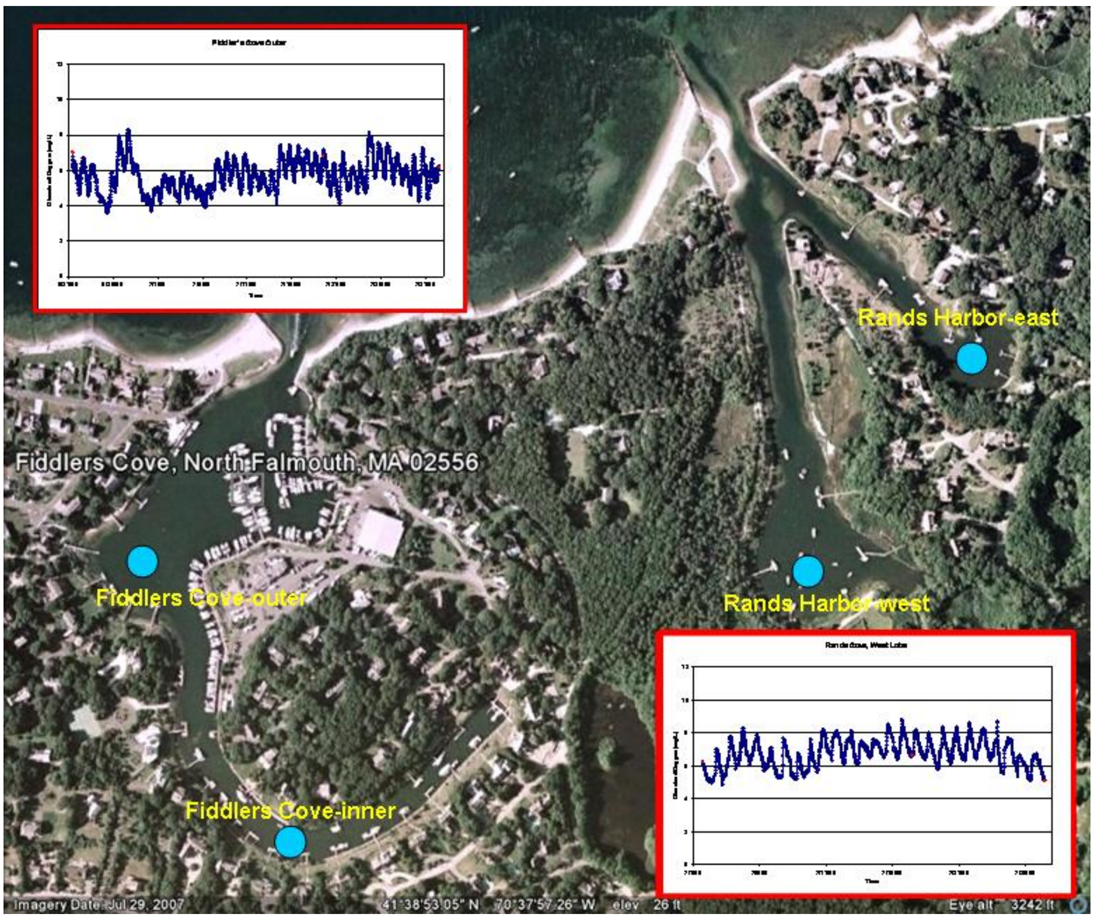
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Fiddlers Cove and Rands Harbor Embayment Systems
Town of Falmouth, Massachusetts



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of Environmental Protection

FINAL REPORT – MARCH 2013

Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Fiddlers Cove and Rands Harbor Embayment Systems Town of Falmouth, Massachusetts

FINAL REPORT – MARCH 2013

Brian Howes
Roland Samimy
Ed Eichner
David Schlezinger

Sean Kelley
John Ramsey

Phil "Jay" Detjens

CAPE COD COMMISSION

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 P.M.)

SMAST Coastal Systems Program
Jennifer Benson, Michael Bartlett, Sara Sampieri

Cape Cod Commission
Tom Cambareri

SMAST
University of Massachusetts Dartmouth
The School for Marine Science and Technology

Massachusetts
Department of
Environmental
Protection

Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Fiddlers Cove and Rands Harbor Embayment Systems, Falmouth, 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 Fiddlers Cove and Rands Harbor embayment system, two coastal embayments within the Town of Falmouth, Massachusetts. Analyses of the Fiddlers Cove and Rands Harbor embayment systems were performed to assist the Town of Falmouth with up-coming nitrogen management decisions associated with the current and future wastewater planning efforts of the Town, 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 embayments 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 Falmouth 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 Fiddlers Cove and Rands Harbor embayments, (2) identification of all nitrogen sources (and their respective N loads) to the waters of each embayment, (3) nitrogen threshold levels for maintaining Massachusetts Water Quality Standards within the waters of each embayment, (4) analysis of watershed nitrogen loading reduction to achieve the N threshold concentrations in each embayment, 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 Fiddlers Cove and Rands Harbor embayment systems.

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 Fiddlers Cove and Rands Harbor embayment systems within the Town of Falmouth are at risk of eutrophication (over enrichment) from enhanced nitrogen loads entering through groundwater from the increasingly developed watershed to these coastal systems. 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 Falmouth has recognized the severity of the problem of eutrophication and the need for watershed nutrient management and is currently developing a Comprehensive Wastewater Management Plan which the Town plans to implement upon its completion. The Town of Falmouth has been working with the Town of Mashpee that has also completed and implemented wastewater planning in other nearby regions not associated with the Fiddlers Cove and Rands Harbor systems, specifically the Waquoit Bay embayment system. In this manner, this analysis of the Fiddlers Cove and Rands Harbor systems is yielding results which can be utilized by the Town of Falmouth along with MEP results developed for the other estuaries of the town (specifically, Quissett Harbor, Wild Harbor, West Falmouth Harbor, Little Pond, Falmouth Inner Harbor, Oyster Pond, Great Pond, Green Pond, Bournes Pond, Eel Pond/Childs River and Waquoit Bay) in order to give the Town of Falmouth the necessary results to plan out and implement a unified town-wide approach to nutrient management. The Town of Falmouth with associated working groups has recognized that a rigorous scientific approach yielding site-specific nitrogen loading targets was required for decision-making and alternatives analysis. The completion 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 Towns. 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 an 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 an 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 (DEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool 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 by the Buzzards Bay Project, in 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 as applicable to the site specific characteristics of a given estuary.

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 both the Fiddlers Cove and the Rands Harbor embayment systems by using site-specific data collected by the MEP and water quality data from the Falmouth PondWatch Program (see Chapter 2) as well as the Coalition for Buzzards Bay (CBB) BayWatchers Program (assisted technically until 2008 by the University of Massachusetts-SMAST Coastal Systems Program). Evaluation of upland nitrogen loading was conducted by the MEP, data was provided by the Town of Falmouth Planning Department, and watershed boundaries delineated by USGS. This land-use data was used to determine watershed nitrogen loads within the Fiddlers Cove and Rands Harbor embayment systems and the sub-embayments of each system 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 Fiddlers Cove and Rands Harbor embayment systems. Once the hydrodynamic properties of the estuarine systems were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates specific to each embayment. 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. 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 Fiddlers Cove and Rands Harbor embayment systems were used to calibrate the water quality models, with validation using measured nitrogen concentrations (under existing loading conditions). The underlying hydrodynamic models were 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 were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Fiddlers Cove and Rands Harbor embayment systems. 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 both the Fiddlers Cove system and the Rands Harbor system. 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 these two nitrogen impaired embayments.

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 Fiddlers Cove and Rands Harbor embayment systems in the Town of Falmouth. Future water quality modeling scenarios should be run which incorporate the spectrum of strategies that result in nitrogen loading reduction to each of the embayments. For Illustrative purposes, 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 systems. The concept was that since nitrogen loads associated with wastewater generally represent 75% - 78% of the controllable watershed load to the Fiddlers Cove and Rands Harbor embayment systems and are more manageable than other nitrogen sources, the ability to achieve needed reductions through this source is a good gauge of the feasibility for restoration of these systems.

2. Problem Assessment (Current Conditions)

A habitat assessment was conducted throughout both the Fiddlers Cove embayment and the Rands Harbor embayment system, based upon available water quality monitoring data, historical changes in eelgrass distribution, time-series water column oxygen measurements of dissolved oxygen and chlorophyll, and benthic community structure. It is important to note that the Fiddlers Cove and Rands Harbor Systems are artificial open water embayments significantly altered by human activity over the past approximately 100 years. Both estuaries were formed primarily as tidal salt marshes associated tidal creeks. Human activity gradually transformed these salt marsh dominated tidal creeks into more open water systems resembling embayments. The tidal wetlands were removed to increase the navigability of the systems and to create protected harbors, though portions of the upper reaches of Fiddlers Cove still supported bordering saltmarsh into the 1970's. At present almost all of the tidal wetlands along the shoreline of Fiddlers Cove have been removed and replaced with hard coastal structures (e.g. riprap). Although Rands Harbor was also constructed from tidal creeks, it still maintains significant fringing salt marsh areas, particularly in the western branch. Regardless of their formation, both estuaries are now functioning as tributary embayments to Buzzards Bay and must be managed as such. Management of ecological changes and impairments of these semi-enclosed systems must be considered not only relative to nutrient enrichment from an increasingly developed coastal watershed but also the structural changes that have occurred over the during the last century.

At present, the Fiddlers Cove/Rands Canal Estuarine System is beyond its ability to assimilate nitrogen without impairment and is showing a moderate level of nitrogen enrichment, with generally moderate impairment of infaunal habitats (Table VIII-1). As eelgrass beds could not be documented to exist, either historically or presently due to structural considerations mentioned above, the thresholds analysis for these systems is necessarily focused on restoration of their impaired infaunal animal habitats resulting in part from oxygen depletion and organic matter enrichment. However, it is likely that nitrogen management within these two embayments will improve eelgrass and infaunal habitat within the down-gradient near shore waters of Buzzards Bay.

Key water quality parameters, oxygen and chlorophyll, supported the contention that the basins of Fiddlers Cove and Rands Harbor are impaired by nitrogen enrichment. Within Fiddlers Cove the level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate moderately nutrient enriched waters within the lower basin and upper Canal region. The main basin of Fiddlers Cove showed moderate daily excursions in oxygen levels. Oxygen regularly exceeded 6 mg L^{-1} and periodically exceeded 8 mg L^{-1}. These moderately high oxygen levels are primarily the result of the combined effects of photosynthesis by the high phytoplankton biomass and relatively quiescent waters. Oxygen conditions within the Canal reach of Fiddlers Cove were similar to the main basin, but did exhibit larger daily excursions in oxygen levels. Oxygen levels periodically regularly exceeded 8 mg L^{-1} and periodically exceeded 10 mg L^{-1}. These high oxygen levels are the result of the combined effects of high phytoplankton biomass (photosynthesis) and high rates of respiration.

Rands Harbor, like Fiddlers Cove, appears to have moderate impairment of benthic habitat through oxygen depletion and periodic phytoplankton blooms, but a slightly lower extent of oxygen depletion when compared to Fiddlers Cove. Oxygen conditions in the west branch were generally similar to conditions observed in the east branch, although oxygen levels in the terminal basin of the west branch showed slightly less depletion and less of a daily excursion. Oxygen levels in both branches were almost always >5 mg L^{-1}. Moderate daily excursions in oxygen levels were observed at this location, ranging from levels at and slightly above air equilibration to moderately low conditions where levels approached 4 mg L^{-1}. Similarly, the water quality monitoring results showed oxygen levels only periodically declining below 5 mg L^{-1} (5% of 195 samples). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress.

The oxygen data is consistent with organic matter enrichment within the Fiddlers Cove and Rands Harbor Systems, as seen from the parallel measurements of chlorophyll a. The measured levels of oxygen depletion and enhanced chlorophyll a levels follows the spatial pattern of total nitrogen levels, and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment. At present, both the Fiddlers Cove and Rands Harbor Systems are beyond their ability to assimilate nitrogen without impairment and are showing a moderate level of nitrogen enrichment, with moderate impairment of infaunal habitats.

Overall, the Infauna Survey indicated that the main basin and the Canal which comprise the Fiddlers Cove Embayment System presently support low to moderately impaired benthic infaunal habitat. It appears that organic deposition in these areas is the cause of the stress, consistent with the bottom water oxygen levels and phytoplankton biomass. There is a gradient in benthic animal habitat impairment with low to moderate impairment nearest the tidal inlet increasing into the Canal. In general the Canal was dominated by a mixture of species indicative of low and moderate levels of enrichment (amphipods, and a variety of crustaceans, mollusks and polychaete worms), while the main basin (particularly near the inlet) supported slightly more diverse communities of polychaetes, mollusks and crustaceans.

Overall, the Infauna Survey indicated that both the east and west branches of the Rands Harbor system are presently supporting impaired benthic infaunal habitat, with the east branch more impaired than the west branch. It appears that organic deposition in these areas is the cause of the stress, consistent with the bottom water oxygen levels and phytoplankton biomass. The highest quality habitat is presently at the tidal inlet, a pattern also found for nearby Fiddlers Cove and many other estuaries in the region. However, even this lower region of Rands Harbor close to the inlet is slightly impaired as seen from its moderate to high number of species (24), individuals (414) *but only moderate diversity and Evenness* (H'= 2.6; E= 0.58) and that 23% of the community is comprised of organic enrichment tolerant species. There is a clear difference between the 2 branches with the West Branch (also called the South Branch) presently supporting higher quality habitat than the East Branch.

Classification of habitat quality in Fiddlers Cove and Rands Harbor necessarily included the structure of the estuarine basins, specifically that these systems are fully representative of a tidal embayment, as opposed to a tidal river or salt marsh basin. Integration of all of the metrics clearly indicates that the basins of Fiddlers Cove and Rands Harbor are generally supporting benthic animal habitat that is moderately impaired. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the upper reach of the Fiddlers Cove Canal and within the upper terminal basins of Rands Harbor are presently 0.558 mg TN L^{-1} and 0.57 mg TN L^{-1}, respectively, levels generally found associated with a low to moderate level of impairment of benthic animal habitat in southeastern Massachusetts estuaries.

3. Conclusions of the Analysis

The approach for determining nitrogen loading rates that will support acceptable habitat quality throughout an embayment system is to first identify a sentinel location within the embayment and secondly, to determine the nitrogen concentration within the water column that will restore the location to the desired habitat quality. 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. 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 (Section VIII.2), the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved (Section VIII.3). Determination of the critical nitrogen threshold for maintaining high quality habitat within the Fiddlers Cove and Rands Harbor Embayment Systems is based primarily upon the nutrient and oxygen levels and current benthic community indicators, as there is no history of eelgrass colonization of these basins.

