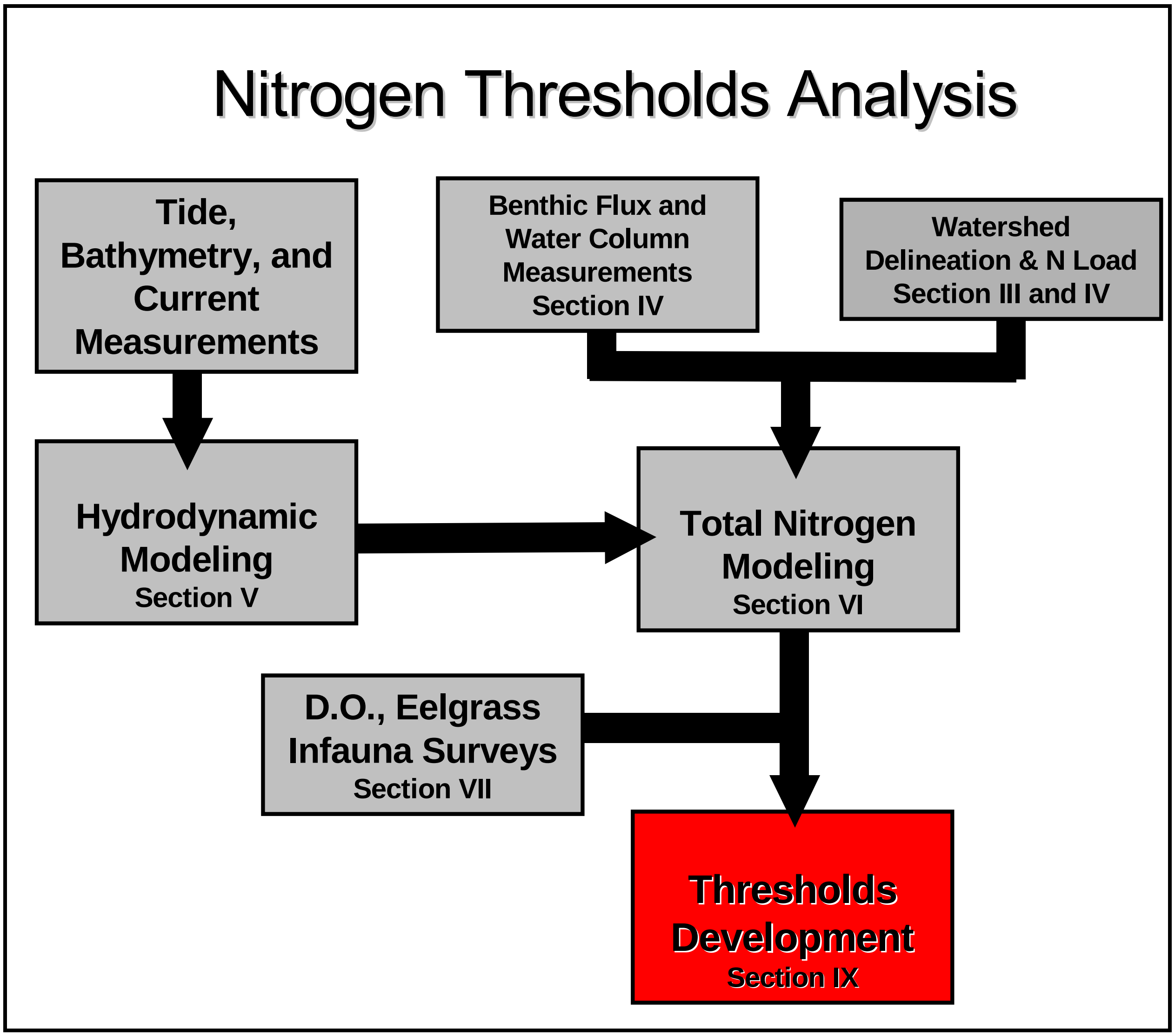


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

I.2 SITE DESCRIPTION

The coastal salt ponds of Cape Cod tributary to Buzzards Bay tend to be lagoonal estuaries with basins running parallel to the barrier beach and inner tributary basins comprised of salt marsh or drowned kettle basin (e.g. West Falmouth Harbor). The Phinneys Harbor Estuary is a moderately complex estuary formed primarily as an artificial lagoon. Phinneys Harbor, formed by the creation of artificial barrier beaches (causeways) from the upland to Mashnee Island (north) and to Toby Island (south). The inner basins are typical of other complex sub-estuaries in the region containing both a major salt marsh creek system (Back River) and a drowned kettle pond (Eel Pond). While the configuration of the outer basin is only ~75 years old, the inner sub-systems were formed by post-glacial processes and rising sea-levels. The Back River and Eel Pond basins are situated within the Buzzards Bay terminal moraine deposited after the retreat of the Buzzards Bay Lobe of the Laurentide Ice sheet and consisting of glacial till, as opposed to the sandy outwash deposits typical of the eastern shore of Buzzards Bay. As post-glacial sea-level rose, Buzzards Bay and then the Back River/Eel Pond basins became marine systems. The entire Phinneys Harbor Estuary is a relatively recent formation, first requiring inundation with marine waters (4,500-3,000 years B.P.).

The watershed to Phinneys Harbor is somewhat geologically complex, being composed primarily of Buzzards Bay Plain glacial deposits near the coast, glacial moraine deposits, the Buzzards Bay Glacial Moraine (inland) and Mashpee Outwash Plain deposits in the uppermost regions of the watershed. These formations consist of material deposited after the retreat of the Cape Cod Lobe of the Laurentide Ice sheet ~18,000 years ago. The material is highly permeable and as such, direct rainwater run-off is typically rather low for this type of coastal system. Therefore, most freshwater inflow to the estuarine system is via groundwater discharge or groundwater fed surface water flow.

At present, Phinneys Harbor is a tidal embayment with a small groundwater fed stream originating in shallow Mill Pond (upgradient of County Road) and discharging to the headwaters of Back River sub-estuary. Almost all of the 85 acres of salt marsh in the Phinneys Harbor System is held within the Back River estuarine reach. The other inner tributary sub-embayment, Eel Pond, is a very different functional unit than the wetland dominated Back River. Eel Pond is a drowned kettle pond which is connected to Back River through a narrow tidal channel. Eel Pond receives relatively low amounts of freshwater inflow (Chapter III) and maintains a salinity greater than 27 ppt compared to ~29 ppt within the outer Harbor. However, it appears Eel Pond may infrequently stratify due to its geomorphology, thus increasing its sensitivity to nitrogen enrichment. Phinneys Harbor acts as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Buzzards Bay, however, the salinity characteristics of the system varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with Buzzards Bay. Overall, the small freshwater contributing area and large tide range result in a relatively high salinity (>27ppt) throughout much of the Phinneys Harbor System.

The inlet between Rocky Point and Phinneys Point provided shallow access to Back River and Eel Pond from what was historically open water Buzzards Bay. Prior to the formation of Phinneys Harbor, coastal processes associated with the spit (Rocky Point) is likely to have periodically restricted tidal flow to Back River/Eel Pond. At present, neither the inlet to Phinneys Harbor nor to Back River are fixed by jetties. However, the channel into the Back River marshes is currently structured by the western Railroad Bridge, constructed in the late 1800's. The adjacent bridge to the east for Shore Road was constructed more recently with a wider span than the railroad bridge.

The habitat quality of the Phinneys Harbor System is linked to the level of tidal flushing through its inlet to Buzzards Bay, which exhibits a moderate tide range of about 5 ft. Since the water elevation difference between the Bay and Harbor is the primary driving force for tidal exchange, the local tide range naturally limits the volume of water flushed during a tidal cycle (note the tide range off Stage Harbor Chatham is ~4.5 ft, Wellfleet Harbor is ~10 ft). The inlets to Phinneys Harbor and to Back River are not presently armored with jetties.

Like the Estuary itself, the watershed areas contributing nitrogen to the harbor are distributed fully within the Town of Bourne, although a small portion of inland forested watershed is within the Town of Sandwich/Massachusetts Military Reservation (MMR). The Phinneys Harbor System is one of the Town of Bourne's significant marine resources. At a time when many other coastal ponds and bays in the Town have been degraded, water quality in this estuary has until recently remained fairly high, as pockets of eelgrass in the 1990's demonstrate. However, the Phinneys Harbor System has been undergoing degradation of its resources over the past decades as a result of nutrient overloading from its watershed, primarily resulting from residential development.

Phinneys Harbor is a shallow mesotrophic (moderately nutrient impacted) coastal estuarine system on the eastern shore of Buzzards Bay. For the MEP analysis, the Phinneys Harbor System was analyzed individually as a stand-alone system. Similar to other embayments on Cape Cod (e.g. West Falmouth Harbor) Phinneys Harbor is an estuary with focused freshwater input at the headwaters of the Back River sub-embayment and tidal exchange of marine waters from Buzzards Bay (tide range of approximately 1.5 m) at the mouth. The Phinneys Harbor estuarine system was partitioned into several regions: 1) the main basin commonly considered Phinneys Harbor, 2) outer Back River near the mouth, 3) inner Back River which receives a freshwater stream discharge from an upgradient bog/Mill Pond, 4) Eel Pond (see Figure I-1). Phinneys Harbor and its associated sub-embayments is a true estuary, acting as the mixing zone of terrestrial freshwater inflow and saline tidal waters from Buzzards Bay. Salinity in the harbor ranges from approximately 30 ppt at the Buzzards Bay inlet to less than 10 ppt at the uppermost end of the Back River estuarine reach. However, salinities throughout all of the basins is generally >27 ppt..

Given the present hydrodynamic characteristics of the Phinneys Harbor embayment system, it appears that estuarine habitat quality is mostly dependent on the level of nutrient loading to embayment waters as opposed to tidal characteristics. In Phinneys Harbor, minimal enhancements to tidal flushing may be achieved via inlet or channel modification to Back River thereby resulting in some mediation of the nutrient loading impacts from the watershed. The details of such are a part of the MEP analysis described later in this report.

Nitrogen loading to the Phinneys Harbor embayment system was determined relative to the regions of the estuary as depicted in Figure I-1. Based upon land-use and the watershed being primarily within Bourne, it appears that nitrogen management for harbor restoration may likely be more rapidly developed and implemented than otherwise. As management alternatives are being developed and evaluated, it is important to note the ecological differences of the 3 major basins comprising the Estuary. The Back River sub-estuary currently functions primarily as a tidal salt marsh system, which has a high tolerance for nitrogen inputs. In contrast, the drowned kettle pond, Eel Pond, is narrow, relatively deep and has a narrow outlet channel, geomorphological characteristics frequently underlying a sensitivity to nitrogen loading. Finally, the deep, generally well flushed outer basin functions as an extension of the estuary, exchanging tidal waters with Buzzards Bay. These physical and ecological characteristics interact with tidal flushing and watershed nitrogen loading to define the nutrient characteristics of the Harbor and the associated habitat impacts. There is a gradient in nitrogen level and health moving from Eel Pond through the Phinneys Harbor basin, with highest nitrogen and lowest environmental health in the terminal areas of the system and lowest nitrogen and greatest health near the inlet to Buzzards Bay. The Eel Pond basin is presently showing moderate to poor water quality and "Mesotrophic" conditions. While Phinneys Harbor generally has high to moderate water quality, the Back River Estuary appears to support healthy tidal salt marshes. Eelgrass is currently absent from the whole of the Phinneys Harbor System. A relatively high level of water clarity will be needed to restore eelgrass to the Phinneys Harbor basin, due to its water depth.

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 Phinneys Harbor 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 the Phinneys Harbor 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, 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 Phinneys Harbor system monitored by the Coalition for Buzzards Bay BayWatchers Monitoring Program with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals) to "tune" general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Unfortunately, within the Phinneys Harbor Estuary, the Eel Pond and Phinneys Harbor basins appear to be beyond their respective abilities to assimilate additional nutrients without impacting ecological health. Nitrogen levels are elevated throughout the system and eelgrass beds only remain on the outer edges of the outer portion of Phinneys Harbor (i.e. outside of the Estuary). The result is that nitrogen management of the primary sub-embayments is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed "eutrophication" and when the nutrient loading is primarily from human activities, it is considered "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 a given embayment system could potentially occur without human 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 Phinneys Harbor 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 the Phinneys Harbor System and each of its basins: Eel Pond, Back River, and Phinneys Harbor. 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 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. Virtually all nitrogen entering Bourne's embayment systems is transported by freshwater, predominantly groundwater, either through direct discharge or after discharging to a stream flowing to estuarine waters. Concentrations of total nitrogen and salinity of Buzzards Bay source waters and throughout the Phinneys Harbor system was taken from the Coalition for Buzzards Bay BayWatchers Monitoring Program (associated with the Coastal Systems Program at SMAST) and from previous sampling of Buzzards Bay nearshore waters by MEP staff. Measurements of nitrogen and salinity distributions throughout estuarine waters of the system were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Phinneys Harbor Estuarine System (Phinneys Harbor, Eel Pond and Back River) for the Town of Bourne. 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 Buzzards Bay (Section IV). Intrinsic to the calibration and validation of the linked-watershed embayment modeling approach is the collection of background water quality monitoring data (conducted by municipalities) as discussed in Section IV. Results of hydrodynamic modeling of embayment circulation are discussed in Section V and nitrogen (water quality) modeling, as well as an analysis of how the measured nitrogen levels correlate to observed estuarine water quality are described in Section VI. This analysis includes modeling of current conditions, conditions at watershed build-out, and with removal of anthropogenic nitrogen sources. In addition, an ecological assessment of each embayment was performed that included a review of existing water quality information, temporal changes in eelgrass distribution, dissolved oxygen records and the results of a benthic infaunal animal analysis (Section VII). The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration of each embayment in Section VIII. Additional modeling is conducted to produce an example of the type of watershed nitrogen reduction required to meet the determined threshold for restoration in a given estuarine basin. 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 Phinneys Harbor System. Finally, analyses of the Phinneys Harbor 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 Eel Pond and Back River. The results of the nitrogen modeling for each scenario have been presented (Section IX).

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 the concomitant 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 shellfisherman 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 pond, it is not a necessarily a part of the natural evolution of a system.

In most marine and estuarine systems, such as the Phinneys 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).

These tools for predicting 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 specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Phinneys 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 Buzzards Bay’s tributary embayments have resulted in a number of studies relating to the nutrient related health of the Phinneys Harbor System over the past 2 decades. These investigations include both habitat assessments and studies relating to nitrogen loading, hydrodynamics and habitat health. While none of the previous studies provided a holistic view of the Phinneys Harbor System or its sub-embayments (Phinneys Harbor, Eel Pond, Back River), they provide useful information to the present MEP effort. These earlier efforts were generally survey studies 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.

An initial watershed land-use and nitrogen loading analysis was conducted by the Buzzards Bay Project (BBP 1996) as part of a survey of all of the tributary embayments to Buzzards Bay. This survey used Mass GIS 1984 coverages and an approximate watershed delineation. The results indicated that the system appeared to be below its nitrogen loading threshold, although it recommended a more detailed analysis due to the complexity generated by the inner versus outer sub-embayments. The Cape Cod Commission, as part of its Coastal Embayment Project (Eichner, *et al*., 1998), conducted a quantitative watershed delineation of the Back River and Eel Pond sub-embayments. The CCC watershed was defined based on regional water table measurements collected from available wells over a number of years and normalized to average conditions; delineations based on this previous effort were incorporated into the Commission's regulations through the Regional Policy Plan (CCC, 1996 & 2001). The CCC also indicated that these sub-embayments were within the middle range of nitrogen sensitivity and should be given a moderate priority for additional assessment. The MEP watershed analysis builds on these earlier efforts, but uses a refined watershed delineation based upon both updated water table data and groundwater modeling (Chapters III & IV).

While the overall watershed nitrogen loading results of the BBP and CCC studies have held true, the analysis is insufficient to simulate changes in nitrogen within the estuary under different management alternatives. In addition, as the landuse models did not account for nitrogen attenuation by the wetland ecosystems (no data available), it over estimated the role of nitrogen sources in upper (inland most) sub-watersheds compared to the direct groundwater watersheds to the estuary. While watershed delineation and nitrogen loading data from this earlier CCC study was incorporated by the MEP, direct use of the modeling results was problematic. Since the landuse model was based upon the 1996 watershed delineations from well data, rather than the MEP's USGS West Cape Model and expanded water table database (see Chapter III), the contributing areas are slightly different. Due to the difference in watershed areas and the MEP's update and refinements to the watershed nitrogen loading model (e.g. to incorporate attenuation and new nitrogen source information), the results from the MEP are different and supercede the earlier studies.

As part of the earlier efforts a semi-quantitative flushing analysis was conducted of the Phinneys Harbor System based primarily upon basin configuration, assumed generalized tide ranges and tidal prism calculations (ACI 1994). The purpose of this study was to support qualitative nitrogen thresholds for the Buzzards Bay sub-embayments and evaluation of the likelihood of current or future watershed nitrogen loads causing water quality degradation. However, given the refinements to the watershed delineation by the CCC and now MEP, and the need for detailed quantitative hydrodynamic analysis, the results from this previous effort could not be directly integrated into the MEP effort.

The Town of Bourne, as part of its Landfill operations, worked with Applied Coastal Research and Engineering and SMAST to conduct a quantitative hydrodynamic assessment and modeling and nitrogen related water quality modeling study of the Eel Pond and Back River sub-embayments to the Phinneys Harbor System. The study included both hydrodynamic data collection and modeling and measurements of nitrogen regeneration and watershed nitrogen inputs. In addition, groundwater modeling (USGS particle tracking) was employed to determine the coastal site of discharge of any contaminant plume, including nitrogen loads, originating from the Town of Bourne Landfill site. The modeling was based upon recharge to different areas of the Landfill site with emphasis on the historic septage disposal lagoons. The results indicated that any contaminant plume travels along, but outside of the Harbor watershed boundary. While the southernmost portion of the landfill site may contribute to the estuarine reach of Back River, at the time of the analysis, this region had been unused for disposal. In contrast, the historic septage lagoons located within the northern portion of the site were found to clearly discharge to the Cape Cod Canal (approximately mid-way between the Railroad and Bournes Bridges). As the operating landfill is lined to prevent contamination of groundwater, and since the historic septage disposal lagoon area is the primary potential nitrogen source within the landfill parcel, nitrogen loading to the Phinneys Harbor System from the landfill was deemed to be negligible. The overall results of this investigation were fully integrated into the present effort when the Town of Bourne partnered with the Massachusetts Estuaries Project. This earlier effort provided most of the Town matching funds for the MEP.

The Town of Bourne, as the primary stakeholder to the Phinneys Harbor embayment system, has been concerned over the quality of this significant coastal resource. The community has worked to implement controls on direct stormwater discharges and the Town of Bourne Task Force on Local Pollution has focused on this and other Town embayments for protection and restoration. As part of this effort the Town of Bourne has supported the Coalition for Buzzards Bay's Water Quality Monitoring Program, which has been collecting data on nutrient related water quality within the Phinneys Harbor System since 1992. The Coalition's BayWatcher Program has collected the principal baseline water quality data set necessary for ecological management of Bourne's embayments and harbors. The BayWatchers is a citizen-based water quality monitoring program run by the Coalition for Buzzards Bay (T. Williams, Project Coordination), with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD.

The common focus of the Coalition for Buzzards Bay Baywatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay to support evaluations of observed water quality and habitat health. This multi-year effort was initiated in 1992, with significant support from the Buzzards Bay Project. The BayWatcher Water Quality Monitoring Program in Phinneys Harbor developed a data set that elucidated the long-term water quality of this system (Costa et al. 1996. Howes et al. 1999). Additionally, as remediation plans for 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 Coalition for Buzzards Bay 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 Phinneys Harbor embayment system and its major sub-embayments (Back River and Eel Pond).

The Coalition for Buzzards Bay's BayWatcher Program provided the quantitative watercolumn nitrogen data (1992-2005) required for the implementation of the MEP's Linked Watershed-Embayment Approach. The MEP effort also builds upon the 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 Phinneys Harbor embayment system. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the Phinneys Harbor System and to reduce costs to the Town of Bourne.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). These USGS groundwater modelers were central to the development of the groundwater modeling approach used by the Estuaries Project. The USGS has a long history of developing regional models for the six-groundwater flow cells on Cape Cod. Through the years, advances in computing, lithologic information from well installations, water level monitoring, stream flow measurements, and reconstruction of glacial history have allowed the USGS to update and refine the groundwater models. The MODFLOW and MODPATH models employed by the USGS to organize and analyze the available data utilize up-to-date mathematical codes and create better tools to answer the wide variety of questions related to: 1) watershed delineation, 2) surface water/groundwater interaction, 3) groundwater travel time, 4) groundwater contaminant plumes, and 5) drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including the Phinneys Harbor (inclusive of the Eel Pond/Back River) embayment system located in Bourne, Massachusetts. The Phinneys Harbor watershed is situated along the northwestern edge of Cape Cod and is bounded by Buzzards Bay.

In the present MEP effort, the USGS was responsible for the application of its groundwater modeling approach to define the watershed or contributing area to the Phinneys Harbor embayment system under evaluation by the Project Team. The Phinneys Harbor estuarine system is a moderately complex estuary comprised of 3 principal basins: a flooded kettle pond (Eel Pond),,a wetland dominated portion (Back River) and an artificial large outer basin (Phinneys Harbor). The present mouth of the Back River (between Rocky Point and Phinneys Point) was the seaward terminus of the functional estuarine system until the 1930's when the causeway to Hog Island and Mashnee Island was constructed. It is this causeway that extended the estuary, by semi-enclosing a basin now Phinneys Harbor. In addition the southern boundary of Phinneys Harbor has also become more enclosed with a causeway to Tobeys Island. Although Phinneys Harbor now functions as an "artificial" sub-embayment to Buzzards Bay, it previously had supported estuarine habitats as a coastal basin along the shore of the central Buzzards Bay Estuary. Therefore, ecological changes resulting from the enclosure are more associated with nutrient enrichment of a semi-enclosed basin receiving upland inputs than a major change in environmental forcing functions (e.g. estuarine/brackish, tidal/non-tidal, etc).

In addition to the delineation of the overall upland contributing area to the Phinneys Harbor Estuarine System, watershed modeling was undertaken to sub-divide the overall watershed into functional sub-units based upon: (a) defining inputs from contributing areas to each major portion within the embayment system, (b) defining contributing areas to major freshwater aquatic systems which generally attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands), and (c) defining 10 year time-of-travel distributions within each sub-watershed as a procedural check to gauge the potential mass of nitrogen from "new" development, which has not yet reached the receiving estuarine waters. Particle tracking was also conducted relative to the now-closed septage disposal sites within the upper watershed. This additional modeling was necessary in order to determine the transport path of residual nitrogen enriched groundwater discharging to the coast. The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in the Sagamore flow cell on Cape Cod. Model assumptions for calibration were matched to surface water inputs and flows from MEP stream flow measurements (2002 to 2003).

The relatively transmissive sand and gravel deposits that comprise most of Cape Cod create a hydrologic environment where watershed boundaries are usually better defined by elevation of the groundwater and its direction of flow, rather than by land surface topography (Cambareri and Eichner 1998, Millham and Howes 1994a,b). Freshwater discharge to estuaries is usually composed of surface water inflow from streams, which receive much of their water from groundwater base flow, and direct groundwater discharge. For a given estuary, differentiating between these two water inputs and tracking the sources of nitrogen that they carry requires determination of the portion of the watershed that contributes directly to a stream and the portion of the groundwater system that discharge directly into an estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Phinneys Harbor system were delineated using a regional model of the Sagamore Lens flow cell (Walter and Whealan, 2005). The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 (Harbaugh, *et al.*, 2000) was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4 (Pollock, 2000), which uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies. This approach was used to determine the contributing areas to Phinneys Harbor system including subwatersheds to Back River and Eel Pond and also to determine portions of recharged water that may flow through fresh water ponds and streams prior to discharging into coastal water bodies.

The Sagamore Flow Model grid consists of 246 rows, 365 columns and 20 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top 17 layers of the model extend to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft. The top of layer 8 resides at NGVD 29 with layers 1-7 stacked above and layers 8-20 below. Layer 18 has a thickness of 40 feet and extends to 140 feet below NGVD 29, while layer 19 extends to 240 feet below NGVD 29. The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics (up to 519 feet below NGVD 29); since bedrock is approximately 150 feet below NGVD 29 in the area of the Phinneys Harbor Estuary the two lowest model layers were generally inactive in this area of the model. The rewetting capabilities of MODFLOW-2000, which allows drying and rewetting of model cells, was used to simulate the top of the water table, which varies in elevation depending on the location in the Lens.

The glacial sediments that comprise the aquifer of the Sagamore Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The sediments generally show a fining downward with sand and gravel deposits deposited in glaciofluvial (river) and near-shore glaciolacustrine (lake) environments underlain by fine sand, silt and clay deposited in deeper, lower-energy glaciolacustrine environments. Most groundwater flow in the aquifer occurs in shallower portions of the aquifer dominated by coarser-grained sand and gravel deposits. The Phinneys Harbor System watershed (including Eel Pond and Back River) is generally situated in the Buzzards Bay Plain outwash deposits with the easternmost portion extending into the Buzzards Bay Moraine; modeling and field measurements of contaminant transport at the MMR has shown that both moraine and outwash materials are highly permeable (Masterson, *et al*., 1996). Given their high permeability, direct rainwater run-off is typically rather low for this type of coastal system. Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from USGS, local Town records and data from previous investigations. Final aquifer parameters were determined through calibration to observed water levels and stream flows. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Towns and streamflow data collected in 2002 - 2003.

The model simulates steady state, or long-term average, hydrologic conditions including a long-term average recharge rate of 27.25 inches/year and the pumping of public-supply wells at average annual withdrawal rates for the period 1995-2000 with a 15% consumptive loss. This recharge rate is based on the most recent USGS information. Large withdrawals of groundwater from pumping wells may have a significant influence on water tables and watershed boundaries and therefore the flow and distribution of nitrogen within the aquifer. After accounting for the consumptive loss and measured discharge at municipal treatment facilities, water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within designated residential areas utilizing on-site septic systems. Since no municipal wastewater treatment facilities discharge within the watershed of the Phinneys Harbor System, modeled return flow is returned to the groundwater in developed areas as septic system recharge.

III.3 PHINNEYS HARBOR, EEL POND AND BACK RIVER CONTRIBUTORY AREAS

Newly revised watershed and sub-watershed boundaries were determined by the United States Geological Survey (USGS) for the Phinneys Harbor System, including the sub-watersheds to the Phinneys Harbor basin, Eel Pond basin and Back River marshes (Figure III-1). Model outputs of MEP watershed boundaries were “smoothed” to (a) correct for the grid spacing, (b) to enhance the accuracy of the characterization of the pond and coastal shorelines, (c) to include water table data in the lower regions of the watersheds near the coast (as available), and (d) to more closely match the sub-embayment segmentation of the tidal hydrodynamic model (Chapter V). The smoothing refinement was a collaborative effort between the USGS and the rest of the MEP Technical Team. The MEP sub-watershed delineation includes 10 yr time of travel boundaries. Overall, ten sub-watershed areas, including one freshwater pond (Clay Pond), were delineated within the watershed to the Phinneys Harbor Estuarine System..

Table III-1 provides the daily discharge volumes for various sub-watersheds as calculated by the groundwater model; these volumes were used to assist in the salinity calibration of the water quality modeling effort (Chapter VI) and to determine hydrologic turnover in the lakes/ponds (Chapter IV), as well as for comparison to measured surface water discharges. The overall estimated groundwater flow into Phinneys Harbor from the MEP delineated watershed is 24,036 m3/d.

The delineations completed for the MEP are the second set of watershed delineations completed in recent years for portions of the Phinneys Harbor estuary. Figure III-2 compares the delineation completed under the current effort with the Eel Pond/Back River delineation completed by the Cape Cod Commission in 1998 as part of the Coastal Embayment Project (Eichner, *et al*., 1998). Note that the direct contributing area to the Phinneys Harbor basin was not delineated in this earlier effort. The delineation completed in 1998 was defined based on regional water table measurements collected from available wells over a number of years and normalized to average conditions; delineations based on this previous effort were incorporated into the Commission’s regulations through the Regional Policy Plan (CCC, 1996 & 2001).

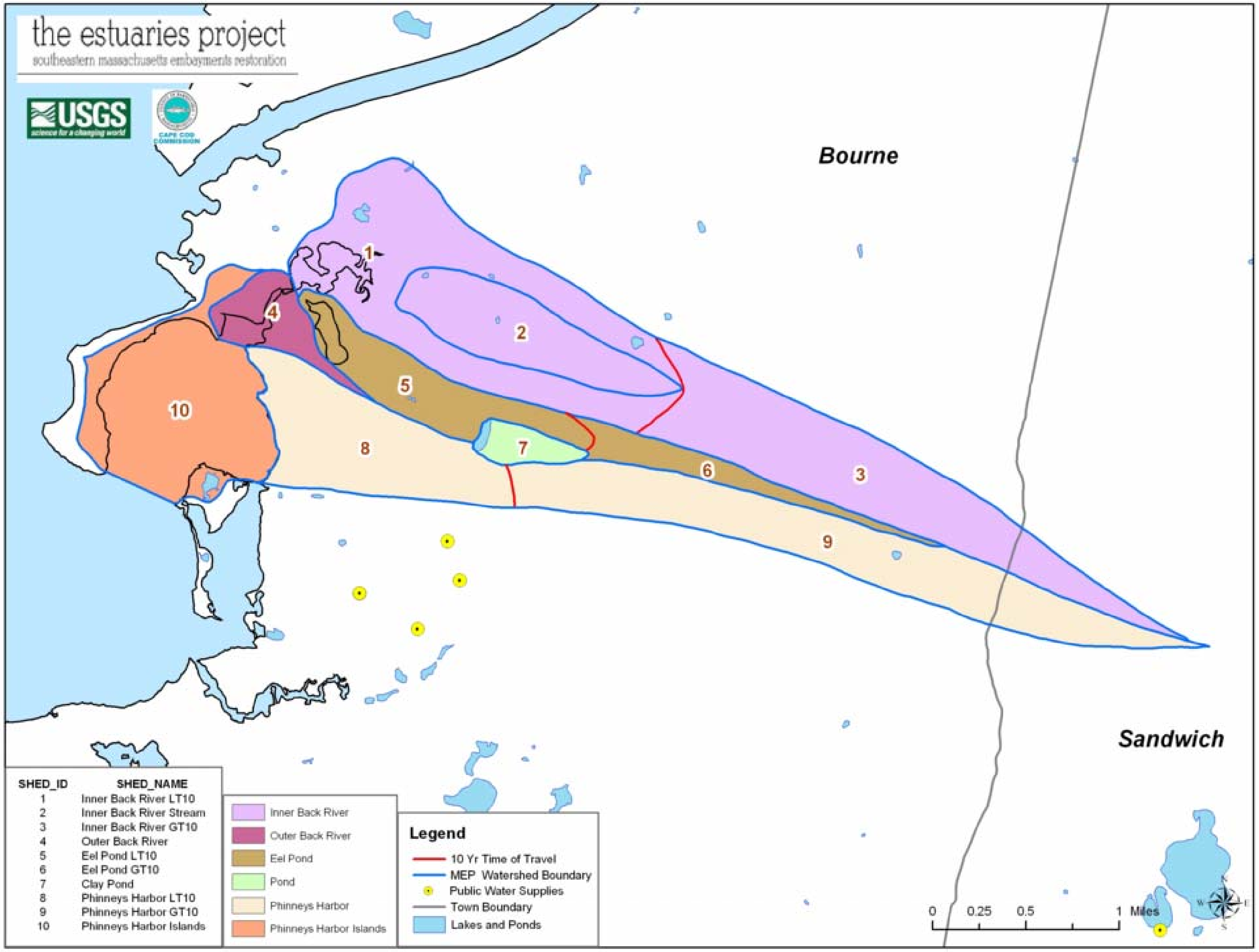


Figure III-1. Watershed and sub-watershed delineations for the Phinneys Harbor Estuarine System. Approximate ten year time-of-travel delineations were produced for quality assurance purposes and are designated with a “10” in the watershed names (above). Sub-watersheds to embayments were selected based upon the functional estuarine sub-units in the water quality model (see section VI).

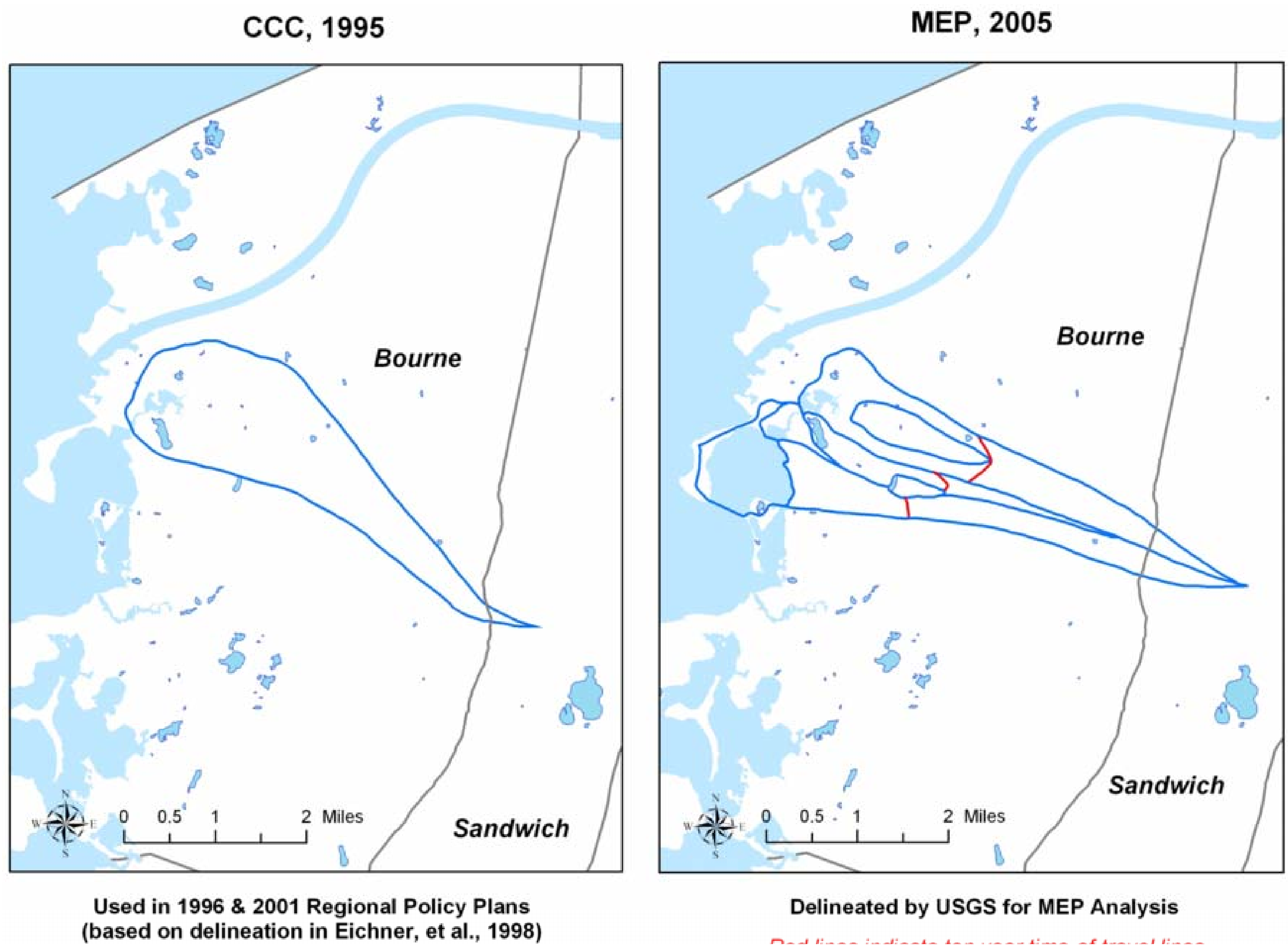


Figure III-2. Comparison of 1998 Cape Cod Commission and current Phinneys Harbor watershed and subwatershed delineations. The watershed area to the Eel Pond and Back River sub-estuaries is 18% smaller in the MEP analysis primarily due to better location of the top of the Sagamore Lens. Red lines represent ten year time of travel.

Table III-1. Daily groundwater discharge from each of the sub-watersheds to the Phinneys Harbor Estuary, as determined from the USGS groundwater model.

Watershed	Watershed #	Discharge	
		m^3/day	ft^3/day
Inner Back River LT10	1	4,633	163,607
Inner Back R Stream	2	2,197	77,580
Inner Back River GT10	3	4,690	165,629
Outer Back R	4	760	26,829
Eel Pd LT10	5	1,739	61,409
Eel Pd GT10	6	963	34,022
Clay Pd	7	473	16,713
Phinneys Hbr LT10	8	3,099	109,445
Phinneys Hbr GT10	9	4,602	162,512
Phinneys Hbr Islands	10	880	31,085
Whole System		24,036	848,832

NOTE: Discharge rates are based on 27.25 inches per year of recharge (Walter and Whealan, 2005).

Although direct comparisons are difficult because the watersheds are drawn from different portions of the Phinneys Harbor system, the MEP watershed area for roughly the same portion of the CCC watershed is 18% smaller. Most of this difference appears to be attributable to a more northern location for the top of the Sagamore Lens; it is approximately 0.5 mile further north in the current USGS configuration. The change in the top of the mound allows more direct flow paths to Phinneys Harbor and reduces some of the “bulge” in the northern boundary (see Figure III-2). Subwatersheds were not delineated in the CCC watershed.