Sentinel stations were established within each estuary for development of nitrogen threshold targets that when met will restore benthic animal habitat throughout the tidal reaches. Since nitrogen levels are highest in the upper reaches of each system the Sentinel Station for Fiddlers Cove was placed within the upper reach of the Canal and in Rands Harbor in the terminal basins of each branch. Rands Harbor requires 2 sentinel stations, since the branches have different watersheds, stream inputs and sediment characteristics.

Watershed nitrogen loads (Tables ES-1 and ES-2) for the Town of Falmouth Fiddlers Cove and Rands Harbor embayment systems were comprised primarily of wastewater nitrogen. Land-use and wastewater analysis found that generally about 75% - 78% 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, and the nearby Hamblin / Jehu Pond / Quashnet River analysis in eastern Waquoit Bay, among many other systems analyzed by the MEP. This is almost certainly going to be true for the other embayments within the MEP area, as well, inclusive of Fiddlers Cove and Rands Harbor.

The threshold nitrogen levels for the Fiddlers Cove and Rands Harbor embayment systems in Falmouth were determined as follows:

Fiddlers Cove and Rands Harbor Threshold Nitrogen Concentrations

- Following the MEP protocol, the restoration target for the Fiddlers Cove and Rands Harbor systems should reflect both recent pre-degradation habitat quality, take into consideration structural characteristics (historic and present) of each embayment and be reasonably achievable. Based upon the assessment data (Chapter VII), the Fiddlers Cove and Rands Harbor systems are presently supportive of habitat in varying states of impairment, depending on the component sub-basins being considered. Overall, each system is only showing signs of moderate to low impairment.

- As there are no long-term water quality monitoring stations in each of the sub-basins to either the Fiddlers Cove or Rands Harbor systems where sentinel stations were located, the water quality model was used to determine the present total nitrogen levels at each sentinel station under present loading conditions, in order to refine nitrogen threshold development (Section VI). Using this approach, total nitrogen levels within the upper reach of the Fiddlers Cove Canal and within the upper terminal basins of Rands Harbor are presently 0.56 mg TN L^{-1} and 0.57 mg TN L^{-1}, respectively.

- These TN levels are comparable to other estuarine basins throughout the region that show similar levels of oxygen depletion, organic enrichment and moderately impaired benthic animal habitat. Given that in numerous estuaries it has been previously determined that 0.500 mg TN L^{-1} is the upper limit to sustain unimpaired benthic animal habitat (Eel Pond, Parkers River, upper Bass River, upper Great Pond, upper Three Bays) this level is deemed most appropriate for restoration of the basins comprising

Fiddlers Cove and Rands Harbor. Watershed management to meet these restoration thresholds for benthic animal habitat is the focus of the nitrogen management threshold analysis (Section VIII.3).

- The nitrogen thresholds developed in Section VIII-2 were used to determine the amount of total nitrogen mass loading reduction required for restoration of infaunal habitats in the Fiddlers Cove and Rands Harbor 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 lowered by reductions only in septic effluent discharges, until the nitrogen levels reached the threshold level at the sentinel station chosen for Fiddlers Cove and Rands Harbor. *It is important to note that load reductions can be produced by reduction of any or all sources. The load reductions presented in Section VIII-3 represent only one of a suite of potential reduction approaches that need to be evaluated by the community.*

- Only considering nitrogen loads associated with septic systems, the nitrogen load reductions within the overall Fiddlers Cove / Rands Harbor system necessary to achieve the threshold nitrogen concentrations in each sub-basin required 33% removal of septic load (associated with direct groundwater discharge to the embayment) for the entire system.

It is important to note that the analysis of future nitrogen loading to the Fiddlers Cove and Rands Harbor estuarine systems 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. 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 Fiddlers Cove and Rands Harbor estuarine systems is that restoration will necessitate a reduction in the present (Falmouth 2009, Bourne 2008 and Sandwich 2010) 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 Fiddlers Cove and Rands Harbor 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)
Rands Harbor	0.707	1.548	4.528	0.000	6.074	0.142	0.676	6.892	0.436	--
Fiddlers Cove	0.184	1.000	3.332	0.000	4.332	0.184	1.254	5.770	0.414	--
Combined Total	**0.891**	**2.548**	**7.86**	**0**	**10.406**	**0.326**	**1.93**	**12.662**	**--**	**0.50[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 2000 – 2009 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 sites located in upper terminal basins of both Rands Harbor and Fiddlers Cove

Table ES-2. Present Watershed Loads, Thresholds Loads, and the percent reductions necessary to achieve the Thresholds Loads for the Fiddlers Cove and Rands Harbor estuarine systems in 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
Rands Harbor	6.074	4.410	0.142	0.582	5.134	-27.4%
Fiddlers Cove	4.332	3.368	0.184	1.208	4.760	-22.2%
Combined Total	**10.406**	**7.778**	**0.326**	**1.790**	**9.894**	**-25.2%**

(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.

ACKNOWLEDGMENTS

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 Town of Falmouth and drove for the completion of the Linked Watershed-Embayment Modeling Approach to Determine Critical Nitrogen Loading Thresholds for the Fiddlers Cove and Rands Harbor Embayment System. Without these stewards and their efforts, this project would not have been possible.

First and foremost we would like to recognize and applaud the commitment shown by the Town of Falmouth in carrying forward with the Massachusetts Estuaries Project as part of its watershed management planning and for their commitment to the restoration of all the estuaries of the Town of Falmouth. Significant time and attention has been dedicated to this effort by Jerry Potamis and Amy Lowell, whose support has been instrumental to completion of these reports. Equally important has been technical support by the Town Planner, Brian Currie. We would also like to acknowledge the field support provided to the MEP by Brewer Fiddler's Cove Marina who gave us unrestricted use of the facility in support of critical field tasks. The MEP Technical Team would also like to thank Tony Williams of the Coalition for Buzzards Bay for providing the water quality monitoring baseline for this system. Without this baseline water quality data the present analysis would not have been possible. We also would like to recognize the Community Preservation Committee (CPC), the Nutrient Management Committee and the CWMP Review Committee for the Town of Falmouth, in moving this MEP analysis forward to support estuarine management of two of Falmouth's prime estuaries.

In addition to local contributions, technical, policy and regulatory support has been freely and graciously provided by the Cape Cod Commission, most notably, Paul Niedzwiecki and Tom Cambareri and GIS support by Phil Detjens. We are also thankful for the long hours in the field and laboratory spent by technical staff (Jen Benson, Michael Bartlett, Sara Sampieri and Dahlia Medieros), interns and students within the Coastal Systems Program at SMAST-UMD.

Support for this project was provided by the Town of Falmouth via the Community Preservation Committee and the MassDEP.

PROPER CITATION

Howes B.L., E.M. Eichner, S. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger (2011). Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Fiddlers Cove and Rands Harbor Embayment Systems, Town of Falmouth, Massachusetts, Massachusetts Department of Environmental Protection. Boston, MA.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

I. INTRODUCTION

The Fiddlers Cove and Rands Harbor Estuarine Systems are located within the Town of Falmouth, on Cape Cod Massachusetts. These two estuaries have a northern shore bounded by outer Megansett Harbor, which exchanges tidal waters with Buzzards Bay (Figure I-1). The developed regions of the watershed to the Fiddlers Cove and Rands Harbor embayment systems is distributed almost entirely within the Town of Falmouth with the exception of that the uppermost portion of the watershed within the Massachusetts Military Reservation (MMR) falls within the Towns of Falmouth, Sandwich and Bourne. This upper watershed within the MMR (~1/4 of watershed) is mainly undeveloped and developed areas are on sewer. As such the upper portion of the watershed within MMR is not contributing a significant nitrogen load to the estuary. As a result, the primary stakeholder for the management and restoration of the Fiddlers Cove and Rands Harbor Systems is the Town of Falmouth.

The Fiddlers Cove and Rands Harbor estuaries are two of the Town of Falmouth's smallest marine resources, however, Fiddlers Cove supports a significant marina and high boating effort during summer months. At a time when many other coastal ponds and bays tributary to Buzzards Bay have been severely degraded, water quality in Fiddlers Cove and Rands Harbor has generally remained moderately high due to the small size of each basin and the large undeveloped areas of their upper watersheds. However, portions of each system (e.g. the narrow canal extending landward from the main basin of Fiddlers Cove and dredged channels of Rands Harbor) have shown indications of nutrient enrichment. Significant in maintaining the water quality within these two systems is the flushing rate and tidal exchange with the low nutrient high quality waters of Buzzards Bay and outer Megansett Harbor.

The present open water embayment structure of both the Fiddlers Cove and Rands Harbor Systems does not represent a natural estuarine structure. Both are artificial open water embayments significantly altered by human activity over the past approximately 100 years. Both estuaries were formed primarily as tidal salt marshes with associated tidal creeks as seen in historical maps (1880 and 1916). Human activity gradually transformed these salt marsh dominated tidal creeks into more open water systems resembling embayments. The tidal wetlands were removed to increase the navigability of the systems and to create protected harbors, though portions of the upper reaches of Fiddlers Cove still supported bordering saltmarsh into the 1970’s. At present almost all of the tidal wetlands along the shoreline of Fiddlers Cove have been removed and replaced with hard coastal structures (e.g. riprap). Although Rands Harbor was also constructed from tidal creeks, it still maintains significant fringing salt marsh areas, particularly in the western branch. Regardless of their formation, both estuaries are now functioning as tributary embayments to Buzzards Bay and must be managed as such. However, based on the history of both these systems, they likely have not supported eelgrass over the past 60 years.

The Fiddlers Cove and Rands Harbor systems are presently relatively simple estuarine systems with Rands Harbor being the more complex of the two given that it has one inlet but two distinct branches. Both Fiddlers Cove and Rands Harbor are part of the larger complex Megansett Harbor / Squeteague Harbor estuary. This larger overall estuary is comprised of 3 principal basins: an open water portion of the system directly connected to Buzzards Bay (outer Megansett Harbor), a more enclosed basin (inner Megansett Harbor) which feeds directly into an enclosed basin (Squeteague Harbor) via a narrow shallow channel. Fiddlers Cove and Rands Harbor are two small tributary embayments to outer Megansett Harbor (Figure I-1). The

Figure I-1. Rands Harbor and Fiddlers Cove (relative to the Megansett Harbor / Squeteague Harbor System) study region for the Massachusetts Estuaries Project nutrient analysis. Tidal waters enter the outer Megansett Harbor from Buzzards Bay and then through the single inlets of the Rands Harbor and Fiddlers Cove sub-embayments.

present inlet to Fiddlers Cove is armored and leads into a main basin that serves as a small mooring area for boats and supports a large marina. The main basin of the Fiddlers Cove system leads into a narrow terminal canal that extends landward towards Fiddlers Cove Road (Figure I-2). The canal is fully armored and is an artificial feature of the system. Historically, Fiddlers Cove was a small salt marsh dominated basin and tidal creek that was modified and dredged to create a protected harbor and canal for boats. Similar to the adjacent Fiddlers Cove, Rands Harbor receives low nutrient water from Buzzards Bay via a single inlet that connects the system to outer Megansett Harbor. The inlet to Rands Harbor is armored to the east and leads to the confluence of two narrow branches, an east branch and a west branch, both of which have dredged channels and end in small terminal basins (Figure I-3). Each terminal basin receives surface water discharge from its upper watershed via a small stream. The east branch stream is sourced in Cedar Lake whereas the west branch stream is sourced in Flax Pond. Until approximately the 1920's Rands Harbor was comprised of tidal wetland basins fed by tidal creeks connected to Buzzards Bay through a common inlet. Around the mid-1920's the salt marsh system was dredged and enlarged creating free tidal exchange and producing an open water system approximating Rands Harbor as it is structured today. Therefore, management of ecological changes and impairments of these semi-enclosed systems must be considered not only relative to nutrient enrichment from an increasingly developed coastal watershed but also the structural changes that have occurred over the last century.

Fiddlers Cove and Rands Harbor (but more so Fiddlers Cove) are important for recreational boating. Brewer Fiddlers Cove Marina supports approximately 135 boat slips with an additional 63 indoor rack storage units. The private marina that represents a large part of the boating activity in Fiddlers Cove has two main docks, which consists of piers with floats, and slips along a seawall. The marina operates a full service boat yard and boat fueling at the marina dock is available as is electricity. Pump-out facilities for boat waste are provided by the marina.

Figure I-2. Fiddlers Cove (relative to outer Megansett Harbor) study region for the Massachusetts Estuaries Project nutrient analysis. Tidal waters enter the main basin of the estuarine system from Buzzards Bay through one inlet (armored) connected to outer Megansett Harbor. Freshwaters enter along the embayment shoreline via direct groundwater seepage only, as there are no freshwater streams discharging to this estuary.

Figure I-3. Rands Harbor (relative to Megansett Harbor) study region for the Massachusetts Estuaries Project nutrient analysis. Tidal waters enter the estuarine system from Buzzards Bay through one inlet (partially armored) connected to outer Megansett Harbor. Freshwaters enter along the embayment shoreline via direct groundwater seepage and via stream discharges to the headwaters of each branch from Cedar Lake (east) and Flax Pond (west).

The habitat quality of the Fiddlers Cove and Rands Harbor Systems is linked to the level of tidal flushing through each system's inlet to outer Megansett Harbor and ultimately Buzzards Bay, which exhibits a moderate tide range of about 5 ft. Since the water elevation difference between the Bay and Harbors 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). Moreover, the degree to which the inlets remain unobstructed is also critical to the exchange of water and the health of each system. In that light, the inlet to Fiddlers Cove is fully armored and that to Rands Harbor is partially armored, both with stone jetties. Maintenance dredging is also performed, as needed. Given the present hydrodynamic characteristics of the Fiddlers Cove and Rands Harbor embayment systems, it appears that estuarine habitat quality is mostly dependent on the level of nutrient loading to embayment waters as opposed to tidal characteristics. In Fiddlers Cove and Rands Harbor, minimal enhancements to tidal flushing may be achieved via inlet or channel modification. Therefore, to maintain or enhance existing habitat quality in these two systems, it will be necessary to manage nutrient inputs and transported through the respective watersheds to associated receiving waters. The details of such are a part of the MEP analysis described later in this report.

The watersheds to Fiddlers Cove and Rands Harbor are somewhat geologically complex, being composed primarily of Falmouth Moraine deposits and sand and gravel outwash glacial deposits. The lower watershed in which Rands Harbor and Fiddlers Cove are situated is mainly comprised of sand and gravel outwash from the Falmouth Moraine, while the upper watershed regions within MMR are primarily bouldery glacial drift deposits of the Falmouth Moraine, These formations consist of material deposited during the retreat of the Cape Cod Lobe of the Laurentide Ice sheet. The material is highly permeable and as such, direct rainwater run-off is typically rather low for this type of coastal system and most freshwater inflow is via groundwater discharge. Originally the basins of the two Harbors were isolated from the sea, but as a result of rising sea level following the last glaciation approximately 18,000 years BP, they became estuarine systems ~6,000-8,000 years BP and colonized by salt marsh vegetation. Although these now open water embayments are converted wetland basins, they are both presently functioning as coastal embayments and need to be managed as such.

At present, Fiddlers Cove does not receive direct stream discharge, with virtually all watershed input being through direct groundwater discharge. Rands Harbor, however, is a tidal embayment with two small streams that are mostly fed from up-gradient ponds. On the east branch there is a small stream originating in shallow Cedar Lake (up gradient of Chester Street) and discharging to the terminal basin of the east branch. Similarly, on the west branch there is a second small stream originating in shallow Flax Pond (also called Trout Pond) which is also up-gradient of Chester Street and discharges to the terminal basin at the head of the West Branch. Both these streams are also likely to be slightly groundwater fed features in addition to receiving freshwater from their up-gradient ponds. Fiddlers Cove and Rands Harbor both act as a mixing zone for terrestrial freshwater inflow and saline tidal flow from Buzzards Bay via outer Megansett Harbor, however, the salinity characteristics of the system varies with the volume of freshwater inflow as well as the effectiveness of tidal exchange with outer Megansett Harbor. Overall, the small freshwater contributing area and large tide range result in a relatively high average salinity (>27ppt) throughout much of Fiddlers Cove and Rands Harbor (>29 ppt and >27 ppt respectively).

Similar to other embayments on Cape Cod, Fiddlers Cove and Rands Harbor are mesotrophic (moderately nutrient impacted) shallow coastal estuarine systems. Neither system presently or historically supports eelgrass beds, most likely because they are artificial dredged basins with moderate levels of nitrogen enrichment. However, extensive eelgrass beds presently exist immediately offshore from the inlets to both Fiddlers Cove and Rands Harbor along the shallow near shore waters of outer Megansett Harbor. The presence of eelgrass is particularly important to the use of outer Megansett Harbor as fish and shellfish habitat and in turn a source of larvae to support benthic and fish communities in Fiddlers Cove and Rands Harbor. The Megansett Harbor System, and by association Fiddlers Cove and Rands Harbor, represents an important shellfish resource to the Town of Falmouth, primarily for quahogs and Bay Scallops. However, while shellfishing is approved year round for outer Megansett Harbor, shellfishing activities in Fiddlers Cove and Rands Harbor are seasonally restricted by the Massachusetts Division of Marine Fisheries as a result of bacterial contamination from watershed run-off and other potential sources such as storm run-off or marina activities as in Fiddlers Cove. Selectively open DMF segments located in the overall outer Megansett Harbor system include BB:50.1 (Fiddlers Cove, conditionally approved) and BB:50.2 (Rands Harbor, conditionally approved). The shellfish closures and possible eelgrass loss in outer Megansett Harbor has raised public concern in recent years with regard to the health of estuarine resources within outer Megansett Harbor, Fiddlers Cove and Rands Harbor. The Town of Falmouth has specifically targeted nutrient management within the watersheds to its estuarine systems as a way towards restoring and/or safe guarding the estuarine resources of the town. Fiddlers Cove and Rands Harbor are slated to be included in coming phases of the Town's Comprehensive Wastewater Management Planning effort.

The nature of enclosed embayments in populous regions brings two opposing elements to bear: As protected marine shorelines they are popular regions for boating, recreation, and land development; but 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 shorelines. In particular, Fiddlers Cove and Rands Harbor, as well as other embayment systems on Cape Cod, are at risk of eutrophication from increasing nitrogen loads in discharging surfacewater and groundwater from land-use changes to associated watersheds. Given their structure, Fiddlers Cove and Rands Harbor currently exhibit a higher overall habitat health then most estuaries along the south shore of the Town of Falmouth and much of Cape Cod.

The primary ecological threat to Fiddlers Cove and Rands Harbor marine 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 Fiddlers Cove and Rands Harbor and other Falmouth embayments (Quissett Harbor, Oyster Pond, Great Pond, Green Pond, Bournes Pond), like almost all embayments in southeastern Massachusetts, results primarily from on-site disposal of wastewater. The Town of Falmouth has been among the fastest growing towns in the Commonwealth over the past three decades and does not have centralized wastewater treatment throughout the entire Town. These unsewered areas contribute significantly to the nitrogen loading of the Fiddlers Cove and Rands Harbor systems, both through transport in direct groundwater discharges to estuarine waters and through surface water flow to the estuarine reach of each system. As existing and probable increasing levels of nutrients impact Falmouth’s coastal embayments, water quality degradation will accelerate, with further harm to invaluable environmental resources.

The Town of Falmouth, as the primary stakeholder to the Fiddlers Cove and Rands Harbor embayment systems, has been concerned over the resource quality of the Towns significant coastal resources, inclusive of Fiddlers Cove and Rands Harbor. In the mid-1980's the Town enacted an innovative Nutrient Overlay By-law that tied watershed development to water quality within the adjacent embayment. Nutrient limits were set for nitrogen in each of the Town's embayments. The goal was to keep nitrogen concentrations in the receiving systems below thresholds that were projected to cause water quality shifts. To acquire baseline water quality data necessary for ecological management of Falmouth's coastal salt ponds and harbors, a citizen-based water quality monitoring program was initiated by the Town of Falmouth. Falmouth Pondwatch, was established to provide on-going nutrient related embayment health information in support of the By-law. The water quality monitoring program was based on a collaborative effort between scientists, citizens and representatives of the Town of Falmouth. As originally conceived, the monitoring program focused on data collection in three initial ponds, Oyster Pond, Little Pond and Green Pond. By 1990, the scope of water quality data collection expanded to include two additional ponds, Great/Perch Pond and Bournes Pond. In 1992, the scope of data collection was once again expanded to include West Falmouth Harbor in order to evaluate the effects from a nutrient enriched wastewater plume generated by the Falmouth Wastewater Treatment Facility. Since 1997, technical aspects of the Falmouth PondWatch Program have been coordinated through the Coastal Systems Program at SMAST-UMassD. In addition, the Town of Falmouth has supported the Coalition for Buzzards Bay's Water Quality Monitoring Program which, through its association with the Coastal Systems Program at UMASS-SMAST, collected data on nitrogen related water quality within the Falmouth estuaries that exist adjacent Buzzards Bay. The collaborative CBB/SMAST water quality monitoring effort covered systems such as Megansett Harbor, Fiddlers Cove and Rands Harbor System beginning in 1992. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of the embayments and harbors adjacent Buzzards Bay. The BayWatchers Program is a citizen-based water quality monitoring program run by the Coalition for Buzzards Bay (T. Williams, Project Coordinator) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD until 2008.

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 Megansett Harbor, Fiddlers Cove and Rands developed a water quality baseline for these systems. 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 water quality monitoring effort and includes high order biogeochemical analyses and water quality modeling necessary for developing critical nitrogen targets for the Fiddlers Cove and Rands Harbor embayment systems. Results of the MEP analysis for Fiddlers Cove and Rands Harbor will ultimately be incorporated in a future MEP analysis of the larger Megansett Harbor and Squeteague Harbor system, to which Fiddlers Cove and Rands Harbor are tributary sub-embayments

In conjunction with other town efforts, the Town of Falmouth 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. The estuarine specific watershed based nutrient loading model, the hydrodynamic models and the water quality models being developed under the MEP for both Fiddlers Cove and Rands Harbor will be an additional set of tools the town can use to inform future nutrient management decisions. 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 Falmouth. While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the programmatic umbrella of the Massachusetts Estuaries Project, the results stem directly from the efforts of large 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 of Falmouth 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 Falmouth) 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 70 of the 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. 44 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-4). 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

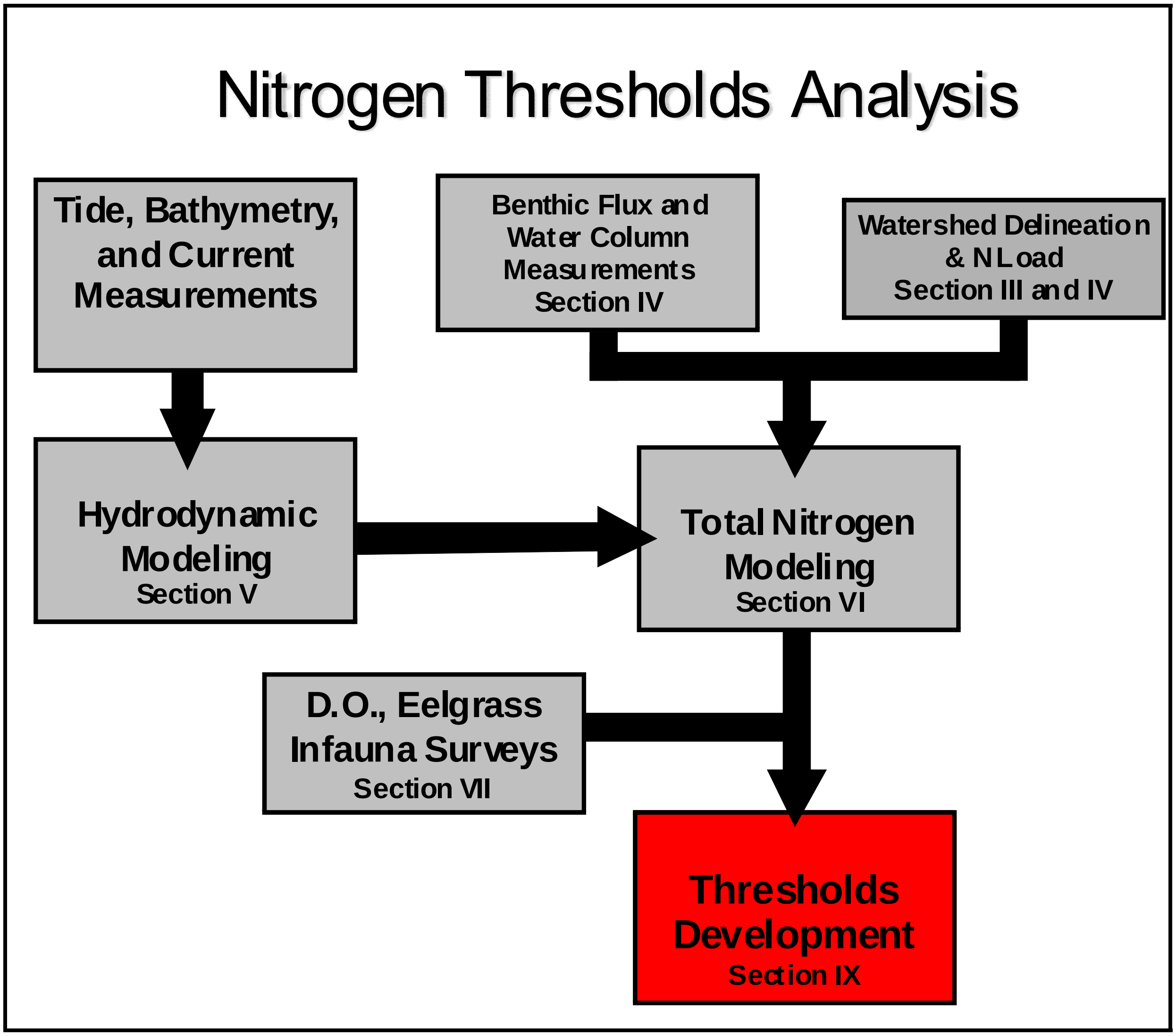


Figure I-4. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP report where the specified information is provided.

I.2 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 Fiddlers Cove and Rands 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

Fiddlers Cove and Rands 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 outer Megansett Harbor, Fiddlers Cove and Rands Harbor systems 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, the Fiddlers Cove and Rands Harbor estuaries may be reaching their respective limits for assimilating additional nutrients without impacting ecological health. Nitrogen levels are elevated throughout the systems and benthic infaunal communities are generally indicative of high quality habitat. However, there are some impaired areas, but these must be assessed relative to both nutrient enrichment and other activities, such as dredging or activities related to the channel areas in the mid reaches, particularly in Rand Harbor. This is discussed in more detail in Section VII below. While eelgrass does not exist in either of the two systems, eelgrass beds appear to have declined along the outer edges of outer Megansett Harbor in the vicinity of the inlets to Fiddlers Cove and Rands Harbor. The result is that nitrogen management of the greater Megansett Harbor system (inclusive of Fiddlers Cove and Rands Harbor), will be 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.3 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important “boundary conditions” for water quality modeling of the Fiddlers Cove and Rands Harbor Systems; 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 Fiddlers Cove and Rands Harbor Systems and each systems component basins: Fiddlers Cove main basin and Fiddlers Cove tributary Canal, Rands Harbor east branch and Rands Harbor west branch. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the systems. Once the hydrodynamic properties of each of the estuarine systems were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates in each estuarine receiving water.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models for each system 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 Falmouth’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 / Megansett Harbor source waters and throughout both the Fiddlers Cove and Rands Harbor systems were taken from the BayWatchers monitoring program and from previous sampling of outer Megansett Harbor waters by MEP staff. Measurements of nitrogen and salinity distributions throughout estuarine waters of each system were used to calibrate and validate the water quality models (under existing loading conditions).

I.4 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Fiddlers Cove and Rands

Harbor Estuarine Systems for the Town of Falmouth. 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 of Falmouth in developing a variety of alternative nitrogen management options for both the Fiddlers Cove and Rands Harbor Systems. Finally, any additional analyses of the two systems relative to potential alterations of circulation and flushing, including analyses to identify hydrodynamic restrictions or the effects of dredging to improve nitrogen related water quality in either Fiddlers Cove or Rands Harbor, is presented in 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 excessive plankton and macrophyte growth, which in turn lead to reduced water clarity, organic matter enrichment of waters and sediments with the concomitant increased rates of oxygen consumption and periodic depletion of dissolved oxygen, especially in bottom waters, and the limitation of the growth of desirable species such as eelgrass. Even without changes to water clarity and bottom water dissolved oxygen, the increased organic matter deposition to the sediments generally results in a decline in habitat quality for benthic infaunal communities (animals living in the sediments). This habitat change causes a shift in infaunal communities from high diversity deep burrowing forms (which include economically important species), to low diversity shallow dwelling organisms. This shift alone causes significant degradation of the resource and a loss of productivity to both the local shell fisherman and to the sport-fishery and offshore fin fishery, which are dependant upon these highly productive estuarine systems as a habitat and food resource during migration or during different phases of their life cycles. In addition, the diverse avian fauna which feed upon infauna or fish communities are also affected and their numbers and diversity declines. This overall nutrient driven process is generally termed “eutrophication” and in embayment systems, unlike in shallow lakes and ponds, it is not necessarily a part of the natural evolution of a system.