The evolution of the watershed delineations for the Phinneys Harbor Estuarine System has provided increasing accuracy as each version adds new hydrologic data to that previously collected; the model allows all this data to be organized and to be brought into congruence with adjacent watersheds. The evaluation of older data and incorporation of new data during the development of the model is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model used for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon the land-uses that are included/excluded within the contributing areas. Small errors in watershed area can result in large errors in loading if a large source is counted in or out. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the downgradient estuary. In the present case of the Phinneys Harbor System watershed, the upper half (east of Rt. 28) is within a generally undeveloped region of the Massachusetts Military Reservation, which further minimizes potential inaccuracies in the nitrogen loading analysis stemming from the watershed delineation. The MEP watershed delineation was used to develop the watershed nitrogen loads to each of the aquatic systems and ultimately to the estuarine waters of the Phinneys Harbor system (Section V.1).

IV. WATERSHED NITROGEN LOADING TO EMBAYMENT: LAND USE, STREAM INPUTS, AND SEDIMENT NITROGEN RECYCLING

IV.1 WATERSHED LAND USE BASED NITROGEN LOADING ANALYSIS

Management of nutrient related water quality and habitat health in coastal waters requires determination of the amount of nitrogen transported by freshwaters (surface water flow, groundwater flow) from the surrounding watershed to the receiving embayment of interest. In southeastern Massachusetts, the nutrient of management concern for estuarine systems is nitrogen and this is true for the Phinneys Harbor system. Determination of watershed nitrogen inputs to these embayment systems requires the (a) identification and quantification of the nutrient sources and their loading rates to the land or aquifer, (b) confirmation that a groundwater transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes. This latter natural attenuation process results from biological processes that naturally occur within ecosystems. Failure to account for attenuation of nitrogen during transport results in an over-estimate of nitrogen inputs to an estuary and an underestimate of the sensitivity of a system to new inputs (or removals). In addition to the nitrogen transport from land to sea, the amount of direct atmospheric deposition on each embayment surface must be determined as well as the amount of nitrogen recycling within the embayment, specifically nitrogen regeneration from sediments. Sediment nitrogen recycling results primarily from the settling and decay of phytoplankton and macroalgae (and eelgrass when present). During decay, organic nitrogen is transformed to inorganic forms, which may be released to the overlying waters or lost to denitrification within the sediments. Burial of nitrogen is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source of nitrogen to embayment waters or in some cases a sink for nitrogen reaching the bottom. Failure to include the nitrogen balance of estuarine sediments generally leads to errors in predicting water quality, particularly in determination of summertime nitrogen load to embayment waters.

The MEP Technical Team includes technical staff from the Cape Cod Commission (CCC). In coordination with other MEP Technical Team members, CCC staff developed nitrogen loading rates (Section IV.1) to the Phinneys Harbor embayment system (Section III). The Phinneys Harbor watershed was sub-divided to define contributing areas to each of the major inland freshwater systems and to each major sub-embayment to Phinneys Harbor. Further sub-divisions were made to identify watershed areas where a nitrogen discharge reaches embayment waters in less than 10 years or greater than 10 years. A total of 10 sub-watersheds were delineated for the Phinneys Harbor Estuarine System. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and each embayment (see Chapter III).

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the embayment. This involves a temporal review of land use changes and the time of groundwater travel provided by the USGS watershed model. After reviewing the percentage of nitrogen loading in the less than 10 year time of travel (LT10) and greater than 10 year time of travel (GT10) watersheds (Table IV-1), land use development records, and water quality modeling, it was determined that Phinneys Harbor is currently in balance with its watershed load. The bulk (94%) of the watershed nitrogen load is within 10 years flow to Phinneys Harbor and its sub-estuaries (primarily due to the undeveloped nature of the GT 10 sub-watersheds that encompass primarily MMR lands). In addition, the 6% of "developed" land area at longer than 10 yr travel times are within the ~12 yr time of travel. Therefore, the distinction of less than 10 year and greater than 10 year time of travel regions within a subwatershed (Figure III-1) was eliminated and the number of subwatersheds was reduced to seven (Figure IV-1). The overall result of the timing of development relative to groundwater travel times is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuaries (after accounting for natural attenuation, see below).

Table IV-1. Percentage of unattenuated nitrogen loads in less than 10 year time of travel subwatersheds to Phinneys Harbor.

WATERSHED		LT10	GT10	TOTAL	%LT10
Name	#	kg/yr	kg/yr	kg/yr	
Inner Back River	1	2,290	123	2,413	95%
Inner Back River Stream	2	1,019	0	1,019	100%
Outer Back River	3	717	0	717	100%
Eel Pond	4	1,594	27	1,620	98%
Clay Pond	5	618	0	618	100%
Phinneys Harbor	6	4,184	723	4,906	85%
Phinneys Harbor Islands	7	2,326	0	2,326	100%
TOTAL		12,747	873	13,620	94%

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other detailed studies is applied to other portions. The Linked Watershed-Embayment Management Model (Howes and Ramsey, 2001) uses a land-use Nitrogen Loading Sub-Model based upon subwatershed-specific land uses and pre-determined nitrogen loading rates. For the Phinneys Harbor embayment system, the model used Bourne and Sandwich/Massachusetts Military Reservation (MMR) specific land-use data transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as parcel by parcel water use or groundwater monitoring wells). Determination of the nitrogen loads required obtaining watershed specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the "potential" or unattenuated nitrogen load to each receiving embayment, since attenuation during transport has not yet been included.

Natural attenuation of nitrogen during transport from land-to-sea (Section IV.2) within the Phinneys Harbor System watershed was determined based upon a site-specific study within the freshwater portions of Back River Stream and through Clay Pond, the only deep freshwater pond with a watershed modeled in the study area. Attenuation during transport through Clay Pond was determined through comparison with other Cape Cod lake studies. Attenuation during transport through Clay Pond was conservatively assumed to equal 50% based on available monitoring of selected Cape Cod lakes. Attenuation associated with shallow Mill Pond was included in the MEP's Back River nitrogen attenuation and freshwater flow investigation, presented in Section IV.2.

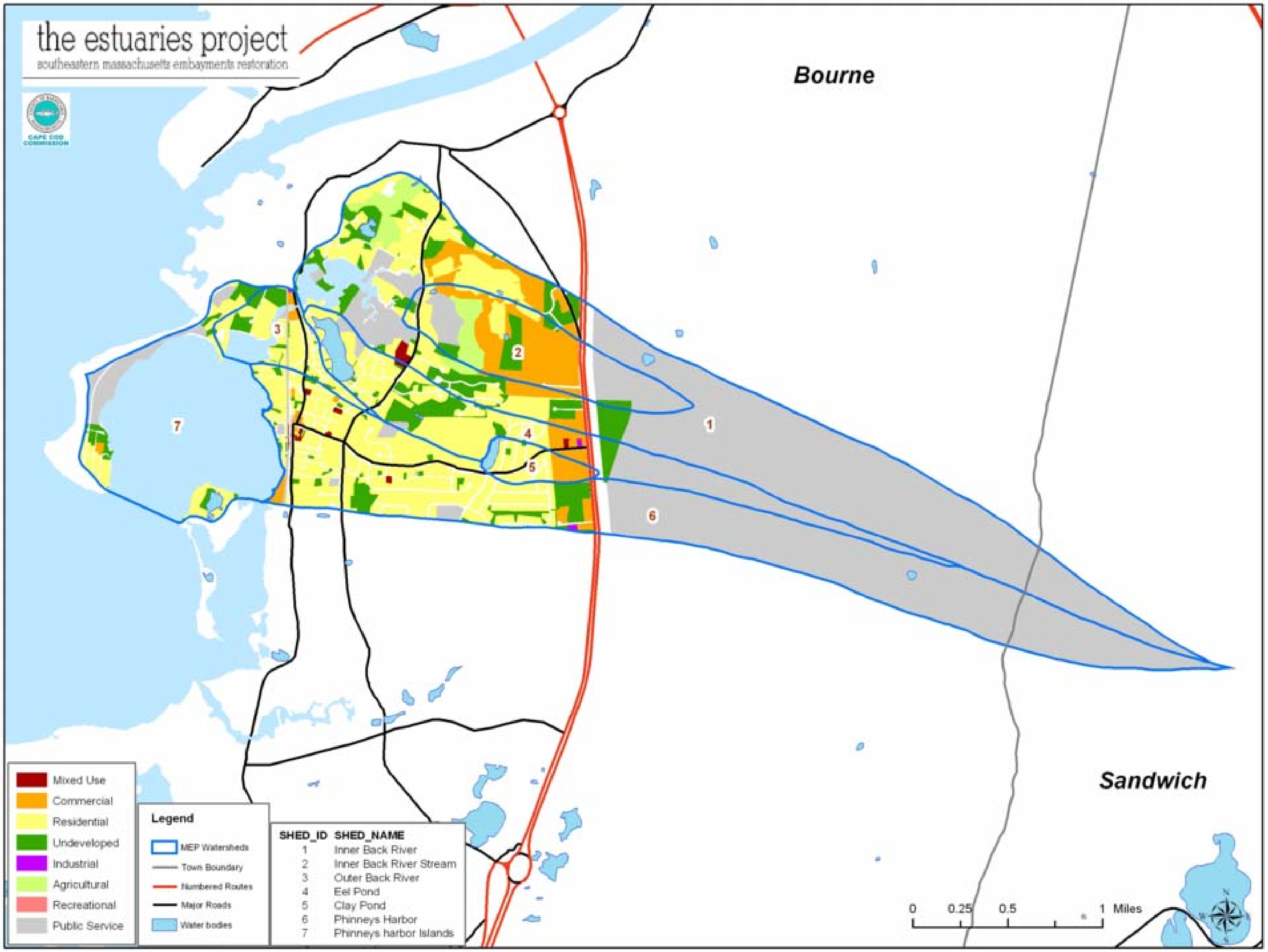


Figure IV-1. Land-use in the Phinneys Harbor watershed. The watershed encompasses portions of the Towns of Bourne and Sandwich. Land use classifications are based on assessors' records provided by each of the towns.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) is a standard part of the data collection effort of the MEP. In the present effort, measurements were made of attenuation by Clay Pond and by the Mill Pond/Back River stream complex. However, if smaller aquatic features that have not been included in this MEP analysis are providing additional attenuation of nitrogen, , nitrogen loading to the estuary would only be slightly (~10%) overestimated given the distribution of nitrogen sources within the watershed. Based upon these considerations, the MEP Technical Team used the conservative estimate of nitrogen loading based upon direct groundwater discharge for the other 5 sub-watersheds (i.e. not Clay Pond or Back River Stream). Internal nitrogen recycling was also determined throughout the tidal reaches of the Phinneys Harbor Estuarine System; measurements were made to capture the spatial distribution of sediment nitrogen regeneration from the sediments to the overlying water-column. Nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

IV.1.1 Land Use and Water Use Database Preparation

Estuaries Project staff obtained digital parcel and tax assessors data from the Town of Bourne Planning Department and reviewed Cape Cod Commission files for Sandwich/MMR land use data. Digital parcels and land use data are from 2005 for Bourne and 2000 for Sandwich/MMR. These land use databases contain traditional information regarding land use classifications (MADOR, 2002) plus additional information developed by each of the towns. The parcel data and assessors' databases for the towns were combined for the MEP analysis by using the Cape Cod Commission Geographic Information System (GIS).

Figure IV-1 shows the land uses within the Phinneys Harbor Estuary watershed area. Land uses in the study area are grouped into nine land use categories: 1) residential, 2) commercial, 3) industrial, 4) undeveloped, 5) agricultural, 6) mixed use, 7) golf course and recreational land, 8) public service/government, including road rights-of-way, and 9) freshwater features (e.g. ponds and streams). These land use categories, except the freshwater features, are aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2002). These categories are common to each town in the watershed. “Public service” in the MADOR system is tax exempt properties, including lands owned by government (e.g., wellfields, schools, open space, roads) and private groups like churches and colleges.

In the overall Phinneys Harbor System watershed, the predominant land use based on area is public service (government owned lands, roads, and rights-of-way), which accounts for 56% of the watershed area (mostly within MMR); residential is the second highest percentage of the watershed (25%) (Figure IV-2). However, 79% of the parcels in the system watershed are classified as residential. Single family residences (MADOR land use code 101) are 93% of the residential parcels and single family residences are 74% of the residential land area. In the individual subwatersheds, residential land uses vary between 14 and 64% of the subwatershed areas. Residential land uses are the dominant category in subwatersheds where public service land uses are the second highest percentage and are usually the second highest percentage use in subwatersheds where public service uses are the highest. One exception is the Clay Pond subwatershed, where commercial land use (i.e., a 16 acre shopping center), is the second highest percentage use. Overall, undeveloped land uses account for 9% of the entire Phinneys Harbor watershed, while commercial properties account for approximately 4% of the watershed area.

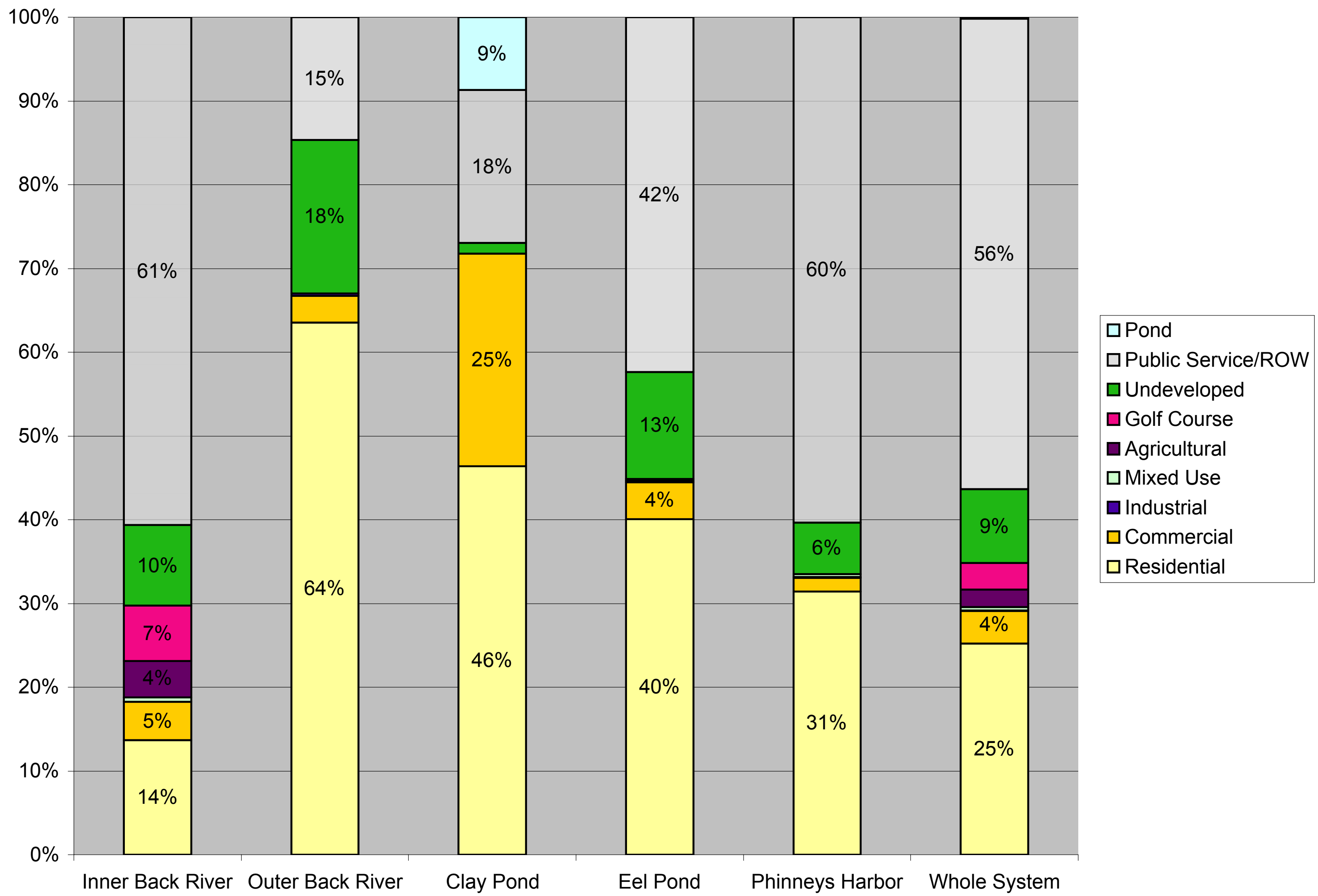


Figure IV-2. Distribution of land-uses within the major subwatersheds and whole watershed to Phinneys Harbor. Only percentages greater than or equal to 4% are shown.

In order to estimate wastewater flows within the Phinneys Harbor study area, the MEP (for the Cape Cod Commission analysis) purchased parcel by parcel water use information for the Bourne Water District. No developments generating wastewater are located in the Sandwich/MMR section of the watershed. The watershed area within the Town of Bourne contributes all of the wastewater nitrogen loading to the estuary. The MEP wastewater loads were determined from water use data from 2002, 2003, and 2004. MEP staff linked water use information to the parcel and assessors data using GIS techniques. Water use for each parcel was averaged to an annual volume for purposes of the nitrogen loading calculations. There are no municipal WWTFs in the Phinneys Harbor watershed. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the measured water-use, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2).

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

The Massachusetts Estuaries Project septic system nitrogen loading rate is fundamentally based upon a per Capita Nitrogen load to the receiving aquatic system. Specifically, the MEP septic system wastewater nitrogen loading is based upon a number of studies and additional information that directly measured septic system and per capita loads on Cape Cod or in similar geologic settings (Nelson et al. 1990, Weiskel & Howes 1991, 1992, Koppelman 1978, Frimpter et al. 1990, Brawley et al. 2000, Howes and Ramsey 2000, Costa et al. 2001). Variation in per capita nitrogen load has been found to be relatively small, with average annual per capita nitrogen loads generally between 1.9 to 2.3 kg person-yr^{-1}.

However, given the seasonal shifts in occupancy and rapid population growth throughout southeastern Massachusetts, decennial census data yields accurate estimates of total population only in selected watersheds. To correct for this uncertainty and more accurately assess current nitrogen loads, the MEP employs a water-use approach. The water-use approach is applied on a parcel-by-parcel basis within a watershed, where annual water meter data is linked to assessors parcel information using GIS techniques. The parcel specific water use data is converted to septic system nitrogen discharges (to the receiving aquatic systems) by adjusting for consumptive use (e.g. irrigation) and applying a wastewater nitrogen concentration. The water use approach focuses on the nitrogen load, which reaches the aquatic receptors down gradient in the aquifer.

All nitrogen losses within the septic system are incorporated. For example, information developed at the MASSDEP Alternative Septic System Test Center at the Massachusetts Military Reservation on Title 5 septic systems have shown nitrogen removals between 21% and 25%. Multi-year monitoring from the Test Center has revealed that nitrogen removal within the septic tank was small (1% to 3%), with most (20 to 22%) of the removal occurring within five feet of the soil adsorption system (Costa et al. 2001). Down gradient studies of septic system plumes indicate that further nitrogen loss during aquifer transport is negligible (Robertson et al. 1991, DeSimone and Howes 1996).

In its application of the water-use approach to septic system nitrogen loads, the MEP has ascertained for the Estuaries Project region that while the per capita septic load is well constrained by direct studies, the consumptive use and nitrogen concentration data are less certain. As a result, the MEP has derived a combined term the effective N Loading Coefficient (consumptive use times N concentration) of 23.63, to convert water (per cubic meter) to nitrogen load (N grams). This coefficient uses a per capita nitrogen load of 2.1 kg N person-yr^{-1} and is based upon direct measurements and corrects for changes in concentration that result from per capita shifts in water-use (e.g. due to installing low plumbing fixtures or high versus low irrigation usage, etc.).

The nitrogen loads developed using this approach have been validated in a number of long and short term field studies where integrated measurements of nitrogen discharge from watersheds could be directly measured. Weiskel and Howes (1991, 1992) conducted a detailed watershed/stream tube study that monitored septic systems, leaching fields and the transport of the nitrogen in groundwater to adjacent Buttermilk Bay. This monitoring resulted in estimated annual per capita nitrogen loads of 2.17 kg (as published) to 2.04 kg (if new attenuation information is included). Modeled and measured nitrogen loads were determined for a small sub-watershed to Mashapaquit Creek in West Falmouth Harbor (Smith and Howes, manuscript in review) where measured nitrogen discharge from the aquifer was within 5% of the modeled N load. Another evaluation was conducted by surveying nitrogen discharge to the Mashpee River in reaches with swept sand channels and in winter when nitrogen attenuation is minimal. The modeled and observed loads showed a difference of less than 8%, easily attributable to the low rate of attenuation expected at that time of year and under the ecological situation (Samimy and Howes, unpublished data).

While census based population data has limitations in the highly seasonal MEP region, part of the regular MEP analysis is to compare expected water used based on average residential occupancy to measured average water uses. This is performed as a quality assurance check to increase certainty in the final results. This comparison has shown that the larger the watershed the better the match between average water use and occupancy. For example, in the cases of the combined Great Pond, Green Pond and Bournes Pond watershed in the Town of Falmouth and the Popponesset Bay/Eastern Waquoit Bay watershed, which cover large areas and have significant year-round populations, the septic nitrogen loading based upon the census data is within 5% of that from the water use approach. This comparison matches some of the variability seen in census data itself. Census blocks, which are generally smaller areas of any given town, have shown up to a 13% difference in average occupancy form town-wide occupancy rates. These analyses provide additional support for the use of the water use approach in the MEP study region.

Overall, the MEP water use approach for determining septic system nitrogen loads has been both calibrated and validated in a variety of watershed settings. The approach: (a) is consistent with a suite of studies on per capita nitrogen loads from septic systems in sandy outwash aquifers; (b) has been validated in studies of the MEP Watershed “Module”, where there has been excellent agreement between the nitrogen load predicted and that observed in direct field measurements corrected to other MEP Nitrogen Loading Coefficients (e.g., stormwater, lawn fertilization); (c) the MEP septic nitrogen loading coefficient agrees in specific studies of consumptive water use and nitrogen attenuation between the septic tank and the discharge site; and (d) the watershed module provides estimates of nitrogen attenuation by freshwater systems that are consistent with a variety of ecological studies. It should be noted that while points b-d support the use of the MEP Septic N Coefficient, they were not used in its development. The MEP Technical Team has developed the septic system nitrogen load over many years, and the general agreement among the number of supporting studies has greatly enhanced the certainty of this critical watershed nitrogen loading term.

The independent validation of the water quality model (Section VI) and the reasonablness of the freshwater attenuation (Section IV.2) add additional weight to the nitrogen loading coefficients used in the MEP analyses and a variety of other MEP embayments. While the MEP septic system nitrogen load is the best estimate possible, to the extent that it may underestimate the nitrogen load from this source reaching receiving waters provides a safety factor relative to other higher loads that are generally used in regulatory situations. The lower concentration results in slightly higher amounts of nitrogen mitigation (estimated at 1% to 5%)) needed to lower embayment nitrogen levels to a nitrogen target (e.g. nitrogen threshold, cf. Section VIII). The additional nitrogen removal is not proportional to the septic system nitrogen level, but is related to the how the septic system nitrogen mass compares to the nitrogen loads from all other sources that reach the estuary (i.e. attenuated loads).

In order to provide an independent validation of the average residential water use within the Phinneys Harbor System watershed, MEP staff reviewed US Census population values for the towns in the watershed. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that two people occupy each bedroom and each bedroom has a wastewater flow of 110 gallons per day (gpd), so each person generates 55 gpd of wastewater. Based on data collected during the 2000 US Census, average occupancy within Bourne is 2.52 people per housing unit, while year-round occupancy of available housing units is 77%. Average water use for single family residences with municipal water accounts in the Phinneys Harbor watershed is 182 gpd. If this flow is multiplied by 0.9 to account for consumptive use, the watershed average is 164 gpd. If this flow is then divided by 55 gpd, the average estimated occupancy in the watershed is 2.98 people per household.

In most previously completed MEP studies, average population and average water use have generally agreed fairly well. Since review of water use in the Phinneys Harbor watershed suggests that on average there is an additional ~0.5 person per housing unit (or 18% higher than predicted), MEP staff reviewed more refined US Census information, 1990 Census information and water use information for each parcel within the watershed. Besides reviewing data on town and state levels, the US Census also develops information for smaller areas (i.e., tracts and blocks). Census tract 139 surrounds most of the western portion of the watershed, extending from the Cape Cod Canal to Valley Bars Road. Average occupancy for this tract reported for the 1990 Census is 2.56, while average occupancy for the 2000 Census is 2.27. While these occupancies suggest that the area is given to a wide range of readings, both of these occupancies are less than the occupancy expected based on water use.

MEP staff then reviewed the average water uses measured in the subwatersheds of the Phinneys Harbor system. While the overall average for single family residences (SFRs) is 182 gpd, averages in the subwatersheds varied widely with a range between 126 and 251 gpd. Review of individual SFR water uses within subwatershed ranged as high as 989 gpd, but this is well within the range of SFR water uses that have been observed in other MEP analyses. The standard deviation among all the watershed averages is 87 gpd; the 139 gpd population estimated average fits well within one standard deviation of the 182 gpd measured water use mean.

Given all the above analysis and the difficulty in accurately gauging actual occupancy in a seasonal community such as within the Phinneys Harbor sub-watershed, and since there are factors suggesting that the measured water uses in this watershed are inappropriate, MEP staff decided to continue to use the Phinneys Harbor watershed-specific water uses without any additional factors and used the average water use for the residential parcels without water use and for the 189 additional residential parcels included in the buildout analysis. It should be noted that the water-use approach for determining residential wastewater generation by septic systems was developed specifically for seasonal parcels, where occupancy can be highly variable and census data may not accurately capture the actual occupancy.

Although water use information exists for 92% of the approximately 1,180 developed parcels in the Phinneys Harbor watershed, there are 90 parcels that are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (e.g., 101 or 325), have been confirmed as having buildings on them through a review of aerial photographs, and do not have a listed account in the water use databases. Of the 90 parcels, 74% of them (67) are classified as single family residences (land use code 101) and another 18% are classified as other types of residential development (e.g. 109 (multiple houses on a single property)). The remaining 8% of the parcels are commercial properties (300s land use codes). MEP staff used current water use to develop a watershed-specific water use estimate for the residential uses that were assumed to utilize private wells (Table IV-2). This flow was also used for the seven existing commercial properties without water use located within the watershed.

Table IV-2. Average Water Use in Phinneys Harbor Watershed.

Land Use	State Class Codes	# of Parcels with Water Use in Watershed	Water Use (gallons per day)	
			Watershed Average	Subwatershed Average Range
Residential	101	995	182	126 to 251
Commercial	300 to 389	28	1,203	512 to 10,406
Industrial	400 to 439	2	22	4 to 41

Note: All data for analysis supplied by Bourne Planning Department and Bourne Water District.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns and golf courses, with lawns being the predominant source within this category. In order to add this source to the nitrogen loading model for the Phinneys Harbor system, MEP staff reviewed available information about residential lawn fertilizing practices and incorporated site-specific information from which to determine nitrogen loading from the Brookside Golf Course, which is the only large tract of turf in the watershed. MEP staff was not successful in contacting the turf manager for the golf course, so fertilizer application rates for use in the watershed nitrogen loading model were developed from a synthesis of application rates of 12 golf courses within the region where nitrogen loading data was previously collected..

Residential lawn fertilizer use has rarely been directly measured in watershed-based nitrogen loading investigations. Instead, lawn fertilizer nitrogen loads have been estimated based upon a number of assumptions: a) each household applies fertilizer, b) cumulative annual applications are 3 pounds per 1,000 sq. ft., c) each lawn is 5000 sq. ft., and d) only 25% of the nitrogen applied reaches the groundwater (leaching rate). Because many of these assumptions had not been rigorously reviewed in over a decade, the MEP Technical Staff undertook an assessment of lawn fertilizer application rates and a review of leaching rates for inclusion in the Watershed Nitrogen Loading Sub-Model.

The initial effort in this assessment was to determine nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. The assessment accounted for proximity to fresh ponds and embayments. Based upon ~300 interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sq. ft., 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a leaching rate of 20% results in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors are used in the MEP nitrogen loading calculations. It is likely that this still represents a conservative estimate of nitrogen load from residential lawns. It should be noted that professionally maintained lawns were found to have the higher rate of fertilizer application and hence higher estimated loss to groundwater of 3 lb/lawn/yr.

Fertilizer application rates at twelve golf courses have been developed in previous MEP watershed nitrogen loading models. Golf courses usually have different fertilizer application rates for different turf areas, usually higher annual application rates for tees and greens (~3-4 pounds per 1,000 square feet) and lower rates for fairways and roughs (~2-3.5 pounds per 1,000 square feet). From the 12 golf courses evaluated to date, MEP staff developed the following average annual nitrogen application rates (in lbs/1,000 ft2) for the various turf areas: greens, 4; tees, 3.6; fairways, 3.2, and roughs, 2.6. As has been done in all MEP reviews, MEP staff reviewed the layout of the Brookside Golf Course, classified the turf types, and assigned these areas to the appropriate subwatersheds. The average nitrogen application rates were then applied to these areas and a load was calculated.

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the Cape Cod Commission's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and Massachusetts DEP's Nitrogen Loading Computer Model Guidance (1999). The recharge rate for natural areas and lawn areas is the same as utilized in the MEP-USGS groundwater modeling effort (Section III). Cranberry bog fertilizer application rate and percent nitrogen attenuation in the bogs is based on the only annual study of nutrient cycling and loss from cranberry agriculture (Howes and Teal, 1995). Only the bog loses measurable nitrogen, the forested upland releases only very low amounts. For the watershed nitrogen loading analysis, the areas of active bog surface are based on 85% of the total area for properties classified as cranberry bogs in the town-supplied land use classifications. Factors used in the MEP nitrogen loading analysis for the Phinneys Harbor watershed are summarized in Table IV-3.

Landfills on Cape Cod can be sources of nitrogen to coastal waters as a result of historic disposal of septage in open lagoons. Although these lagoons have now been closed and capped, nitrogen can still be moving toward coastal discharge sites. The Phinneys Harbor System watershed contains the southern portion of the Town of Bourne Landfill. Determination of the nitrogen loading from the landfill site was based upon 3 sets of information: (a) the specific locations within the overall site of the historic septage disposal lagoons, present lined and unlined landfill areas, (b) groundwater modeling (particle tracking), and (c) review of monitoring well data and available groundwater flow path information. All of these site-specific data indicate that the contaminant plume, including nitrogen loads, from the buried materials and historic septage disposal lagoons travels along, but outside of the Harbor watershed boundary. While the southernmost portion of the landfill site may contribute to the estuarine reach of Back River, at the time of the analysis, this region had been unused for disposal. In contrast, the historic septage lagoons located within the northern portion of the site clearly discharge to the Cape Cod Canal (approximately mid-way between the Railroad and Bourne Bridges), based upon USGS groundwater particle tracking modeling. As the operating landfill is lined to prevent contamination of groundwaters, and since the historic septage disposal lagoon area is the primary potential nitrogen source within the landfill parcel, nitrogen loading to the Phinneys Harbor System from the landfill appears to be negligible. Although the watershed boundary is based on results from the regional USGS modeling (see Section III), available contaminant measurements, from the network of groundwater monitoring wells surrounding the landfill site, confirm the modeled groundwater flow paths, which indicate negligible nitrogen loading from the landfill to the Phinneys Harbor Estuarine System.

Table IV-3. Primary Nitrogen Loading Factors used in the Phinneys Harbor MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Bourne data. *Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.

Nitrogen Concentrations:	mg/l	Recharge Rates:	in/yr
Road Run-off	1.5	Impervious Surfaces	40
Roof Run-off	0.75	Natural and Lawn Areas	27.25
Direct Precipitation on Embayments and Ponds	1.09	Water Use/Wastewater:	
Natural Area Recharge	0.072	Existing developed parcels wo/water accounts:	182 gpd
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (ft^2)*	5,000		
Residential Watershed Nitrogen Rate (lbs/lawn)*	1.08	Existing developed parcels w/water accounts:	Measured annual water use
Cranberry Bogs nitrogen application (lbs/ac)	31	Buildout Parcels Assumptions:	
Cranberry Bogs nitrogen attenuation	34%	Residential parcels:	149 gpd
Nitrogen Fertilizer Rate for golf courses, cemeteries, and public parks determined from site-specific information		Commercial and industrial parcels:	21 gpd/1,000 ft2 of building
		Commercial and industrial building coverage	28%

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, parcels were assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel was located within a respective watershed. Following the assigning of boundary parcels, all large parcels were examined individually and were split (as appropriate) in order to obtain less than a 2% difference between the total land area of each subwatershed and the sum of the area of the parcels within each subwatershed. The resulting "parcelized" watersheds to Phinneys Harbor are shown in Figure IV-3.

The review of individual parcels straddling watershed boundaries included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Individualized information for parcels with atypical nitrogen loading (condominiums, golf courses, etc.) was also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the Phinneys Harbor estuary. The assignment effort was undertaken to better define the sub-embayment loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Following the assignment of all parcels, subwatershed modules were generated for each of the ten sub-watersheds summarizing water use, parcel area, frequency, sewer connections, private wells, and road area. As mentioned above, these results were then condensed to seven subwatersheds based upon the time of travel analysis (less than 10 years vs. greater than 10 years) discussed above. The individual sub-watershed modules were then integrated to create the Phinneys Harbor Watershed Nitrogen Loading module with summaries for each of the individual subembayments. The subembayments represent the functional embayment units for the Linked Watershed-Embayment Model's water quality component.

For management purposes, the aggregated embayment watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Phinneys Harbor System, the major types of nitrogen loads are: wastewater (e.g., septic systems), fertilizer, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-4). The output of the watershed nitrogen loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-4 a-c). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model.

Since groundwater outflow from a pond can enter more than one downgradient sub-watershed, the length of shoreline on the downgradient side of the pond was used to apportion the pond-attenuated nitrogen load to respective downgradient watersheds. The apportionment was based on the percentage of discharging shoreline bordering each downgradient sub-watershed. So for example, Clay Pond has a downgradient shoreline of 1,149 feet; 82% of that shoreline discharges into the Eel Pond watershed (watershed 4 in Figure IV-1) and 18% goes to the Phinneys Harbor watershed (watershed 6 in Figure IV-1). The attenuated nitrogen load discharging from Clay Pond is divided among these subwatersheds based on these percentages of the downgradient shoreline.

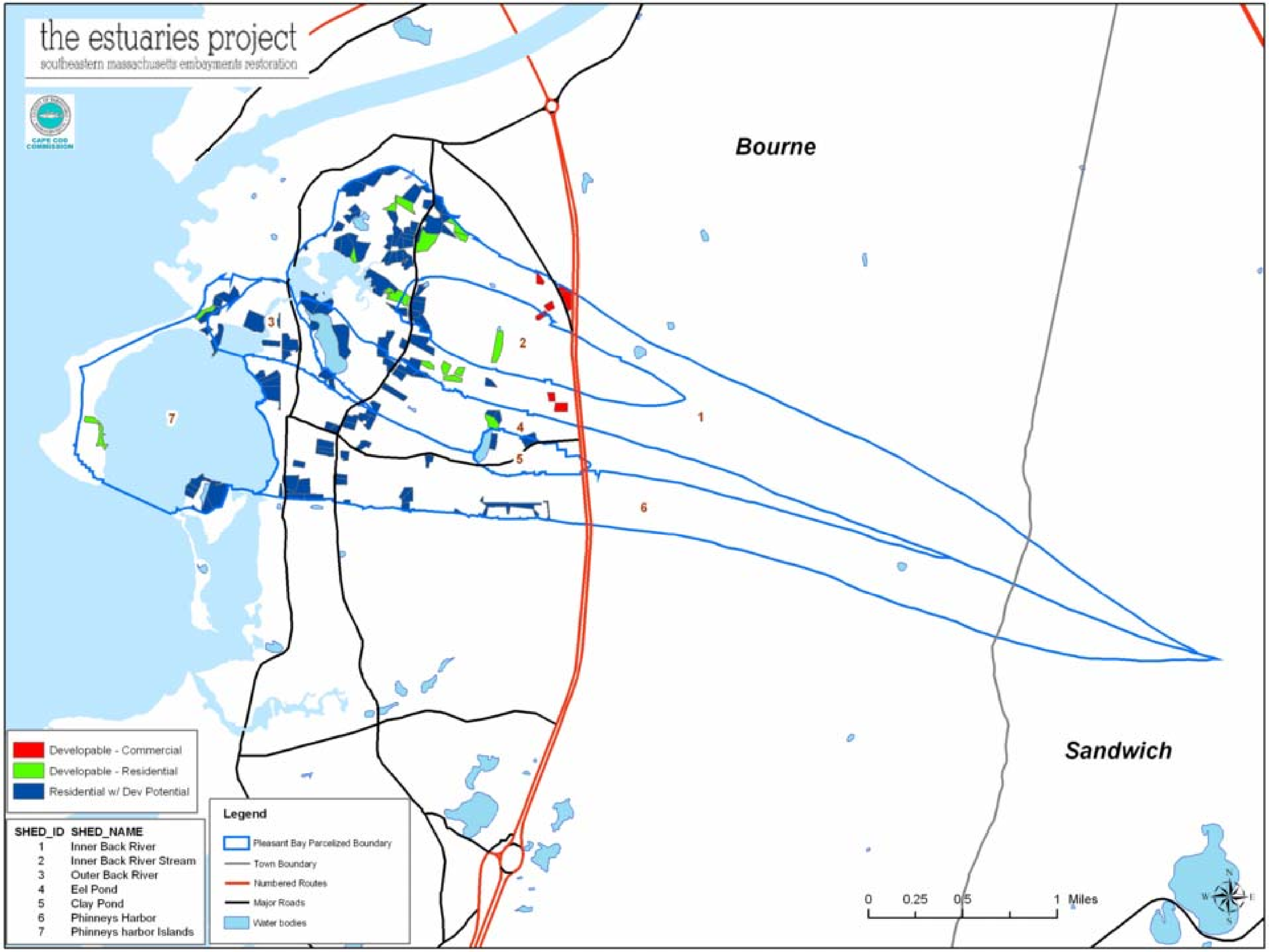
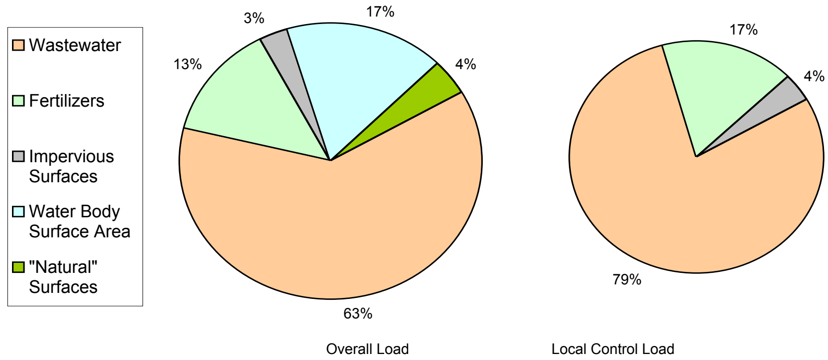


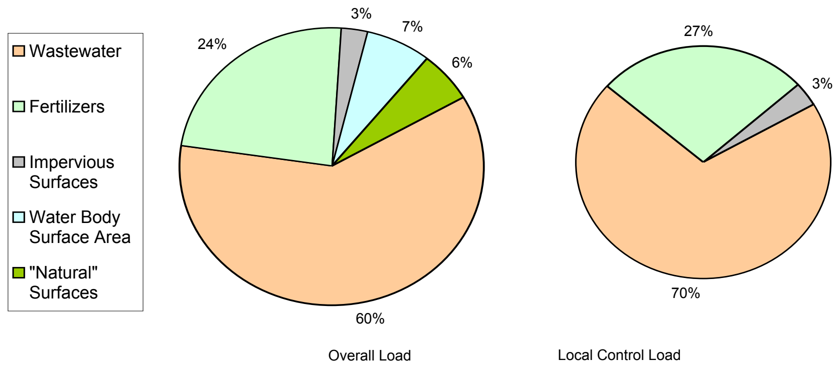
Figure IV-3. Parcels, Parcelized Watersheds, and Developable Parcels in the Phinneys Harbor watersheds.

Table IV-4. Phinneys Harbor Nitrogen Loads. Attenuation of Phinneys Harbor system nitrogen loads occurs as nitrogen moves through upgradient ponds and streams during transport to the estuary. All values are kg N yr^{-1}.

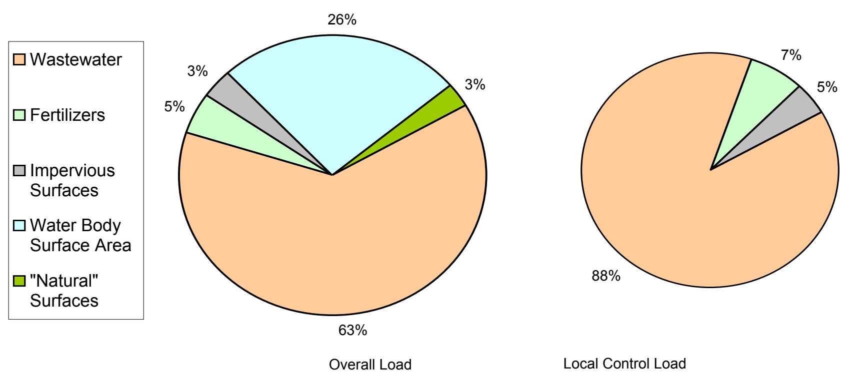
		Phinneys Hbr/Eel Pond/Back R N Loads by Input:						% of Pond Outflow	***Present N Loads***			***Buildout N Loads***		
Name	**Watershed ID#**	**Wastewater**	**Fertilizers**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**		**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Phinneys Harbor/Back River/Eel Pond		8466	1833	417	2347	558	4293		13620		12903	17913		17057
Back River/Eel Pond	1 to 6 + CP	3815	1477	177	449	358	3315		6276		5615	9591		8791
Inner Back River	1,2	1544	1332	72	215	269	2674		3432		3025	6107		5563
Inner Back R Stream	2	388	570	16	0	45	341		1019	40%	611	1359	40%	816
Inner Back River Estuary surface deposition					215				215		215	215		215
Outer Back R	3	503	43	30	124	17	188		717		717	905		905
Outer Back River Estuary surface deposition					124				124		124	124		124
Eel Pond	4 + CP	1768	102	75	110	72	453		2127		1874	2579		2324
Clay Pd (CP)	5	437	26	15	20	8	5	82%	506	50%	253	512	50%	256
Eel Pond Estuary surface deposition					90				90		90	90		90
Phinneys Harbor	6, 7 + CP	4651	356	240	1897	200	978		7345		7288	8323		8266
Phinneys Hbr Islands	7	346	33	34	0	20	128		433		433	561		561
Clay Pd (CP)	5	97	6	3	4	2	1	18%	112	50%	56	113	50%	57
Phinneys Harbor Estuary surface deposition					1893				1893		1893	1893		1893



a. Phinneys Harbor System Overall



b. Back River/Eel Pond Subwatershed



c. Phinneys Harbor Subwatershed

Figure IV-4 (a-c). Land use-specific unattenuated nitrogen load (by percent) to the (a) overall Phinneys Harbor System watershed, (b) Back River/Eel Pond subwatershed, and (c) Phinneys Harbor subwatershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control.

Freshwater Pond Nitrogen Loads

Freshwater ponds on Cape Cod are generally kettle hole depressions that intercept the surrounding groundwater table revealing what some call “windows on the aquifer.” Groundwater typically flows into the pond along the upgradient shoreline, then lake water flows back into the groundwater system along the downgradient shoreline. Occasionally a Cape Cod pond will also have a stream outlet or herring run that also acts as a discharge point. Since the nitrogen loads flow into the pond with the groundwater, the relatively more productive pond ecosystems incorporate some of the nitrogen, retain some nitrogen in the sediments, and change the nitrogen among its various oxidized and reduced forms. As result of these interactions, some of the nitrogen is removed from the watershed system, mostly through burial in the sediments and denitrification that returns it to the atmosphere. Following these reductions, the remaining (reduced or attenuated) loads flow back into the groundwater system along the downgradient side of the pond or through a stream outlet and eventual discharge into the downgradient embayment. The nitrogen load summary in Table IV-4 includes both the unattenuated (nitrogen load to each subwatershed) and attenuated nitrogen loads.

Pond nitrogen attenuation in freshwater ponds has generally be found to be at least 50% in MEP analyses, so the watershed model contains a conservative attenuation rate of 50%. However, in some cases, if sufficient monitoring information is available, a pond-specific attenuation rate is incorporated into the watershed nitrogen loading modeling (Three Bays MEP Report, 2005). Detailed studies of other southeastern Massachusetts freshwater systems including Ashumet Pond (AFCEE, 2000) and Agawam/Wankinco River Nitrogen Discharges (CDM, 2001) have supported a 50% attenuation factor. In order to estimate nitrogen attenuation in the ponds physical and chemical data for each pond is reviewed. Available bathymetric information is reviewed relative to measured pond temperature profiles to determine whether an epilimnion (*i.e.*, well mixed, homothermic, upper portion of the water column) exists in each pond. Bathymetric information is necessary to develop a residence or turnover time and complete an estimate of nitrogen attenuation. Clay Pond does not have bathymetric information.

In MEP analyses, available nitrogen concentrations from individual ponds are reviewed to establish whether sediment regeneration is a significant factor in a pond and, if not, the entire volume of the pond is used to determine a turnover time. Turnover time is how long it takes the recharge from the upgradient watershed to completely exchange the water in the pond or, in the case of a thermally stratified pond, exchange just the epilimnion. The total mass of nitrogen in the pond or epilimnion is adjusted using the pond turnover time to determine the annual nitrogen load returned to the aquifer through the downgradient shoreline. This mass is then compared to the nitrogen load coming from the pond’s watershed to determine the nitrogen attenuation factor for the pond. Generally, monitoring is insufficient to support use of a factor different than the standard 50% attenuation.

Pond water quality information collected from the annual Cape Cod Pond and Lake Stewardship (PALS) water quality snapshot is generally reviewed to assess the reliability of the standard attenuation assumption for a given pond. The PALS Snapshot is a collaborative Cape Cod Commission/SMAST Program that allows trained, citizen volunteers of each of the 15 Cape Cod towns to collect pond samples in August and September using a standard protocol. Snapshot samples have been collected every year between 2001 and 2005. The standard protocol for the Snapshot includes field collection of dissolved oxygen and temperature profiles, Secchi disk depth readings and water samples at various depths depending on the total depth of the pond. Water samples were analyzed at the SMAST laboratory for total nitrogen, total phosphorus, chlorophyll *a*, alkalinity, and pH. Although Clay Pond (PALS# BO-365) has not been sampled under any of the PALS Snapshots, the standard 50% attenuation factor is applied to subwatershed loads flowing out of Clay Pond. Analysis from other MEP assessments has shown that the 50% attenuation factor is generally conservative.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development within the study area watershed. For the Phinneys Harbor modeling, MEP staff consulted with Bourne town planners to determine the factors that would be used in the assessment. MEP staff developed the buildout by reviewing the development potential of each property. A standard buildout procedure is to evaluate town zoning to determine minimum lot sizes in each of the zoning districts, including overlay districts (*e.g.*, water resource protection districts). Larger lots are subdivided by the minimum lot size to determine the total number of new lots and existing developed properties are reviewed for additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence. MEP staff also included additional development on residential parcels that are classified as developable residential (state class land use codes 130 and 131) but are less than the minimum lot size and are greater than 5,000 square feet. These parcels are assigned one residence in the buildout; 5,000 square feet is a common minimum buildable lot size in Cape Cod town regulations. Properties classified by the Bourne assessor as “undevelopable” (e.g., codes 132, 392, and 442) were not assigned any development at buildout. Commercially developable properties were not subdivided; the area of each parcel and the factors in Table IV-3 were used to determine a wastewater flow for these properties. All the parcels included in the buildout assessment of the Phinneys Harbor watershed are shown in Figure IV-3.

One large nitrogen addition that is not indicated in the present land-use (Figure IV-3), but is included in the buildout loading rates in Table IV-5 is the planned and permitted additional development on the Brookside Golf Course site. Brookside was originally planned as a combined golf course and residential development that was approved prior to the creation of the Cape Cod Commission. Since that time, its configuration has changed a number of times, but the most recent configuration in Cape Cod Commission files is for 212 residential units. Since the original project proposed the construction of a WWTF with its discharge field within the Inner Back River subwatershed, each of the 212 units is assigned the average residential flow and the overall flow is combined with a wastewater nitrogen discharge concentration of 10 ppm (i.e., the conventional permit limit assigned to private WWTF by the state MassDEP) resulting in an additional load that is part of the buildout load for Inner Back River.

Overall, a nitrogen load for each additional residence or business is included in the cumulative unattenuated buildout indicated in a separate column in Table IV-4. Buildout additions within the overall Phinneys Harbor System watershed will increase the unattenuated loading rate by 32%.

IV.2 ATTENUATION OF NITROGEN IN SURFACE WATER TRANSPORT

IV.2.1 Background and Purpose

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on determination of the inputs of nitrogen from the surrounding contributing land or watershed. This watershed nitrogen input parameter is the primary term used to relate present and future loads (build-out, sewering analysis, enhanced flushing, pond/wetland restoration for natural attenuation, etc.) to changes in water quality and habitat health. Therefore, nitrogen loading is the primary threshold parameter for protection and restoration of estuarine systems. Rates of nitrogen loading to the sub-watersheds of the Phinneys Harbor System (inclusive of Eel Pond and Back River estuarine reaches) being investigated under this nutrient threshold analysis was based upon the delineated watersheds (Section III) and their land-use coverages (Section IV.1). If all of the nitrogen applied or discharged within a watershed reaches an embayment the watershed land-use loading rate represents the nitrogen load to the receiving waters. This condition exists in watersheds where nitrogen transport from source to estuarine waters is through groundwater flow in sandy outwash aquifers (such as the developed region of the Phinneys Harbor System watershed). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. However, in most watersheds in southeastern Massachusetts, nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the case of the Phinneys Harbor embayment system watersheds, a portion of the freshwater flow and transported nitrogen passes through a surface water system (Back River) prior to entering the estuaries, producing the opportunity for significant nitrogen attenuation.

Failure to determine the attenuation of watershed derived nitrogen overestimates the nitrogen load to receiving estuarine waters. If nitrogen attenuation is significant in one portion of a watershed and insignificant in another the result is that nitrogen management would likely be more effective in achieving water quality improvements if focused on the watershed region having unattenuated nitrogen transport (other factors being equal). In addition to attenuation by freshwater ponds (see Section IV.1.3, above), attenuation in surface water flows is also important. An example of the significance of surface water nitrogen attenuation relating to embayment nitrogen management was seen in the Agawam River, where >50% of nitrogen originating within the upper watershed was attenuated prior to discharge to the Wareham River Estuary (CDM 2001). Similarly, MEP analysis of the Quashnet River indicates that in the upland watershed, which has natural attenuation predominantly associated with riverine processes, the integrated attenuation was 39% (Howes et al. 2004). In addition, a preliminary study of Great, Green and Bournes Ponds in Falmouth, measurements indicated a 30% attenuation of nitrogen during stream transport (Howes and Ramsey 2001). An example where natural attenuation played a significant role in nitrogen management can be seen relative to West Falmouth Harbor (Falmouth, MA), where ~40% of the nitrogen discharge to the Harbor originating from the groundwater effluent plume emanating from the WWTF was attenuated by a small salt marsh prior to reaching Harbor waters. Clearly, proper development and evaluation of nitrogen management options requires determination of the nitrogen loads reaching an embayment, not just loaded to the watershed.

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP Approach. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the head of the embayment system (estuarine reach of Back River) in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). This additional site-specific study was conducted in the 1 major surface water flow system, the freshwater portion of the Back River originating in Mill Pond and discharging to the head of the tidal portion of Back River.

Quantification of watershed based nitrogen attenuation is contingent upon being able to compare nitrogen load to the embayment system directly measured in freshwater stream flow (or in tidal marshes, net tidal outflow) to nitrogen load as derived from the detailed land use analysis (Section IV.1). Measurement of the flow and nutrient load associated with the freshwater reach of the Back River (at County Road) provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area upgradient from the gauging site. Flow and nitrogen load were measured at the Back River freshwater stream site for 24 months of record (Figure IV-5). During study period, velocity profiles were completed on each river every month to two months. The summation of the products of stream subsection areas of the stream cross-section and the respective measured velocities represent the computation of instantaneous stream flow (Q).

Determination of stream flow was calculated and based on the measured values obtained for stream cross sectional area and velocity. Stream discharge was represented by the summation of individual discharge calculations for each stream subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire stream cross section were not averaged and then applied to the total stream cross sectional area.

The formula that was used for calculation of stream flow (discharge) is as follows:

$$Q = \Sigma(A * V)$$

where by:

Q = Stream discharge (m^3/s)
A = Stream subsection cross sectional area (m^2)
V = Stream subsection velocity (m/s)

Thus, each stream subsection will have a calculated stream discharge value and the summation of all the sub-sectional stream discharge values will be the total calculated discharge for the stream.

Periodic measurement of flows over the entire stream gauge deployment period allowed for the development of a stage-discharge relationship (rating curve) that could be used to obtain flow volumes from the detailed record of stage measured by the continuously recording stream gauges. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given river. These hourly stages values where then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. In the case of tidal influence on stream stage, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of strictly freshwater flow. The two low tide stage values for any given day were averaged and the average stage value for a given day was then entered into the stage – discharge relation in order to compute daily flow. A complete annual record of stream flow (365 days) was generated for the surface water discharge flowing into the estuarine portion of Back River.

Figure IV-5. Location of Stream gauge (yellow triangle) in the Phinneys Harbor / Eel Pond / Back River embayment system.

The annual flow record for the surface water flow was merged with the nutrient data set generated through the weekly water quality sampling to determine nitrogen loading rates to the head (tidally influenced) of Back River. Nitrogen discharge from the stream was calculated using the paired daily discharge and daily nitrogen concentration data to determine the mass flux of nitrogen through the gauging site. For the Back River gauging location, weekly water samples were collected (at low tide for a tidally influenced stage) in order to determine nutrient concentrations from which nutrient load was calculated. In order to pair daily flows with daily nutrient concentrations, interpolation between weekly nutrient data points was necessary. These data are expressed as nitrogen mass per unit time (kg/d) and can be summed in order to obtain weekly, monthly, or annual nutrient load to the embayment system as appropriate. Comparing these measured nitrogen loads based on stream flow and water quality sampling to predicted loads based on the land use analysis allowed for the determination of the degree to which natural biological processes within the watershed to each pond currently reduces (percent attenuation) nitrogen loading to the embayment system.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge to Back River portion of Phinneys Harbor System

Mill Pond located upgradient of the Back River gauge site is a small freshwater pond on Cape Cod and unlike many of the freshwater ponds, this pond has stream outflow rather than discharging solely to the aquifer along its down-gradient shore. This stream outflow, the Back River, may serve to decrease the pond attenuation of nitrogen, but it also provides for a direct measurement of the nitrogen attenuation. In addition, nitrogen attenuation also occurs within the wetlands and streambed associated with the Back River. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the sub-watershed region contributing to the Back River above the gauge site and the measured annual discharge of nitrogen to the tidal portion of the Back River, Figure IV-6.

At the Back River gauge site, a continuously recording vented calibrated water level gauge was installed to yield the level of water in the freshwater portion of the Back River that carries the flows and associated nitrogen load to the head of the upper portion of the estuarine reach of the Back River. As the Back River is tidally influenced the gauge was located above the saltwater reach such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average low tide salinity was determined to be <0.2 ppt (Back River estuarine reach averages 29 ppt). Therefore, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked monthly. The gauge on the Back River was installed on January 14, 2002 and was set to operate continuously for 16 months such that two summer seasons would be captured in the flow record. Stage data collection continued until February 27, 2004 for a total deployment of 25 months. The 12-month uninterrupted record used in this analysis encompasses the summer 2003 field season.

River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter. A rating curve was developed for the Back River site based upon these flow measurements and measured water levels at the gauge site. The rating curve was then used for conversion of the continuously measured stage data to obtain daily freshwater flow volume. Water samples were collected weekly for nitrogen analysis. Integrating the flow and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the estuarine portion of the Back River (Figure IV-6 and Table IV-5). In addition, a water balance was constructed based upon the US Geological Survey groundwater flow model to determine long-term average freshwater discharge expected at each gauge site.

Table IV-5. Comparison of water flow and nitrogen discharges from Back River (freshwater) discharging to estuarine reach of Back River. The "Stream" data is from the MEP stream gauging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	Stream Discharge to Back River[(a)]	Data Source
Total Days of Record	365[(b)]	(1)
Flow Characteristics		
Stream Average Discharge (m3/day)	1822	(1)
Contributing Area Average Discharge (m3/day)	2197	(2)
Discharge Stream 2002-03 vs. Long-term Discharge (% difference)	17%	
Nitrogen Characteristics		
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.385	(1)
Stream Average Total N Concentration (mg N/L)	0.749	(1)
Nitrate + Nitrite as Percent of Total N (%)	51%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	1.36	(1)
TN Average Contributing Area Attenuated Load (kg/day)	1.68	(2)
TN Average Contributing UN-attenuated Load (kg/day)	2.79	(3)
Attenuation of Nitrogen in Pond/Stream (%)	51%	(4)

(a) Flow and N load to stream discharging to Back River includes Mill Pond contributing area.
(b) Stream measurements October 16, 2002 to October 15, 2003.

(1) MEP gage site data
(2) Calculated from MEP watershed nitrogen loading (Section IV.1) for delineations to Mill Pond and to Back River; the fractional flow path from each sub-watershed which contribute to the flow in the stream to Back River; and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates.
(4) Calculated based upon the measured TN discharge from the rivers vs. the unattenuated watershed load from the land-use N loading moc

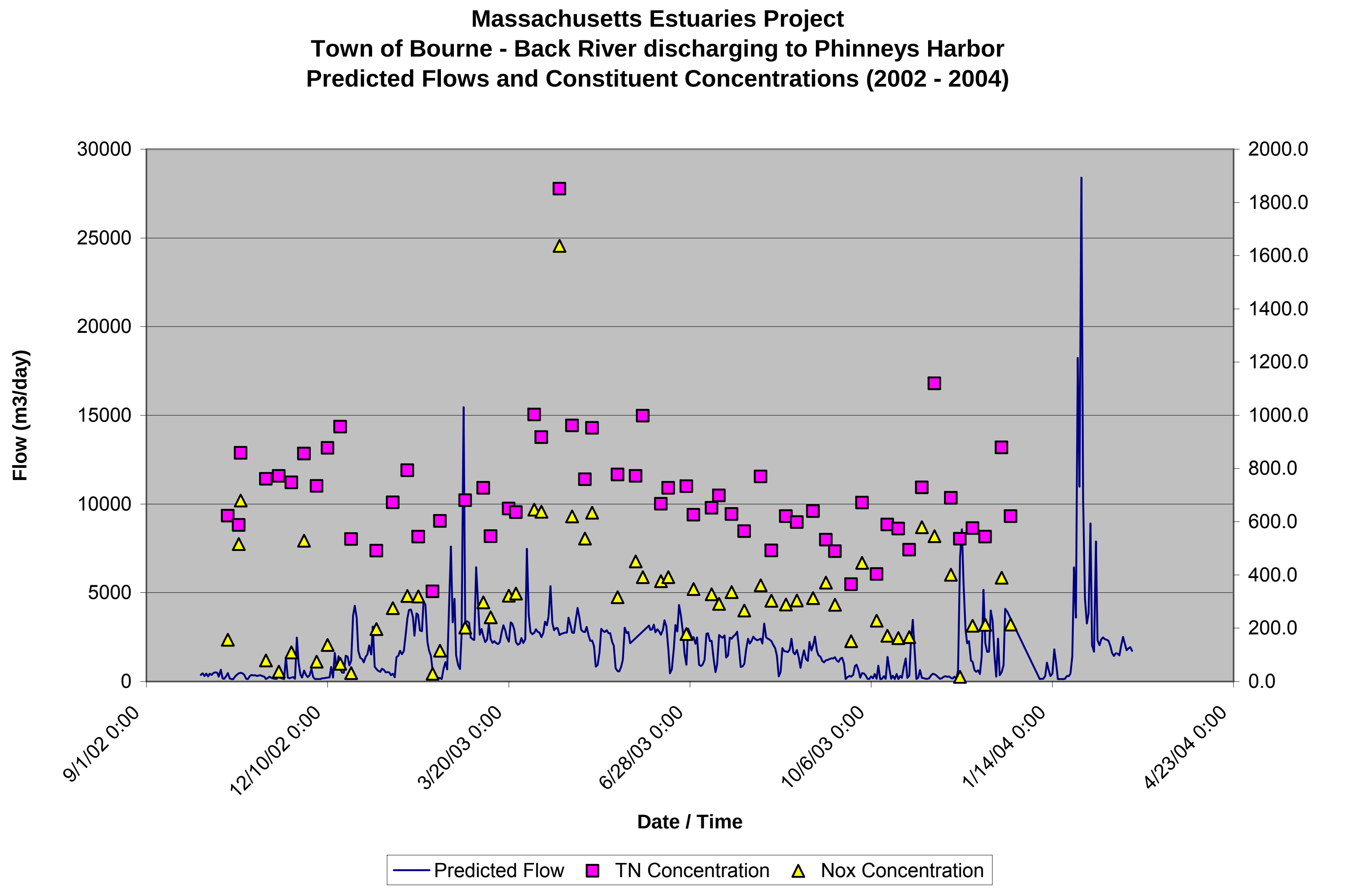


Figure IV-6. Back River discharge (solid blue line), nitrate+nitrite (yellow triangle) and total nitrogen (pink box) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to the Back River Estuary (Table IV-6).

The annual freshwater flow record for the Back River measured by the MEP was compared to the long-term average flows determined by the USGS modeling effort (Table III-1). The measured freshwater discharge from the Back River was 17% lower than the long-term average modeled flows. The difference may in part be due to below average rainfall during the first portion of the stream gauge deployment and compounded by below average rainfall in the two years prior to the stream gauge deployment based on rainfall records obtained from a rain gauge in the Town of Falmouth. Based on ten years of rainfall data (1993-2003) the average rainfall was in the vicinity of the Phinneys Harbor system was 44.87 inches. By comparison, rainfall in 2000 and 2001 was 40.71 and 37.81 inches respectively. Rainfall in 2002 was 47.93 inches (only slightly above average) though the first part of the deployment period was during a particularly dry period and this was in contrast to rainfall amounts totaling 54.35 inches in 2003. It should be recognized that although 2002 rainfall was slightly above average the water table is likely to have been lower than usual due to the previous 2 years low rainfall amounts. This is significant relative to measured flow in the Back River surface water system as it is essentially a groundwater fed feature. Based upon the rainfall and groundwater levels associated with the stream measurement (suggesting a lower flow than the long-term average) and the only slightly lower stream discharge predicted (-17%) it appears that the stream is capturing the upgradient recharge (and loads) accurately.

Total nitrogen concentrations within the Back River outflow were moderate, 0.749 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 1.36 kg/day and a measured total annual TN load of 498 kg/yr. In the Back River River, nitrate was the predominant form of nitrogen (51%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the pond or stream ecosystems. The high concentration of inorganic nitrogen in the outflowing stream waters also suggests that plant production within the upgradient freshwater ecosystems is not nitrogen limited. In addition, the high nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system either within Mill Pond or along the freshwater reach of the Back River.

From the measured nitrogen load discharged by the Back River to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the Bay. Based upon lower nitrogen load (498 kg yr^{-1}) discharged from the freshwater Back River compared to that added by the various land-uses to the associated watershed (1019 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 51% (i.e. 51% of nitrogen input to watershed does not reach the estuary). This level of attenuation is only slightly greater than the integrated attenuation rate determined from the watershed nitrogen model of 40% (Table IV-4). This is expected given the conservative assumptions of nitrogen attenuation used in the model. The directly measured nitrogen loads from the river was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

Table IV-6. Summary of annual volumetric discharge and nitrogen load (nitrate+nitrite and total nitrogen) from the Back River (freshwater) discharging to the head of the estuarine reach of Back River based upon the data presented in Figures IV-6 and Table IV-5.				
Embayment System	Period of Record	Discharge (m^3/yr)	Attenuated Load (Kg/yr) NOx	TN
Back River (Freshwater)	October 16, 2002 to October 15, 2003	664950	256	498
Back River Freshwater	Based on Watershed Area and Recharge	801842	--	--

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of the Benthic Nutrient Flux Surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters within each major basin area within the Phinneys Harbor / Eel Pond / Back River embayment system. The mass exchange of nitrogen between watercolumn and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

As stated in above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the Phinneys Harbor embayment system predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the watercolumn (once it entered), then predicting watercolumn nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds it is predominantly in the bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the watercolumn for sufficient time to be flushed out to a downgradient larger waterbody (like Buzzards Bay). However, some of these phytoplankton particles are grazed by zooplankton or filtered from the water by shellfish and other benthic animals and deposited on the bottom. Also, in longer residence time systems (greater than 8 days) these nitrogen rich particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with their associated nitrogen “load” become incorporated into the surficial sediments of the bays.

In general the fraction of the phytoplankton population which enters the surficial sediments of a shallow embayment: (1) increases with decreased hydrodynamic flushing, (2) increases in low velocity settings, (3) increases within enclosed tributary basins, particularly if they are deeper than the adjacent embayment (e.g. Eel Pond). To some extent, the settling characteristics can be evaluated by observation of the grain-size and organic content of sediments within an estuary.

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment watercolumn for another round of uptake by phytoplankton. This recycled nitrogen adds directly to the eutrophication of the estuarine waters in the same fashion as watershed inputs. In some systems that have been investigated by SMAST and the MEP, recycled nitrogen can account for about one-third to one-half of the nitrogen supply to phytoplankton blooms during the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with deep depositional basins or salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer. Failure to account for the nitrogen balance of the sediments generally results in significant errors in determination of threshold nitrogen loadings. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for determining sediment-watercolumn nitrogen exchange

For the Phinneys Harbor system, in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected from 10 sites in Phinneys Harbor (July 2005), 6 sites in Eel Pond and 8 sites in Back River Marshes and 1 site in the outlet basin of Back River (Figure IV-7 and IV-8) in August 2001. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The number of core samples from each site (see Figure IV-7 and IV-8) per incubation were as follows:

Eel Pond Benthic Nutrient Regeneration Cores

- Station EP-1 1 core (Upper Region)
- Station EP-2 1 core (Upper Region)
- Station EP-3 1 core (Upper Region)
- Station EP-4 1 core (Lower Region)
- Station EP-5 1 core (Lower Region)
- Station EP-6 1 core (Lower Region)

Back River Benthic Nutrient Regeneration Cores

- Station BMR-1 1 core (Upper Region)
- Station BMR-2 1 core (Middle Region)
- Station BMR-3 1 core (Middle Region)
- Station BMR-4 1 core (Middle Region)
- Station BMR-5 1 core (Middle Region)
- Station BMR-6 1 core (Lower Region)

- Station BMR-7 1 core (Lower Region)
- Station BMR-8 1 core (Lower Region)
- Station BRO 1/2 2 cores (Outlet Basin)

Phinneys Harbor Benthic Nutrient Regeneration Cores

- Station PNH-1 1 core (Outer Region)
- Station PNH-2 1 core (Outer Region)
- Station PNH-3 1 core (Outer Region)
- Station PNH-4 1 core (Middle Region)
- Station PNH-5 1 core (Middle Region)
- Station PNH-6 1 core (Middle Region)
- Station PNH-7 1 core (Middle Region)
- Station PNH-8 1 core (Middle Region)
- Station PNH-9 1 core (Inner Region)
- Station PNH-10 1 core (Inner Region)
- Station PNH-11 1 core (Inner Region)
- Station PNH-12 1 core (Inner Region)

Sampling was distributed throughout the embayment system and the results for each site combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

Sediment-watercolumn exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1995) for nutrients and metabolism. Upon return to the field laboratory (Harbormasters Office) the cores were transferred to pre-equilibrated temperature baths. The headspace water overlying the sediment was replaced, magnetic stirrers emplaced, and the headspace enclosed. Periodic 60 ml water samples were withdrawn (volume replaced with filtered water), filtered into acid leached polyethylene bottles and held on ice for nutrient analysis. Ammonium (Scheiner 1976) and ortho-phosphate (Murphy and Reilly 1962) assays were conducted within 24 hours and the remaining samples frozen (-20^{o}C) for assay of nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON (D'Elia *et al.* 1977). Rates were determined from linear regression of analyte concentrations through time.

Chemical analyses were performed by the Coastal Systems Analytical Facility at the School for Marine Science and Technology (SMAST) at the University of Massachusetts in New Bedford, MA. The laboratory follows standard methods for saltwater analysis and sediment geochemistry.

Figure IV-7. Phinneys Harbor embayment system sediment sampling sites (green symbols) for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-7.

Figure IV-8. Eel Pond and Back River portion of the Phinneys Harbor embayment system sediment sampling sites (green symbols) for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-7.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

Watercolumn nitrogen levels are the balance of inputs from direct sources (land, rain etc), losses (denitrification, burial), regeneration (watercolumn and benthic), and uptake (e.g. photosynthesis). As stated above, during the warmer summer months the sediments of shallow embayments typically act as a net source of nitrogen to the overlying waters and help to stimulate eutrophication in organic rich systems. However, some sediments may be net sinks for nitrogen and some may be in "balance" (organic N particle settling = nitrogen release). Sediments may also take up dissolved nitrate directly from the watercolumn and convert it to dinitrogen gas (termed "denitrification"), hence effectively removing it from the ecosystem. This process is typically a small component of sediment denitrification in embayment sediments, since the watercolumn nitrogen pool is typically dominated by organic forms of nitrogen, with very low nitrate concentrations. However, this process can be very effective in removing nitrogen loads in some systems, particularly in streams, ponds and salt marshes, where overlying waters support high nitrate levels.

In addition to nitrogen cycling, there are ecological consequences to habitat quality of organic matter settling and mineralization within sediments, these relate primarily to sediment and watercolumn oxygen status. However, for the modeling of nitrogen within an embayment it is the relative balance of nitrogen input from watercolumn to sediment versus regeneration which is critical. Similarly, it is the net balance of nitrogen fluxes between water column and sediments during the modeling period that must be quantified. For example, a net input to the sediments represents an effective lowering of the nitrogen loading to down-gradient systems and net output from the sediments represents an additional load.

The relative balance of nitrogen fluxes ("in" versus "out" of sediments) is dominated by the rate of particulate settling (in), the rate of denitrification of nitrate from overlying water (in), and regeneration (out). The rate of denitrification is controlled by the organic levels within the sediment (oxic/anoxic) and the concentration of nitrate in the overlying water. Organic rich sediment systems with high overlying nitrate frequently show large net nitrogen uptake throughout the summer months, even though organic nitrogen is being mineralized and released to the overlying water as well. The rate of nitrate uptake, simply dominates the overall sediment nitrogen cycle.

In order to model the nitrogen distribution within an embayment it is important to be able to account for the net nitrogen flux from the sediments within each part of each system. This requires that an estimate of the particulate input and nitrate uptake be obtained for comparison to the rate of nitrogen release. Only sediments with a net release of nitrogen contribute a true additional nitrogen load to the overlying waters, while those with a net input to the sediments serve as an "in embayment" attenuation mechanism for nitrogen.

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure IV-9).

Unfortunately, the tendency for net release of nitrogen during warmer periods, coincides with the periods of lowest nutrient related water quality within temperate embayments. This sediment nitrogen release is in part responsible for poor summer nutrient related health. Other major factors causing the seasonal water quality decline are the lower solubility of oxygen during summer, the higher oxygen demand by marine communities, and environmental conditions supportive of high phytoplankton growth rates.

In order to determine the net nitrogen flux between watercolumn and sediments, all of the above factors were taken into account. The net input or release of nitrogen within a specific embayment was determined based upon the measured total dissolved nitrogen uptake or release, and estimate of particulate nitrogen input.

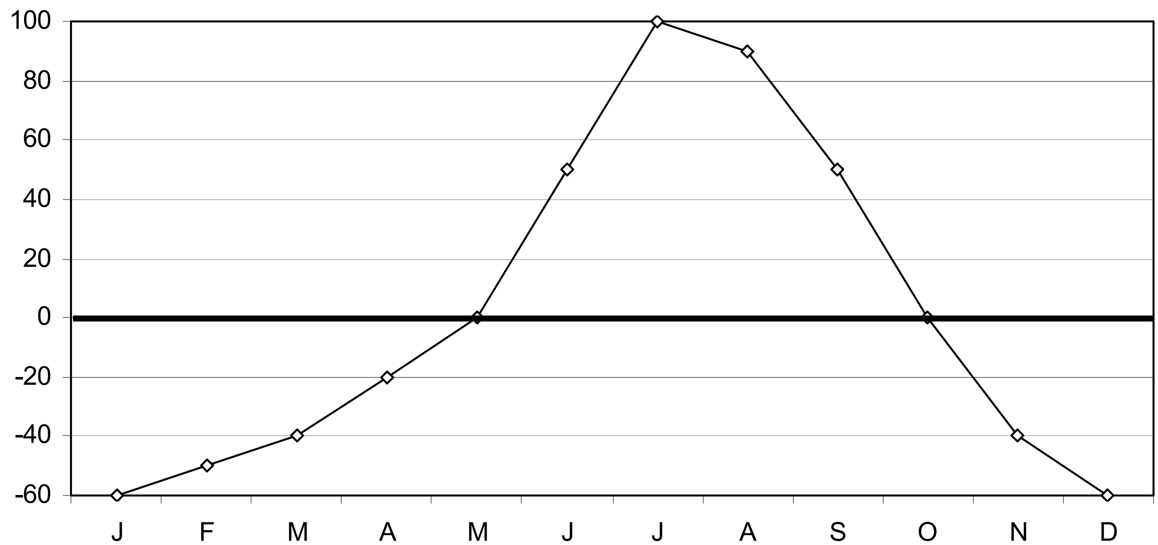


Figure IV-9. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Sediment sampling was conducted within the inner and outer portions of the Phinneys Harbor basin and in the small basin between Phinneys Harbor and the channel to the Back River Marshes as well as the upper and lower regions of Eel Pond and throughout the Back River tidal creeks in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

The magnitude of the settling of particulate organic carbon and nitrogen into the sediments was accomplished by determining the average depth of water within each sediment site, the average summer particulate carbon and nitrogen concentration within the overlying water and the tidal velocities from the hydrodynamic model (Chapter V). Two levels of settling were used. If the sediments were organic rich and fine grained, and the hydrodynamic data showed low tidal velocities, then a water column particle residence time of 8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins). If the sediments indicated coarse grained sediments and low organic content and high velocities, then half this settling rate was used. Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas which are net nitrogen sinks for the aquatic system. This approach has been previously validated in outer Cape Cod embayments (Town of Chatham embayments) by examining the relative fraction of the sediment carbon turnover (total sediment metabolism) which would be accounted for by daily particulate carbon settling. This analysis indicated that sediment metabolism in the highly organic rich sediments of the wetlands and depositional basins is driven primarily by stored organic matter (ca. 90%). Also, in the more open lower portions of larger embayments, storage appears to be low and a large proportion of the daily carbon requirement in summer is met by particle settling (approximately 33% to 67%). This range of values and their distribution is consistent with ecological theory and field data from shallow embayments. Additional, validation has been conducted on deep enclosed basins (with little freshwater inflow), where the fluxes can be determined by multiple methods. In this case the rate of sediment regeneration determined from incubations was comparable to that determined from whole system balance.