In most marine and estuarine systems, such as the Fiddlers Cove and Rands Harbor Systems, the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is controlled, then eutrophication is controlled. As a result, there has been significant effort to develop tools for predicting how modification of watershed nitrogen loads and changes in tidal flushing quantitatively cause changes in the concentrations of water column nitrogen in the receiving estuary. Further development of these approaches 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. In contrast, some approaches can be tailored for each individual estuary of interest, but require large amounts of site-specific information and therefore are not generally applied. The present Massachusetts Estuaries Project (MEP) effort uses one such site-specific approach. The assessment 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 within individual estuaries. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for the specific set of conditions in each of the coastal embayments of southeastern Massachusetts, including the Fiddlers Cove and Rands 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 and unique features.

Few studies relating to nitrogen loading, hydrodynamics and habitat health have been conducted within the Fiddlers Cove and Rands Harbor System over the past two decades to help inform the MEP process. Directly supporting the present Massachusetts Estuaries Project effort to develop a nitrogen threshold for Rands Harbor was a historic investigation of benthic infauna which provided a point of comparison to assess habitat conditions at a time when nutrient loading was likely significantly less than at present. This benthic infaunal study along with quantitative information on water column parameters over multiple summers (including nitrogen) and surveys of eelgrass distribution in outer Megansett Harbor have helped inform the MEP development of nutrient thresholds in both Fiddlers Cove and Rands Harbor. These studies are summarized below.

***A Study of the Bottom Fauna of Rand's Harbor, Massachusetts: An Application of the Ecotone Concept (Burbanck, Pierce, Whitely 1956)*:** This early investigation of Rands Harbor is one of the few early studies of the system and provides a relatively detailed description of the bottom sediment characteristics of the system as well as the benthic infauna community in the mid to late 1940's as well as 1950, at a time when nutrient loading to Rands Harbor was likely much less than what it is currently. Sediment sampling for benthic infaunal characterization was undertaken along multiple transects established across both branches of the system. Sampling was conducted in 1946, 1948, 1949 and 1950. The investigators collected samples using a variety of methods, most notably a modified Ekman Dredge, not too different from the VanVeen Grab utilized by the MEP, as well as a Hayward Dwarf Orange Peel No. 1 grab. Physical and chemical measurements were also undertaken in conjunction with sediment samples that were collected primarily in the summer months during the infauna feeding, breeding and reproduction period. The work reported provides a detailed summary of the infauna observed throughout Rands Harbor and was used as a point of comparison to the record of infauna developed by the MEP. The study concluded that the infauna observed was typical of estuaries in the northeast (at that time and under nutrient loading conditions of the mid-twentieth century) and not surprisingly, it was difficult to make generalizations or predictions regarding population trends given the unstable environment of an estuary. Animals showed shifts in location from year to year as well as fluctuations in number at specific locations or complete disappearance. No correlations could be found between the variability in the populations through out the system and physical/chemical characteristics. Interestingly, the investigators were very clear about the difference between the two arms based on numbers of invertebrate species. This difference was consistent over the entire seven year period that the study took place. Generally, there was a greater number of invertebrate species in the larger south arm than the smaller north arm. Also of significance are the numbers of abundant species in the Rands Harbor system. At the time of the study, approximately 1945 to 1950, thirty-two species were most abundant in Rands Harbor. A total of 67 different species were observed with 63 different species being taken from the large arm and 49 different species taken from the small arm. The species observed in this study were compared to the species observed by the MEP to inform the present analysis of the benthic habitat of the Rands Harbor system.

Fiddlers Cove and Rands Harbor Nutrient Related Water Quality Monitoring: The MEP analysis requires high quality water quality data in order to complete its assessment and modeling approach. The Coalition for Buzzards Bay's Water Quality Monitoring Program has been collecting data on nutrient related water quality throughout Buzzards Bay estuaries inclusive of outer Megansett, Fiddlers Cove and Rands Harbor for more than a decade. The Coalition's BayWatcher Program has collected the principal baseline water quality to support ecological management of each of Buzzards Bay'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 until 2008. The program has a USEPA and MassDEP approved Quality Assurance Project Plan (QAPP), which was operational over the entire period of 1999-2009 (data period for this MEP analysis).

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. The BayWatcher Water Quality Monitoring Program in the Fiddlers Cove and Rands Harbor Embayment Systems developed a data set that elucidated the long-term water quality of this system (Figure II-1). The monitoring undertaken was a collaborative effort with CBB (Tony Williams) coordinating the field effort and chemical assays being completed by the SMAST Coastal Systems Analytical Facility. The Coastal Systems Analytical Facility is located in the School for Marine Science and Technology UMASS-Dartmouth, 706 S. Rodney French Blvd, New Bedford, MA, and the laboratory Points of Contact are Sara Sampieri 508-910-6325 (ssampieri@umassd.edu) or Mike Bartlett (mbartlett@umassd.edu). Use of the SMAST Analytical Facility ensured sufficient sensitivity and accuracy of the analytical protocols and that proper QA/QC procedures were followed to allow incorporation of the data into the MEP analysis. The baseline water quality data are a prerequisite for entry into the MEP. Implementation of the MEP's Linked Watershed-Embayment Approach necessarily incorporates the quantitative water column nitrogen data (1999-2009) gathered by the Monitoring Program and watershed and embayment data collected by MEP staff.

Since the results of the long term Water Quality Monitoring Program (1999-2009) and initial habitat assessments, suggest that that portions of the Fiddlers Cove and Rands Harbor Embayment Systems are presently beyond their ability to assimilate nitrogen without impairment to key estuarine habitats, the Town of Falmouth undertook participation in the Massachusetts Estuaries Project to complete ecological assessment, nitrogen source identification and water quality modeling. The purpose of this effort being to quantitatively assess existing habitat quality of each of the Harbor basins and to develop nutrient thresholds to guide the Town's estuarine management planning relative to restoration of the Fiddlers Cove and Rands Harbor estuaries.

Regulatory Assessments of Fiddlers Cove and Rands Harbor Resources - In addition to locally generated studies, Fiddlers Cove and Rands Harbor are part of the Commonwealth's environmental surveys to support regulatory needs. Both the Fiddlers Cove and Rands harbor Estuaries contain a variety of marine resources of value to the citizens of Falmouth as well as to the Commonwealth. As such, over the years surveys have been conducted to support protection and management of these natural resources. The MEP also gathers the available information on these resources as part of its assessment, and presents some of them here for reference by those providing stewardship for this estuary and some in Chapter 7 to support the nitrogen thresholds analysis. For the Fiddlers Cove and Rands Harbor Estuaries these include:

- Designated Shellfish Growing Area – MassDMF (Figure II-2)
- Shellfish Suitability Areas – MassDMF (Figure II-3a, 3b)
- Anadromous Fish Runs - MassDMF (Figure II-4)
- Estimated Habitats for Rare Wildlife and State Protected Rare Species – NHESP (Figure II-5a, 5b)
- Mouth of Coastal Rivers – MassDEP Wetlands Program (Figure II-6)

The MEP effort builds upon earlier watershed delineations by the Cape Cod Commission and land-use analyses by the Buzzards Bay Project, the hydrodynamic modeling, historical eelgrass surveys and water quality surveys discussed above. This information is integrated with MEP higher order biogeochemical analyses and water quality modeling to develop critical nitrogen thresholds for nitrogen management planning of the Fiddlers Cove and Rands Harbor Estuarine Systems. The MEP has incorporated appropriate and available data from pertinent previous studies to enhance the determination of nitrogen thresholds for the Fiddlers Cove and Rands Harbor Systems and to reduce costs to the Town of Falmouth.

Figure II-1. Coalition for Buzzards Bay Water Quality Monitoring Program for Fiddlers Cove and Rands Harbor. Estuarine water quality monitoring stations sampled by the Coalition and analyzed by SMAST staff during summers 1999 to 2009.

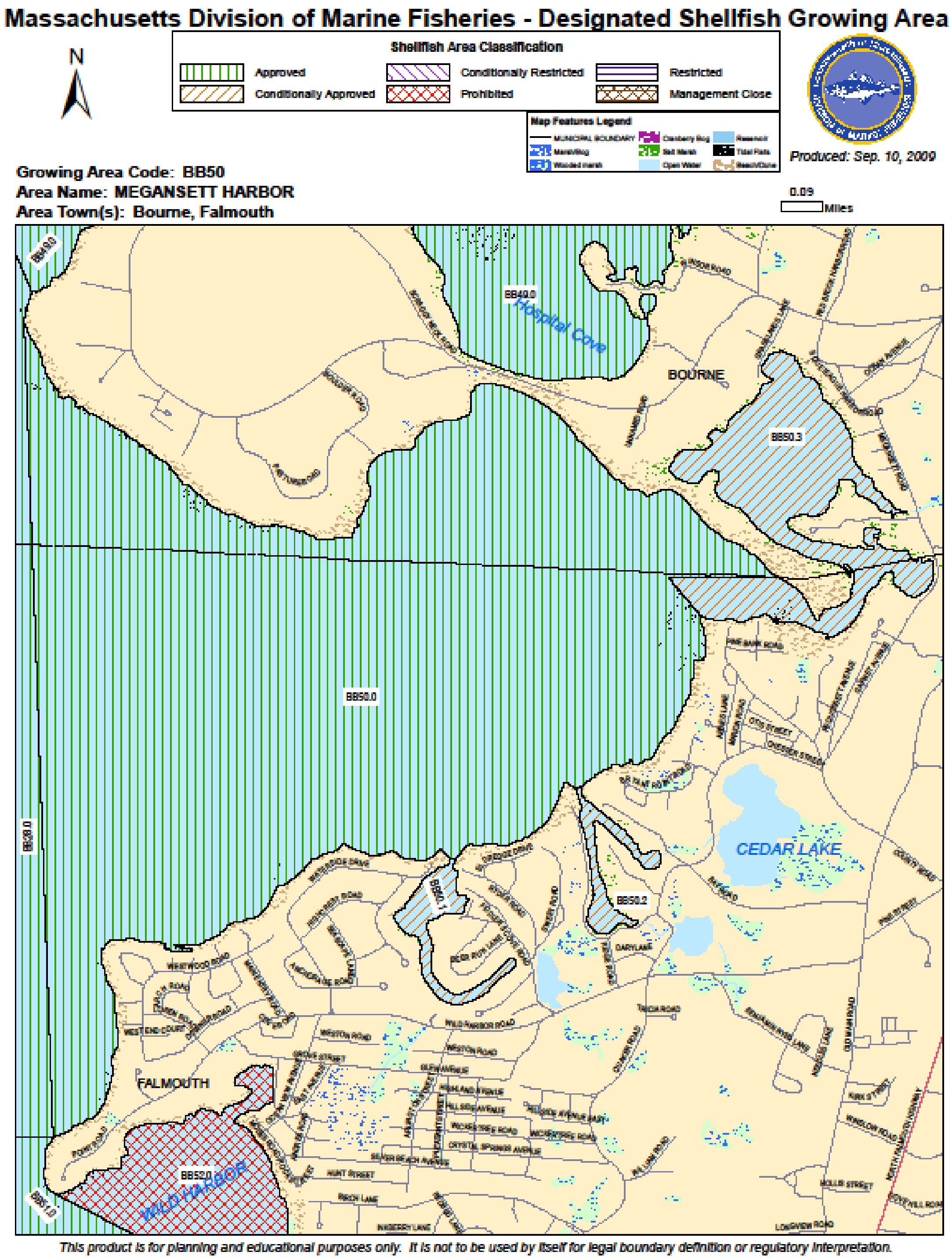


Figure II-2. Location of shellfish growing areas and their status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

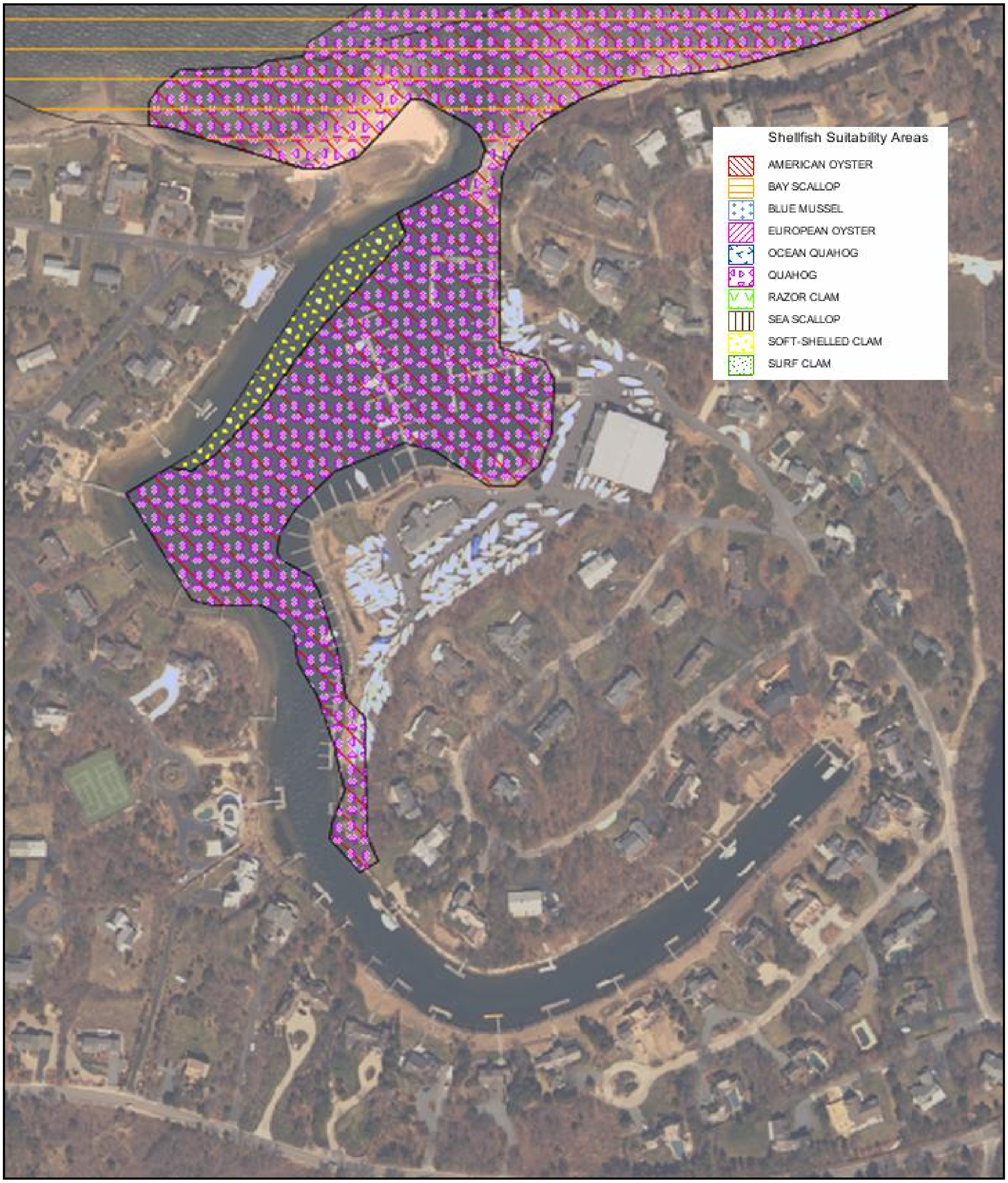


Figure II-3a. Location of shellfish suitability areas within the Fiddlers Cove Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