Net nitrogen release or uptake from the sediments within the Phinneys Harbor System were comparable to other similar embayments with similar configuration and flushing rates. Overall, sediment nitrogen release was low or negative 22.1 to -8.6 mg N m^{-1} d^{-1}, much less than in heavily nitrogen loaded sub-embayments within the Pleasant Bay Estuary (~100 mg N m^{-1} d^{-1}), but comparable to the rates for the West Falmouth Harbor Estuary (outer basin Phinneys Harbor and outer basin West Falmouth Harbor, 3 and –11 mg N m^{-1} d^{-1}, respectively). Similarly, the rates fell within the wide range found for the Vineyard Sound, Popponesset Bay Estuary, which ranged from 85 to - 17 mg N m^{-2} d^{-1}.

Net nitrogen release rates for use in the water quality modeling effort for the component sub-basins of the Phinneys Harbor System (Chapter VI) are presented in Table IV-7. The general pattern is consistent with other estuaries. The depositional basin of Eel Pond showed a slight uptake of nitrogen. The Back River salt marsh creeks showed a small nitrogen release, as a result of the low levels of nitrate in this sub-system. Salt marshes receiving significant nitrate enriched groundwater tend to be net sinks of nitrogen due to denitrification in the organic rich sediments at low tide (e.g. Mashapaquit Creek in West Falmouth Harbor). Phinneys Harbor sediments showed a gradient in nitrogen flux with the more organic rich inner basin releasing nitrogen, while the less organic sandy outer sediments showed a small net uptake. Overall, the sediments within the Phinneys Harbor system showed little variability compared to other systems in the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the moderate nitrogen loading to this system and it relatively high flushing rate.

Table IV-7. Rates of net nitrogen return from sediments to the overlying waters of the Phinneys Harbor / Eel Pond / Back River embayment system. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July -August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			i.d.
	Mean	S.E.	N	
Phinneys Harbor Estuary				
Outer Region	2.9	4.8	3	PNH 1-3
Inner Region	9.4	1.2	9	PNH 4-12
Back River Estuary				
Outer Basin	22.1	6.1	2	BRO 1-2
Salt Marsh Creeks	6.5	3.6	8	BMR 1-8
Eel Pond Estuary				
Main Basin	-8.6	1.8	5	EP 1-6
Station numbers refer to Figures IV-7 and IV-8.				

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes field data collection effort and the development of hydrodynamic models for the Phinneys Harbor/Back River estuary system (Figure V-1). For this system, the final calibrated model offers an understanding of water movement through the estuary, and provides the first step towards evaluating the water quality of these estuarine systems, as well as understanding nitrogen loading "thresholds" for each system. Tidal flushing information will be utilized as the basis for a quantitative evaluation of water quality. Nutrient loading data combined with measured environmental parameters within the various sub-embayments become the basis for an advanced water quality model based on total nitrogen concentrations. This type of model provides a tool for evaluating existing estuarine water quality, as well as determining the likely positive impacts of various alternatives for improving overall estuarine health, enabling the bordering towns (Wareham and Marion) to understand how pollutant loadings into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

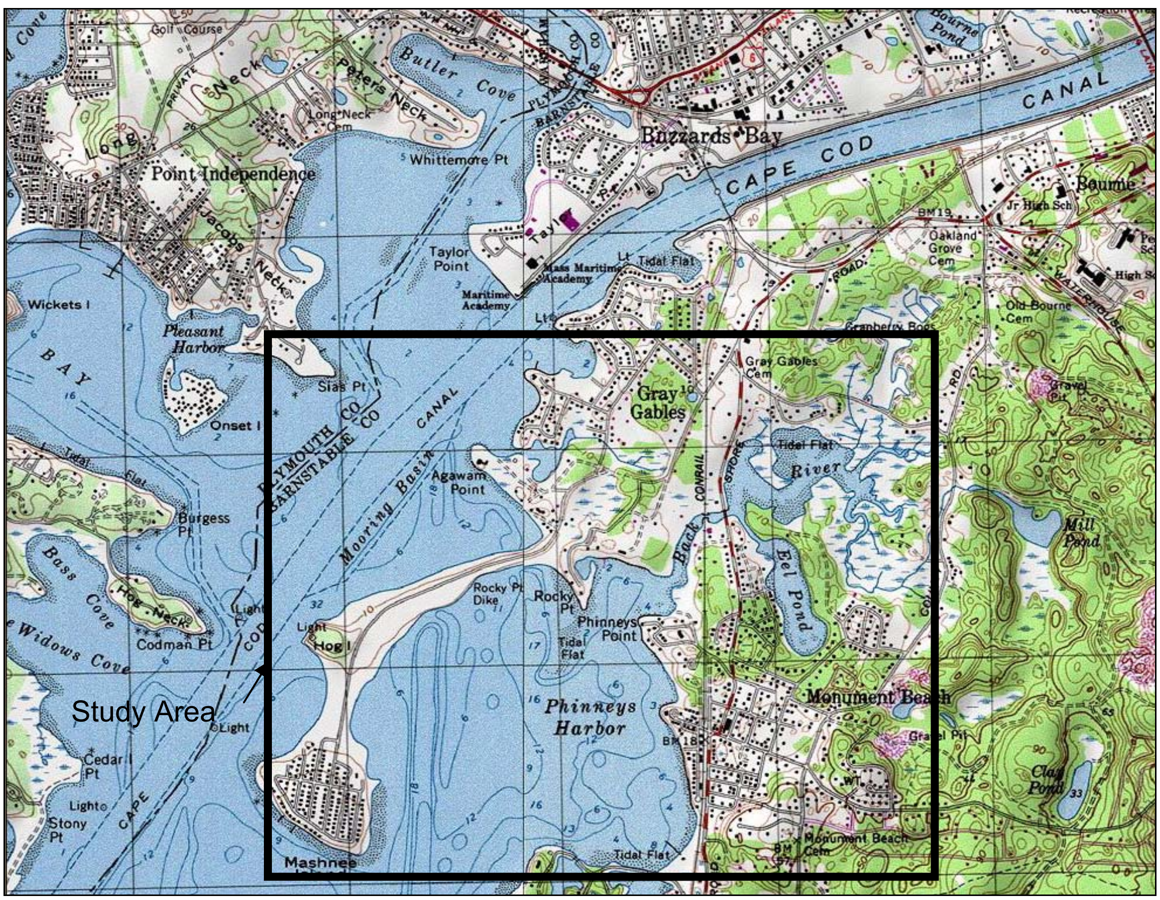


Figure V-1. Topographic map of the northern extent of Buzzards Bay, with an outline designating the study area of the Back River system.

In general, water quality studies 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. For example, the spread of pollutants may be analyzed from tidal current information developed by the numerical models.

Estuarine water quality is dependent upon nutrient and pollutant loading and the processes that help flush nutrients and pollutants from the estuary (e.g., tides and biological processes). Relatively low nutrient and pollutant loading and efficient tidal flushing are indicators of high water quality. The ability of an estuary to flush nutrients and pollutants is proportional to the volume of water exchanged with a high quality water body (i.e. the Atlantic Ocean). Several embayment-specific parameters influence tidal flushing and the associated residence time of water within an estuary. For the Pleasant Bay system, the most important parameters are the tide attenuation along with the shape, length and depth of the estuary and its attached sub-systems.

Shallow coastal embayments are the initial recipients of freshwater flows (i.e., groundwater and surfacewater) and the nutrients they carry. An embayment's shape influences the time that nutrients are retained in them before being flushed out to adjacent open waters, and their shallow depths both decrease their ability to dilute nutrient (and pollutant) inputs and increase the secondary impacts of nutrients recycled from the sediments. Degradation of coastal waters and development are tied together through inputs of pollutants in runoff and groundwater flows, and to some extent through direct disturbance, i.e. boating, oil and chemical spills, and direct discharges from land and boats. Excess nutrients, especially nitrogen, promote phytoplankton blooms and the growth of epiphytes on eelgrass and attached algae, with adverse consequences including low oxygen, shading of submerged aquatic vegetation, and aesthetic problems.

This hydrodynamic study was performed for the Phinneys Harbor/Back River system, which is located within the town of Bourne, Massachusetts, in the northern reaches of Buzzards Bay. A section of a topographic map in Figure V-1 shows the general study area. The Back River system has two major subdivisions, Back River and Eel Pond. Back River is a tidal river that connects Phinneys Harbor to a moderately shallow embayment with approximately 70 acres of salt marsh. This upper portion of Back River has a mean depth of approximately 3.3 feet. The other main division of the Back River system is Eel Pond, which has a deeper mean depth of approximately 5.2 feet, and has much less salt marsh resources. Eel Pond is connected to Back River via a relatively narrow, boulder strewn inlet channel that is about 480 feet long. The total surface coverage of the Back River system, including the salt marsh is approximately 150 acres. Phinneys Harbor connects Back River to Buzzards Bay and has a 440 acre coverage with and average depth of 7.1 feet.

Circulation in the Back River system is dominated by tidal exchange with Buzzards Bay through Phinneys Harbor. From measurements made in the course of this study, the average tide range in Phinneys Harbor is approximately 3.8 feet. By flow restrictions caused by two pairs of bridge abutments, the tide range in upper Back River is slightly smaller, or approximately 3.4 feet. Additional restrictions in the inlet channel to Eel Pond cause more damping of the tide range, where it is approximately 3.2 feet.

This hydrodynamic study proceeded as two component efforts. In the first portion of the study, bathymetry and tide data were collected in order to accurately characterize the physical system, and to provide data necessary for the modeling portion of the study. The bathymetry survey of Back River and Eel Pond was performed to determine the variation of embayment and channel depths throughout the system. This survey addressed the previous lack of adequate bathymetry data for this area. In addition to the survey, tides were recorded at three locations within Back River and Eel Pond for 38 days. This tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of the Back River system was developed in he second portion of this study. Using the bathymetry survey data, a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data from Phinneys Harbor were used to define the open boundary condition that drives the circulation of the model, and data from the two locations within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the real, physical system.

The calibrated computer model of the Back River system was used to compute the flushing rates of each of the sub-embayments of the system. Though water quality in an embayment cannot be directly inferred by use of the computed flushing rate alone, it can serve as a useful indicator of an embayments flushing performance relative to others in the system. The ultimate utility of this hydrodynamic model is as input into a constituent transport model, where water quality constituents like nitrogen are modeled to determine the real water quality dynamics of a system.

V.2 GEOMORPHIC AND ANTHROPOGENIC EFFECTS TO THE SYSTEM

Buzzards Bay generally runs northeast to southwest, bordered by the Massachusetts mainland to the west, Cape Cod to the east and northeast, and the Elizabeth Islands to the southeast. The bay was formed as a result of the most recent ice age and retreat of the glaciers (about 16,000 to 18,000 years ago). Along the eastern shore of the bay, these geologic processes created a number of shallow coastal embayments along the relatively irregular shoreline. Due to the proximity of the Buzzards Bay Moraine in this region, the watersheds to many of these embayments (including Eel Pond, Back River, and Phinney's Harbor) are relatively small; however the underlying geology make analyses of groundwater flow patterns complex.

Along with the geologic mechanisms that formed the shoreline and coastal embayments along the east side of Buzzards Bay, ongoing coastal processes also influence estuarine circulation and water quality. Although natural wave and tidal forces continue to reshape the shoreline, day-to-day conditions have limited impact on the shoreline migration and/or inlet stability. For typical wave conditions, longshore transport of sand is from south-to-north along the west coast of Bourne, due primarily to the predominant local wind-driven waves (see Figure V-2 for a summary of long-term wind data). In contrast to the mild day-to-day conditions, infrequent hurricane events such as the hurricanes of 1938, 1944, and 1954, as well as Hurricane Bob in 1991, all caused significant overwash and transport of beach sediments.

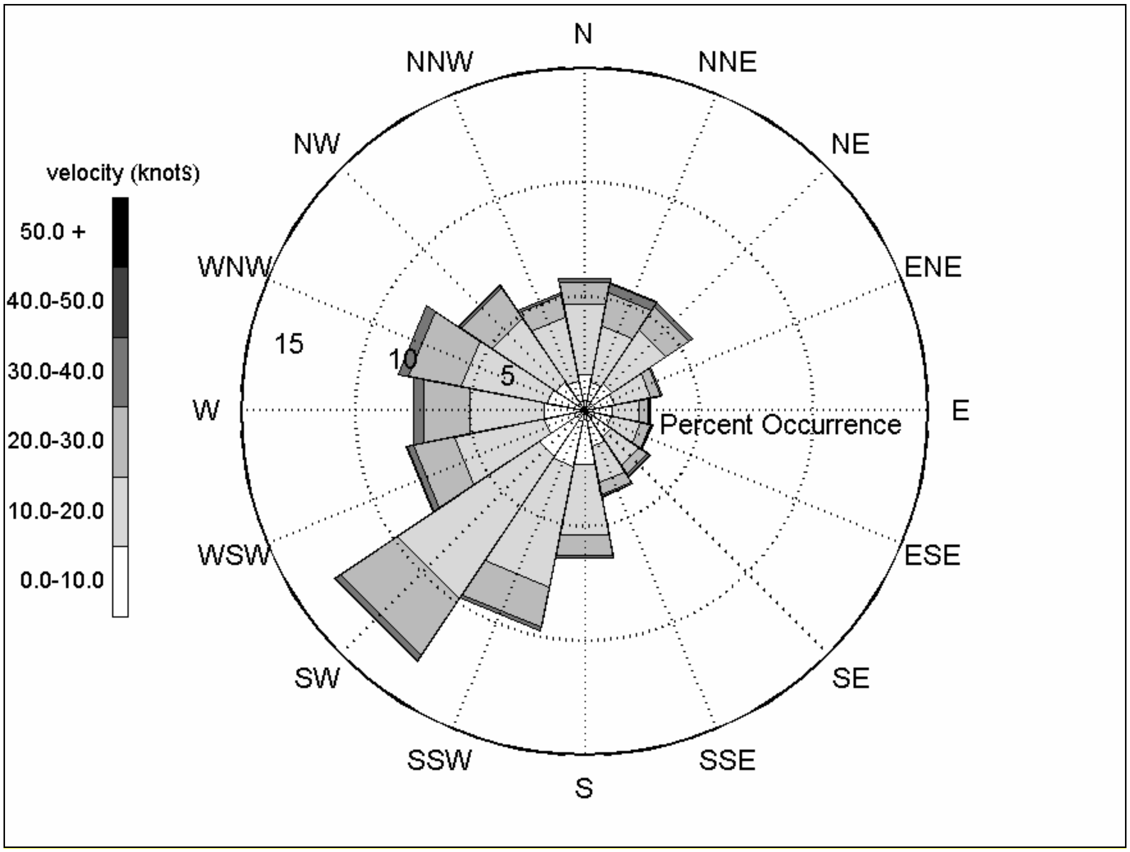


Figure V-2. Wind rose for the BUZM3 Station located near the southern entrance to Buzzards Bay. Wind data is for the time 20-year time period between 1985 and 2004.

For the Eel Pond/Back River system, the glacial nature of the regional shoreline has limited the sediment supply that potentially could create shoaling problems within the inlet throat. The 2001 aerial photograph shown in Figure V-3 illustrates the boulder strewn regions offshore of Phinneys Point, indicative of glacial deposits that are naturally erosion-resistant. In addition, this figure indicates the location of the two major hydrodynamic restrictions to the Eel Pond/Back River system: the railroad bridge and the Shore Road bridge. These restrictions have existed since at least the early 1900s.

Figure V-3. 2001 aerial photograph showing Phinneys Point and the two bridges across the inlet to the Eel Pond/Back River system.

Historically, the navigation channel servicing the Cape Cod Canal ran along the east side of Mashnee Island (see Figure V-4). Improvements to the Cape Cod Canal during the mid-1930s created the Mashnee Island causeway, effectively reducing the tidal circulation within Phinneys Harbor. The remnant 1931 Canal navigation channel south of the causeway still exists.

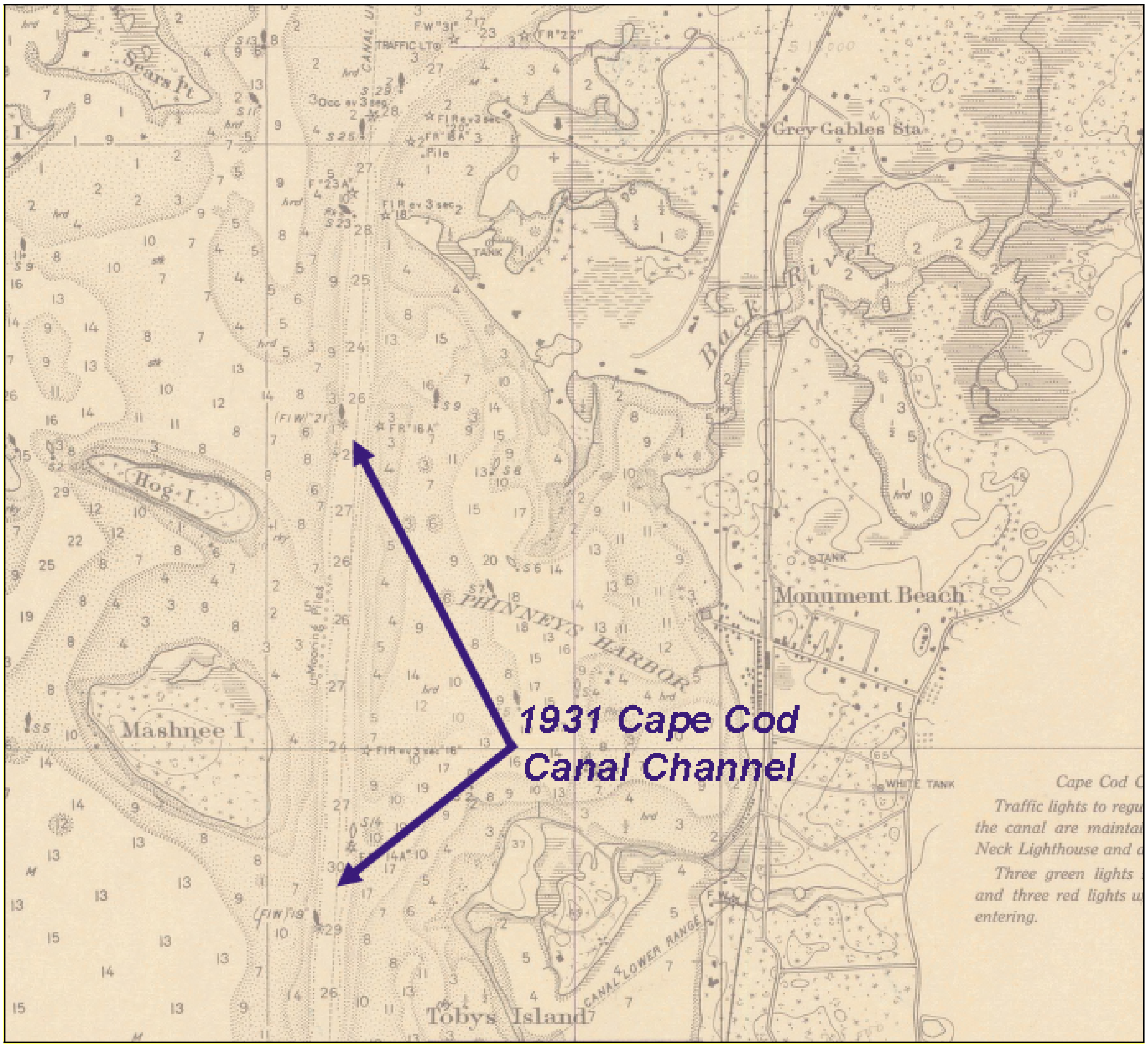


Figure V-4. A portion of the NOAA 1931 nautical chart showing the former dredged channel for the Cape Cod Canal. As indicated on the figure, this channel passed to the east of Mashnee Island.

As shown in Figure V-5, hurricanes can have a significant impact on both the shoreline and the inlets. Due to the relatively quiescent wave and tide regime within this region, the impact of infrequent storms, primarily a result of storm surge, can be dramatic. According to historic flooding information (U.S. Army Corps of Engineers, 1939), the storm surge level in Phinneys Harbor was approximately 14 to 16 feet above mean tide level during the peak of the 1938 Hurricane. Due to this elevated water level, the low-lying land features that separate Eel Pond/Bach River from Buzzards Bay were overtopped. These infrequent storms can reshape the shoreline in ways that would require many years or decades under the typical wave, wind, and tide regime of the Buzzards Bay coast. During the twentieth century, the severe hurricanes influencing the Bourne shoreline include the hurricanes of 1938, 1944, and 1954, as well as Hurricane Bob in 1991. Of these storms, the Hurricane of 1938 had the largest storm surge along the Buzzards Bay shore of Falmouth (U.S. Army Corps of Engineers, 1988). Figure V-6 illustrates the significant storm surge during the 1938 hurricane in nearby Buzzards Bay village.

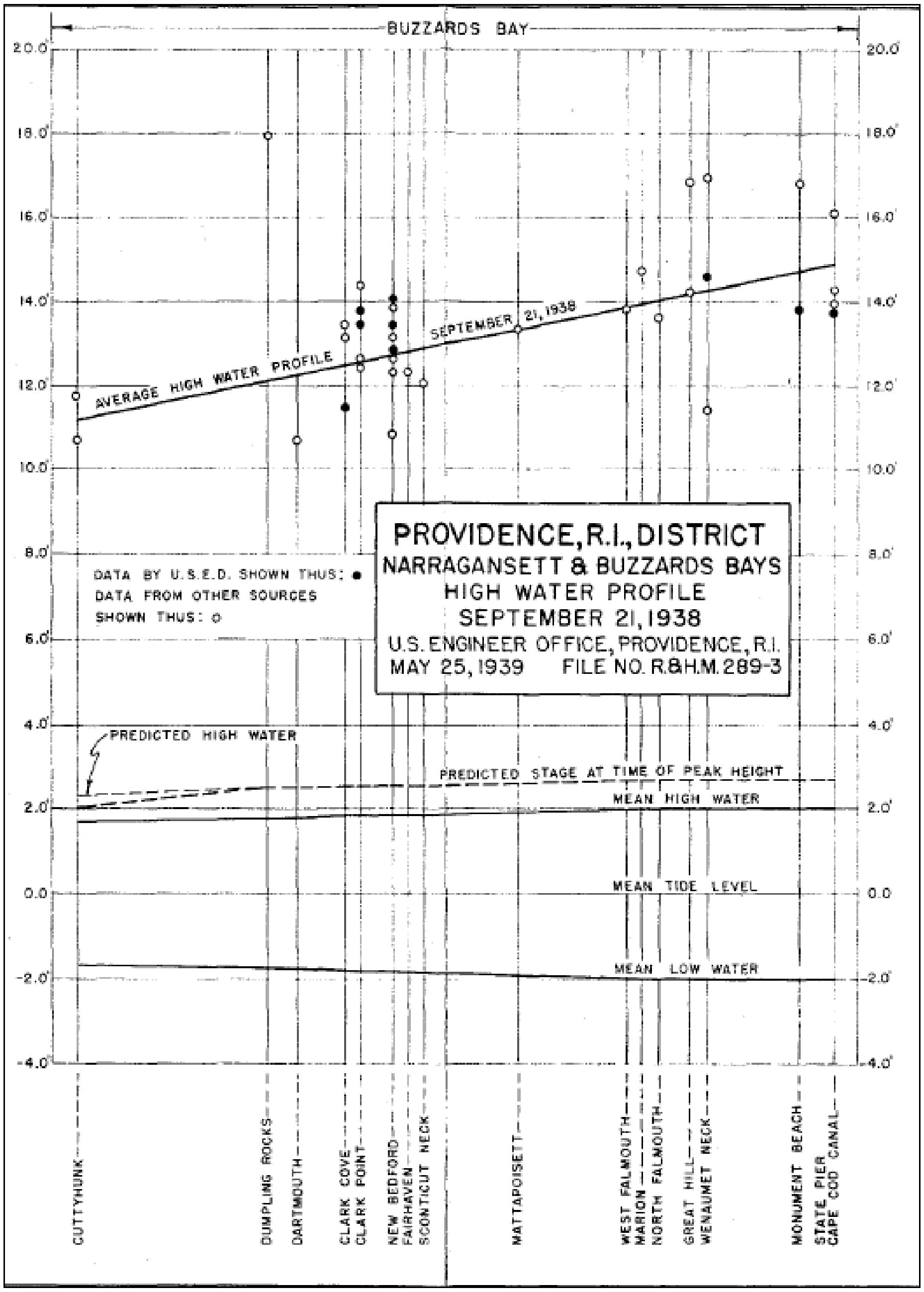


Figure V-5. Flood levels at various locations in Buzzards Bay resulting from the September 21, 1938 Hurricane (USACE, 1939).

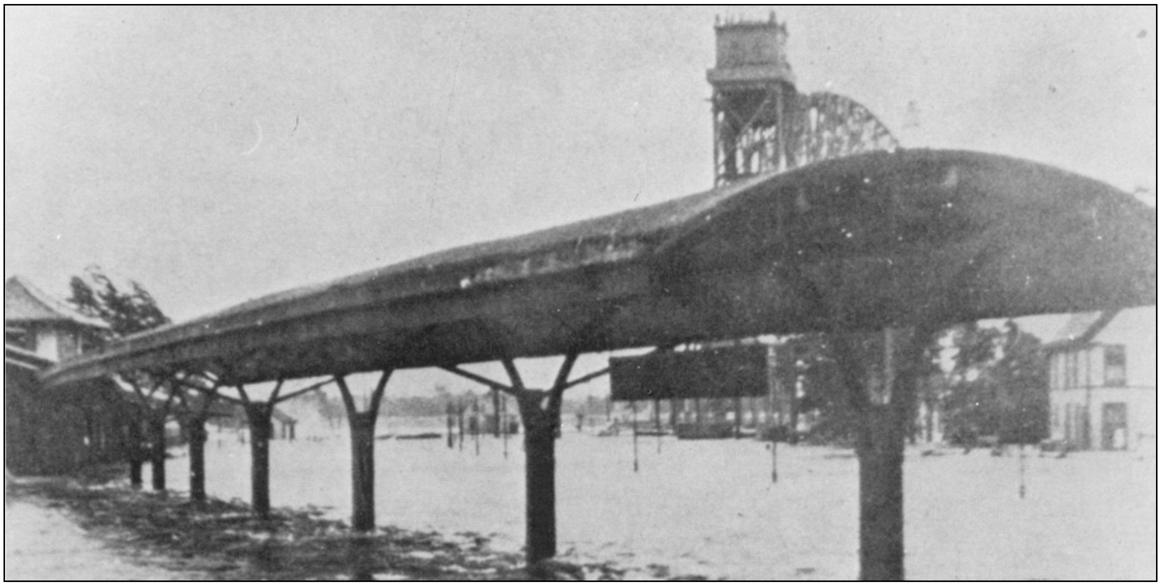


Figure V-6. The Buzzards Bay railroad station the September 21, 1938 Hurricane illustrating the level of storm surge.

V.2 DATA COLLECTION AND ANALYSIS

The field data collection portion of this study was performed to characterize the physical properties of the Back River system. Bathymetry was collected throughout the system so that it could be accurately represented as a computer hydrodynamic model, and so that flushing rates could be determined for the system sub-embayments. In addition to the bathymetry, tide data were also collected at three locations in the system, to run the circulation model with real tides, and also to calibrate and verify its performance.

V.2.1 Bathymetry Data

The two sources of bathymetric data used in the development of the Back River system hydrodynamic model were the NOAA GEODAS database and an August 2001 survey. The GEODAS data were from a 1977 survey of northern Buzzards Bay, and were used in the main basin of Phinneys Harbor. The 2001 survey covered areas not included GEODAS database, namely Back River and Eel Pond.

The 2001 bathymetry survey in Back River and Eel Pond survey employed a bottom tracking Acoustic Doppler Current Profiler (ADCP) mounted on a 12 ft motor skiff. Positioning data were collected using a differential GPS. The survey design included transects at 200 ft spacings in Back River, and 500 ft spacings in Eel Pond. Marsh channels in the upper portion of Back River were also surveyed with the ADCP, where depths allowed the passage of the survey boat. The actual survey paths are shown in Figure V-7. The resulting bathymetric surface created by interpolating the data to a finite element mesh is shown in Figure V-8. All bathymetry was tide corrected, and referenced to the North American Vertical Datum (NAVD 88), using a NGS benchmark located on the Shore Road bridge.

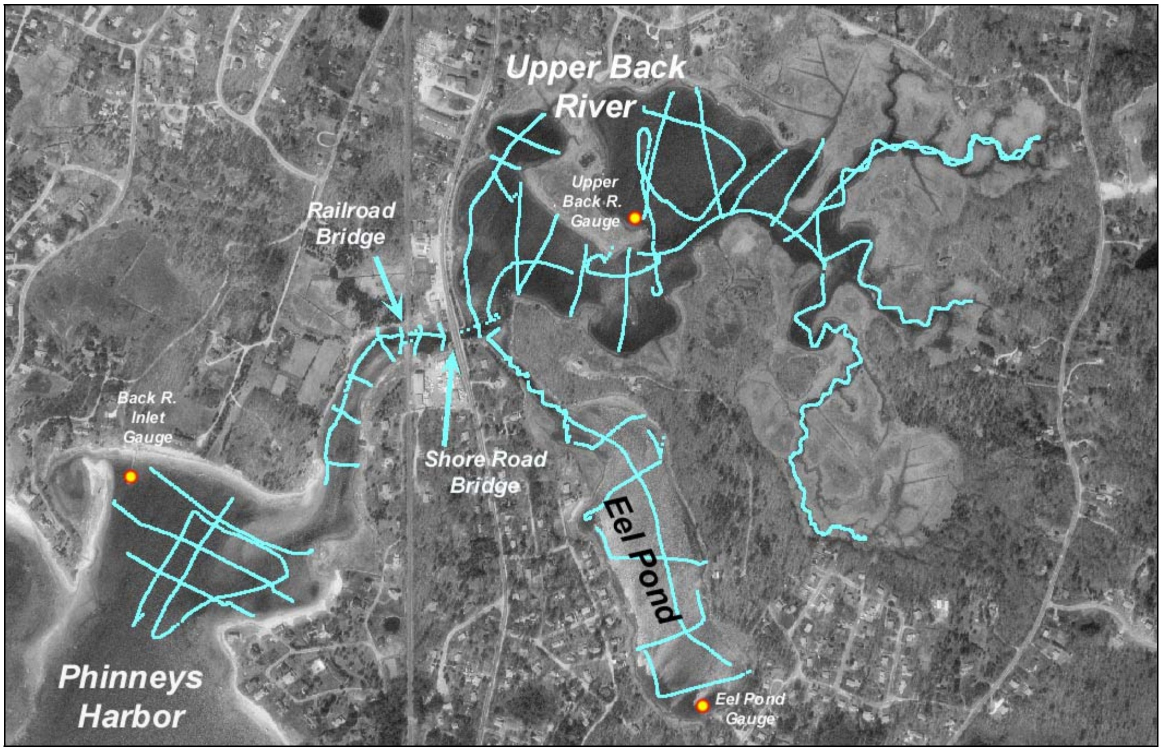


Figure V-7. Transects from the August 2001 bathymetry survey of the Back River system. Yellow markers show the locations of the three tide recorders deployed for this study.

Results from the survey show that the deepest point in the Back River system is located just downstream of the railroad bridge, and is -19.3 ft NAVD. Aside from the inlet to Phinneys Harbor, maximum depths in the Back River system occur in the vicinity of the two bridges, and are likely the effect of scouring from increased current velocities caused by flow restrictions at the bridge abutments. The maximum depth in Eel Pond is -10.9 ft NAVD, and is located at the southern end of the pond.

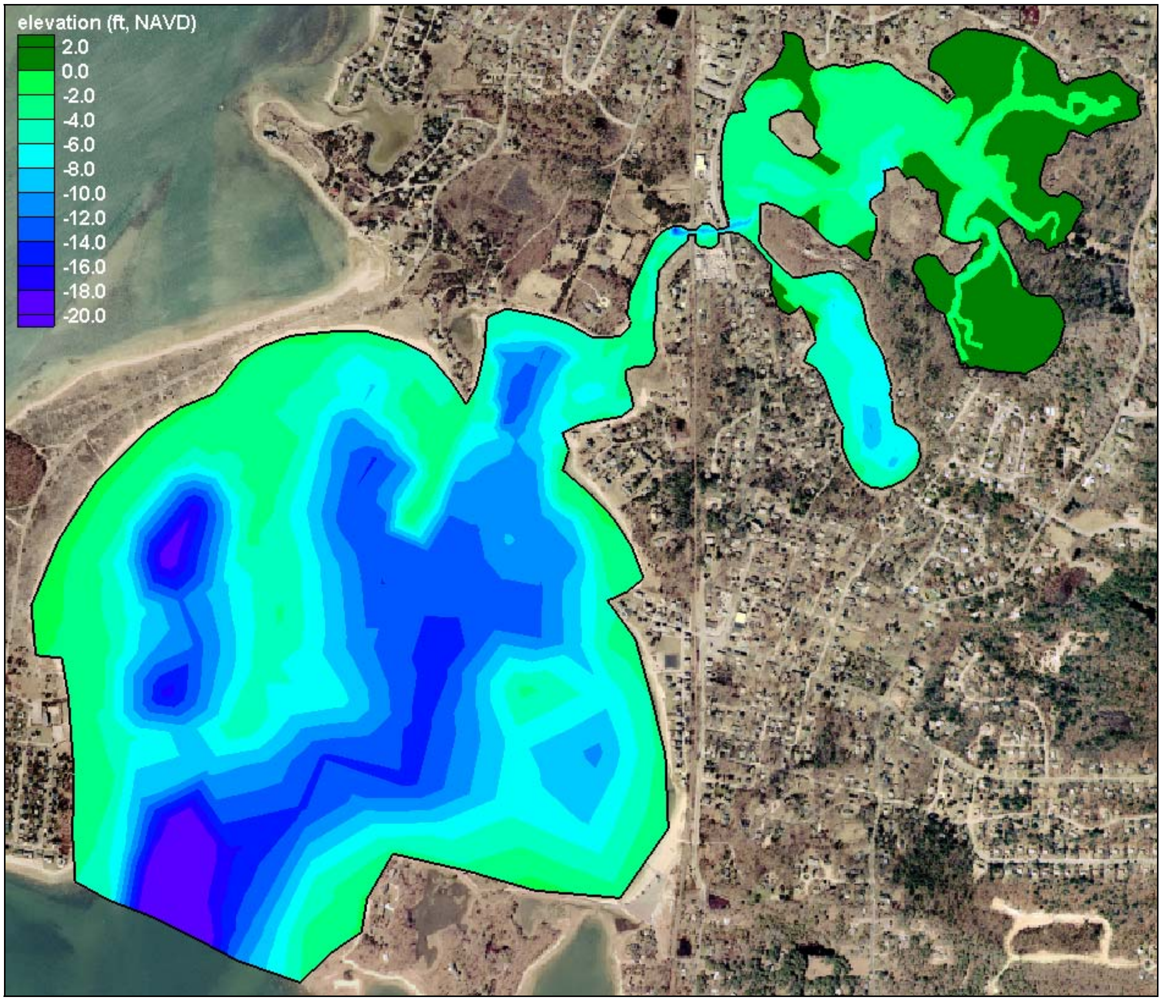


Figure V-8. Bathymetry data interpolated to the finite element mesh used with the RMA-2 hydrodynamic model. Contours represent the bottom elevation relative to NAVD 88. Data sources are the August 2001 survey of the Back River system, and the NOAA GEODAS database for Phinneys Harbor.

V.2.2 Tide Data Collection and Analysis

Tide data records were collected at three stations in the Back River system: Back River inlet to Phinneys Harbor, Eel Pond, and in the upper portion of Back River. The locations of the stations are shown in Figure V-7. The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 38-day period between August 3, 2001 and September 10, 2001. The elevation of each gauge was surveyed relative to NAVD 88. The tide record at the inlet to Phinneys Harbor was used as the open boundary condition of the hydrodynamic model. Data from the other two locations were used to calibrate the model.

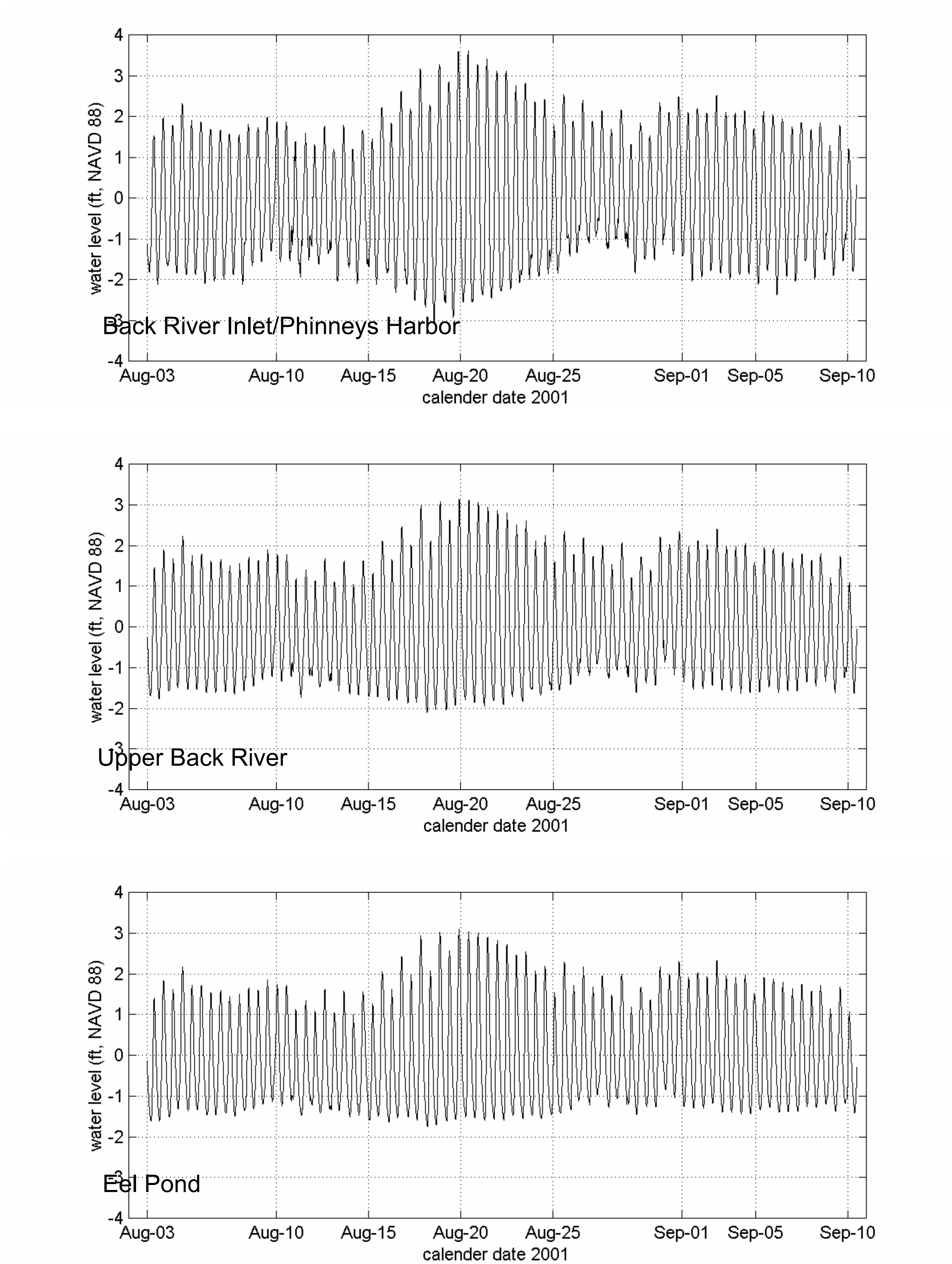


Figure V-9. Plots of observed tides for the Back River system, for the 38-day period between August 3 and September 10, 2001. The top plot shows tides for Back River Inlet, at Phinneys Harbor. The middle plot shows tides recorded in the upper portion of Back River, and the bottom plot shows tides recorded at the southern portion of Eel Pond. All water levels are referenced to the North American Vertical Datum (NAVD 88).

Plots of the tide data from the three gauges are shown in Figure V-9, for the entire 38-day deployment. The spring-to-neap variation in tide range is easily discernable in these plots. From the plot of the data from Back River Inlet, the tide reaches its maximum spring tide range of approximately 6 feet around August 20, but about seven days before and after this date, the neap tide range is much smaller, as small as 2 feet. A visual comparison between tide elevations at the three stations shows that there is a reduction in the tide range in the upper Back River, and in Eel Pond. The loss of amplitude with distance from the inlet is described as tidal attenuation. Frictional mechanisms dissipate tidal flow energy, resulting in a reduction of the height of the tide. In Eel Pond the difference is most apparent, where the low tide level does not vary as much as it does in Phinneys Harbor. This attenuation of the tide signal from Phinneys Harbor is due to flow restrictions caused by the inlet channels and the bridge abutments.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 38-day records. These datums are presented in Table V-1. For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data was available, however, these datums still provide a useful comparison of tidal dynamics within the system. The Mean Higher High (MHH) and Mean Lower Low (MLL) levels represent the mean of the daily highest and lowest water levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW.

Table V-1. Tide datums computed from 38-day records collected at Phinneys Harbor, Upper Back, R., and Eel Pond in August/September 2001. Datum elevations are given relative to NAVD 88.

Tide Datum	Phinneys Harbor (feet)	Upper Back River (feet)	Eel Pond (feet)
Maximum Tide	3.6	3.1	3.1
MHHW	2.3	2.1	2.1
MHW	2.0	1.9	1.8
MTL	0.1	0.2	0.2
MLW	-1.8	-1.5	-1.4
MLLW	-2.0	-1.6	-1.4
Minimum Tide	-3.1	-2.1	-1.8

The tides in Buzzards Bay are semi-diurnal, meaning that there are typically two tide cycles in a day. There is usually a small variation in the level of the two daily tides. This variation can be seen in the differences between the MHHW and MHW, as well as the MLLW and MLW levels.

Frictional damping is evident in the reduction of the High Water (HW) and Low Water (LW) levels from Phinneys Harbor to upper Back River and Eel Pond. Damping effects are seen in the Eel Pond record, where the MLLW and MLW levels are the same, and at a higher elevation than Phinneys Harbor. Damping not only effects the range of the observed tide, it also causes a time lag in the time of high and low tide. Figure V-10 shows how the time of high and low tides lags approximately one hour from the tide in Phinneys Harbor.

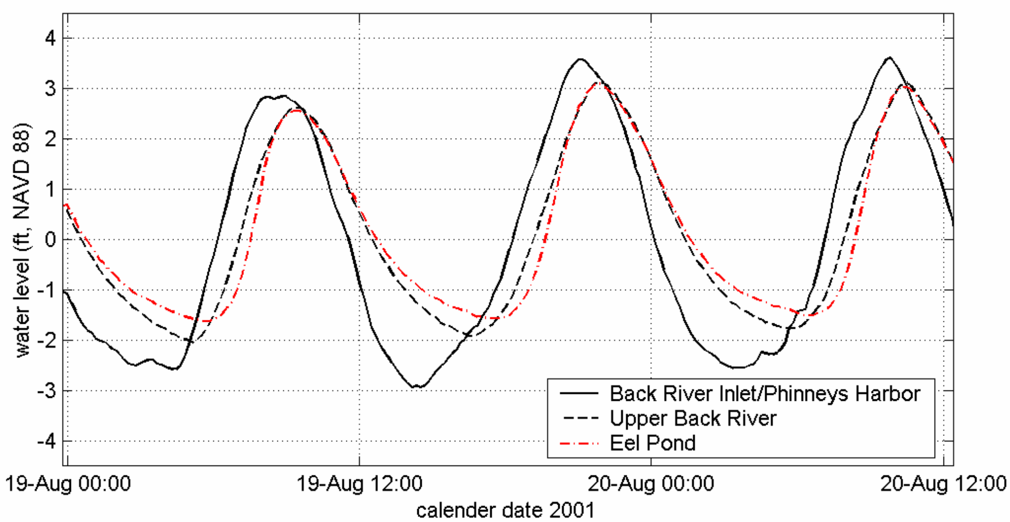


Figure V-10. Two-day tide plot showing tides in the Back River system plotted together. Demonstrated in this plot is the frictional damping effect caused by flow restrictions at the two bridges over Back River, and the additional damping caused by the inlet channel to Eel Pond. The damping effects are seen as a reduction in tidal amplitude, as well as the lag in time of high and low tides from Phinneys Harbor.

A more thorough harmonic analysis of the tidal time series was also performed to produce tidal amplitude and phase of the major tidal constituents, and provide assessments of hydrodynamic 'efficiency' of each system in terms of tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each system.

An harmonic analysis was performed on the time series from each gauge location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 known tidal constituents result from this procedure. Table V-2 presents the amplitudes of eight tidal constituents in the Back River system. The M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an amplitude of 1.86 at the Back River inlet (Phinneys Harbor). The total range of the M_2 tide is twice the amplitude, or 3.72 feet. The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.2 feet. Other semi-diurnal tides, the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides, contribute significantly to the total tide signal, with amplitudes of 0.41 feet and 0.56 feet, respectively. The M_4 and M_6 tides are higher frequency harmonics of the M_2 lunar tide (exactly half the period of the M_2 for the M_4, and one third of the M_2 period for the M_6), results from frictional attenuation of the M_2 tide in shallow water. The M_4 is already large at the system inlet, with an amplitude of 0.3 feet. The M_6 has a very small amplitude throughout the system (about 0.05 feet at the inlet and 0.08 feet in Eel pond). The M_{sf} is a lunarsolar fortnightly constituent with a period of approximately 14 days, and is the result of the periodic conjunction of the sun and moon.

Table V-2. Tidal Constituents, Back River sub-embayments, August to September 2001.

	Amplitude (feet)							
Constituent	M_2	M_4	M_6	S_2	N_2	K_1	O_1	M_{sf}
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Back River Inlet	1.86	0.30	0.05	0.41	0.56	0.22	0.16	0.04
Upper Back River	1.60	0.26	0.04	0.30	0.44	0.21	0.17	0.10
Eel Pond	1.50	0.35	0.08	0.26	0.38	0.21	0.17	0.12

The observed astronomical tide is therefore the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in Figure V-11.

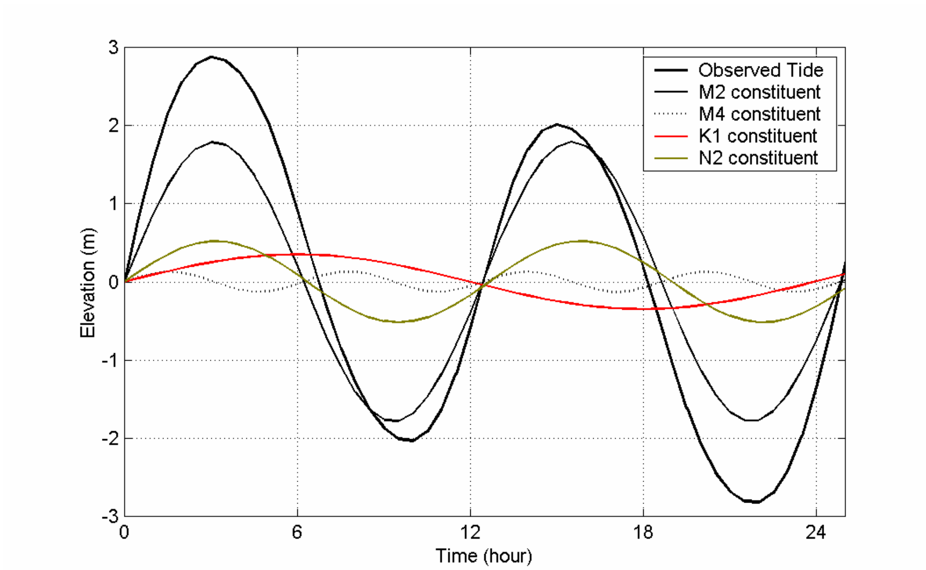


Figure V-11. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-2 also shows how the constituents vary as the tide propagates into the upper reaches of the system. Note the reduction in the M_2 amplitude between the inlet and Eel Pond and the upper portion of Back River. Frictional damping is evident as a decrease in the amplitude of M_2 constituent. Usually, a portion of the energy lost from the M_2 tide is transferred to higher harmonics (i.e., the M_4 and M_6), and is observed as an increase in amplitude of these constituents over the length of an estuary. However, in the upper Back River, the M_2, M_4, and M_6, are all clearly smaller than the amplitudes at the inlet. This is likely because the tidal attenuation caused by the bridge abutments and the inlet channel is much stronger than the possible transfer of energy from the M_2 to its harmonics (resulting from frictional drag through tidal channels). In Eel Pond, additional attenuation of the M_2 signal from upper Back River is accompanied by growth in both the M_4 and M_6 harmonics. This result shows that though frictional damping does occur in the inlet channel to Eel Pond, it is not as severe an effect as caused by the channel and bridge abutments of the Back River.

As discussed previously, phase delay is another indication of tidal damping, and results with a later high tide at inland locations. The greater the frictional effects, the longer the delay between locations. The phase delay of the M_2 tide at upper Back River compared to the gauge at Phinneys Harbor was determined to be 48 minutes, by the harmonic analysis. For Eel Pond, the phase delay of the M_2 tide was determined to be 66 minutes from Phinneys Harbor, or an additional 18 minutes delay from upper Back River. For the M_4 overtide, the phase delay is 6 minutes for upper Back River, and 4 minutes for Eel Pond, relative to Phinneys Harbor.

In addition to the tidal analysis, the data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. These other processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow. The results of an analysis to determine the energy distribution (or variance) of the original water elevation time series for the Back River system is presented in Table V-3 compared to the energy content the astronomical tidal signal (re-created by summing the contributions from the 23 constituents determined by the harmonic analysis). Subtracting the tidal signal from the original elevation time series resulted with the non-tidal, or residual, portion of the water elevation changes. The energy of this non-tidal signal is compared to the tidal signal, and yields a quantitative measure of how important these non-tidal physical processes can be to hydrodynamic circulation within the estuary.

Table V-3 shows that the variance of tidal energy was largest in the signal in Phinneys Harbor; as should be expected given the tidal attenuation through the system. In general, the energy of the signal decreases with distance from the offshore gauge, with the lowest energy found in upper regions of the ponds. The analysis also shows that tides are responsible for approximately 97% of the water level changes in Back River system; wind effects in these data sets were negligible.

Table V-3. Percentages of Tidal versus Non-Tidal Energy for Back River embayments, August to September 2001.

TDR LOCATION	Total Variance (ft^2·sec)	Tidal (%)	Non-tidal (%)
Back River Inlet/Phinneys Harbor	1.94	97.3	2.7
Upper Back River	1.47	97.2	2.8
Eel Pond	1.34	96.7	3.3

V.3 HYDRODYNAMIC MODELING

For the modeling of the Back River system, Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in these systems. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers. Applied Coastal staff members have utilized RMA-2 for numerous flushing studies on Cape Cod, including West Falmouth Harbor, Popponesset Bay, Chatham embayments (Kelley, *et al*, 2001), Falmouth "finger" Ponds (Ramsey, *et al*, 2000), and Barnstable Harbor (Wood, *et al*, 1999).

V.3.1 Model Theory

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers (Norton et al., 1973). Further development included the introduction of one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post-processing routines were updated by a Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). Graphics generated in support of this report primarily were generated within the SMS modeling package.

RMA-2 is a finite element model designed for simulating one- and two-dimensional depth-averaged hydrodynamic systems. The dependent variables are velocity and water depth, and the equations solved are the depth-averaged Navier Stokes equations. Reynolds assumptions are incorporated as an eddy viscosity effect to represent turbulent energy losses. Other terms in the governing equations permit friction losses (approximated either by a Chezy or Manning formulation), Coriolis effects, and surface wind stresses. All the coefficients associated with these terms may vary from element to element. The model utilizes quadrilaterals and triangles to represent the prototype system. Element boundaries may either be curved or straight.

The time dependence of the governing equations is incorporated within the solution technique needed to solve the set of simultaneous equations. This technique is implicit; therefore, unconditionally stable. Once the equations are solved, corrections to the initial estimate of velocity and water elevation are employed, and the equations are re-solved until the convergence criteria is met.

V.3.2 Model Setup

There are three main steps required to implement RMA-2:

- Grid generation
- Boundary condition specification
- Calibration

The extent of each finite element grid was generated using 1994 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of each system based on the tide gauge data collected in Phinneys Harbor, at the entrance to Back River. Once the grid and boundary conditions were set, the model was calibrated to ensure accurate predictions of tidal flushing. Various friction and eddy viscosity coefficients were adjusted, through several (20+) model calibration simulations for each system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. A 1994 digital aerial orthophoto and recent bathymetry survey data were imported to SMS, and a finite element grid was generated to represent the estuary. The aerial photograph was used to determine the land boundary of the system, as well as determine the surface coverage of salt marsh. The bathymetry data was interpolated to the developed finite element mesh of the system. The completed grid consists of 5,939 nodes, which describe 2,489 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth is -15.9 ft (NAVD 88), in the vicinity of the railroad bridge, and the maximum modeled marsh plain elevation is 2.7 ft. In the model grid, a typical marsh plain elevation of +1.8 ft NAVD was used, based on spot surveys across the marsh. The model marsh topography was varied to provide a monotonically sloping surface, in order to enhance the stability of the hydrodynamic model. The completed grid mesh of the Back River system is shown in Figure V-12.

The finite element grid for each system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties of the Back River system. Areas of marsh were included in the model because they represent a large portion of the total area of this system, and have a significant effect on system hydrodynamics. Fine resolution was required to simulate the numerous channel constrictions that significantly impact the estuarine hydrodynamics, such as the bridge abutments, as well as the marsh creeks. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary.

Grid resolution was governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution was employed where complex flow patterns were expected. For example, smaller node spacing in marsh creeks and channels was designed to provide a more detailed analysis in these regions of rapidly varying flow. Widely spaced nodes were often employed in areas where flow patterns are not likely to change dramatically, such as in Eel Pond, the upper portion of Back River, and on the marsh plain. Appropriate implementation of wider node spacing and larger elements reduced computer run time with no sacrifice of accuracy.

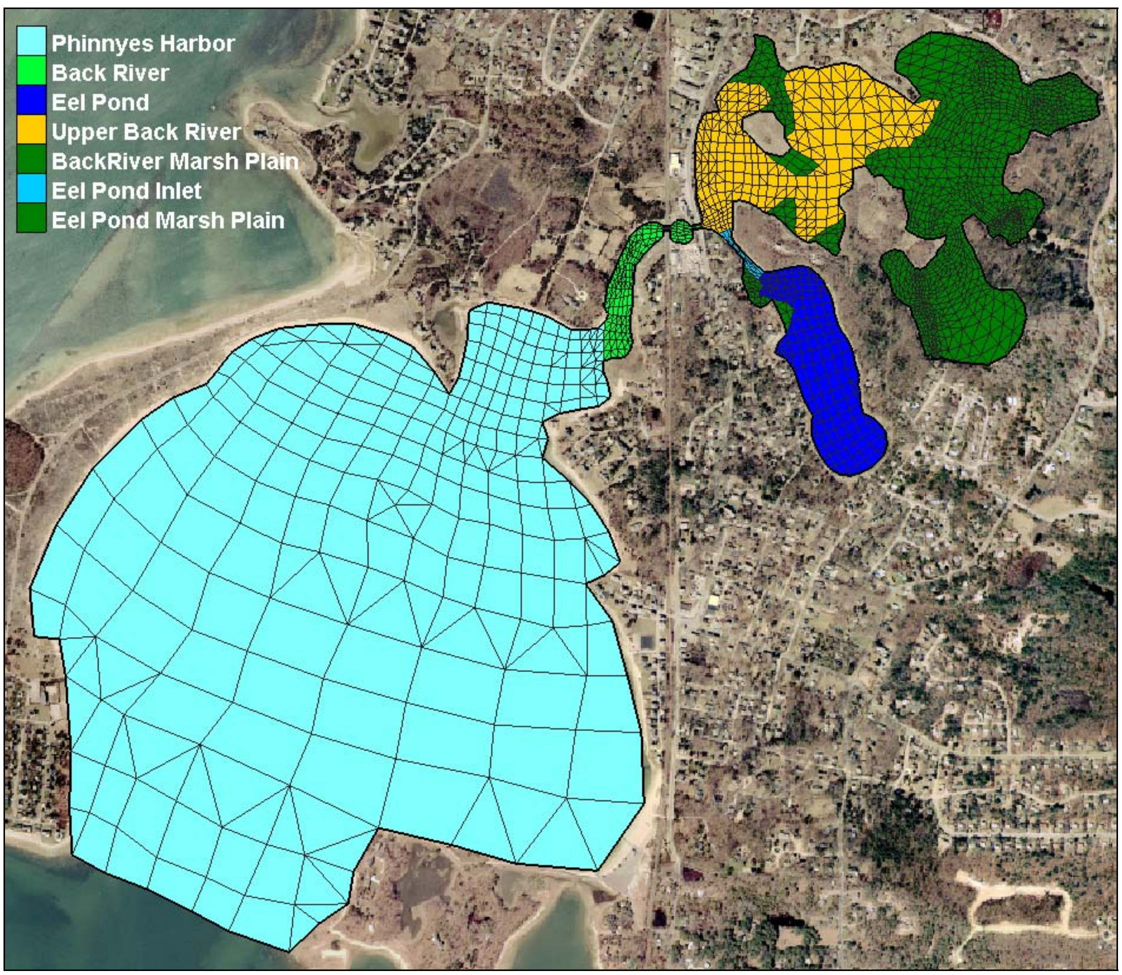


Figure V-12. Plot of hydrodynamic model grid mesh for the Back River system. Color patterns designate the different model material types used to vary model calibration parameters and compute flushing rates.

V.3.2.2 Boundary condition specification

Two types of boundary conditions were employed for the RMA-2 model of the Back River system: 1) "slip" boundaries, and 2) tidal elevation boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. A tidal boundary condition was specified at the inlet from Phinneys Harbor. TDR measurements provided the required data. The rise and fall of the tide in Buzzards Bay is the primary driving force for estuarine circulation in this system. Dynamic (time-varying) model simulations specified a new water surface elevation in Phinneys Harbor every model time step (12 minutes).

V.3.2.3 Calibration

After developing the finite element grids, and specifying boundary conditions, the model for the Back River system was calibrated. The calibration procedure ensures that the model predicts accurately what was observed in nature during the field measurement program. Numerous model simulations are required (typically 20+) for an estuary model, specifying a range of friction and eddy viscosity coefficients, to calibrate the model.

Calibration of the hydrodynamic model required a close match between the modeled and measured tides in each of the sub-embayments where tides were measured (i.e., from the TDR deployments). Initially, the model was calibrated to obtain visual agreement between modeled and measured tides. Once visual agreement was achieved, an approximate five-day period (10 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section V-2. The five-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents

The calibration was performed for a five-day period beginning August 17, 2001 at 1800 EDT. This representative time period included the spring tide range of conditions, where the tide range and tidal currents are greatest. To provide average tidal forcing conditions for model verification and the flushing analysis, a separate time period was chosen that spanned the transition between spring and neap tide ranges (bi-weekly maximum and minimum tidal ranges, respectively). For the flushing analysis the 7.25 day period (14 tide cycles) beginning August 13 2001, at 1500 EDT was used.

The calibrated model was used to analyze existing detailed flow patterns and compute residence times. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire seven-day simulation. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events.

V.3.2.3.a Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient, and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.02 and 0.07 were specified for all element material types. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels and marsh plains with higher friction (Henderson, 1966).

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning's coefficients were matched to bottom type. For example, lower friction coefficients were specified for the smooth sandy channels found in the lower portion of the Back River, versus the rock strewn bottom of the shallow inlet to Eel Pond, which provides greater flow resistance. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based ranges provided by the Civil Engineering Reference Manual (Lindeburg, 1992), and values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in the Table V-4.

Table V-4. Manning's Roughness coefficients used in simulations of modeled embayments. These embayment delineations correspond to the material type areas shown in V-7.

System Embayment	Bottom Friction
Back River Entrance/Phinneys Harbor	0.030
Back River	0.030
Upper Back River	0.030
Back River Marsh Plain	0.100
Eel Pond Inlet	0.040
Eel Pond	0.035
Eel Pond Marsh Plain	0.100

V.3.2.3.b Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 50 and 100 lb-sec/ft^2. Higher values (up to 200 lb-sec/ft^2) were used on the marsh plain, to ensure solution stability.

V.3.2.3.c Marsh porosity processes

Modeled hydrodynamics were complicated by wetting/drying cycles on the marsh plain included in the model of the Back River system. Cyclically wet/dry areas of the marsh will tend to store waters as the tide begins to ebb and then slowly release water as the water level drops within the creeks and channels. This store-and-release characteristic of these marsh regions was partially responsible for the distortion of the tidal signal, and the elongation of the ebb phase of the tide. On the flood phase, water rises within the channels and creeks initially until water surface elevation reaches the marsh plain, when at this point the water level remains nearly constant as water 'fans' out over the marsh surface. The rapid flooding of the marsh surface corresponds to a flattening out of the tide curve approaching high water. Marsh porosity is a feature of the RMA-2 model that permits the modeling of hydrodynamics in marshes. This model feature essentially simulates the store-and-release capability of the marsh plain by allowing grid elements to transition gradually between wet and dry states. This technique allows RMA-2 to change the ability of an element to hold water, like squeezing a sponge. The marsh porosity feature of RMA-2 is typically utilized in estuarine systems where the marsh plain has a significant impact on the hydrodynamics of a system, such Back River.

V.3.2.3.d Comparison of modeled tides and measured tide data

A best-fit of model predictions for the first TDR deployment was achieved using the aforementioned values for friction and turbulent exchange. Figures V-13 and V-14 illustrate the five-day calibration simulation along with 50-hour sub-section, for upper Back River and Eel Pond. Modeled (solid line) and measured (dotted line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled systems. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1, M_2, M_4, and M_6. Measured tidal constituent heights (H) and time lags (ϕ_{lag}) shown in Table V-5 for the calibration period differ from those in Table V-2 because constituents were computed for only the five-day section of the 38-days represented in Table V-2. Table V-5 compares tidal constituent height and time lag for modeled and measured tides at the TDR locations. Time lag represents the time required for a constituent to propagate from Phinneys Harbor to either TDR location.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.01 ft, which is of the same order of the accuracy of the tide gauges (0.032 ft). Time lag errors were typically less than the time increment resolved by the model (0.20 hours or 12 minutes), indicating good agreement between the model and data.

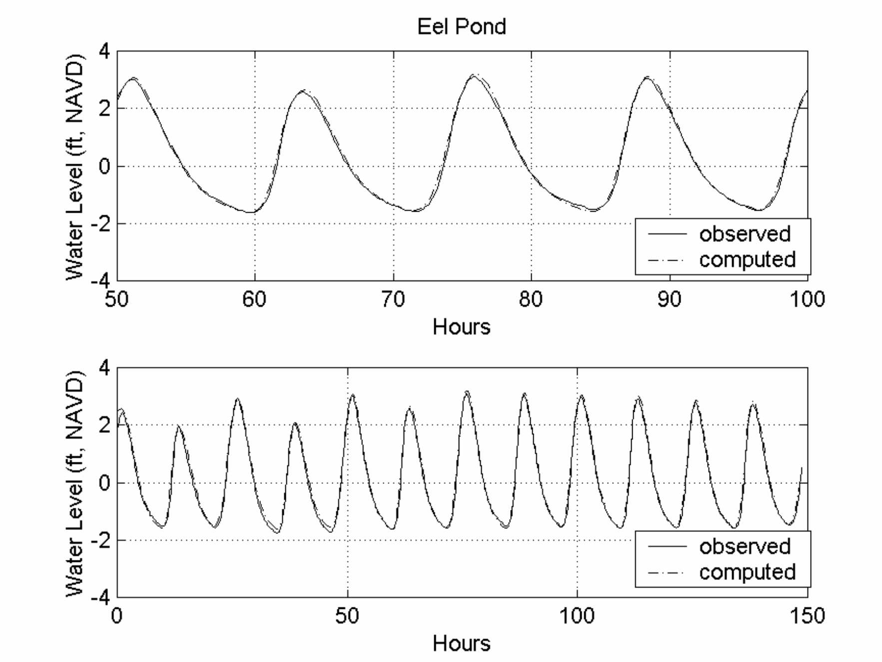


Figure V-13. Comparison of model output and measured tides for the TDR location in Eel Pond. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

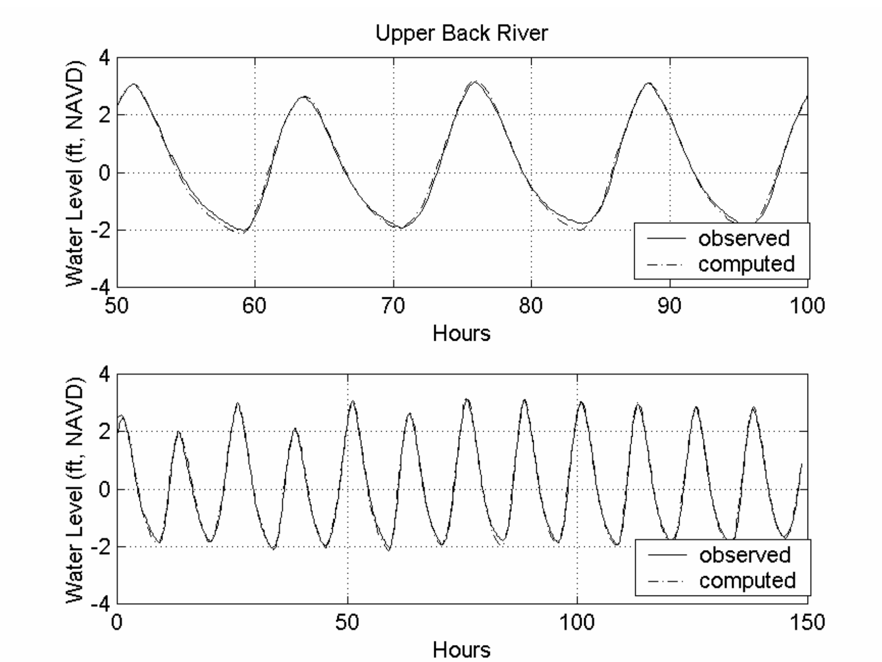


Figure V-14. Comparison of model output and measured tides for the TDR location in Eel Pond. The top plot is a 50-hour sub-section of the total modeled time period, shown in the bottom plot.

Table V-5. Tidal constituents for measured water level data and calibrated model output for northern embayments.

Location	Constituent Amplitude (ft)				Phase (deg)	
Model calibration run						
Location	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Upper Back R.	2.31	0.39	0.01	0.20	80.0	122.1
Eel Pond	2.11	0.59	0.14	0.19	88.5	135.5
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Upper Back R.	2.26	0.45	0.04	0.20	80.3	120.3
Eel Pond	2.07	0.63	0.19	0.20	87.7	133.4
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Upper Back R.	-0.05	0.06	0.03	0.00	0.6	-1.9
Eel Pond	-0.04	0.04	0.05	0.01	-1.5	-2.3

V.3.2.4 Model Circulation Characteristics

The final calibrated model serves as a useful tool in investigating the circulation characteristics of the Back River system. Using model inputs of bathymetry and tide data, current velocities and flow rates can be determined at any point in the model domain. This is a very useful feature of a hydrodynamic model, where a limited amount of collected data can be expanded to determine the physical attributes of the system in areas where no physical data record exists.

From the model run of the Back River system, flood velocities in the channels are slightly larger than velocities during maximum ebb. At the two bridges over Back River, maximum depth-averaged flood velocities in the model are approximately 6.5 feet/sec, while maximum ebb velocities are about 5.5 feet/sec. In the inlet channel to Eel Pond, maximum depth averaged flood velocities are approximately 4.0 feet/sec, and maximum ebb velocities are 2.0 feet/sec. A close-up of the model output is presented in Figure V-15, which shows contours of velocity magnitude, along with velocity vectors which indicate the direction of flow, for a single model time-step, at the portion of the tide where maximum flood velocities occur.

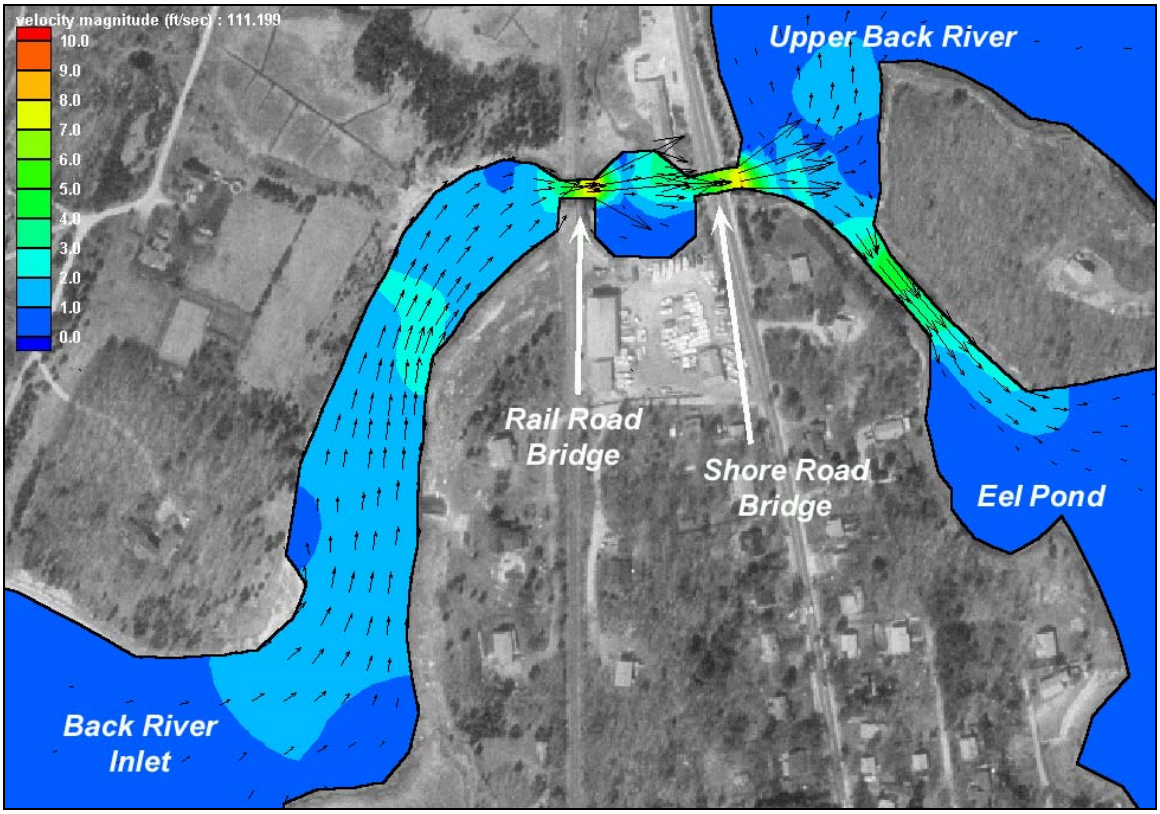


Figure V-15. Example of hydrodynamic model output for a single time step where maximum flood velocities occur for this tide cycle. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

In addition to depth averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. For the flushing analysis in the next section, flow rates where computed across three separate transects in the Back River system: at the Back River Inlet, at the inlet channel to Eel Pond, and also at a transect near the Shore Road bridge for the upper portion of Back River. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in Figure V-16. Maximum flow rates occur during flood tides in this system, an indication that this estuary system is flood dominant, and likely a sediment sink (a system that accumulates sediment). During spring tides, the maximum flood flow rates reach 1800 ft^3/sec at the Back River inlet. Maximum ebb flow rates during spring tides are slightly less, or about 1500 ft^3/sec. Minimum flood flows at the inlet during neap tides are 800 ft^3/sec, and minimum ebb flows during neap tides are approximately 600 ft^3/sec.

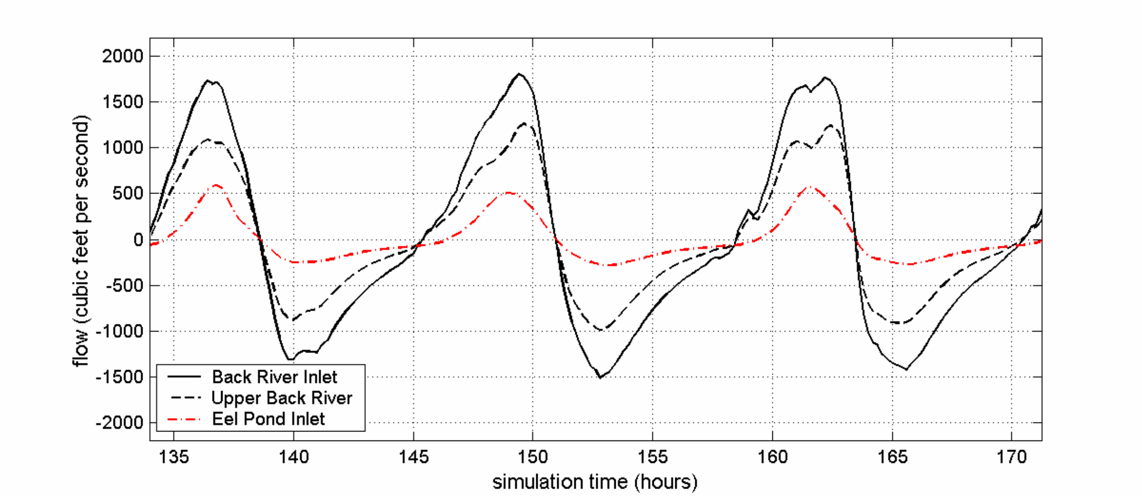


Figure V-16. Time variation of computed flow rates for three transects in the Back River system. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Plotted time period represents three tide cycles (12.42 h cycle). Positive flow indicated flooding tide, while negative flow indicates ebbing tide.

V.4 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through each inlet, the primary mechanism controlling estuarine water quality within the modeled Back River system is tidal exchange. A rising tide offshore in Buzzards Bay creates a slope in water surface from the ocean into the modeled systems. Consequently, water flows into (floods) the system. Similarly, each estuary drains into the open waters of Buzzards Bay on an ebbing tide. This exchange of water between each system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitatively tidal flushing of each system, and was used to compute flushing rates (residence times) and tidal circulation patterns.