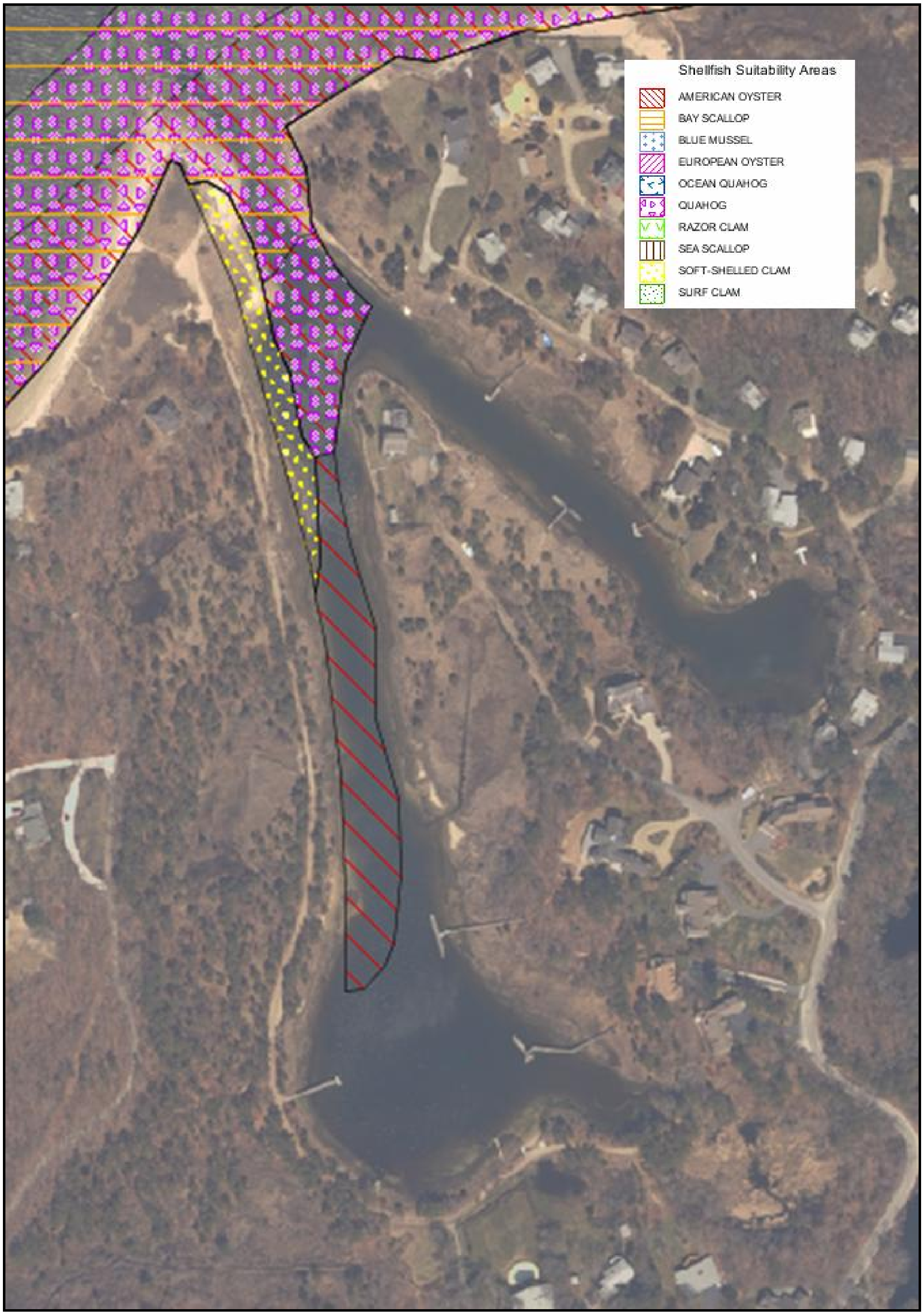


Figure II-3b. Location of shellfish suitability areas within the Rands Harbor Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

Figure II-4. Anadromous fish runs within the Rands Harbor Estuary as determined by Mass Division of Marine Fisheries. The red diamonds show areas where fish were observed. There are no anadromous fish runs in the Fiddlers Cove system.

Figure II-5a. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Fiddlers Cove Estuary as determined by - NHESP.

Figure II-5b. Estimated Habitats for Rare Wildlife and State Protected Rare Species within the Rands Harbor Estuary as determined by - NHESP.

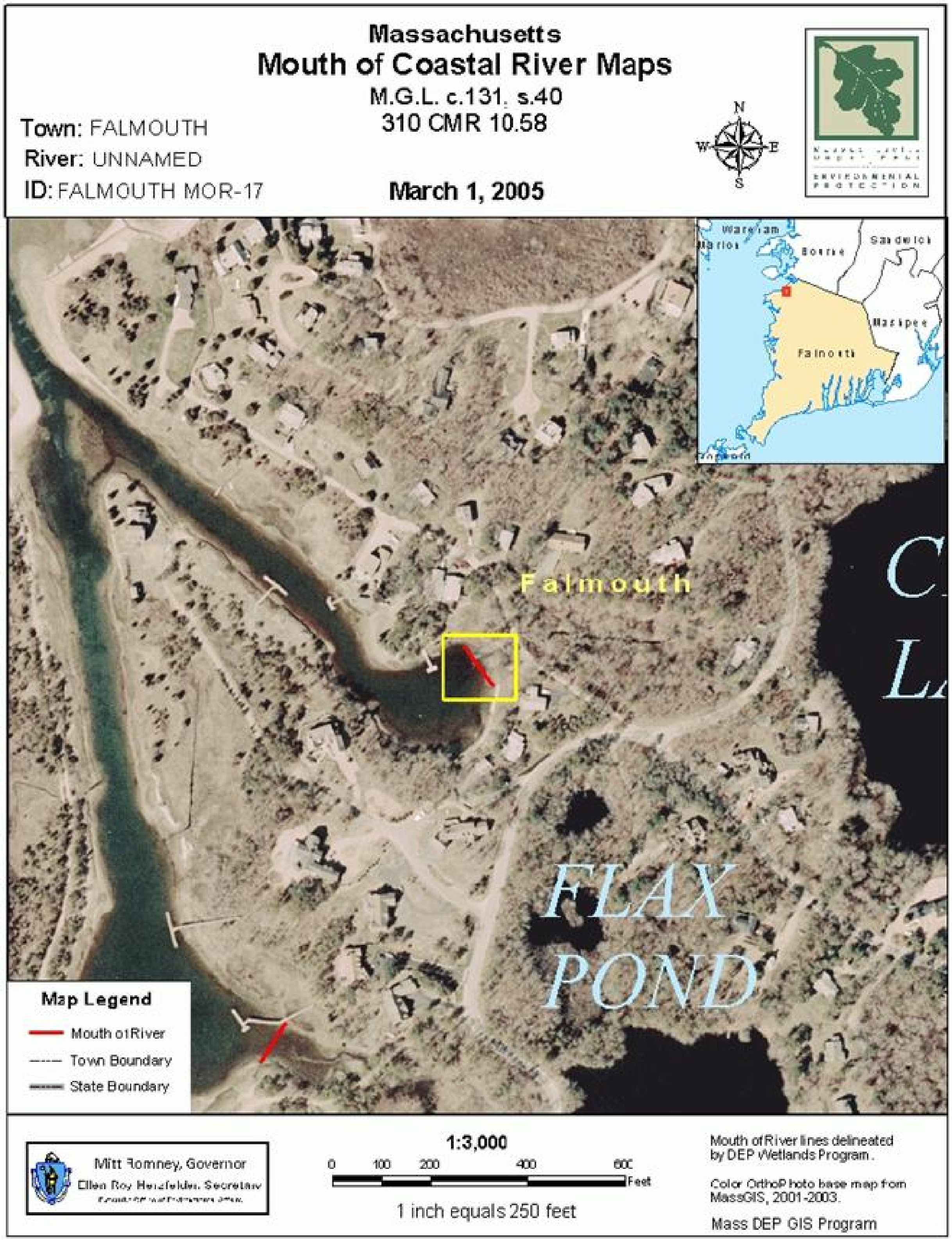


Figure II-6. Mouth of Coastal Rivers designation for Rands Harbor as determined by – MassDEP Wetlands Program. Fiddlers Cove does not have this designation due to the absence of stream inflows.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

The Massachusetts Estuaries Project team includes technical staff from the United States Geological Survey (USGS). The 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 utilized by the USGS organize and analyze the available data using up-to-date mathematical codes and create better tools to answer the wide variety of questions related to watershed delineation. These questions include surface water/groundwater interactions, groundwater travel times, and drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including the Rands Harbor and Fiddlers Cove embayment systems. The Rands Harbor and Fiddlers Cove watersheds are primarily located within the Town of Falmouth with its upper portions reaching into the Towns of Bourne and Sandwich as well as the Massachusetts Military Reservation.

In the present investigation, the USGS was responsible for the application of its groundwater modeling approach to define the watersheds or contributing areas to the Rands Harbor and Fiddlers Cove embayment systems under evaluation by the Project Team. The Rands Harbor estuarine system has a single inlet to Buzzards Bay and then is split into two arms, the southern one bigger than the northern one. The Fiddlers Cove estuarine system also has a single inlet to Buzzards Bay with a small basin connected to a channel that follows the curve of Deer Run Lane. Watershed modeling was undertaken to sub-divide the overall watersheds to the Rands Harbor and Fiddlers Cove systems 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 attenuate nitrogen passing through them on the way to the estuary (lakes, streams, wetlands), and (c) defining the land areas with groundwater travel times that are greater and less than 10 years time-of-travel to the estuary. These time of travel distributions within each sub-watershed are used as a procedural check to gauge the potential mass of nitrogen from “new” development, which has not yet reached the receiving estuarine waters at the time of the MEP analysis. The three-dimensional numerical model employed is also being used to evaluate the contributing areas to public water supply wells in both the Sagamore and Monomoy flow cells on Cape Cod; the Rands Harbor and Fiddlers Cove watersheds are located along the western edge of the Sagamore flow cell. Model assumptions for calibration of the Rands Harbor and Fiddlers Cove Estuaries included surface water discharges (Rands Harbor only) measured as part of the MEP stream flow program (2005 to 2006).

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 (where applicable) and the portion of the groundwater system that discharges directly into an estuary as groundwater seepage.

III.2 MODEL DESCRIPTION

Contributing areas to the Rands Harbor and Fiddlers Cove systems and their various sub-watersheds, such as Cedar Lake, Flax Pond, Edmunds Pond and Trout Pond, were delineated using the 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 the Rands Harbor and Fiddlers Cove systems and their sub-watersheds and also to determine portions of recharged water that may flow through fresh water ponds and streams prior to discharging into the 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 in the Sagamore Lens); since bedrock is approximately 150 feet below NGVD 29 in the Rands Harbor and Fiddlers Cove area the lowest model layer was inactive in this area of the model with variable thickness in the layer directly above. 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 within 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 watersheds to Fiddlers Cove and Rands Harbor are somewhat geologically complex, being composed primarily of Falmouth Moraine deposits and sand and gravel outwash glacial deposits. The lower watershed in which Rands Harbor and Fiddlers Cove are situated is mainly comprised of sand and gravel outwash from the Falmouth Moraine, while the upper watershed regions within MMR are primarily bouldery glacial drift deposits of the Falmouth Moraine, These formations consist of material thought to have been deposited in place by melting ice in a low energy depositional environment at the edge of a rapidly retreating ice lobe (Walter and Whealan, 2005). Modeling and field measurements of contaminant transport at the Massachusetts Military Reservation have shown that similar materials are permeable (*e.g.*, Masterson, *et al*., 1996) with lower hydraulic conductivity than the outwash plains that comprise most of the Cape. This distinction does not tend to impact groundwater flow direction and direct rainwater run-off is typically rather low as with most of the Cape. Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from the USGS, local Town records and data from previous investigations. Final aquifer parameters in the groundwater models 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 stream flow data collected in 1989-1990 as well as 2003.

The Sagamore Lens groundwater 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, water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within residential areas designated as using on-site septic systems.

III.3 RANDS HARBOR AND FIDDLERS COVE SYSTEM CONTRIBUTORY AREAS

The refined watershed and sub-watershed boundaries for the Rands Harbor and Fiddlers Cove embayment systems, including Cedar Lake, Flax Pond, Edmunds Pond and Trout Pond, as well as sub-estuaries (Figure III-1), were determined by the United States Geological Survey (USGS). Model outputs of the 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), (d) to more closely match the sub-estuary segmentation of the tidal hydrodynamic model and (e) to address streamflow measurements collected as part of the MEP. 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, 17 sub-watershed areas, were delineated within the combined Rands Harbor and Fiddlers Cove study area with 13 in the Rands Harbor watershed and three (3) in the Fiddlers Cove watershed, with Trout Pond shared between the two systems.

Table III-1 provides the daily freshwater discharge volumes for various sub-watersheds as calculated from the groundwater model; these volumes were used in the salinity calibration of the tidal hydrodynamic model and to determine hydrologic turnover in the lakes/ponds, as well as for comparison to the directly measured surface water discharges. The overall estimated freshwater flow into the Fiddlers Cove system from the MEP delineated watershed is 1,792 m3/d, while the overall estimated freshwater flow into the Rands Harbor system from the MEP delineated watershed is 7,737 m3/d. The flow for Rands Harbor includes a correction for outflow out of watershed from Cedar Lake, which straddles the northern boundary of the Rands Harbor system watershed.

The MEP watershed delineations are the second watershed delineations completed in recent years for the Rands Harbor and Fiddlers Cove Systems. Figure III-2 compares the delineations completed under the current effort with the delineations completed by the Cape Cod Commission as part of the Coastal Embayment Project (Eichner, *et al*., 1998). The CCC delineation was developed based on regional water table measurements collected from available well data over a number of years and normalized to average conditions. The Commission's delineation was incorporated into the Commission's regulations through the three versions of the Regional Policy Plan (CCC, 1996, 2001, and 2009).