Flushing rate, or residence time, is defined as the average time required for a parcel of water to migrate out of an estuary from points within the system. For this study, **system residence times** were computed as the average time required for a water parcel to migrate from a point within the each embayment to the entrance of the system. System residence times are computed as follows:

$$T_{system} = \frac{V_{system}}{P} t_{cycle}$$

where T_{system} denotes the residence time for the system, V_{system} represents volume of the (entire) system at mean tide level, P equals the tidal prism (or volume entering the system through a single tidal cycle), and t_{cycle} the period of the tidal cycle, typically 12.42 hours (or 0.52 days). To compute system residence time for a sub-embayment, the tidal prism of the sub-embayment replaces the total system tidal prism value in the above equation.

In addition to system residence times, a second residence, the **local residence time**, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using Eel Pond as an example, the **system**

residence time is the average time required for water to migrate from Eel Pond, through Back River, and into Phinneys Harbor, where the **local residence time** is the average time required for water to migrate from Eel Pond to just Back River (not all the way to the harbor). Local residence times for each sub-embayment are computed as:

$$T_{local} = \frac{V_{local}}{P} t_{cycle}$$

where T_{local} denotes the residence time for the local sub-embayment, V_{local} represents the volume of the sub-embayment at mean tide level, P equals the tidal prism (or volume entering the local sub-embayment through a single tidal cycle), and t_{cycle} the period of the tidal cycle (again, 0.52 days).

Residence times are provided as a first order evaluation of estuarine water quality. Lower residence times generally correspond to higher water quality; however, residence times may be misleading depending upon pollutant/nutrient loading rates and the overall quality of the receiving waters. As a qualitative guide, **system residence times** are applicable for systems where the water quality within the entire estuary is degraded and higher quality waters provide the only means of reducing the high nutrient levels. For the Back River system this approach is applicable, since it assumes the main system has relatively low quality water relative to Buzzards Bay.

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the estuary faster than the tidal circulation can flush the system. Neither are low residence times an indicator of high water quality if the water flushed into the estuary is of poor quality. Advanced understanding of water quality will be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Back River system.

Since the calibrated RMA-2 model simulated accurate two-dimensional hydrodynamics in the system, model results were used to compute residence times. Residence times were computed for the entire estuary, as well the two main sub-embayments within the system. In addition, **system** and **local residence times** were computed to indicate the range of conditions possible for the system. Residence times were calculated as the volume of water (based on the mean volumes computed for the simulation period) in the entire system divided by the average volume of water exchanged with each sub-embayment over a flood tidal cycle (tidal prism). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Sub-embayment mean volumes and average tide prisms computer for the Back River system are presented in Table V-6.

Residence times were averaged for the tidal cycles comprising a representative 7.25 day period (14 tide cycles), and are listed in Table V-7. The modeled time period used to compute the flushing rates was different from the modeled calibration period, and included the transition from neap to spring tide conditions. Model divisions used to define the system sub-embayments include 1) the entire Back River system, 2) the upper portion of Back River from the eastern side of the Shore Road bridge, and 3) Eel Pond, including its inlet channel to Back River. The model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume. Since the 7.25-day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

The computed flushing rates for the Phinneys Harbor/Back River system show that as a whole, the system flushes well. A flushing time of 0.9 days for the entire estuary shows that on average, water is resident in the system less than a half of a day. This is also evident by the fact that the tidal prism of the whole estuary is greater than its mean volume. The upper portion of Back River shows a similar result. Eel Pond has the greatest system residence time. A system residence time of 29 days for Eel Pond indicates that it is particularly sensitive to the condition of the rest of the system, as it does not flush as well as upper Back River. Eel Pond does not flush as well because it has a large embayment volume relative to its mean tidal prism.

Table V-6. Embayment mean volumes and average tidal prism during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Phinneys Harbor (system)	184,546,000	103,964,000
Back River (with Eel Pond)	14,955,000	14,731,000
Upper Back River	8,312,000	10,451,000
Eel Pond	5,489,000	3,289,000

Table V-7. Computed System and Local residence times for embayments in the Phinneys Harbor/Back River system.

Embayment	System Residence Time (days)	Local Residence Time (days)
Phinneys Harbor (system)	0.9	0.9
Back River (with Eel Pond)	6.5	0.5
Upper Back River	9.1	0.4
Eel Pond	29.0	0.9

Generally, possible errors in computed residence times can be linked to two sources: the bathymetry information and simplifications employed to calculate residence time. In this study, the most significant errors associated with the bathymetry data result from the process of interpolating the data to the finite element mesh, which was the basis for all the flushing volumes used in the analysis. In addition, limited topographic measurements were available on the extensive marsh plains of the upper Back River. Minor errors may be introduced in residence time calculations by simplifying assumptions. Flushing rate calculations assume that water exiting an estuary or sub-embayment does not return on the following tidal cycle. For regions where a strong littoral drift exists, this assumption is valid. However, water exiting a small sub-embayment on a relatively calm day may not completely mix with estuarine waters. In this case, the "strong littoral drift" assumption would lead to an under-prediction of residence time. Since littoral drift in the upper portion of Buzzards Bay typically is strong because of the effects of the Cape Cod Canal and local winds induce tidal mixing within the regional estuarine systems, the "strong littoral drift" assumption only will cause minor errors in residence time calculations. Based on our knowledge of estuarine processes, we estimate that the combined errors due to bathymetric inaccuracies represented in the model grid and the “strong littoral drift” assumption are within 10% to 15% of “true” residence times.

VI. WATER QUALITY MODELING

VI.1 DATA SOURCES FOR THE MODEL

Several different data types and calculations are required to support the water quality modeling effort for the Phinney's Harbor estuary system. These include the output from the hydrodynamics model, calculations of external nitrogen loads from the watersheds, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayment

Extensive field measurements and hydrodynamic modeling of the embayment were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated model output representing the transport of water within the system embayment. Files of node locations and node connectivity for the RMA-2V model grid were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic output for the water quality model calibration was a 10-tidal cycle period in August 2003. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model had reached a dynamic "steady state", and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayment

Three primary nitrogen loads to embayment are recognized in this modeling study: external loads from the watersheds, nitrogen load from direct rainfall on the embayment surface, and internal loads from the sediments. Additionally, there is a fourth load to Phinney's Harbor, consisting of the background concentrations of total nitrogen in the waters entering from Buzzards Bay. This load is represented as a constant concentration along the seaward boundary of the model grid.

VI.1.3 Measured Nitrogen Concentrations in the Embayment

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in Figure VI-1. The multi-year averages present the "best" comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data is the minimum required to provide a baseline for MEP analysis. Fourteen years of data (collected between 1992 and 2005) were available for stations monitored by SMAST in the Phinney's Harbor and the Back River system.

Table VI-1. Pond-Watcher measured data, and modeled Nitrogen concentrations for the Phinney's Harbor and the Back River system used in the model calibration plots of Figure VI-2. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means.

Sub-Embayment	Phinney's Harbor	Phinney's Harbor	Phinney's Harbor	Phinney's Harbor	Phinney's Harbor	Eel Pond - Inner	Eel Pond - Middle	Eel Pond-Back River
Monitoring station	PH2	PH3	PH4	PH5	PH6	EP1	EP2	EP3
1992 mean	0.284	--	--	--	--	0.411	0.455	0.470
1993 mean	--	--	--	--	--	0.324	0.297	0.333
1994 mean	0.341	0.371	0.423	0.404	0.326	0.520	0.481	0.487
1995 mean	0.400	0.350	0.318	0.531	0.362	0.411	0.399	0.449
1996 mean	0.431	0.289	0.297	0.410	0.426	0.378	0.379	0.405
1997 mean	0.373	0.362	0.461	0.363	0.336	0.503	0.420	0.424
1998 mean	--	--	--	--	--	0.437	0.388	0.355
1999 mean	0.290	0.364	0.461	0.417	0.358	0.415	0.317	0.385
2000 mean	0.311	0.344	0.315	0.418	0.302	0.483	0.395	0.348
2001 mean	0.364	0.396	0.417	0.356	0.348	0.644	0.452	0.470
2002 mean	0.357	0.360	0.373	0.381	0.319	0.487	0.459	0.452
2003 mean	0.423	0.372	0.438	0.414	0.365	0.568	0.422	0.547
2004 mean	0.354	0.276	0.374	0.430	0.352	0.556	0.478	0.398
2005 mean	0.350	0.383	0.313	0.404	0.368	0.454	0.425	0.390
s.d. all data	0.354	0.358	0.375	0.410	0.348	0.473	0.413	0.427
N	0.089	0.063	0.079	0.080	0.051	0.116	0.077	0.086
model min	0.343	0.346	0.355	0.360	0.336	0.462	0.401	0.371
model max	0.351	0.358	0.388	0.430	0.349	0.477	0.459	0.470
model average	0.347	0.351	0.369	0.390	0.343	0.470	0.437	0.423

VI.2 MODEL DESCRIPTION AND APPLICATION

A two-dimensional finite element water quality model, RMA-4 (King, 1990), was employed to study the effects of nitrogen loading in the Phinney's Harbor and the Back River estuary system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of the Phinney's Harbor and Back River. Like RMA-2 numerical code, RMA-4 is a two-dimensional, depth averaged finite element model capable of simulating time-dependent constituent transport. The RMA-4 model was developed with support from the US Army Corps of Engineers (USACE) Waterways Experiment Station (WES), and is widely accepted and tested. Applied Coastal staff have utilized this model in water quality studies of other Cape Cod embayments, including systems in Falmouth (Ramsey *et al*., 2000); Mashpee, MA (Howes *et al*., 2004) and Chatham, MA (Howes *et al*., 2003).

The overall approach involves modeling total nitrogen as a non-conservative constituent, where bottom sediments act as a source or sink of nitrogen, based on local biochemical characteristics. This modeling represents summertime conditions, when algal growth is at its maximum. Total nitrogen modeling is based upon various data collection efforts and analyses presented in previous sections of this report. Nitrogen loading information was derived from the Cape Cod Commission watershed loading analysis (based on the USGS watersheds), as well as the measured bottom sediment nitrogen fluxes. Water column nitrogen measurements were utilized as model boundaries and as calibration data. Hydrodynamic model output (discussed in Section V) provided the remaining information (tides, currents, and bathymetry) needed to parameterize the water quality model of the system.

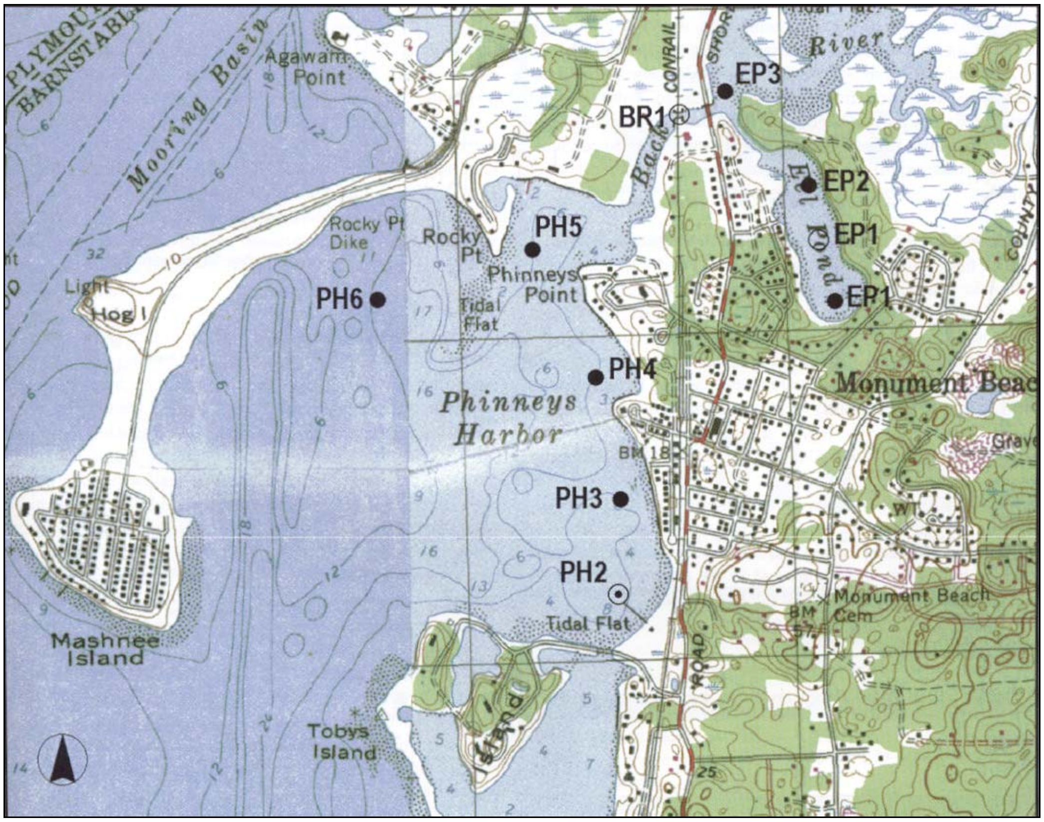


Figure VI-1. Estuarine water quality monitoring station locations in Phinney's Harbor and Back River systems. Station labels correspond to those provided in Table VI-1. Solid symbol adjacent EP-1 label indicates a nutrient monitoring station while the outline symbol adjacent the EP-1 label denotes a dissolved oxygen station.

VI.2.1 Model Formulation

The formulation of the model is for two-dimensional depth-averaged systems in which concentration in the vertical direction is assumed uniform. The depth-averaged assumption is justified since vertical mixing by wind and tidal processes prevent significant stratification in the modeled sub-embayments. The governing equation of the RMA-4 constituent model can be most simply expressed as a form of the transport equation, in two dimensions:

$$\left(\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y}\right) = \left(\frac{\partial}{\partial x}D_x\frac{\partial c}{\partial x} + \frac{\partial}{\partial y}D_y\frac{\partial c}{\partial y} + \sigma\right)$$

where c in the water quality constituent concentration; t is time; u and v are the velocities in the x and y directions, respectively; D_x and D_y are the model dispersion coefficients in the x and y directions; and σ is the constituent source/sink term. Since the model utilizes input from the

RMA-2 model, a similar implicit solution technique is employed for the RMA-4 model.

The model is therefore used to compute spatially and temporally varying concentrations *c* of the modeled constituent (i.e., total nitrogen), based on model inputs of 1) water depth and velocity computed using the RMA-2 hydrodynamic model; 2) mass loading input of the modeled constituent; and 3) user selected values of the model dispersion coefficients. Dispersion coefficients used for each system sub-embayment were developed during the calibration process. During the calibration procedure, the dispersion coefficients were incrementally changed until model concentration outputs matched measured data.

The RMA-4 model can be utilized to predict both spatial and temporal variations in total for a given embayment system. At each time step, the model computes constituent concentrations over the entire finite element grid and utilizes a continuity of mass equation to check these results. Similar to the hydrodynamic model, the water quality model evaluates model parameters at every element at 10-minute time intervals throughout the grid system. For this application, the RMA-4 model was used to predict tidally averaged total nitrogen concentrations throughout Phinney's Harbor and Back River.

VI.2.2 Water Quality Model Setup

Required inputs to the RMA-4 model include a computational mesh, computed water elevations and velocities at all nodes of the mesh, constituent mass loading, and spatially varying values of the dispersion coefficient. Because the RMA-4 model is part of a suite of integrated computer models, the finite-element meshes and the resulting hydrodynamic simulations previously developed for the Phinney's Harbor and Back River system was used for the water quality constituent modeling portion of this study.

Based on groundwater recharge rates from the USGS, the hydrodynamic model was set-up to include the latest estimate of ground water flowing into the system from watersheds. The overall groundwater flow rate into the system is 11.26 ft^3/sec (27,548 m^3/day) distributed amongst the watersheds.

For the model, an initial total N concentration equal to the concentration at the open boundary was applied to the entire model domain. The model was then run for a simulated month-long (28 day) spin-up period. At the end of the spin-up period, the model was run for an additional 5 tidal-day (125 hour) period. Model results were recorded only after the initial spin-up period. The time step used for the water quality computations was 10 minutes, which corresponds to the time step of the hydrodynamics input for the Phinney's Harbor and Back River system.

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the results of the watershed analysis, 2) estimates of direct atmospheric deposition, 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed direct atmospheric deposition load for Eel Pond was evenly distributed at grid cells that formed the perimeter of the embayment. Benthic regeneration load was distributed among another sub-set of grid cells which are in the interior portion of each basin.

The loadings used to model present conditions in Phinney's Harbor estuary systems are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Section IV. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For present conditions, some sub-embayments have almost twice the loading rate from benthic regeneration as from watershed loads. For other sub-embayments, the benthic flux is relatively low or negative indicating a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration in Buzzards Bay was set at 0.303 mg/L, based on SMAST data from the Bay. The open boundary total nitrogen concentration represents long-term average summer concentrations found within Buzzards Bay.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Phinney's Harbor and Back River, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent **present loading conditions.**

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Back River Inner	7.699	0.589	0.976
Back River Outer	1.964	0.340	0.562
Eel Pond	4.888	0.246	-0.709
Phinney's Harbor	14.781	5.186	14.525

VI.2.4 Model Calibration

Calibration of the total nitrogen model proceeded by changing model dispersion coefficients so that model output of nitrogen concentrations matched measured data. Generally, several model runs of each system were required to match the water column measurements. Dispersion coefficient (*E*) values were varied through the modeled system by setting different values of *E* for each grid material type, as designated in Section V. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent Phinney's Harbor embayment system require values of *E* that are lower compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979). Observed values of *E* in these calmer areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of *E* used in each sub-embayment of the modeled systems are presented in Table VI-3. These values were used to develop the "best-fit" total nitrogen model calibration. For the case of TN modeling, "best fit" can be defined as minimizing the error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

Comparisons between model output and measured nitrogen concentrations are shown in plots presented in Figure VI-2. In these plots, means of the water column data and a range of two standard deviations of the annual means at each individual station are plotted against the modeled maximum, mean, and minimum concentrations output from the model at locations which corresponds to the SMAST monitoring stations.

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for Phinney's Harbor estuary system.	
Embayment Division	E m^2/sec
Phinney's Harbor	2.2
Inner Phinney's Harbor	2.0
Back River Outer	2.5
Back River Inner	1.7
Eel Pond	1.7
Channel to Eel Pond	1.8
Marsh	0.5

For model calibration, the mid-point between maximum modeled TN and average modeled TN was compared to mean measured TN data values, at each Pond-Watcher water-quality monitoring station. The calibration target would fall between the modeled mean and maximum TN because the monitoring data are collected, as a rule, during mid ebb tide.

Also presented in this figure are unity plot comparisons of measured data verses modeled target values for the system. The model fit is exceptional for the Phinney's Harbor and Back River model, with rms error of 0.01 mg/L and an R^2 correlation coefficient of 0.91.

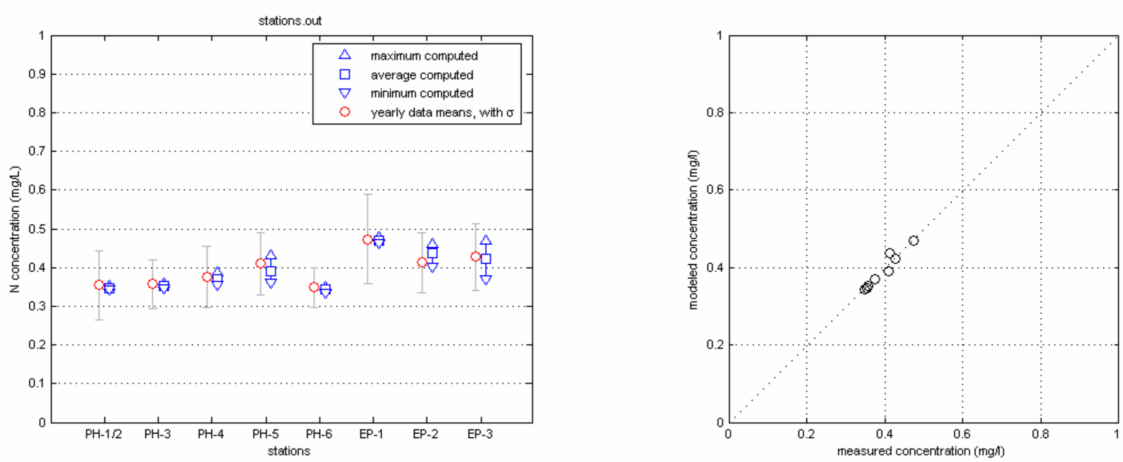


Figure VI-2. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Phinney's Harbor system. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

A contour plot of calibrated model output is shown in Figure VI-3 for Phinney's Harbor and Back River. In the figure, color contours indicate nitrogen concentrations throughout the model domain. The output in the figure show average total nitrogen concentrations, computed using the full 5-tidal-day model simulation output period.

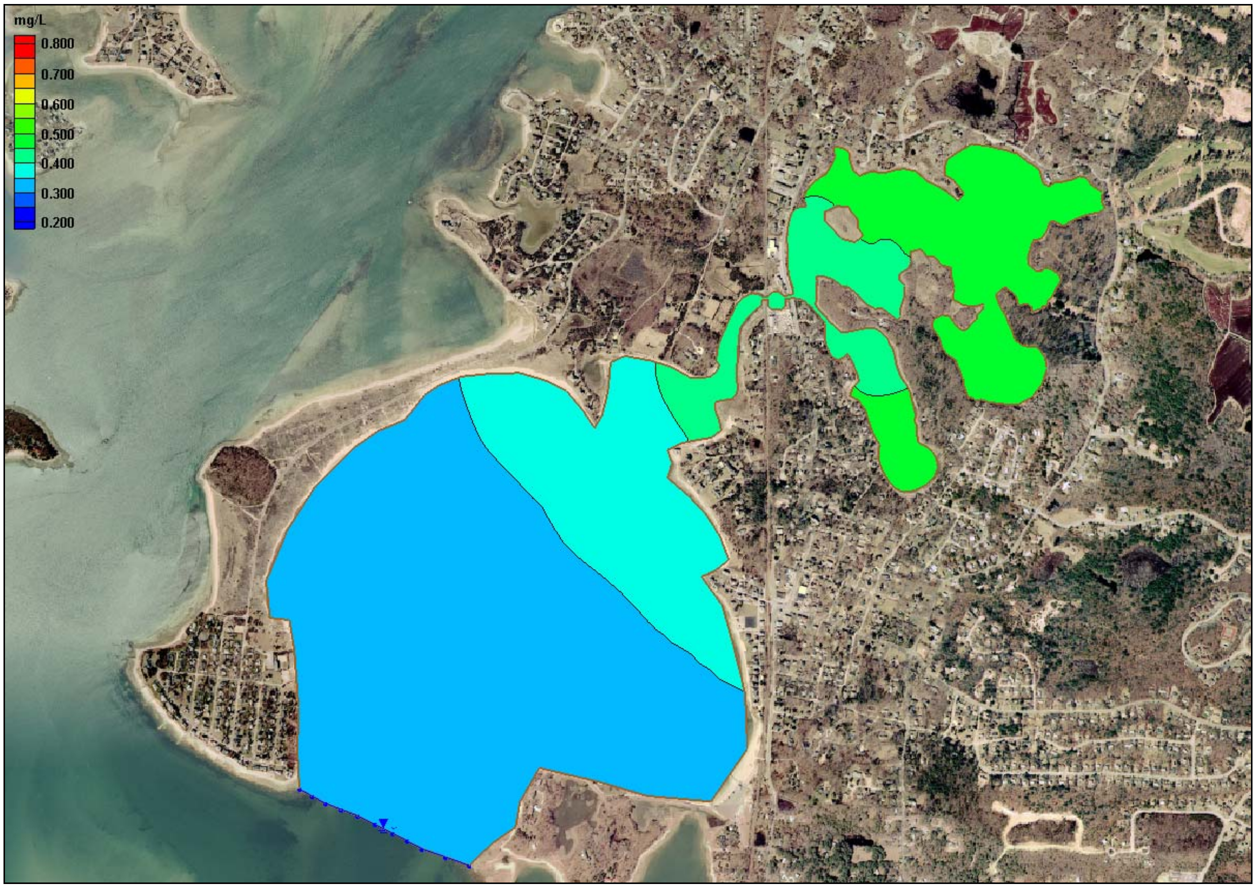


Figure VI-3. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario and the bathymetry, for Phinney's Harbor system. The approximate location of the sentinel threshold station for Phinney's Harbor estuary system (PH4) is shown.

VI.2.5 Model Salinity Verification

In addition to the model calibration based on nitrogen loading and water column measurements, numerical water quality model performance is typically verified by modeling salinity. This step was performed for the Phinney's Harbor estuary system using salinity data collected at the same stations as the nitrogen data. The only required inputs into the RMA4 salinity model of each system, in addition to the RMA2 hydrodynamic model output, were salinities at the model open boundary, and groundwater inputs. The open boundary salinity was set at 29.3 ppt. For groundwater inputs salinities were set at 0 ppt. Groundwater input used for the model was 11.26 ft^3/sec (27,548 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed evenly in each model through the use of several 1-D element input points positioned along each model's land boundary.

Comparisons of modeled and measured salinities are presented in Figure VI-4, with contour plots of model output shown in Figure VI-5. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in Phinney's Harbor estuary system. The rms error of the models was 0.22 ppt, and correlation coefficient was 0.78. The salinity verification provides a further independent confirmation that model dispersion coefficients and represented freshwater inputs to the model correctly simulate the real physical systems.

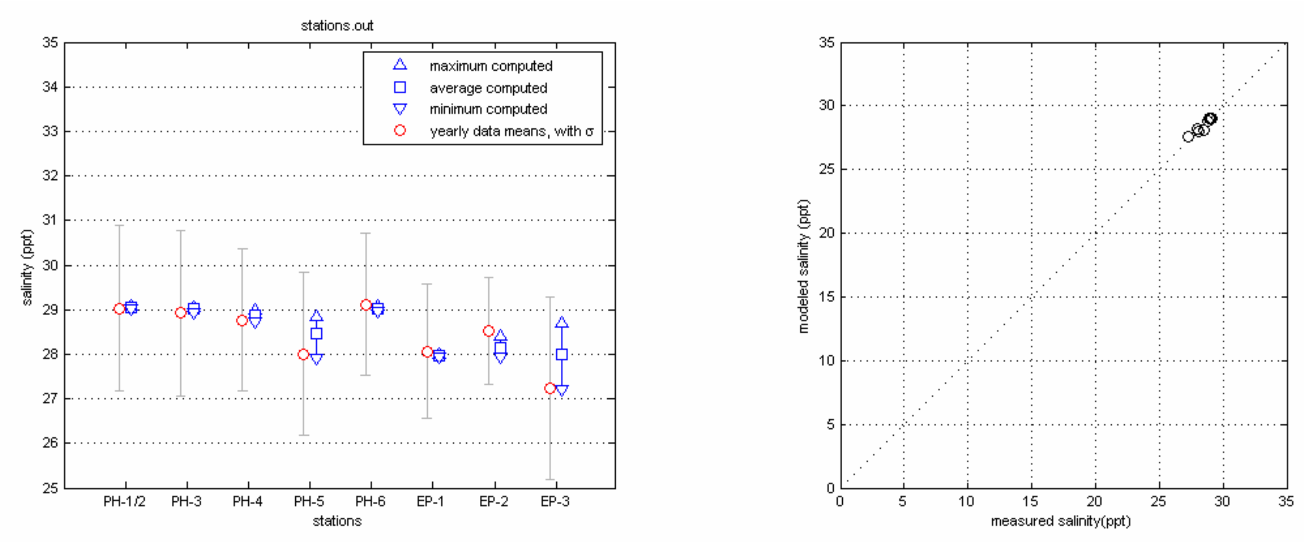


Figure VI-4. Comparison of measured and calibrated model output at stations in Phinney's Harbor system. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

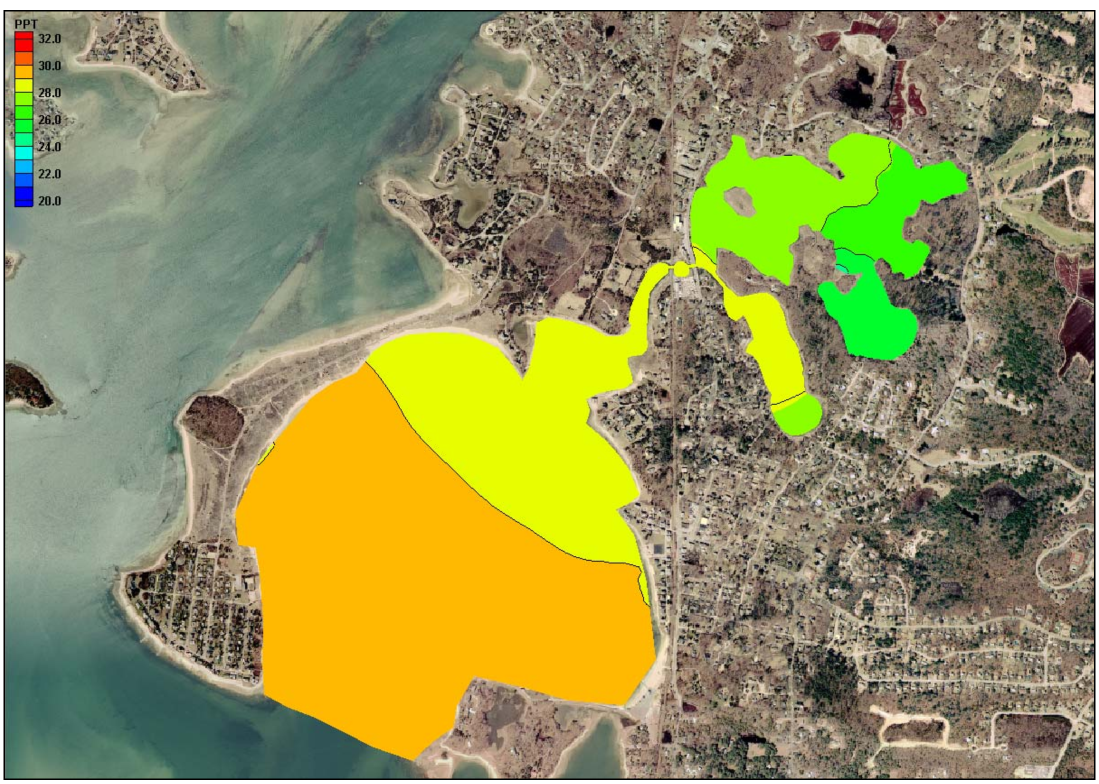


Figure VI-5. Contour plots of modeled salinity (ppt) and bathymetry in Phinney's Harbor system.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

To assess the influence of nitrogen loading on total nitrogen concentrations within the embayment system, two standard water quality modeling scenarios were run: a "build-out" scenario based on potential development (described in more detail in Section IV) and a "no anthropogenic load" or "no load" scenario assuming only atmospheric deposition on the watershed and sub-embayment, as well as a natural forest within each watershed. Comparisons of the alternate watershed loading analyses are shown in Table VI-4. Loads are presented in kilograms per day (kg/day) in this Section, since it is inappropriate to show benthic flux loads in kilograms per year due to seasonal variability.

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Phinney's Harbor estuary system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	build out (kg/day)	build-out % change	no load (kg/day)	no load % change
Back River Inner	7.699	14.652	+90.3%	0.932	-87.9%
Back River Outer	1.964	3.926	+99.9%	0.474	-75.9%
Eel Pond	4.888	6.121	+25.2%	0.411	-91.6%
Phinney's Harbor	14.781	17.460	+18.1%	1.252	-91.5%

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be more than a 90% increase in watershed nitrogen load to the outer and inner portions of Back River as a result of potential future development. Other watershed areas would experience much greater load increases, for example the loads to Eel Pond would increase 25% from the present day loading levels. For the no load scenarios, a majority of the load entering the watershed is removed; therefore, the load is generally lower than existing conditions by over 75%.

For the build-out scenario, a breakdown of the total nitrogen load entering the Phinney's Harbor estuary system sub-embayments is shown in Table VI-5. The benthic flux for the build-out scenarios is assumed to vary proportional to the watershed load, where an increase in watershed load will result in an increase in benthic flux (i.e., a positive change in the absolute value of the flux), and *vise versa*.

Projected benthic fluxes (for both the build-out and no load scenarios) are based upon projected PON concentrations and watershed loads, determined as:

$$(\textit{Projected N flux}) = (\textit{Present N flux}) * [PON_{projected}]/[PON_{present}]$$

where the projected PON concentration is calculated by,

$$[PON_{projected}] = R_{load} * \Delta PON + [PON_{(present\ offshore)}],$$

using the watershed load ratio,

$$R_{load} = (\textit{Projected N load}) / (\textit{Present N load}),$$

and the present PON concentration above background,

$$\Delta PON = [PON_{(present\ flux\ core)}] - [PON_{(present\ offshore)}].$$

Table VI-5. Build-out sub-embayment and surface water loads used for total nitrogen modeling of the Phinney's Harbor estuary system, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Back River Inner	14.652	0.589	1.126
Back River Outer	3.926	0.340	0.584
Eel Pond	6.121	0.246	-0.849
Phinney's Harbor	17.640	5.186	16.015

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of Phinney's Harbor estuary system was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most in the upper portion of the system, with the largest change at the intersection of Back River and Eel Pond (13.1%) and the least change in outer portion of Phinney's Harbor (3.3%). Color contours of model output for the build-out scenario are present in Figure VI-6. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-3, which allows direct comparison of nitrogen concentrations between loading scenarios.

Table VI-6. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Phinney's Harbor estuary system. Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Phinney's Harbor	PH2	0.347	0.3582	+3.3%
Phinney's Harbor	PH3	0.351	0.3646	+3.8%
Phinney's Harbor	**PH4**	**0.369**	**0.3883**	**+5.3%**
Phinney's Harbor	PH5	0.390	0.4252	+8.9%
Phinney's Harbor	PH6	0.343	0.3539	+3.3%
Eel Pond - Inner	EP1	0.470	0.5291	+12.5%
Eel Pond - Middle	EP2	0.437	0.4875	+11.5%
Eel Pond – Back River	EP3	0.423	0.4778	+13.1%

VI.2.6.2 No Anthropogenic Load

A breakdown of the total nitrogen load entering each sub-embayment for the no anthropogenic load ("no load") scenario is shown in Table VI-7. The benthic flux input to each embayment was reduced (toward zero) based on the reduction in the watershed load (as discussed in §VI.2.6.1). Compared to the modeled present conditions and build-out scenario, atmospheric deposition directly to each sub-embayment becomes a greater percentage of the total nitrogen load as the watershed load and related benthic flux decrease.

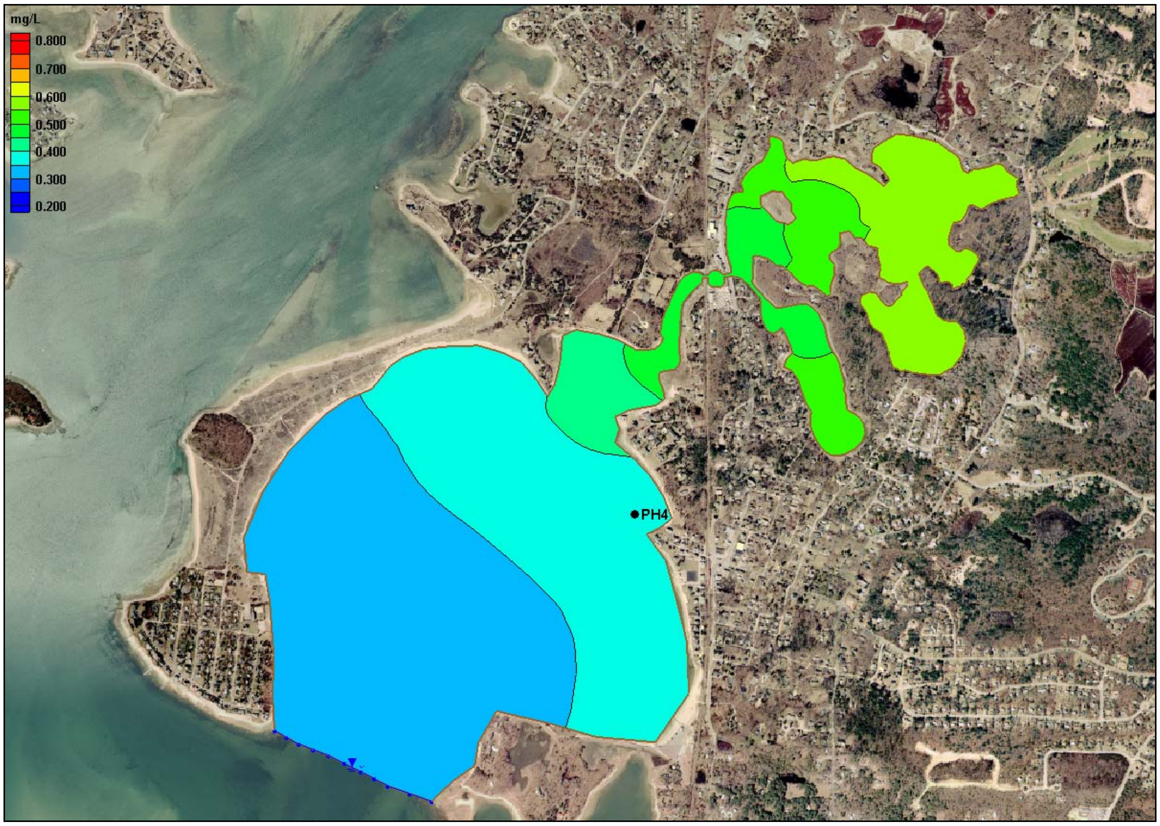


Figure VI-6. Contour plots of modeled total nitrogen concentrations (mg/L) in Phinney's Harbor estuary system, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Phinney's Harbor estuary system (PH4) is shown.

Table VI-7. "No anthropogenic loading" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of Phinney's Harbor estuary system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Back River Inner	0.932	0.589	2.553
Back River Outer	0.474	0.340	0.114
Eel Pond	0.411	0.246	-0.437
Phinney's Harbor	1.252	5.186	11.359

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Again, total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was moderate as shown in Table VI-8, with reductions greater than 15% occurring for Back River and Eel Pond. Results for each system are shown pictorially in Figure VI-7.

Table VI-8. Comparison of model average total N concentrations from present loading and the no anthropogenic ("no load") scenario, with percent change, for the Phinney's Harbor estuary system. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). Sentinel threshold stations are in bold print.				
Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Phinney's Harbor	PH2	0.347	0.322	-7.1%
Phinney's Harbor	PH3	0.351	0.324	-7.8%
Phinney's Harbor	**PH4**	**0.369**	**0.3307**	**-10.4%**
Phinney's Harbor	PH5	0.390	0.3383	-13.3%
Phinney's Harbor	PH6	0.343	0.3219	-6.1%
Eel Pond - Inner	EP1	0.470	0.3485	-25.9%
Eel Pond - Middle	EP2	0.437	0.3449	-21.1%
Eel Pond – Back River	EP3	0.423	0.3497	-17.2%

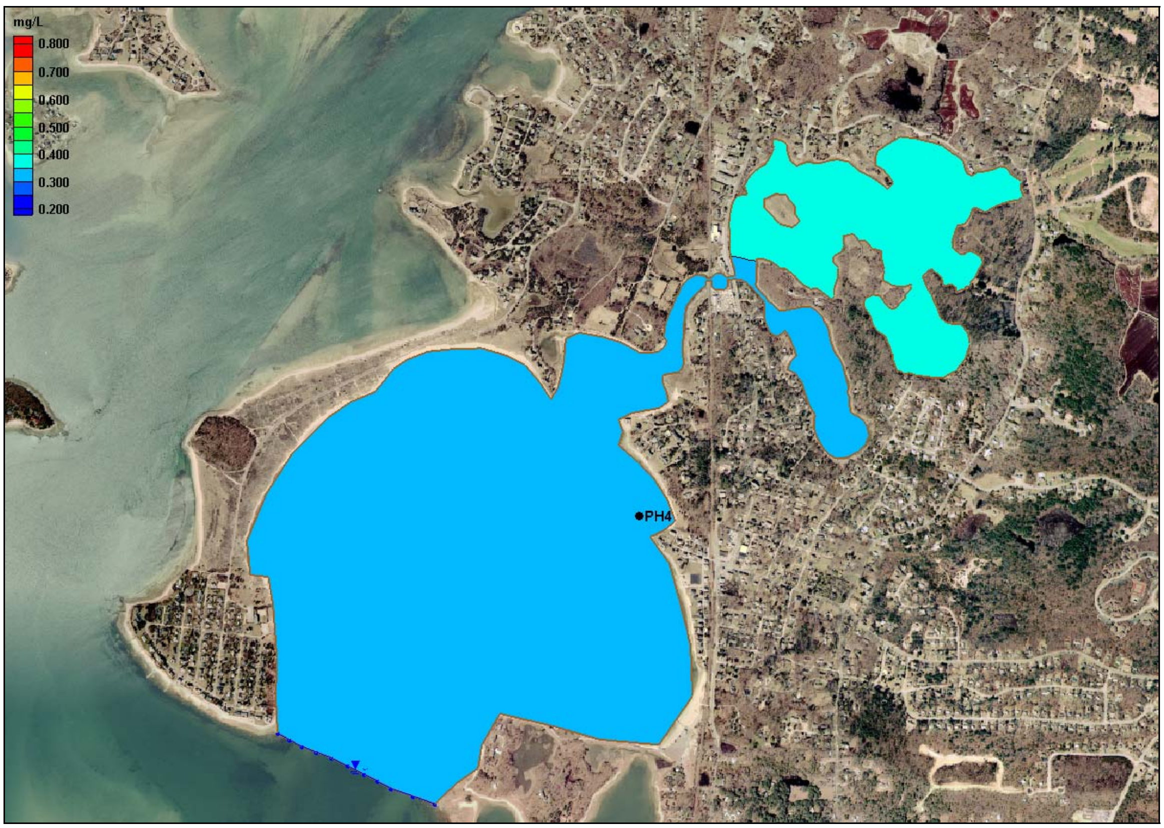


Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in Phinney's Harbor estuary system, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold station for Phinney's Harbor estuary system (PH4) is shown.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Phinneys Harbor / Eel Pond / Back River embayment system in the Town of Bourne, Cape Cod, MA, our assessment is based upon data from the water quality monitoring database and our surveys of eelgrass distribution from the MASSDEP mapping program (1951, 1995, 2001) and Buzzards Bay Project (1985-86), benthic animal communities (Fall 2003, 2005) and sediment characteristics, and dissolved oxygen records obtained during the summer of 2002. These data form the basis of an assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for these systems (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

There are a variety of indicators that can be used in concert with water quality monitoring data for evaluating the ecological health of embayment systems. The best biological indicators are those species which are non-mobile and which persist over relatively long periods, if environmental conditions remain constant. The concept is to use species which integrate environmental conditions over seasonal to annual intervals. The approach is particularly useful in environments where high-frequency variations in structuring parameters (e.g. light, nutrients, dissolved oxygen, etc.) are common, making adequate field sampling difficult.

As a basis for a nitrogen thresholds determination, MEP focused on major habitat quality indicators: (1) bottom water dissolved oxygen and chlorophyll a (Section VII.2), (2) eelgrass distribution over time (Section VII.3) and (3) benthic animal communities (Section VII.4). Dissolved oxygen depletion is frequently the proximate cause of habitat quality decline in coastal embayments (the ultimate cause being nitrogen loading). However, oxygen conditions can change rapidly and frequently show strong tidal and diurnal patterns. Even severe levels of oxygen depletion may occur only infrequently, yet have important effects on system health. To capture this variation, the MEP Technical Team deployed dissolved oxygen sensors within the upper portions of the Phinneys Harbor system (Eel Pond, Back River) to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Phinneys Harbor system was conducted for comparison to historic records (MASSDEP Eelgrass Mapping Program, C. Costello). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the Phinneys Harbor system, temporal changes in eelgrass distribution provides a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing) in nutrient enrichment.

In areas that do not support eelgrass beds, benthic animal indicators were used to assess the level of habitat health from "healthy" (low organic matter loading, high D.O.) to "highly stressed" (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of their habitat. Benthic animal species from sediment samples were identified and the environments ranked based upon the fraction of healthy, transitional, and stressed indicator species. The analysis is based upon life-history information on the species and a wide variety of field studies within southeastern Massachusetts waters, including the Wild Harbor oil spill, benthic population studies in Buzzards Bay (Woods Hole Oceanographic Institution) and New Bedford (SMAST), and more recently the Woods Hole Oceanographic Institution Nantucket Harbor Study (Howes *et al.* 1997). These data are coupled with the level of diversity (H') and evenness (E) of the benthic community and the total number of individuals to determine the infaunal habitat quality.

VII.2 BOTTOM WATER DISSOLVED OXYGEN

Dissolved oxygen levels near atmospheric equilibration are important for maintaining healthy animal and plant communities. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. For example, for the Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 3.8 mg L^{-1}. Massachusetts State Water Quality Classification indicates that SA (high quality) waters maintain oxygen levels above 6 mg L^{-1}. The tidal waters of the Phinneys Harbor System (Phinneys Harbor, Eel Pond, Back River) are currently listed under this Classification as SA. It should be noted that the Classification system represents the water quality that the embayment should support, not the existing level of water quality. It is through the MEP and TMDL processes that management actions are developed and implemented to keep or bring the existing conditions in line with the Classification.

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Phinneys Harbor system (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the Phinneys Harbor System was collected during the summer of 2002.

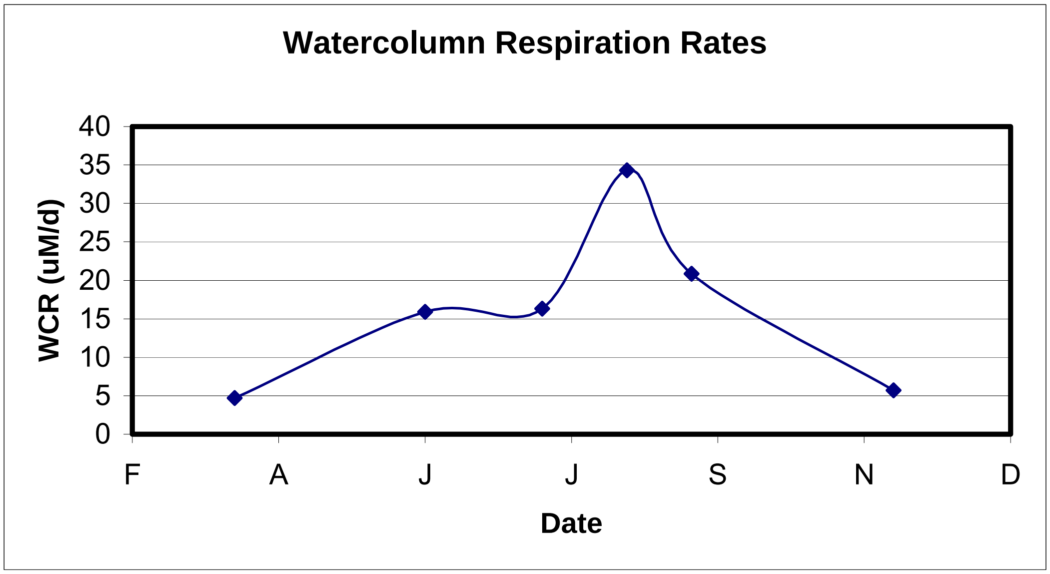


Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Back River and Eel Pond portions of the Phinneys Harbor system evaluated in this assessment showed high frequency variation, apparently related to diurnal and sometimes tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration at each mooring site, underscores the need for continuous monitoring within these systems.

Dissolved oxygen and chlorophyll a records were examined both for temporal trends and to determine the percent of the 25-31 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions. The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate highly nutrient enriched waters and impaired habitat quality at all mooring sites within each estuary (Figures VII-3 through VII-6). The oxygen data is consistent with a moderate level of organic matter loading from phytoplankton production (chlorophyll a levels) indicative of nitrogen enrichment of these component estuarine systems. The oxygen records further indicate that the upper tidal reaches (Back River and Eel Pond) of the Phinneys Harbor embayment system have a daily oxygen excursion (although not generally over air equilibration), which further supports the assessment of modest level of nutrient enrichment. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of habitat impairment in these locations. The effect of nitrogen enrichment is to cause oxygen depletion; however, with increased phytoplankton (or epibenthic algae) production, oxygen levels will rise in daylight to above atmospheric equilibration levels in shallow systems (generally

~7-8 mg L^{-1} at the mooring sites). While daily oxygen excursions occurred, generally day time levels did not exceed atmospheric equilibration, indicating moderate enrichment.
The oxygen balance and chlorophyll levels recorded by the moorings are consistent with grab sample data collected by the BayWatcher Program (Howes et al. 1998). These data need to be evaluated relative to the specific basin from which oxygen data was obtained.

The dissolved oxygen records indicate that Eel Pond is nitrogen enriched, but the oxygen depletion was generally to the 4-5 mg/L level, consistent with the chlorophyll average of 11.8 ug/L. There was clear daily and tidal variation in dissolved oxygen and chlorophyll levels. Similarly, the Back River also showed oxygen depletion consistent with its function as a salt marsh. Both inner basins showed greater nitrogen enrichment and subsequent oxygen depletions and chlorophyll levels, different than for the outer basin of Phinneys Harbor. However, the cause of these conditions appears to stem primarily from the naturally organic enriched nature of salt marshes (Back River) and the structure of the drowned kettle pond, Eel Pond (see below). At present nitrogen enrichment to Eel Pond appears related to its nature as a depositional basin, as removal of anthropogenic nitrogen inputs in the Linked Watershed-Embayment Model did little to lower watercolumn nitrogen levels (Chapter VI, VIII).

Eel Pond is a relatively deep basin (2-3 meters) with a narrow tidal channel to lower Back River. The depth of the basin restricts ventilation of bottom waters. During darkness, oxygen levels decline as a result of respiration of live phytoplankton and decaying detritus in bottom waters and sediments. However, oxygen depletion is generally to the 4-5 mg/L range. The phytoplankton biomass is indicated by the moderately high summer chlorophyll a levels, averaging 11.8 ug/L and generally ranging from 8-18 ug/L (Figure VII-4 & VII-6). The physical structure of this basin appears to result in an enrichment of nitrogen and phytoplankton. Given the relatively low watershed nitrogen loading (Chapter IV) and the minor change in predicted nitrogen levels with removal of anthropogenic sources (modeled, Chapters VI, VIII), it appears that this is predominantly “natural” condition and is consistent with the absence of eelgrass in the 1951 survey (Section VII.3) and relatively healthy infaunal habitat (Section VII.4).

Back River presently shows greater oxygen depletions (to 3 mg/L), but lower chlorophyll a levels (average 5.5 ug/L, general range 4-8 ug/L). This is consistent with it functioning primarily as a tidal salt marsh sub-basin. The low chlorophyll a levels result from its near complete exchange of tidal waters on each tide (compared to the deep basin of Eel Pond), which prevents a significant “build-up” of phytoplankton biomass. The low oxygen levels are also consistent with a salt marsh tidal creek, where the organic matter enriched sediments support high levels of oxygen uptake at night and deplete the overlying waters. While oxygen depletion to 3 mg/L would indicate impairment in an embayment like Phinneys Harbor basin, it is consistent with the organically enriched nature of smaller salt marsh creeks.

Figure VII-2. Aerial Photograph of the Phinneys Harbor, Eel Pond and Back River system in Bourne showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2005.

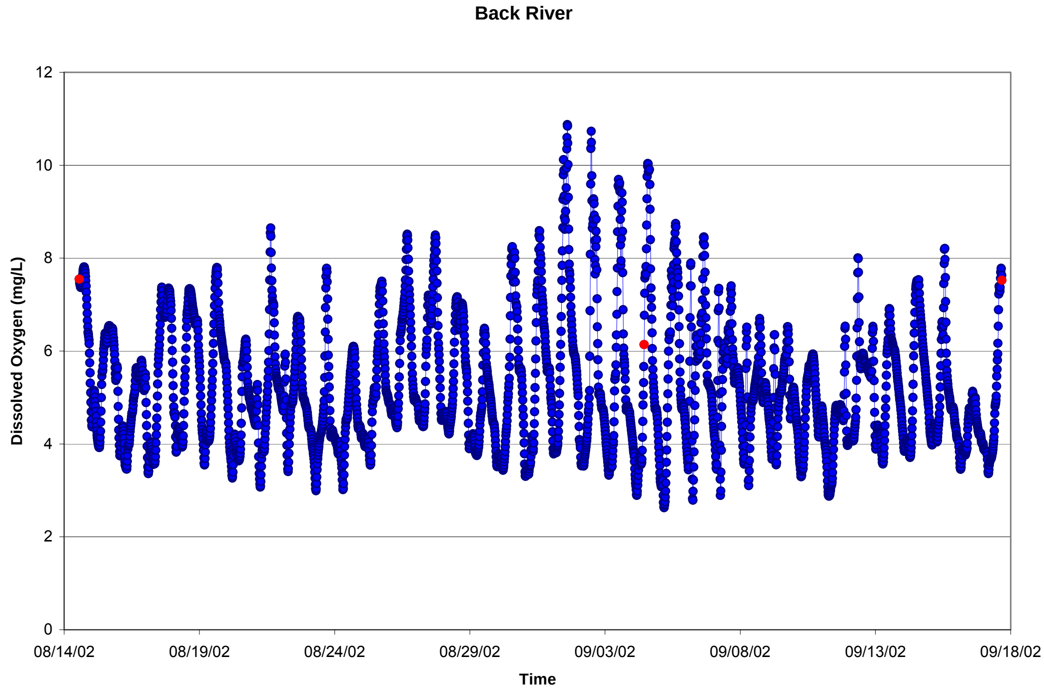


Figure VII-3. Bottom water record of dissolved oxygen at the Back River station, Summer 2002. Calibration samples represented as red dots.

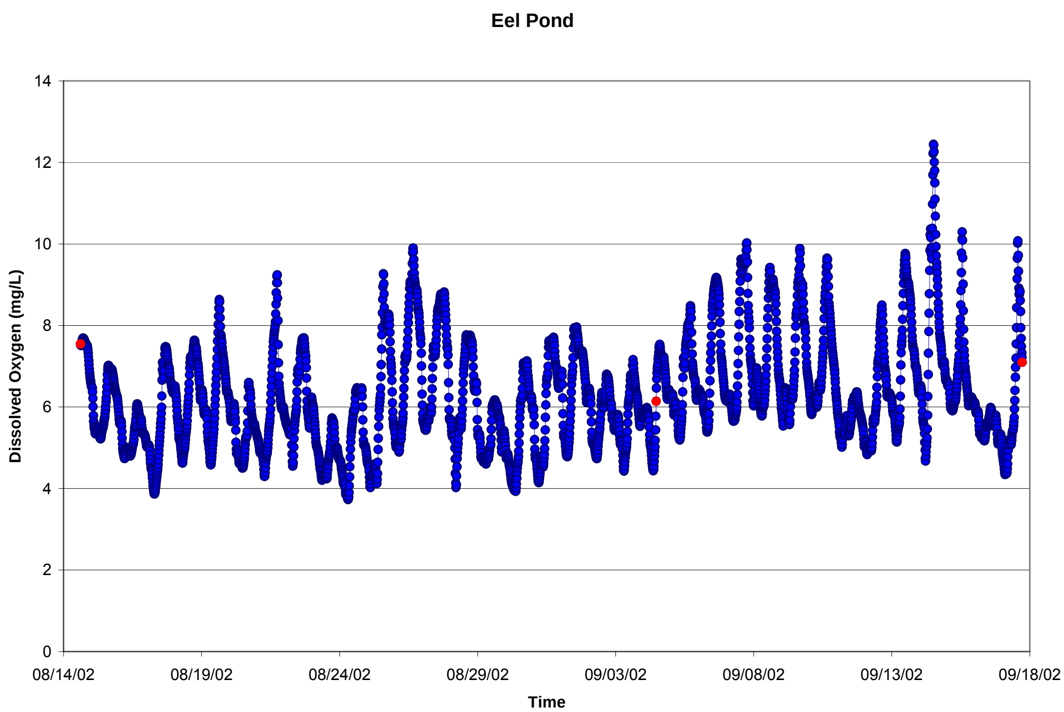


Figure VII-4. Bottom water record of dissolved oxygen at the Eel Pond station, Summer 2002. Calibration samples represented as red dots.

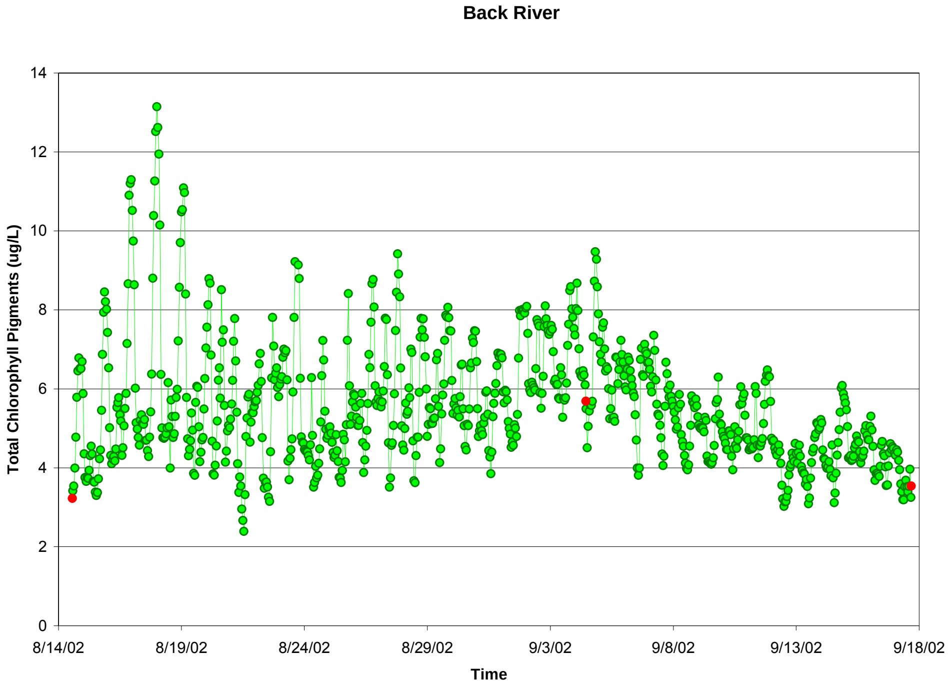


Figure VII-5. Bottom water record of Chlorophyll-*a* at the Back River station, Summer 2002. Calibration samples represented as red dots.

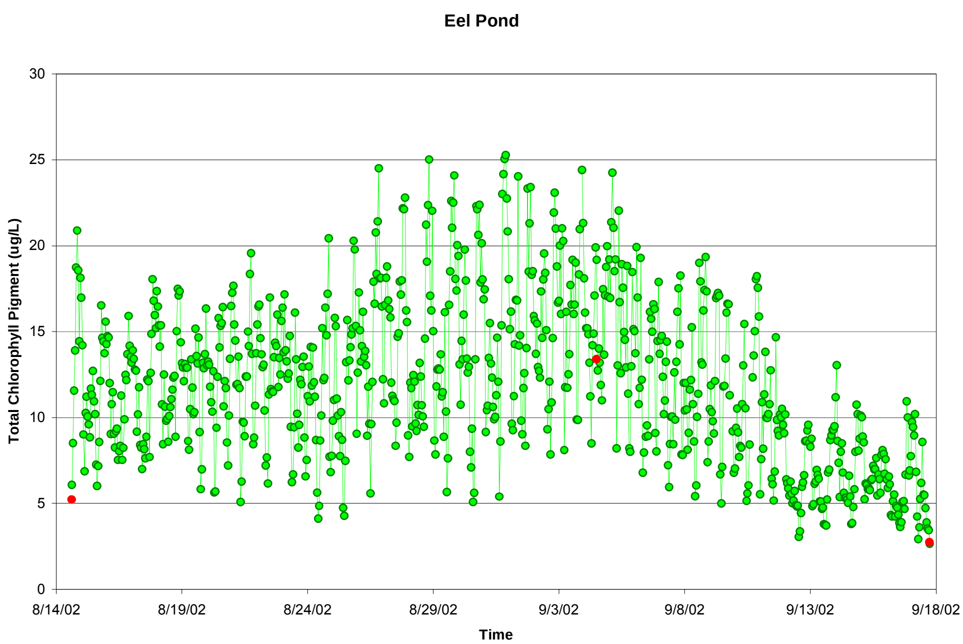


Figure VII-6. Bottom water record of Chlorophyll-*a* at the Eel Pond station, Summer 2002. Calibration samples represented as red dots.

Table VII-1. Number of days during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels.

System	Start Date	End Date	Total Deployment (Days)	<6 mg/L Duration (Days)	<5 mg/L Duration (Days)	<4 mg/L Duration (Days)	<3 mg/L Duration (Days)
Back River	8/14/2002	9/17/2002	34.1	25.20	17.66	6.48	0.29
			Mean	0.66	0.40	0.14	0.05
			Min	0.10	0.04	0.03	0.01
			Max	2.05	1.03	0.38	0.09
			S.D.	0.42	0.23	0.10	0.04
Eel Pond	8/14/2002	9/17/2002	34.1	16.14	5.41	0.30	0.00
			Mean	0.41	0.21	0.10	N/A
			Min	0.03	0.03	0.08	0.00
			Max	1.51	0.49	0.14	0.00
			S.D.	0.34	0.15	0.03	N/A

Table VII-2. Duration (number of deployment days) that chlorophyll a levels exceed various benchmark levels within the embayment system. “Mean” represents the average duration of each event over the benchmark level and “S.D.” its standard deviation. Data collected by the Coastal Systems Program, SMAST.

System	Start Date	End Date	Total Deployment (Days)	>5 ug/L Duration (Days)	>10 ug/L Duration (Days)	>15 ug/L Duration (Days)	>20 ug/L Duration (Days)	>25 ug/L Duration (Days)
Back River	8/14/2002	9/17/2002	34.1	19.79	0.63	0.00	0.00	0.00
Mean Chl Value = 5.50 ug/L			Mean	0.38	0.21	N/A	N/A	N/A
			Min	0.04	0.17	0.00	0.00	0.00
			Max	2.83	0.29	0.00	0.00	0.00
			S.D.	0.47	0.07	N/A	N/A	N/A
Eel Pond	8/14/2002	9/17/2002	34.1	32.25	21.33	9.04	1.92	0.13
Mean Chl Value = 11.84 ug/L			Mean	2.02	0.27	0.13	0.08	0.06
			Min	0.08	0.04	0.04	0.04	0.04
			Max	9.75	0.96	0.46	0.25	0.08
			S.D.	3.07	0.22	0.12	0.05	0.03

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data was conducted for the Phinneys Harbor system by the MASSDEP Eelgrass Mapping Program as part of the MEP Technical Team. Surveys were conducted in 1995 and 2001, as part of this program. Additional analysis of available aerial photos from 1951 was used to reconstruct the eelgrass distribution prior to any substantial development of the watershed. The 1951 data were only anecdotally validated, while the 1995 and 2001 maps were field validated. In addition the MEP Technical Team has incorporated an additional survey of Phinneys Harbor (Costa 1988) based upon aerial photography (1971, 1974, 1975, 1981) and field surveys (1985, 1986). This data provides a quality field validated 1985 benchmark, greatly enhancing the temporal resolution of eelgrass change in the Phinneys Harbor System.

The primary use of the eelgrass data is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 (Figure VII-7) and 1985; the 1985 to 2001 period being the time in which watershed nitrogen loading significantly increased to its present level. This temporal information can be used to determine the stability of the eelgrass community.

The eelgrass surveys indicated that eelgrass habitat within this estuary is limited to the Phinneys Harbor basin, as there is no evidence that eelgrass has colonized either Eel Pond or Back River. The 1951 survey indicated eelgrass beds primarily in the shallower water depths (<2 m) along the northern shore (Mashnee Island). The eelgrass beds in 1951 do not extend into the deep waters of the historic shipping channels that existed prior to the construction of the causeway (see Chapter V). The 1985 survey data indicated eelgrass similar to the 1951 distribution, with the additional documentation of eelgrass within the southeastern area bounded by Monument Beach and Tobys Island. It is not clear if the southeastern beds formed after the 1951 survey or could not be discerned by photo-interpretation. In either case, the 1985 data indicates that eelgrass habitat was relatively stable from 1951 to 1985. Within the 1951-1985 time-frame, eelgrass appears to have colonized most of the basin to depths of ~2 meters. This distribution indicates the habitat area potentially restorable under watershed nitrogen management (see below). The bathymetry of Phinneys Harbor limits the proportion of the basin that can support eelgrass, with much of the basin >3 meters in depth.

In contrast to the large coverages in the 1951 and 1985 surveys, at present there is virtually no eelgrass habitat within the Phinneys Harbor System. Based on the 1995 and 2001 eelgrass surveys conducted by the MASSDEP Eelgrass Mapping Program the remaining eelgrass bed appears to be limited to two small fringing areas on each side of the mouth of Phinneys Harbor along Mashnee and Tobys Islands (Figure VII-7). In addition, to the MASSDEP mapping, the absence of eelgrass within Phinneys Harbor has been confirmed by the multiple MEP staff conducting the infaunal and sediment sampling and the mooring studies. However, MEP staff did not survey the mouth of Phinneys Harbor to confirm the presence of the small eelgrass patches reported by the MASSDEP Eelgrass Mapping Program.

The temporal surveys also indicate that eelgrass habitat loss in Phinneys Harbor is a relatively recent phenomenon. The decline of eelgrass beds appears to have occurred primarily between 1985 and 1995 and continued to 2001. The current absence of eelgrass throughout Phinneys Harbor is consistent with the depth of the basin and the chlorophyll levels (5-10 ug/L) as measured by the BayWatcher Program (Howes et al. 1998). The eelgrass loss is further supported by the basin-wide tidally averaged total nitrogen levels of 0.36 mg N/L (higher than the 0.35 threshold for eelgrass in nearby West Falmouth Harbor). The timing of the eelgrass habitat loss is also consistent with changes in land-use within the watershed. In addition, the spatial pattern of bed loss is consistent with the typical pattern of habitat decline related to increasing nitrogen loading from a watershed. The pattern is for highest nitrogen levels to be found within the innermost basins, with concentrations declining moving toward the tidal inlet. This pattern is also observed in nutrient related habitat quality parameters, like phytoplankton, turbidity, oxygen depletion, etc. The consequence is that eelgrass bed decline typically follows a pattern of initial loss in the innermost basins (and sometimes also from the deeper waters of other basins). The temporal pattern is a “retreat” of beds toward the region of the tidal inlet. This appears to be the pattern of retreat observed within Phinneys Harbor. Although Phinneys Harbor presently supports healthy infaunal habitat (tolerant of higher levels of enrichment), it appears to have become sufficiently nutrient enriched to impair its eelgrass habitat. However, it is likely that if nitrogen loading were to decrease, eelgrass could first be restored in the lower portion of the main basin, assuming eelgrass bed loss is not being driven by some other factor. With further reductions in nitrogen load there is a strong likelihood that eelgrass beds could be further restored to the 1951-1985 pattern.

It is significant that eelgrass was not detected in the Back River and Eel Pond regions of the Phinneys Harbor system in the 1951 (or 1985) data. It appears that these areas may not be supportive of eelgrass habitat due to the structure of these water bodies. Eel Pond is generally considered a kettle with relatively deep water (2-3 meters) and at the limit of the depths historically colonized in the Phinneys Harbor basin. In addition, the system will naturally be enriched over the outer basin given its location, structure and sharing waters with the Back River, even with no anthropogenic loading (Chapter VI). In the case of the Back River salt marshes, eelgrass habitat is not expected given the intertidal nature of the salt marsh creeks.

Other factors which influence eelgrass bed loss in embayments may also be at play in the Phinneys Harbor system, though the loss seems completely in-line with nitrogen enrichment. However, a brief listing of non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, as the Phinneys harbor system generally supports a low density of boat moorings in many of the areas where eelgrass loss has occurred, although there are a number of mooring concentrated in the southeastern basin. Similarly, pier construction and boating pressure may be adding additional stress but seem to be relatively minor factors in the overall system. It is not possible at this time to determine the potential effect of shellfishing on eelgrass bed distribution, although it is mediated by periodic closures in the many of the shallower areas.

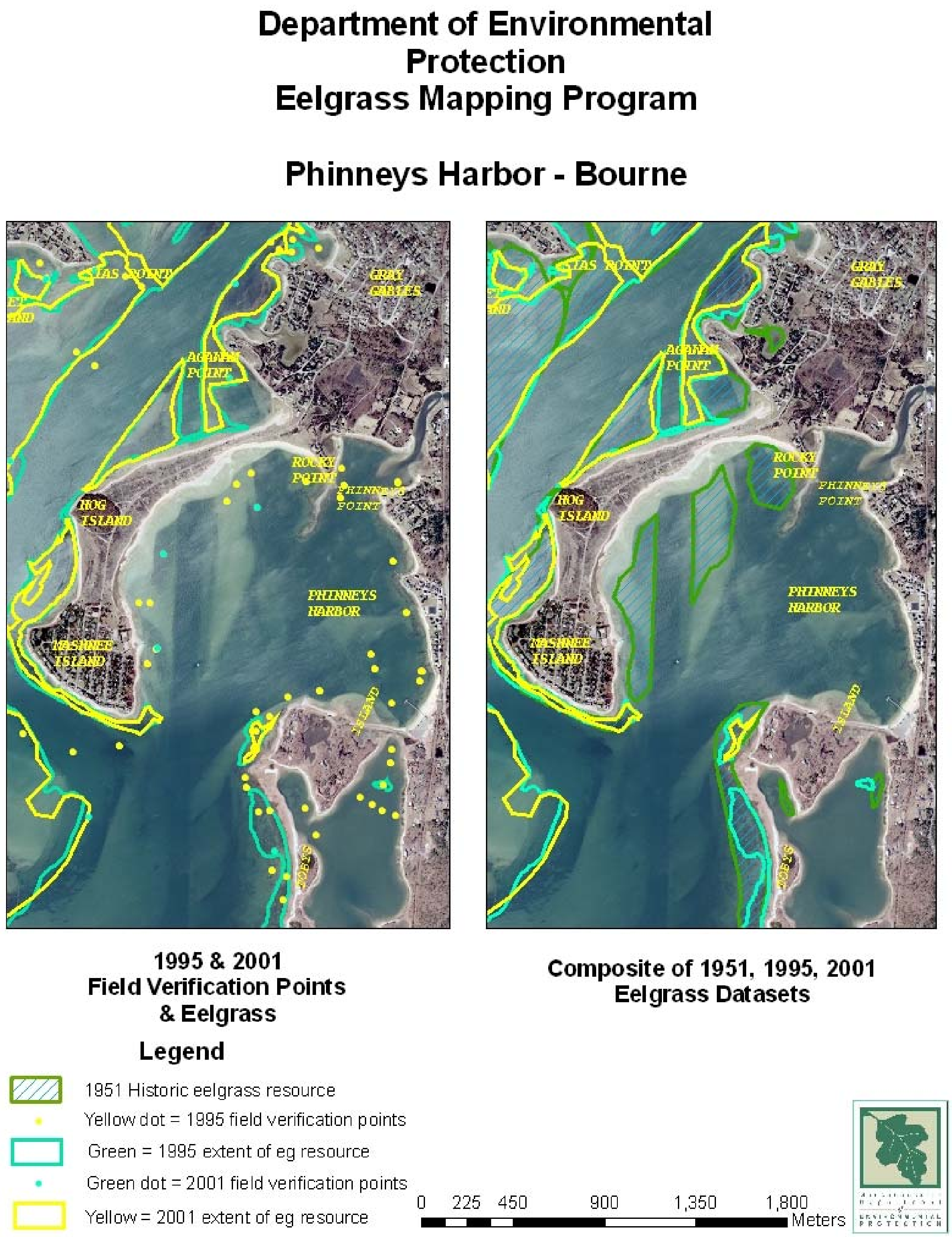


Figure VII-7. Eelgrass bed distribution within the Phinneys Harbor / Eel Pond / Back River System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were mapped by MASSDEP. All data was provided by the MASSDEP Eelgrass Mapping Program.

Based on the available data, it is possible to utilize the 1951 coverage data as an indication that eelgrass beds might be recovered, if nitrogen management alternatives were implemented (Table VII-3). This determination is based upon the MASSDEP Mapping Program and would indicate an area of eelgrass habitat within Phinneys Harbor of 70 acres. However, based upon observations by the 1985 survey of 18 acres of eelgrass beds within the southeastern region of the Harbor (Costa 1988), a better estimate of the total area eelgrass habitat is 88 acres. Note that restoration of this habitat will necessarily result in lower nitrogen levels in Eel Pond, as well (see Chapter VIII).

The relative pattern of these data is consistent with the results of the benthic infauna analysis and the observed eelgrass loss is typical of nutrient enriched shallow embayments (see below).

Table VII-3. Changes in eelgrass coverage in the Phinneys Harbor / Eel Pond / Back River System within the Town of Bourne over the past half century (MASSDEP Mapping Program, C. Costello).

Embayment	1951 (acres)	1995 (acres)	2001 (acres)	% Difference (1951 to 2001)
Phinneys Harbor	69.52	5.49	3.45	95%
Note: No Eelgrass Present in Eel Pond or Back River				

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 21 stations in the Phinneys Harbor System, with 5 sites within Eel Pond, 5 within Back River (3 in the salt marsh creeks, 2 in the outer basin) and 11 sites throughout the main basin of Phinneys Harbor (Figure VII-8 and 9). Sampling of Eel Pond and Back River occurred in Fall 2003 and Phinneys Harbor in Fall 2005. In some cases multiple assays were conducted at a site. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the loss of eelgrass beds, the Phinneys Harbor System is clearly impaired by nutrient overloading. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

Analysis of the evenness and diversity of the benthic animal communities was also used to support the density data and the natural history information. The evenness statistic can range from 0-1 (one being most even), while the diversity index does not have a theoretical upper limit. The highest quality habitat areas, as shown by the oxygen and chlorophyll records and eelgrass coverage, have the highest diversity (generally >3) and evenness (~0.7). The converse is also true, with poorest habitat quality found where diversity is <1 and evenness is <0.5.

The infaunal study indicated an overall system supporting generally healthy infaunal habitat relative to the ecosystem types represented. The Phinneys Harbor System is a complex estuary composed of 3 component basins: a large embayment (Phinneys Harbor), a small drowned kettle pond (Eel Pond) and a tidal salt marsh (Back River). Each of these 3 basins has different natural sensitivities to nitrogen enrichment and organic matter loading. Evaluation of infaunal habitat quality must consider the natural structure of each system and the types of infaunal communities that they support.

The Phinneys Harbor basin has a range of depths and sediment types (cf. Chapter V for bathymetry). The central basin is >4 meters in depth with marginal areas <1.5 meters, previously vegetated by eelgrass (Section VII.3). The deep basin areas typically support fine grained sands and muds, while the margins (particularly to the southeast) also have gravels and rocks. Overall, the Phinneys Harbor basin is presently supporting a healthy infaunal habitat (Table VII-4). Six of the eleven sites supported infaunal communities of 20-25 species and ~250 or more individuals. Diversity and eveness were excellent, generally >2.5 and >0.65, respectively. The 5 locations sampled with lower species and population counts were generally within present or historic deep channels (PNH 2,3,4,10) with one station located in an area of gravels (PNH 9). The gravel area, particularly, was clearly a physically unstable area. Equally important, the community was dominated by mollusks and crustaceans (40 species total) with polychaetes comprising 44% or 31 of the total species observed. The polychaetes were dominated by hesonids. There were deep burrowing forms (e.g. *Tellina, Tagelus*), shellfish (Mercenaria, Mya) and numerous large burrows noted in the field surveys.