The MEP watershed area for the Rands Harbor system as a whole is 21% smaller than 1998 CCC delineation (1,020 acres vs. 1,287 acres, respectively). This significant difference is largely due to a change in flow paths just inland of the coast. The outer boundary of the MEP and CCC watersheds are coincident until approximately Quaker Road, then the MEP watershed lines continue east, while the CCC lines begin to bend toward the north. The MEP watershed delineation also includes interior sub-watersheds to various components of the Rands Harbor system, such as ponds and streams that were not included in the CCC delineation. These refinements are another benefit of the update of the regional groundwater model (Walter and Whealan, 2005)

The MEP watershed for the Fiddlers Cove system, on the other hand, is nearly three times as big as the 1998 CCC delineation (249 acres vs. 87 acres, respectively). This significant difference is due to the MEP watershed extending to the west beyond Route 28. The CCC watershed is largely confined to the area around Fiddlers Cove and just extends beyond Wild Harbor Road. The MEP watershed delineation also includes interior sub-watersheds to various components of the Fiddlers Cove system, such as the main basin and the creek, that were not included in the CCC delineation. These refinements are another benefit of the update of the regional groundwater model (Walter and Whealan, 2005).

The evolution of the watershed delineations for the Rands Harbor and Fiddlers Cove systems has allowed increasing accuracy as each new version of the delineations 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 and enhances the use of this model 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 down gradient estuary. The MEP watershed delineations were used to develop the watershed nitrogen loads to each of the aquatic systems and ultimately to the estuarine waters of the Rands Harbor and Fiddlers Cove systems (Section V.1).

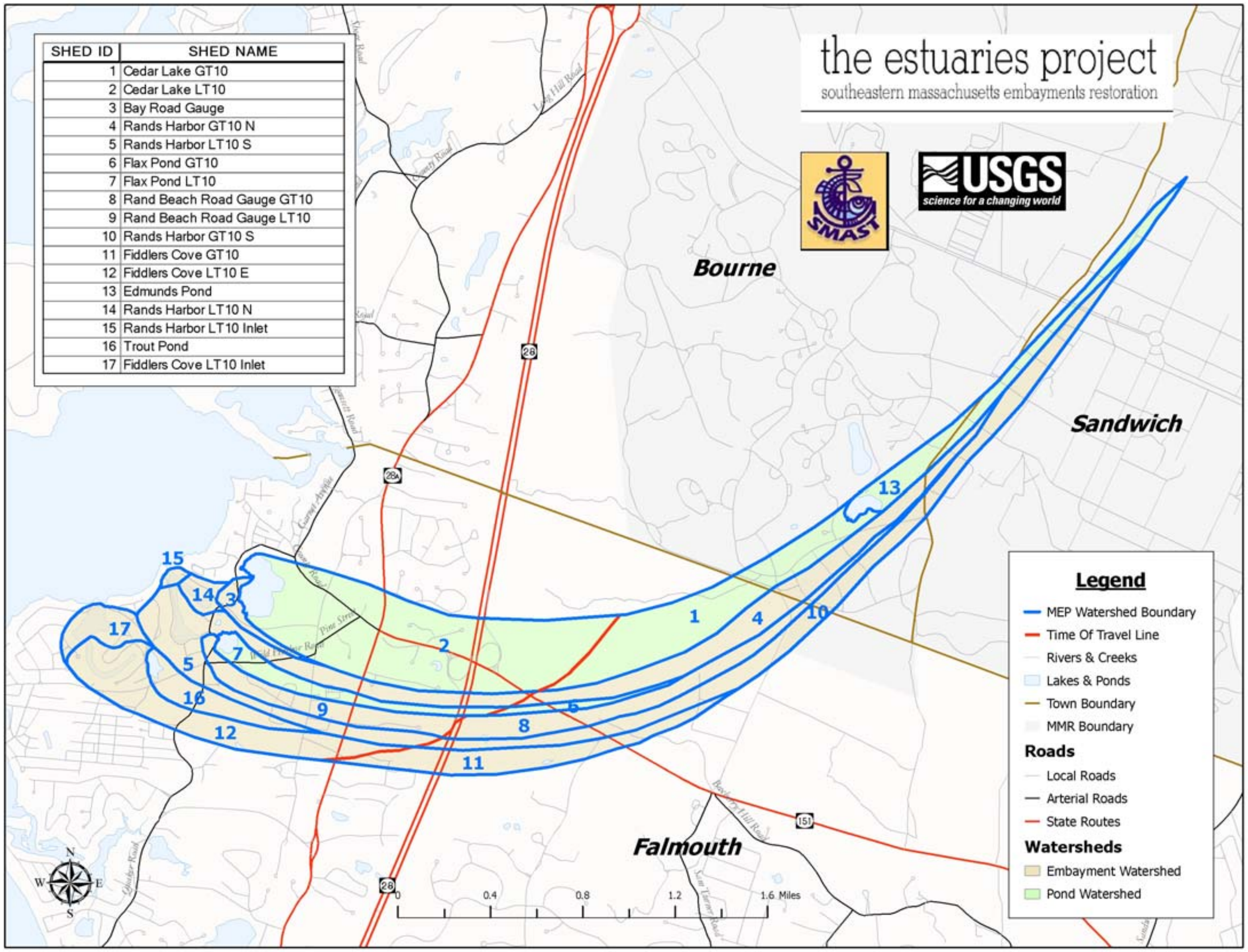


Figure III-1. Watershed delineation for the Rands Harbor and Fiddlers Cove Embayment Systems. Sub-watershed delineations are based on USGS groundwater model output with modifications to better address pond and estuary shorelines and MEP stream flow measurements. Ten-year time-of-travel delineations were produced for quality assurance purposes and are designated with a "10" in the watershed names (above). Sub-watershed groups (*e.g.*, Rands Harbor and Fiddlers Cove River) were selected based upon the functional estuarine sub-units in the water quality model (see Section VI).

Table III-1. Daily groundwater discharge from each of the sub-watersheds in the watershed to the Rands Harbor and Fiddlers Cove system estuary, as determined from the regional USGS groundwater model.

Watershed	#	Watershed Area (acres)	% contributing to Estuaries	Discharge m^3/day
Rands Harbor				
Cedar Lake GT10	1	153	54%	629
Cedar Lake LT10	2	339	54%	1,392
Bay Road Gauge	3	16	100%	120
Rands Harbor GT10N	4	120	100%	923
Rands Harbor LT10S	5	145	100%	1,112
Flax Pond GT10	6	13	100%	103
Flax Pond LT10	7	48	100%	369
Rands Beach Rd Gauge GT10	8	90	100%	691
Rands Beach Rd Gauge LT10	9	63	100%	483
Rands Harbor GT10S	10	160	100%	1,227
Edmunds Pond	13	82	100%	627
Rands Harbor LT10N	14	12	100%	89
Rands Harbor LT10 Inlet	15	2	100%	19
Trout Pond	16	44	73%	245
RANDS HARBOR SYSTEM TOTAL				7,737
Fiddlers Cove				
Fiddlers Cove GT10	11	82	100%	630
Fiddlers Cove LT10E	12	117	100%	896
Trout Pond	16	44	27%	91
Fiddlers Cove LT10 Inlet	17	23	100%	175
FIDDLERS COVE SYSTEM TOTAL				1,792

Notes: 1) discharge volumes are based on 27.25 inches of annual recharge on watershed areas; 2) percentage of inflow from Cedar Lake, which straddles the northern boundary of the overall Rands Harbor watershed boundary, is determined by length of down gradient watershed boundary, 3) these flows do not include precipitation on the surface of the estuary, 4) totals may not match due to rounding.

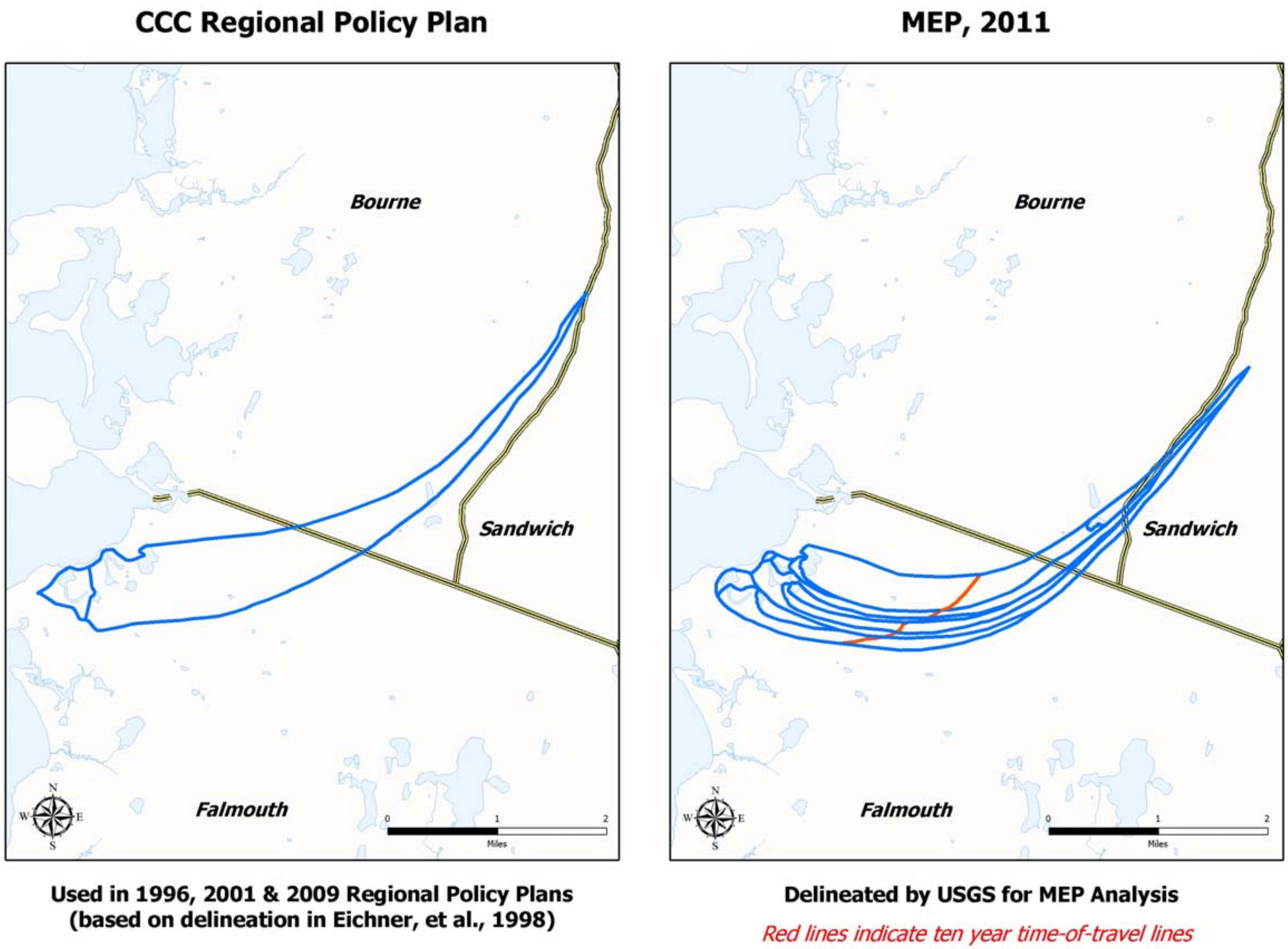


Figure III-2. Comparison of MEP Rands Harbor and Fiddlers Cove watersheds and sub-watershed delineations used in the current assessment and the Cape Cod Commission watershed delineations (Eichner, *et al*., 1998), which has been used in three Barnstable County Regional Policy Plans (CCC, 1996, 2001, 2009).

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 Rands Harbor and Fiddlers Cove estuary systems. 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 prior to reaching the estuary. This latter natural attenuation process results from biological processes that naturally occur within these 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. Permanent burial of nitrogen in the sediments 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 and the watershed attenuation generally leads to errors in predicting water quality, particularly in determination of summertime nitrogen load to embayment waters.

In order to determine watershed nitrogen loading inputs to the Rands Harbor and Fiddlers Cove estuary systems, the MEP Technical Team developed nitrogen-loading rates (Section IV.1) to each component of the estuary and its watersheds (Section III). The Rands Harbor and Fiddlers Cove watersheds were sub-divided to define contributing areas or sub-watersheds to each of the major inland freshwater systems and to each major portion of the estuaries. Further sub-divisions were made to identify watershed areas where a nitrogen discharge reaches estuary waters in less than 10 years or greater than 10 years. A total of 17 sub-watershed areas, were delineated within the combined Rands Harbor and Fiddlers Cove study area with 14 in the Rands Harbor watershed and three (3) in the Fiddlers Cove watershed with Trout Pond shared between the two systems. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and each portion of the estuary (see Section III).

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the estuary. This involves a temporal review of land use changes, the time of groundwater travel provided by the USGS watershed model, and review of data at natural collections points, such as streams and ponds. Evaluation and delineation of ten-year time of travel zones are a regular part of the watershed analysis. Ten-year time of travel sub-watersheds in the Rands Harbor and Fiddlers Cove watersheds have been delineated for ponds, streams and the estuaries themselves. Review of less than and greater than time of travel watersheds indicates that 85% and 79% of the unattenuated nitrogen load from the Rands Harbor and Fiddlers Cove watersheds, respectively, are within less than 10 year travel time to the estuary (Table IV-1). This review includes corrections to split the loads from Trout Pond and the removal of load from Cedar Lake by discharge outside of the Rands Harbor watershed. 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 estuary (after accounting for natural attenuation, see below). Moreover, the distinction between time of travel in the sub-watersheds is not significant for modeling existing conditions. Overall, based on the review of all this information, it was determined that the Rands Harbor and Fiddlers Cove estuaries are currently in balance with their respective watershed loads.

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 site-specific 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 sub-watershed specific land uses and pre-determined nitrogen loading rates based on regional analyses. For the Rands Harbor and Fiddlers Cove estuary systems, the models used land-use data from the Towns of Falmouth, Bourne, and Sandwich transformed into nitrogen loads using both regional nitrogen loading factors and local watershed-specific data (such as parcel-by-parcel water use and alternative septic system monitoring). 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 is included at a later stage.

Natural attenuation of nitrogen during transport from land-to-sea (Section IV.2) within the Rands Harbor and Fiddlers Cove watersheds was determined based upon a site-specific study of stream flow and theoretical and measured attenuation in the up-gradient freshwater ponds. Stream flow was characterized at two locations within the Rands Harbor watershed: 1) at Bay Road, capturing a portion of the Cedar Lake outflow, and 2) at Rands Beach Road, capturing all of the outflow from Flax Pond. Analysis of the sub-watersheds to these stream discharge points allowed comparison between field collected data from the stream and estimates from the nitrogen-loading sub-model. Nitrogen attenuation in individual ponds is generally estimated based on available information. In general, attenuation through the ponds is conservatively assumed to equal 50% unless available monitoring and pond physical data is reliable enough to calculate a pond-specific nitrogen attenuation factor. Stream flow and associated surface water attenuation is included in the MEP’s nitrogen attenuation and freshwater flow investigation, presented in Section IV.2.