Eel Pond and Back River also showed healthy to moderately healthy infaunal habitat based upon their ecosystem type. Back River is a tidal salt marsh system and as such supports infaunal communities tolerant of the organic enriched sediments typical of salt marshes. Salt marsh sediments are naturally enriched by organic matter as a result of their high productivity and the deposition in the tidal creeks of detritus originating on the emergent vegetated marsh plain. Additional organic matter enrichment results from the generally high nitrogen levels within the creeks which also support benthic production by microphytes. Salt marsh creeks generally have significant grazing pressure by fish. The Back River marshes support healthy infaunal habitat, with ~10 species per sample, but high numbers of individuals (500-1500). Diversity and Eveness are high 2.1 – 2.7 and >0.66, respectively. The population was dominated by *Gemma* (a small bivalve), and polychaetes (Hesonids and Capitellids). The presence of the organic enrichment indicator, *Capitella capitata* (16% of individuals) reflects the natural organic enrichment of these systems.

In contrast to Back River, Eel Pond is a drowned kettle pond which is sensitive to nitrogen enrichment that can result in organic matter enrichment and oxygen depletion (Section VII.2). Consistent with its generally good oxygen condition, Eel Pond is presently supportive of a healthy to moderately healthy infaunal habitat. Given the relatively deep nature of the kettle (2-3 m) and narrow outlet channel, the sediments of Eel Pond are organically enriched mud. However, both the species numbers (11-17) and numbers of individuals (650-1900) indicate a productive benthic animal community. The community was again dominated by hesonids (carnivorous polychaetes) and *Gemma* (small bivalve), which small polychaetes also being important (*Streblospio, Capitella, Carezziella*). However, the diversity and eveness indices were again indicative of a healthy environment being 2.2-3.1 and 0.64-0.84, respectively. In other small enclosed basins investigated by MEP, amphipods or capitellids have been frequently been overwhelmingly dominant and indicate a moderately to significantly impaired habitat. This is not the case for Eel Pond. In fact, mollusks and crustaceans accounted for 34% of the species and deeper burrowing forms were observed.

The overall results indicate a system generally supportive of diverse healthy communities relative to each of the 3 component basin types. The infaunal habitat quality within each of the 3 basins of the Phinneys Harbor System is fully consistent with the oxygen and chlorophyll measurements (Section VII.2), temporal trend in eelgrass (i.e. only recent loss from outer basin) and relatively low tidally averaged total nitrogen concentration for each basin, ranging from 0.45 mgN/L in Eel Pond, 0.42 mgN/L in Back River to 0.36 in Phinneys Harbor (basin average). These levels compare well to the levels to support healthy infauna found in West Falmouth Harbor (main basin) of 0.38 mgN/L and in enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mgN/L were found to be supportive of healthy infaunal habitat. All of these results are integrated into the assessment of habitat quality throughout the Phinneys Harbor System relative to nitrogen levels in Chapter VIII.

Figure VII-8. Aerial photograph of the Eel Pond and Back River sub-embayments to Phinneys Harbor showing location of benthic infaunal sampling stations (red symbol).

Figure VII-9. Aerial photograph of the Phinneys Harbor system showing location of benthic infaunal sampling stations (red symbol).

Table VII-4. Benthic infaunal community data for the Phinneys Harbor Estuary by component sub-embayment (Phinneys Harbor, Eel Pond, Back River). Estimates of the number of species adjusted to the number of individuals and diversity (H') and Evenness (E) of the community allow comparison between locations (Samples represent surface area of 0.0625 m2). Station ID's refer to Figures VII-9, VII-10.

Location	N	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Phinneys Harbor						
PNH –1	1	25	127	20.6	3.77	0.81
PNH –2	1	12	92	14.2	3.24	0.90
PNH –3	1	10	247	10.6	2.62	0.79
PNH –4	1	12	93	14.1	2.62	0.73
PNH –5	2	23	238	19.7	2.77	0.62
PNH –6	1	20	248	13.1	3.00	0.69
PNH -7/8	2	24	811	11.9	2.91	0.64
PNH –9	2	10	20	N/A	3.00	0.93
PNH –10	1	12	144	13.0	2.76	0.77
PNH –11	2	22	690	9.4	2.15	0.49
PNH –12	2	24	262	17.2	3.39	0.75
Eel Pond						
EP-1	2	17	647	13.5	3.10	0.77
EP-3	2	12	1321	9.9	2.75	0.78
EP-4	2	12	1984	10.8	2.97	0.84
EP-5	2	11	1941	7.7	2.19	0.64
EP-6	2	16	1623	12.3	3.11	0.79
Back River Marsh						
BMR-1	1	11	489	9.4	2.75	0.80
BMR-2	1	9	886	6.9	2.10	0.66
BMR-7	2	8	1432	7.0	2.32	0.77
Back River Outer Basin						
BRO-1	1	8	1732	5.7	1.79	0.60
BRO-2	1	10	577	8.9	2.79	0.84

VIII. CRITICAL NUTRIENT THRESHOLD DETERMINATION AND DEVELOPMENT OF WATER QUALITY TARGETS

VIII.1. ASSESSMENT OF NITROGEN RELATED HABITAT QUALITY

Determination of site-specific nitrogen thresholds for an embayment requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics, and nutrient related water quality information (particularly dissolved oxygen and chlorophyll-a). Additional information on temporal changes within each sub-embayment and its associated watershed nitrogen load further strengthens the analysis. These data were collected by the MEP Team to support threshold development for the Phinneys Harbor System and are discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline BayWatcher Water Quality Monitoring Program, conducted by the Coalition for Buzzards Bay with technical support from the Coastal Systems Program at SMAST.

The Phinneys Harbor System is a complex estuary composed of 3 component basins: a large embayment (Phinneys Harbor), a small drowned kettle pond (Eel Pond) and a tidal salt marsh (Back River). Each of these 3 basins has different natural sensitivities to nitrogen enrichment and organic matter loading. Evaluation of habitat quality must consider the natural structure of each system and the types of eelgrass habitat and infaunal communities that they naturally support. At present, the Phinneys Harbor System is showing variations in nitrogen enrichment among its 3 principal component basins. The inner basins of Eel Pond and Back River are clearly nitrogen enriched over Phinneys Harbor and Phinneys Harbor is clearly enriched over the adjacent Buzzards Bay waters. The evaluation of habitat quality within each of these 3 basins was based upon the level of nitrogen enrichment, resultant oxygen depletion and chlorophyll enhancement, eelgrass and infaunal indicators. Moreover, the evaluation of habitat quality was made relative to the ecology of each specific basin. The results indicate a system currently supportive of healthy infaunal habitat for the salt marsh basin of Back River, the kettle basin of Eel Pond and the outer basin of Phinneys Harbor. However, the Phinneys Harbor basin must be classified as impaired as a result of its virtual total loss of eelgrass habitat over the past 10-15 years (Table VIII-1).

Unlike many estuaries where the greatest nitrogen loading and impairment is in the inner basins, in the Phinneys Harbor System, most of the nitrogen loading is focused on the outer basin of Phinneys Harbor, as is the impairment. It is the outer basin which is capable of supporting eelgrass and which presently contains no eelgrass habitat. In contrast, the inner 2 basins are either naturally nutrient and organic matter enriched (Back River salt marsh) or are depositional basins not supportive of eelgrass, yet supportive of infaunal habitat (which was found to be relatively healthy). The result is a system with relatively healthy inner basins (based upon infaunal habitat) and an impaired outer basin (based on eelgrass loss).

Eelgrass: The Phinneys Harbor Estuary is moderately deep compared to others along the south shore of Cape Cod and even nearby West Falmouth Harbor. However, water depths are well within the range for eelgrass growth in Massachusetts, given suitable conditions of light penetration.

The eelgrass surveys reviewed for this threshold analysis indicated that eelgrass habitat within this estuary is limited to the Phinneys Harbor basin as there is no evidence that eelgrass has colonized either Eel Pond or Back River. Based upon eelgrass distributions in 1951 and 1985, eelgrass habitat is primarily within the shallower water depths (<2 m) along the northern shore (Mashnee Island) and southeastern basin of the Harbor. The 1985 data indicates that eelgrass habitat was relatively stable from 1951 to 1985. Within the 1951-1985 time-frame, eelgrass appears to have colonized most of the basin to depths of ~2 meters. It appears that the bathymetry of Phinneys Harbor limits the proportion of the basin that can support eelgrass, with much of the basin >3 meters in depth.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Phinneys Harbor Estuary on the eastern coast of Buzzards Bay within the Town of Bourne, MA., based upon assessment data presented in Chapter VII. The estuarine reach of the Back River is presently a tidal salt marsh receiving freshwater discharge from the upper Back River. Eel Pond is a drowned kettle pond and Phinneys Harbor forms the lower estuary, which was formed in the 1930's by the construction of causeways to Mashnee Island to the north and Tobys Island to the south.

Health Indicator	Phinneys Harbor Estuarine System		
	Back River (salt marsh)	**Eel Pond**	**Phinneys Harbor**
Dissolved Oxygen	H[1]	MI[2]/H[3]	H[3]
Chlorophyll	H[4]	MI[5]	MI/H[3]
Macroalgae	--[6]	--[6]	--[6]
Eelgrass	--[9]	--[9]	MI/SI
Infaunal Animals	H	H/MI	H
Overall:	**H**	**H/MI**	**MI**

H = Healthy;
SD = Severe Degradation; -- = not applicable to this estuarine reach
MI = Moderately Impaired;
SI = Severely Impaired;

At present there is virtually no eelgrass habitat within the Phinneys Harbor System at a tidally averaged total nitrogen level for the Harbor basin of 0.36 mg N/L, higher than the 0.35 threshold for eelgrass in nearby West Falmouth Harbor, with even higher total nitrogen levels in the inner nearshore areas. The temporal surveys indicate that eelgrass habitat loss in Phinneys Harbor is a relatively recent phenomenon. The decline of eelgrass beds appears to have occurred primarily between 1985 and 1995 and continued to 2001. The current absence of eelgrass throughout Phinneys Harbor is consistent with the depth of the basin and the chlorophyll levels of 5-10 ug/L as measured by the BayWatcher Program (Howes et al. 1998). The timing of the eelgrass habitat loss is also consistent with changes in land-use within the watershed. In addition, the spatial pattern of bed loss is consistent with the typical pattern of habitat decline related to increasing nitrogen loading from a watershed.

Based on the available data (1951, 1985) it appears that the total area of impaired eelgrass habitat within the Phinneys Harbor basins is approximately 70-80 acres. Although Phinneys Harbor presently supports healthy infaunal habitat (tolerant of higher levels of enrichment), it appears to have become sufficiently nutrient enriched to impair its eelgrass habitat. However, it is likely that if nitrogen loading were to decrease, eelgrass could first be restored in the lower portion of the main basin. With further reductions it may be possible for beds to be restored to the historic pattern, assuming other factors are not at play relative to eelgrass bed loss in Phinneys Harbor. Eelgrass recovery following nitrogen management would likely follow the pattern of beds first being re-established in the marginal areas in the outer region of Phinneys Harbor and then move to the inner regions. Note that restoration of this habitat will necessarily result in lower nitrogen levels in Eel Pond, as well (see Chapter VIII). Based upon the above analysis, eelgrass habitat should be the primary nitrogen management goal for the Phinneys Harbor System and is the focus of the management alternatives analysis (Chapter IX).

Water Quality: Overall, the oxygen levels within the 3 major sub-basins to the Phinneys Harbor System are not showing significant impairment when their physical structure and natural biogeochemical cycling is considered. Similar to other embayments in southeastern Massachusetts, the Back River and Eel Pond portions of the Phinneys Harbor system evaluated in this assessment showed high frequency variation, apparently related to diurnal and sometimes tidal influences. Nitrogen enrichment of embayment waters generally manifests itself in the dissolved oxygen record, both through oxygen depletion and through the magnitude of the daily excursion. The high degree of temporal variation in bottom water dissolved oxygen concentration at each mooring site, underscores the need for continuous monitoring within these systems.

The dissolved oxygen records indicate that Eel Pond is nitrogen enriched, but the oxygen depletion was generally to the 4-5 mg/L level, consistent with the chlorophyll average of 11.8 ug/L. There was clear daily and tidal variation in dissolved oxygen and chlorophyll levels. Similarly, the Back River also showed oxygen depletion consistent with its function as a salt marsh. Both inner basins showed greater nitrogen enrichment and subsequent oxygen depletions and chlorophyll levels than for the outer basin of Phinneys Harbor. However, the cause of these conditions appears to stem primarily from the naturally organic enriched nature of salt marshes (Back River) and the structure of the drowned kettle pond, Eel Pond (2-3 m deep). At present nitrogen enrichment to Eel Pond appears related to its nature as a depositional basin, as removal of anthropogenic nitrogen inputs in the Linked Watershed-Embayment Model did little to lower watercolumn nitrogen levels (Chapter VI, VIII). Given the relatively low watershed nitrogen loading (Chapter IV) and the minor change in predicted nitrogen levels with removal of anthropogenic sources (modeled, Chapters VI, VIII), it appears that this is predominantly “natural” condition and is consistent with the absence of eelgrass in the 1951 survey (Section VII.3) and relatively healthy infaunal habitat (Section VII.4).

Similarly, Back River presently shows greater oxygen depletions (to 3 mg/L), but lower chlorophyll a levels than Eel Pond (average 5.5 ug/L, general range 4-8 ug/L). This is consistent with it functioning primarily as a tidal salt marsh sub-basin. The low chlorophyll a levels result from its near complete exchange of tidal waters on each tide (compared to the deep basin of Eel Pond), which prevents a significant “build-up” of phytoplankton biomass. The low oxygen levels are also consistent with a salt marsh tidal creek, where the organic matter enriched sediments support high levels of oxygen uptake at night and deplete the overlying waters. While oxygen depletion to 3 mg/L would indicate impairment in an embayment like Phinneys Harbor basin, it is consistent with the organically enriched nature of smaller salt marsh creeks.

Infaunal Communities: The infaunal study indicated an overall system supporting generally healthy infaunal habitat relative to the ecosystem types represented. The Phinneys Harbor System is a complex estuary composed of 3 component basins: a large embayment (Phinneys Harbor), a small drowned kettle pond (Eel Pond) and a tidal salt marsh (Back River). Each of these 3 basins has different natural sensitivities to nitrogen enrichment and organic matter loading. Evaluation of infaunal habitat quality considered the natural structure of each system relative to the type of infaunal communities that they support.

The Phinneys Harbor basin has a range of depths and sediment types, with the central basin (>4 m) primarily composed of fine grained sands and muds. Marginal areas (<1.5 m) of the Harbor are composed of primarily sands and, particularly to the southeast, also gravel and rocks. Overall, Phinneys Harbor basin is presently supporting a healthy infaunal habitat. Six of the eleven sites supported infaunal communities of 20-25 species and ~250 or more individuals. Diversity and eveness were excellent, generally >2.5 and >0.65, respectively. The 5 locations sampled with lower species and population counts were generally within present or historic deep channels (PNH 2,3,4,10) with one station located in an area of gravels (PNH 9). The community was dominated by mollusks and crustaceans (40 species total) with polychaetes comprising 44% or 31 of the total species observed. Deep burrowing forms were common.

Eel Pond and Back River also showed healthy to moderately healthy infaunal habitat relative to the ecosystem type. Back River is a tidal salt marsh system and as such supports infaunal communities tolerant of the organic enriched sediments typical of salt marshes. Salt marsh sediments are naturally enriched by organic matter as a result of their high productivity and the deposition in the tidal creeks of detritus originating on the emergent vegetated marsh plain. Additional organic matter enrichment results from the generally high nitrogen levels within the creeks which also support benthic production by microphytes. Salt marsh creeks generally have significant grazing pressure by fish. The Back River marshes support healthy infaunal habitat, with ~10 species per sample, but high numbers of individuals (500-1500), with high diversity and Eveness (H'= 2.1 – 2.7; E >0.66). The population was dominated by *Gemma* (a small bivalve), and polychaetes (Hesonids and Capitellids). The presence of the organic enrichment indicator, *Capitella capitata* (16% of individuals) reflects the natural organic enrichment of these systems.

In contrast to Back River, Eel Pond is a drowned kettle pond which is sensitive to nitrogen enrichment that can result in organic matter accumulation and oxygen depletion (Section VII.2). Consistent with its generally good oxygen condition, Eel Pond is presently supportive of a healthy to moderately healthy infaunal habitat. Given the relatively deep nature of the kettle (2-3 m) and narrow outlet channel, the sediments of Eel Pond are composed of organically enriched mud. However, both the species numbers (11-17) and numbers of individuals (650-1900) indicate a productive benthic animal community dominated by hesonids (carnivorous polychaetes) and Gemma (small bivalve), which small polychaetes also being important (*Streblospio, Capitella, Carezziella*). The diversity and eveness indices were indicative of a healthy environment being 2.2-3.1 and 0.64-0.84, respectively. In other small enclosed basins investigated by MEP, amphipods or capitellids have frequently been overwhelmingly dominant and indicate a moderately to significantly impaired habitat. This is not the case for Eel Pond. In fact, mollusks and crustaceans accounted for 34% of the species and deeper burrowing forms were observed.

The overall results indicate a system generally supportive of diverse and healthy communities appropriate to each of the 3 component basin types. The infaunal habitat quality within each of the 3 basins of the Phinneys Harbor System is fully consistent with the oxygen and chlorophyll measurements, temporal trend in eelgrass (i.e. only recent loss from outer basin) and relatively low tidally averaged total nitrogen concentration for each basin, ranging from 0.45 mg N/L in Eel Pond, 0.42 mg N/L in Back River to 0.36 in Phinneys Harbor (basin average). These levels compare well to the levels supportive of healthy infauna found in West Falmouth Harbor (main basin) of 0.38 mg N/L and in enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg N/L were found to be supportive of healthy infaunal habitat.

VIII.2. THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates, which will maintain acceptable habitat quality throughout an embayment system, is to first identify a sentinel location within the embayment and second, to determine the nitrogen concentration within the water column which will restore that location to the desired habitat quality. The sentinel location is selected such that the restoration of that one site will necessarily bring the other regions of the system to acceptable habitat quality levels. Once the sentinel site and its target nitrogen level are determined, the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved.

Determination of the critical nitrogen threshold for maintaining high quality habitat within Phinneys Harbor Estuarine System is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution and current benthic community indicators. Given the database, it is possible to develop a site-specific threshold, which is a refinement upon general threshold analysis frequently employed.

The Phinneys Harbor System is presently supportive of infaunal habitat throughout its 3 main basins, but is clearly impaired by nitrogen enrichment in the largest component basin of Phinneys Harbor. Given the documented importance of eelgrass habitat to this outer basin and the virtual loss of all 88 acres of eelgrass that it historically supported, eelgrass restoration in this basin was set as the primary nitrogen management goal for the overall System. Based upon the water quality monitoring data, there is a gradient in nitrogen within the outer basin, with the southeastern region showing slightly higher total nitrogen levels than the northern region or near the inlet. Tidally averaged total nitrogen (TN) levels in the southeastern region (station PH-4) were 0.369 mg N/L compared to 0.343-0.351 mg N/L for the other stations (PH 2,3,6). Station PH-5 within the outflow from the Back River was higher reflecting the nitrogen levels in the ebbing water from the upper 2 basins. Based upon the eelgrass habitat restoration objective and the distribution of total nitrogen within the Harbor basin, most appropriate sentinel station is PH-4, as lowering TN levels at this station will also result in even lower levels at the other stations in the outer basin.

Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fisheries resources), benthic infaunal habitat quality must also be supported as a secondary condition. At present, the inner basins of Back River and Eel Pond appear to be relatively healthy and supportive of infaunal habitat. Given their structure and the historic absence of eelgrass in these systems, the MEP Technical Team selected infaunal habitat quality as the primary management target for these systems. The total nitrogen levels in these 2 upper basins for management are based upon the Back River Station EP-3 and the average Eel Pond watercolumn TN levels (average of EP-1 and EP-2).

The threshold level to restore eelgrass within the outer basin of Phinneys Harbor was set at 0.35 mg N/L based upon the detailed quantitative analysis of nearby West Falmouth Harbor where both temporal nitrogen and eelgrass distribution trends could be assessed as well as comparative analysis of total nitrogen levels within healthy eelgrass beds. This threshold TN level is supported by site-specific factors from the Phinneys Harbor basin:

(a) at present there is virtually no eelgrass habitat within the Phinneys Harbor System at a tidally averaged TN level for the Harbor basin of 0.36 mgN/L;

(b) the present absence of eelgrass is at a tidally averaged TN level for the sentinel station of 0.37 mgN/L;

(c) the outer basin has only recently lost its eelgrass habitat and still supports healthy infaunal habitat, suggesting that it is only slightly over its nitrogen threshold level;

The secondary nitrogen threshold to ensure healthy infaunal habitat is set at <0.45 mg N/L based upon current conditions, 0.46 mg N/L where a slight level of impairment is indicated based upon the indicator species present (capitellids and spionids). The MEP has found a variety of nitrogen levels to be supportive of infaunal habitat based upon the basin type. Shallow vertically well-mixed basins tend to allow higher TN levels (e.g. Popponesset Bay, Three Bays at <0.5 mg N/L) and deeper basins, like Eel Pond, lower levels. However, the analysis of total nitrogen levels for Eel Pond with removal of all anthropogenic nitrogen loading from the entire System watershed still projects a tidally averaged level of 0.35 mg N/L. (which would not support eelgrass due to basin depth). However, the present high quality of Eel Pond infaunal habitat supports only the need for a small TN reduction and is consistent with the selected infaunal TN threshold. Note that when the TN threshold to support eelgrass habitat in the Phinneys Harbor basin is achieved, nitrogen levels within Eel Pond will also be lower than at present, a significant change relative to the secondary threshold level.

The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location within the Phinneys Harbor System was determined to be 0.35 mg TN L^{-1}. This nitrogen level is lower than found for other complex systems such as Stage Harbor (0.38 N/L^{-1}) and analysis of nitrogen levels within the eelgrass bed in Waquoit Bay, near the inlet (measured TN of 0.395 mg N L^{-1}, tidally corrected <0.38 mg N L^{-1}), and (3) a similar analysis in Bournes Pond. The sentinel station under present loading conditions supports a tidally corrected average concentration of 0.37 mg TN L^{-1}, so a watershed nitrogen management will be required for restoration of the estuarine habitats within this system.

It must be stressed that the nitrogen threshold for the Phinneys Harbor Estuary is at the sentinel location. The secondary criteria should be met when the threshold is met at the sentinel station used for setting the nitrogen threshold for the Phinneys Harbor basin and serve as a “check”. The nitrogen loads associated with the threshold concentration at the sentinel location are discussed in Section VIII.3, below.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Phinney’s Harbor estuary system. Tidally averaged total nitrogen thresholds derived in Section VIII.1 were used to adjust the calibrated constituent transport model developed in Section VI. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at the sentinel stations chosen for Phinney’s Harbor. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a suite of potential reduction approaches that need to be evaluated by the community. The presentation is to establish the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required 80% removal of septic load (associated with direct groundwater discharge to the embayment) for the Phinney's Harbor and Phinney's Harbor Islands watersheds. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the Phinney's Harbor and Back River system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.

sub-embayment	present septic load (kg/day)	threshold septic load (kg/day)	threshold septic load % change
Back River Inner	3.805	3.805	+0.0%
Back River Outer	1.381	1.381	+0.0%
Eel Pond	4.244	4.244	+0.0%
Phinney's Harbor	12.608	2.522	-80.0%

Tables VIII-3 and VIII-4 provide additional loading information associated with the thresholds analysis. Table VIII-3 shows the change to the total watershed loads, based upon the removal of septic loads depicted in Table VIII-2. Removal of 80% of the septic load from the Phinney's Harbor and Phinney's Harbor Islands watersheds results in a 68% reduction in total nitrogen load. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent 'worst-case' summertime conditions. The benthic flux for this modeling effort is reduced from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Buzzards Bay.

Table VIII-3. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Phinney's Harbor and Back River system. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	threshold load (kg/day)	threshold % change
Back River Inner	7.699	7.699	+0.0%
Back River Outer	1.964	1.964	+0.0%
Eel Pond	4.888	4.888	+0.0%
Phinney's Harbor	14.781	4.694	-68.2%

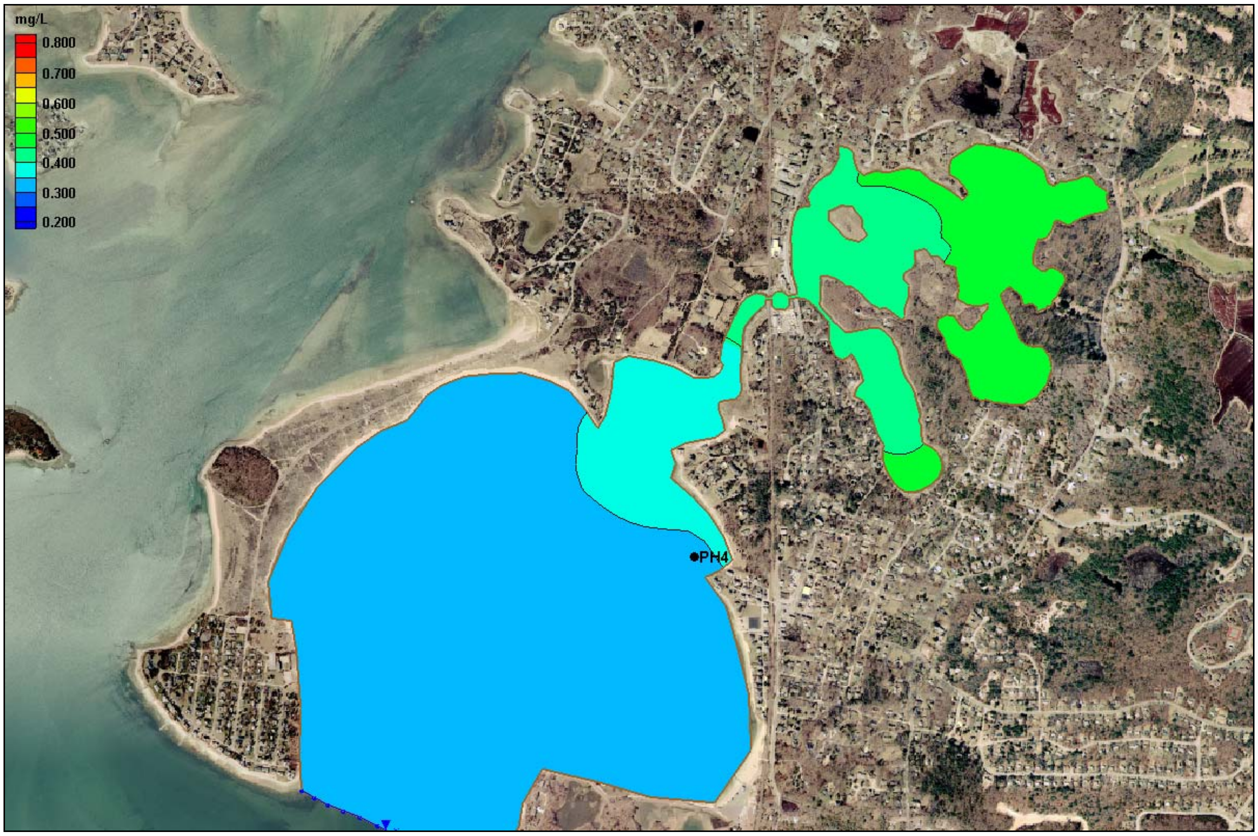


Figure VIII-1. Contour plot of modeled average total nitrogen concentrations (mg/L) in the Phinney's Harbor estuary system, for threshold conditions (0.35 mg/L at water quality monitoring.

Table VIII-4. Threshold sub-embayment loads and attenuated surface water loads used for total nitrogen modeling of the Phinney's Harbor and Back River system, with total watershed N loads, atmospheric N loads, and benthic flux

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Back River Inner	7.699	0.589	0.976
Back River Outer	1.964	0.340	0.562
Eel Pond	4.888	0.246	-0.709
Phinney's Harbor	4.694	5.186	12.165

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, a reduction in TN concentration of approximately 5% is required at Phinney's Harbor station PH4. The reduction in septic load to Phinney's Harbor results in a reduction in TN concentration of approximately 3% across the entire system.

The basis for the watershed nitrogen removal strategy utilized to achieve the embayment thresholds may have merit, since this example nitrogen remediation effort is focused on watersheds where groundwater is flowing directly into the estuary. For nutrient loads entering the systems through surface flow, natural attenuation in freshwater bodies (i.e., streams and ponds) can significantly reduce the load that finally reaches the estuary. Presently, this attenuation is occurring due to natural ecosystem processes and the extent of attenuation being determined by the mass of nitrogen which discharges to these systems. The nitrogen reaching these systems is currently “unplanned”, resulting primarily from the widely distributed non-point nitrogen sources (e.g. septic systems, lawns, etc.). Future nitrogen management should take advantage of natural nitrogen attenuation, where possible, to ensure the most cost-effective nitrogen reduction strategies. However, “planned” use of natural systems has to be done carefully and with the full analysis to ensure that degradation of these systems will not occur. One clear finding of the MEP has been the need for analysis of the potential associated with restored wetlands or ecologically engineered ponds/wetlands to enhance nitrogen attenuation. Attenuation by ponds in agricultural systems has also been found to work in some cranberry bog systems, as well. Cranberry bogs, other freshwater wetland resources, and freshwater ponds provide opportunities for enhancing natural attenuation of their nitrogen loads. Restoration or enhancement of wetlands and ponds associated with the lower ends of rivers and/or streams discharging to estuaries are seen as providing a dual service of lowering infrastructure costs associated with wastewater management and increasing aquatic resources associated within the watershed and upper estuarine reaches.

Table VIII-5. Comparison of model average total N concentrations from present loading and the modeled threshold scenario, with percent change, for the Phinney’s Harbor and Back River system. Sentinel threshold station are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Phinney’s Harbor	PH2	0.347	0.335	-3.5%
Phinney’s Harbor	PH3	0.351	0.339	-3.6%
Phinney’s Harbor	**PH4**	**0.369**	**0.352**	**-4.6%**
Phinney’s Harbor	PH5	0.390	0.377	-3.5%
Phinney’s Harbor	PH6	0.343	0.334	-2.6%
Eel Pond - Inner	EP1	0.470	0.456	-3.1%
Eel Pond - Middle	EP2	0.437	0.423	-3.3%
Eel Pond – Back River	EP3	0.423	0.408	-3.4%

Although the above modeling results provide one manner of achieving the selected threshold level for the sentinel site within the estuarine system, the specific example does not represent the only method for achieving this goal. However, the thresholds analysis provides general guidelines needed for the nitrogen management of this embayment.

IX. ALTERNATIVES TO IMPROVE WATER QUALITY

IX.1 PRESENT LOADING WITH SEWERING OF EEL POND, INNER BACK RIVER, OUTER BACK RIVER, AND THE POND WATERSHEDS

The size of Phinney's Harbor relative to the other embayments within the system limits the effectiveness of sewering the Eel Pond and Back River watersheds to reduce the overall nitrogen load. To demonstrate this, an alternative was developed to assess impact of removing 100-percent of the septic load from the Eel Pond and Back River watersheds while using the present loading conditions in Phinney's Harbor. Table IX-1 and Table IX-2 illustrate the overall change to septic and watershed loads resulting from this alternative. Septic removal from the Eel Pond and Back River watersheds results in significant reductions in the watershed loads in those sub-embayments. Based on the assumptions developed for this alternative, Table IX-3 presents the various components of nitrogen loading for the Phinney's Harbor system.

Table IX-1. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present conditions in Phinney's Harbor with septic loads removed from Eel Pond, Inner back River, Outer Back River, and the Pond Watersheds. These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.

sub-embayment	present septic load (kg/day)	scenario septic load (kg/day)	threshold septic load % change
Back River Inner	3.805	0.000	-100.0%
Back River Outer	1.381	0.000	-100.0%
Eel Pond	4.244	0.000	-100.0%
Phinney's Harbor	12.608	12.608	+0.0%

Table IX-2. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present conditions in Phinney's Harbor with septic loads removed from Eel Pond, Inner back River, Outer Back River, and the Pond Watersheds. These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

sub-embayment	present load (kg/day)	scenario load (kg/day)	threshold % change
Back River Inner	7.699	3.893	-49.4%
Back River Outer	1.964	0.584	-70.3%
Eel Pond	4.888	0.644	-86.8%
Phinney's Harbor	14.781	14.781	+0.0%

Table IX-3. Sub-embayment loads used for total nitrogen modeling of the Phinney's Harbor system for present loading scenario with septic loads removed from Eel Pond, Inner back River, Outer Back River, and the Pond Watersheds, with total watershed N loads, atmospheric N loads, and benthic flux.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Back River Inner	3.893	0.589	1.863
Back River Outer	0.584	0.340	0.148
Eel Pond	0.644	0.246	-0.451
Phinney's Harbor	14.781	5.186	14.525

Total nitrogen modeling results for existing conditions minus the septic loads for Eel Pond and Back River watersheds indicate that the Phinneys Harbor would not meet the nitrogen threshold target at Station PH4 (Table IX-4 and Figure IX-1). The water quality modeling indicates relatively significant reductions in nitrogen concentrations within the two sub-embayments; however, negligible reductions within Phinney's Harbor. Nitrogen concentration reductions range from approximately 2% in outer Phinney's Harbor to nearly 19% in Eel Pond. Overall, this scenario indicates that to meet the nitrogen concentration threshold within Phinneys Harbor, removing septic loads from the Phinney's Harbor watershed is the most practical and effective approach.

Table IX-4. Comparison of model average total N concentrations from present loading scenarios (with and without the septic loads removed from Eel Pond, Inner back River, Outer Back River, and the Pond Watersheds), with percent change, for the Phinney's Harbor system. The threshold station is shown in bold print.

Sub-Embayment	monitoring station	present (mg/L)	scenario (mg/L)	% change
Phinney's Harbor	PH2	0.347	0.340	-1.9%
Phinney's Harbor	PH3	0.351	0.344	-2.2%
Phinney's Harbor	**PH4**	**0.369**	**0.357**	**-3.3%**
Phinney's Harbor	PH5	0.390	0.365	-6.6%
Phinney's Harbor	PH6	0.343	0.336	-2.0%
Eel Pond - Inner	EP1	0.470	0.381	-18.9%
Eel Pond - Middle	EP2	0.437	0.376	-14.1%
Eel Pond – Back River	EP3	0.423	0.383	-9.4%

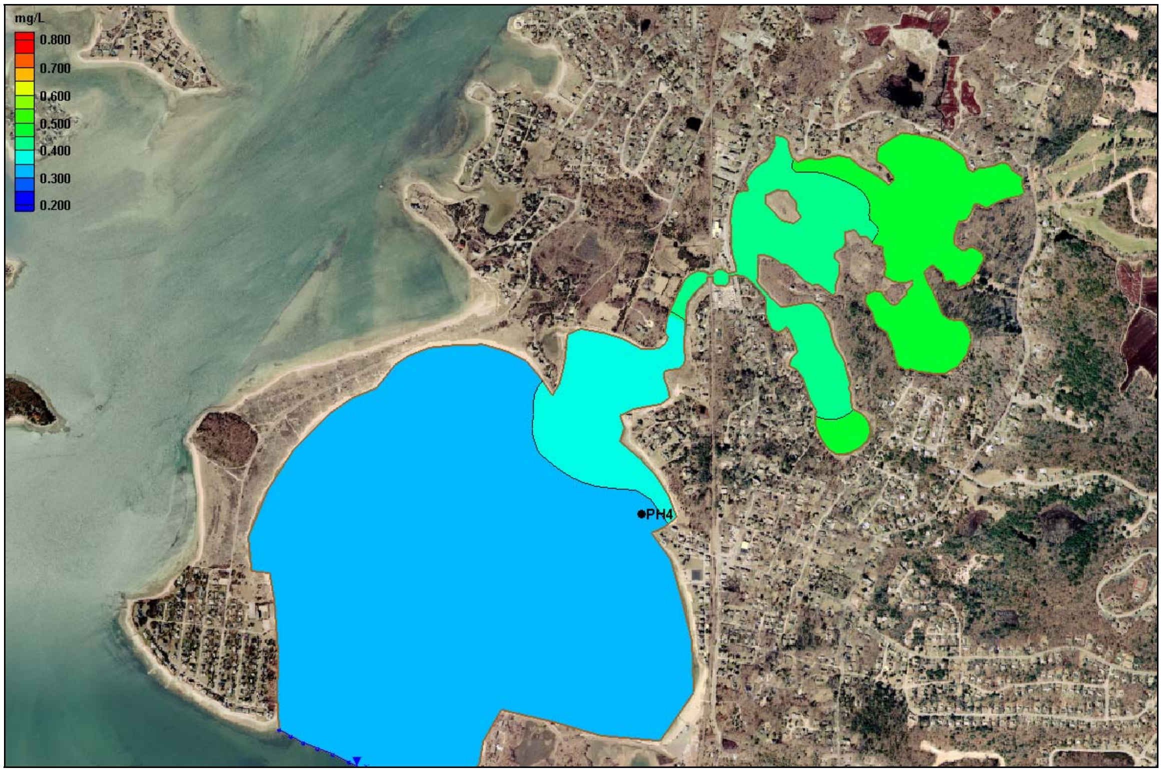


Figure IX-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Phinney's Harbor system, for present loading conditions with a 100-percent of the septic load removed from the Eel Pond and Back River watersheds.

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