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, four freshwater ponds have delineated sub-watersheds within the Rands Harbor and Fiddlers Cove watersheds: Cedar Lake, Edmunds Pond, Flax Pond, and Trout Pond. If smaller aquatic features that have not been included in this MEP analysis were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly overestimated (<10%), given the distribution of nitrogen sources within the watershed.

Table IV-1. Percentage of unattenuated nitrogen loads in less than ten year time-of-travel sub-watersheds to Rands Harbor and Fiddlers Cove.

WATERSHED		LT10	GT10	TOTAL	%LT10
Name	#	kg/yr	kg/yr	kg/yr	
Rands Harbor					
Cedar Lake GT10	1		32	32	0%
Cedar Lake LT10	2	791		791	100%
Bay Road Gauge	3	99		99	100%
Rands Harbor GT10N	4		57	57	0%
Rands Harbor LT10S	5	629		629	100%
Flax Pond GT10	6		4	4	0%
Flax Pond LT10	7	131		131	100%
Rands Beach Rd Gauge GT10	8		57	57	0%
Rands Beach Rd Gauge LT10	9	285		285	100%
Rands Harbor GT10S	10		167	167	0%
Edmunds Pond	13		48	48	0%
Rands Harbor LT10N	14	77		77	100%
Rands Harbor LT10 Inlet	15	5		5	100%
Trout Pond	16	86		86	100%
Rands Harbor System TOTAL		**2,102**	**365**	**2,467**	**85%**
Fiddlers Cove					
Fiddlers Cove GT10	11		341	341	0%
Fiddlers Cove LT10E	12	899		899	100%
Trout Pond	16	32		32	100%
Fiddlers Cove LT10 Inlet	17	325		325	100%
Fiddlers Cove System TOTAL		**1,256**	**341**	**1,597**	**79%**

Notes: 1) these loads are corrected to account for stream flows and outflow out of the ponds, 2) if loads from precipitation on the estuary surface are included the percentage of watershed nitrogen load within 10-year time-of-travel to estuary increases by 1% for each system, 3) sums may not add due to rounding

Based upon the evaluation of the watersheds to each estuary, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the sub-watersheds that directly discharge groundwater to the estuary without flowing through one of these interim pond and stream measuring points. Internal nitrogen recycling was also determined throughout the tidal reaches of the Rands Harbor and Fiddlers Cove Embayment Systems; 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

Since the watersheds to Rands Harbor and Fiddlers Cove include portions of the towns of Falmouth, Bourne, and Sandwich, Estuaries Project staff obtained digital parcel and tax assessor's data from the towns to serve as a base for the watershed nitrogen loading model. Digital parcels and land use/assessors data for Falmouth are from 2009, while similar data from Bourne is from 2008 and Sandwich data is from 2010. The Bourne and Sandwich parcels are located within the Massachusetts Military Reservation (MMR) and the watershed areas are enclosed in one parcel from each town. The land use databases contain traditional information regarding land use classifications (MassDOR, 2009) plus additional information developed by the towns and, in the case of development within the MMR, information developed by the Cape Cod Commission (CCC) GIS staff. The overall effort was completed with the assistance from GIS staff from the CCC.

Figure IV-1 shows the land uses within the watersheds to the Rands Harbor and Fiddlers Cove estuaries. Land uses in the study area are grouped into nine (9) land use categories: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) agricultural (cranberry bogs), 6) undeveloped, 7) public service/government, including road rights-of-way, 8) open space, and 9) unclassified properties. These land use categories are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2009). "Public service" in the MADOR system is tax-exempt properties, including lands owned by government (*e.g.*, wellfields, schools, golf courses, open space, roads) and private groups like churches and colleges. It should be noted that there are some similar land uses that are classified in different categories; in this watershed, for example, the Golf Club of Cape Cod is classified by the town assessor as a commercial property (land use code 380), while the Ballymeade Country Club is classified as a multi-use property (land use code 038). Unclassified parcels are properties without any assessor land use classifications.

Public service land uses are the dominant land use type in the both the overall Rands Harbor and the overall Fiddlers Cove watersheds; public service lands are 60% of the Rand Harbor overall watershed and 38% of the overall Fiddlers Cove watershed (Figure IV-2). Examples of these land uses are lands owned by town and state government (including open space and state-owned properties at the MMR), housing authorities, and churches. Residential land uses occupy the second largest area within both watershed (23% and 32%, respectively). It is notable that land classified by the town assessor as undeveloped (including open space) is 10% of the overall watershed area to Rands Harbor and 14% of the overall watershed area to Fiddlers Cove.

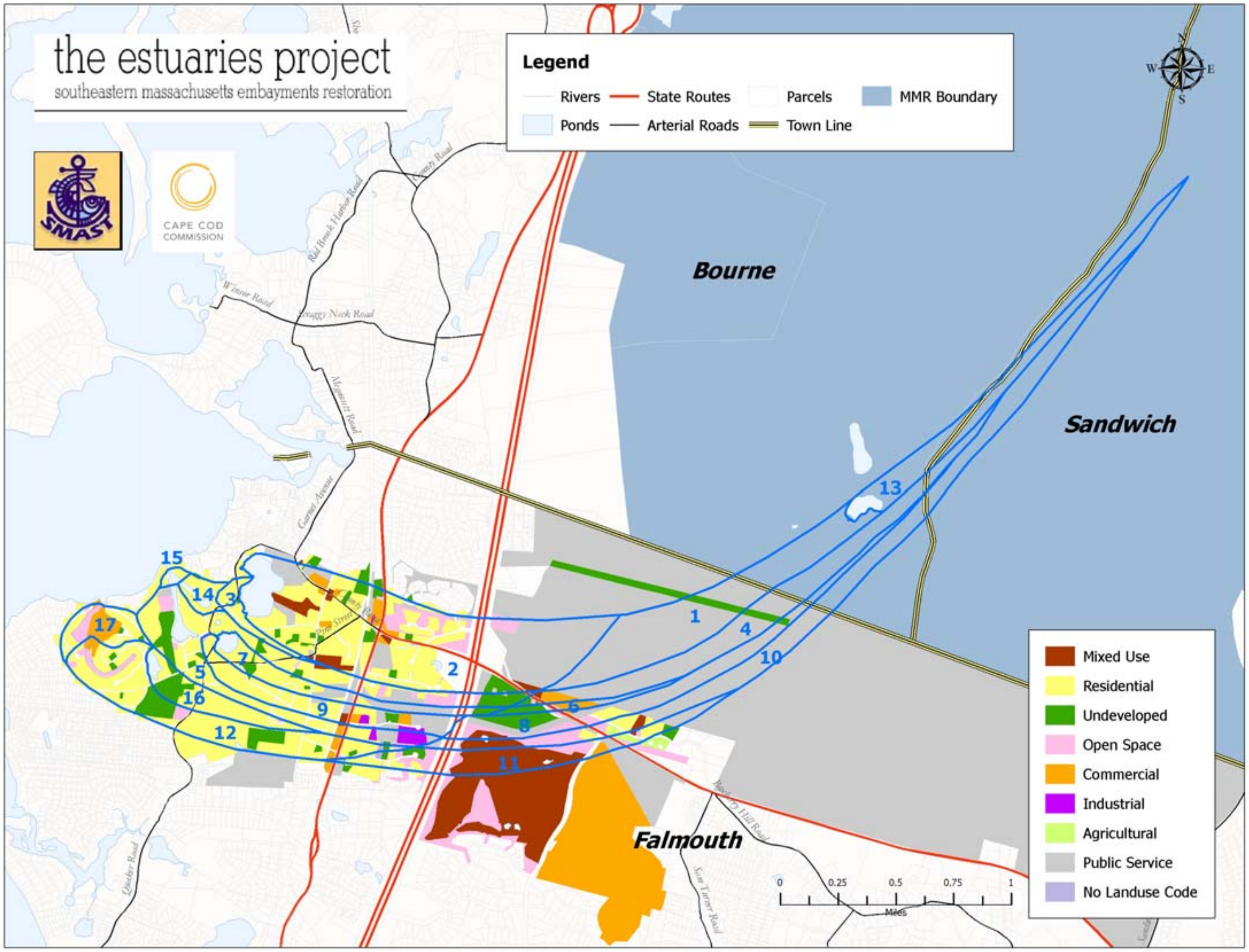


Figure IV-1. Land-use within the sub-watersheds to the Rands Harbor and Fiddlers Cove estuaries. The watershed for each system extends over portions of the Towns of Falmouth, Bourne, and Sandwich. Land use classifications are based on respective town assessor classifications and MADOR (2009) categories. Base assessor and parcel data for Falmouth are from the year 2009, while corresponding data from Bourne is from the year 2008 and Sandwich is from 2010. Bourne and Sandwich parcels are represented as individual parcels completely within the boundary of the Massachusetts Military Reservation (MMR).

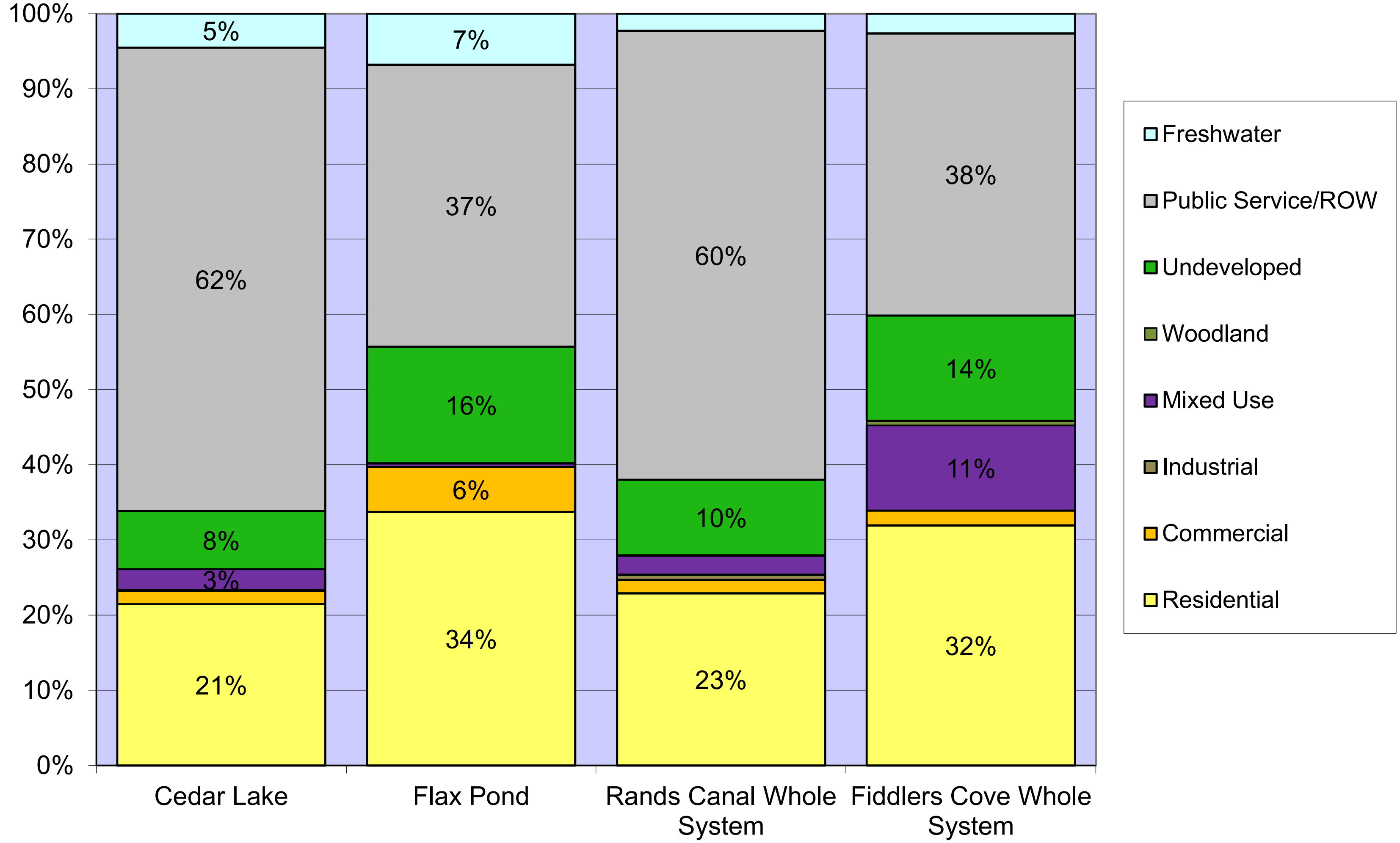


Figure IV-2. Distribution of land-use types by area for the Rands Harbor and Fiddlers Cove watersheds and for the 2 major pond sub-watersheds associated with Rands Harbor. Land use categories are generally based on town assessor's land use classification and groupings recommended by MADOR (2009). Unclassified parcels do not have an assigned land use code in the town assessor's databases. Only percentages greater than or equal to 3% are shown.

In all the sub-watershed groupings shown in Figure IV-2, residential parcels are the dominant parcel type, ranging between 42% in the Flax Pond sub-watershed and 62% in the Cedar Lake sub-watershed. Residential parcels are also the dominant parcel type in the overall Rands Harbor (54%) and overall Fiddlers Cove (67%) watersheds. Public service and undeveloped parcels are the next two highest percentages in both watersheds. Single-family residences (MassDOR land use code 101) are the dominant type of residential parcel; these represent 91% to 96% of residential parcels in the individual sub-watershed groupings. Single-family residences are 93% of the residential parcels throughout the Rands Harbor system watershed and 97% of the residential parcels in the Fiddlers Cove system watershed.

In order to estimate wastewater flows within the Rands Harbor and Fiddlers Cove study areas, MEP staff also obtained parcel-by-parcel water use data from the Town of Falmouth (personal communication, Bob Shea, GIS Coordinator, 11/10). Three years of water use (fiscal years 2008, 2009 and 2010 was obtained from the town. The water use data was linked to the respective town parcel databases by the town GIS Department staff. Measured water use is used to estimate wastewater-based nitrogen loading from the individual parcels; average water use for each parcel is used for parcels with multiple years of data. The final wastewater nitrogen load for each parcel is based upon the measured water-use, wastewater nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2). All parcels are assumed to use on-site septic systems unless additional information is available.

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 assessor's 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 that reaches the aquatic receptors down gradient in the aquifer.

All nitrogen losses within the septic system are incorporated into the MEP analysis. 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 in similar soils 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, MEP staff 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, MEP staff has derived a combined term for an effective N Loading Coefficient (consumptive use times N concentration) of 23.63, to convert water (per volume) to nitrogen load (N mass). 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).

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). Further, 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 in this type of 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 covers 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 from 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 soils and 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 with 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 reasonableness 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 for septic systems 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 Rands Harbor and Fiddlers Cove watersheds, MEP staff reviewed US Census population values for the Town of Falmouth. Since Bourne and Sandwich occupy such a small portion of the watershed and all of the land area is within the MMR, they were not included in this validation analysis. 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 for the purposes of Title 5 each person generates 55 gpd of wastewater. Based on data collected during the 2000 US Census, average occupancy within Falmouth is 2.36 people per housing unit with 69% year-round occupancy, while 2010 Census information indicates that the average occupancy dropped to 2.24 people per housing unit and the year-round occupancy also dropped to 64%. Average water use for single-family residences with municipal water accounts in the combined Rands Harbor and Fiddlers Cove MEP study area is 192 gpd. If this flow is multiplied by 0.9 to account for consumptive use, the study area average is 173 gpd.

In order to provide a check on the water use, the Falmouth Census average occupancies were multiplied by the state Title 5 estimate of 55 gpd of wastewater per capita results, The resulting flow estimates are 130 gpd of average estimated water use per residence based on 2000 Census occupancy and 123 gpd based on 2010 Census occupancy. Estimates of summer populations on Cape Cod derived from a number of approaches (*e.g.*, traffic counts, garbage generation, WWTF flows) suggest average population increases from two to three times year-round residential populations measured by the US Census. If it is assumed that the Falmouth population doubles for three months during the summer, the adjusted year-round occupancy would rise to 2.95 or 2.80 people per housing unit for the 2000 and 2010 Census occupancies, respectively. These occupancies multiplied by 55 gpd/person result in respective average flows of 162 gpd and 154 gpd. If population is assumed to triple, the respective average flows are 194 gpd and 185 gpd. Review of Census data from the North Falmouth census-designated place (CDP) shows that in 2000 54% of the housing units were vacant and that in 2010 47% of the housing units were vacant compared to Falmouth town-wide percentages of 31% and 36%, respectively. This suggests that North Falmouth is much more seasonal than the town as a whole and also suggests that higher seasonal occupancy is more of an issue in North Falmouth and the Rands Harbor and Fiddlers Cove watersheds. The high seasonality must be accounted for in watershed nutrient management planning, as decreases in seasonal usage can significantly alter nitrogen loads to these estuaries without changes in numbers of residences. This analysis suggests that significant seasonal adjustments of population in these watersheds are reasonable and the measured average water use in these watersheds is reasonably reflective of average wastewater estimates.

At the outset of the MEP, project staff decided to utilize the water use approach for determining residential wastewater generation by septic systems because of the inherent difficulty in accurately gauging actual occupancy in areas impacted by seasonal population fluctuations such as most of Cape Cod. The above analysis suggests that water use, on average, is a reasonable estimate of wastewater generation within the study area.

Water use information exists for 93% of the 488 developed parcels in the combined Rands Harbor and Fiddlers Cove watersheds. Developed parcels without water use accounts 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 or town assessor valuations, and do not have a listed account in the water use databases. Of the 36 developed parcels without water use accounts, 25 (69%) are classified as single-family residences (land use code 101). These parcels are assumed to utilize private wells and are assigned the Rands Harbor and Fiddlers Cove study area average water use of 192 gpd in the watershed nitrogen loading modules. Of the 11 remaining developed parcels, eight are other residential land uses. Given the preponderance of residential land uses among developed parcels without water use accounts, all parcels without water use in the Rands Harbor and Fiddlers Cove study area were assigned 192 gpd as their water use in the watershed nitrogen loading model.

Wastewater Treatment Facilities and Alternative Septic Systems

When developing watershed nitrogen loading information, MEP project staff typically seek additional information on enhanced wastewater treatment in the project study area. This information is reviewed and if judged reliable is included in the watershed nitrogen loading model.

MEP staff received a list of alternative, denitrifying septic system in Falmouth and total nitrogen effluent monitoring data from the Barnstable County Department of Health and the Environment (personal communication, Brian Baumgaertel, 1/11). From the BCDHE database, project staff identified five denitrifying septic systems within the Rands Harbor watershed. No denitrifying septic systems are listed in the Fiddlers Cove watershed. Four of the five systems in the Rands Harbor watershed have more than three sampling runs that include total nitrogen effluent concentrations; the average TN concentrations for these systems are included in the Rands Harbor watershed nitrogen loading model.

MEP staff also contacted MassDEP to review whether any Groundwater Discharge Permits (GWDPs) are on file for any sites in the Rands Harbor and Fiddlers Cove study area. A GWDP is required under MassDEP regulations for wastewater treatment systems with design flows greater than 10,000 gallons per day. According the MassDEP databases, no GWDPs exist in either the Rands Harbor or the Fiddlers Cove system watersheds.

Nitrogen Loading Input Factors: Fertilized Areas

The second largest source of watershed nitrogen loading to estuaries is usually fertilized areas: lawns, golf courses, and cranberry bogs. Residential lawns are usually the predominant source within this category. In order to add this source to the nitrogen loading model for the Rands Harbor and Fiddlers Cove systems, MEP staff reviewed available regional information about residential lawn fertilizing practices and sought site-specific information for the following golf courses in the watersheds: Golf Club of Cape Cod and Ballymeade Country Club. No cranberry bogs exist in the watershed. MEP staff contacted the golf course superintendents in order to obtain course-specific fertilizer application rates.

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 nitrogen 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 in the three town survey were found to have the higher rate of fertilizer application and hence higher estimated annual contribution to groundwater of 3 lb/lawn/yr.

In order to obtain a site-specific estimate of nitrogen loading from the Golf Club of Cape Cod and Ballymeade Country Club, MEP staff contacted Charles Passios, Chief Operating Officer. When site-specific, golf course fertilizer application rates are not available, MEP staff assign average application rates from courses that have provided this information to the MEP. Mr. Passios approved the use of the averages for the two courses in the Rands Harbor and Fiddlers Cove watershed. Current MEP nitrogen application rate averages (all in pounds per 1,000 square feet per year) based on reporting from 19 courses are: greens, 3.6; tees, 3.3; fairways, 3.3, and roughs, 2.5.

As has been done in all MEP reviews, MEP staff reviewed the layout of both golf courses from aerial photographs, classified the various turf types, and, using GIS, assigned these areas to the appropriate sub-watersheds. The MEP average golf course nitrogen application rates were then applied to the respective turf areas, a standard MEP 20% leaching rate was applied, and annual load from each golf course to each sub-watershed was calculated.

Nitrogen Loading Input Factors: Other

The nitrogen loading factors for atmospheric deposition, impervious surfaces and natural areas in the Rands Harbor and Fiddlers Cove assessment are from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001). The factors are similar to those utilized by the CCC's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992) and MassDEP'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). Factors used in the MEP nitrogen loading analysis for the Rands Harbor and Fiddlers Cove watersheds are summarized in Table IV-2.

Table IV-2. Primary Nitrogen Loading Factors used in the Rands Harbor and Fiddlers Cove MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Dennis, Harwich and Brewster-specific data.

Nitrogen Concentrations:	**mg/l**
Road Run-off	1.5
Roof Run-off	0.75
Natural Area Recharge	0.072
Direct Precipitation on Embayments and Ponds	1.09
Wastewater Coefficient	23.63
Fertilizers:	
Average Residential Lawn Size (sq ft)[1]	5,000
Residential Watershed Nitrogen Rate (lbs/lawn)[1]	1.08
Golf course fertilizer applications based on MEP averages derived from 19 other courses	
Average Single Family Residence Building Size from watershed data (sq ft)	1,763

Recharge Rates:	**in/yr**
Impervious Surfaces	40
Natural and Lawn Areas	27.25
Water Use/Wastewater:	
Existing developed parcels wo/water accounts and buildout single-family residential parcels:	192 gpd[2]
Existing developed parcels w/water accounts:	Measured annual water use
Commercial and Industrial Buildings buildout additions[3]	
Commercial	
Wastewater flow (gpd/1,000 ft2 of building):	180
Building coverage:	15%
Industrial	
Wastewater flow (gpd/1,000 ft2 of building):	44
Building coverage:	5%

Notes:
1) Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.
2) Based on average flow of all single-family residences in the watershed
3) based on existing water use and water use for similarly classified properties throughout the Town of Falmouth

Road areas are based on MassHighway GIS information, which provides road width for various lengths of road segments. MEP staff utilized the GIS to sum these segments and their various widths by sub-watershed. Project staff also checked this information against parcel-based rights-of-way.

IV.1.3 Calculating Nitrogen Loads

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

The review of individual parcels straddling watershed boundaries includes corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. The Town of Falmouth provided GIS coverages of building footprints for the roof area calculations; MMR buildings, parking lots, and roads areas were digitized from aerial photos. Individualized information for parcels with atypical nitrogen loading (golf courses, denitrifying septic systems) is 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 Rands Harbor and Fiddlers Cove estuary. The assignment effort is undertaken to better define sub-estuary loads and enhance the use of the Linked Watershed-Embayment Model for the analysis of management alternatives.

Following the assignment of all parcels, sub-watershed modules were generated for each of the 17 sub-watersheds in the total Rands Harbor and Fiddlers Cove study area. These sub-watershed modules summarize, among other things: water use, parcel area, parcel frequency by land use category, private wells, and road area. All relevant nitrogen loading data is assigned to each sub-watershed. Individual sub-watershed information is then integrated to create the Rands Harbor and Fiddlers Cove Watershed Nitrogen Loading summary module with summaries for each of the individual 17 sub-watersheds and the totals for each of estuary systems. The sub-watersheds are generally paired with functional embayment/estuary units for the Linked Watershed-Embayment Model's water quality component.

For management purposes, the aggregated estuary watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Rands Harbor and Fiddlers Cove study area, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), fertilizers, impervious surfaces, direct atmospheric deposition to water surfaces, the solid waste sites, and recharge within natural areas (Table IV-3). 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). 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.

One of these attenuation adjustments occurs in the freshwater ponds. Since groundwater outflow from a pond can enter more than one down gradient sub-watershed, the length of shoreline on the down gradient side of the pond is used to apportion the pond-attenuated nitrogen load to respective down gradient watersheds unless modified by measured stream flow. The apportionment is based on the percentage of discharging shoreline bordering each down gradient sub-watershed. In the Rands Harbor and Fiddlers Cove study area, there are four ponds with delineated sub-watersheds: Trout Pond, Flax Pond, Cedar Lake, and Edmunds Pond. Among these only Edmunds Pond has only groundwater discharge and it is

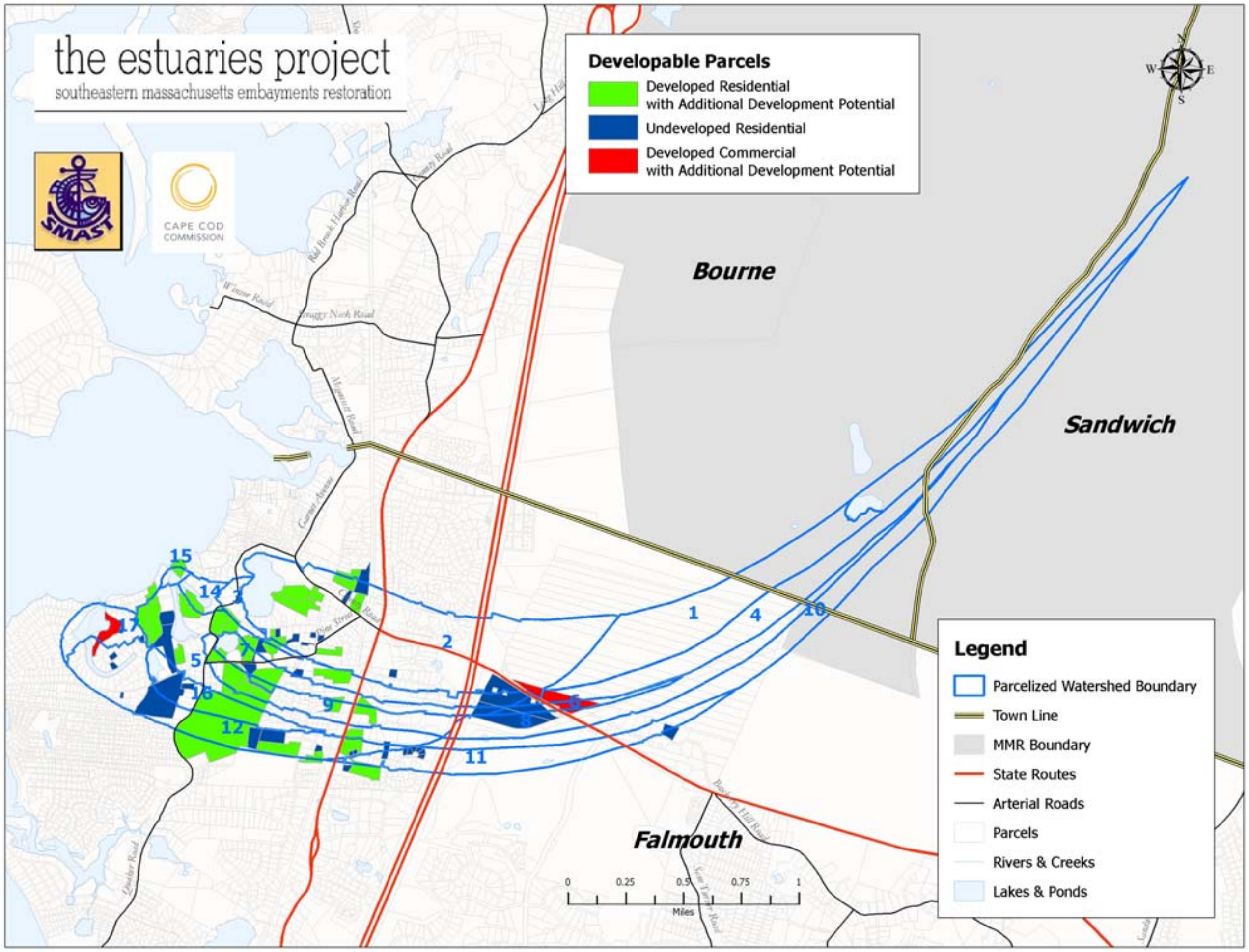


Figure IV-3. Parcels, Parcelized Watersheds, and Developable Parcels within the Rands Harbor and Fiddlers Cove watersheds. Parcels colored green and red are developed parcels (residential and commercial, respectively) with additional development potential based on current zoning, while parcels colored blue are undeveloped residential parcels classified as developable by the town assessor. The parcelized watersheds are drawn to minimize the division of properties for management purposes while achieving a match of area with the modeled watersheds of 2% or less. Developable parcels are based on town assessor classifications and minimum lot sizes specified in town zoning; these parcels are assigned estimated nitrogen loads in MEP buildout calculations. All buildout results were reviewed with town staff and modified based on comments (personal communication, Brian Currie, Town of Falmouth, 4/11).

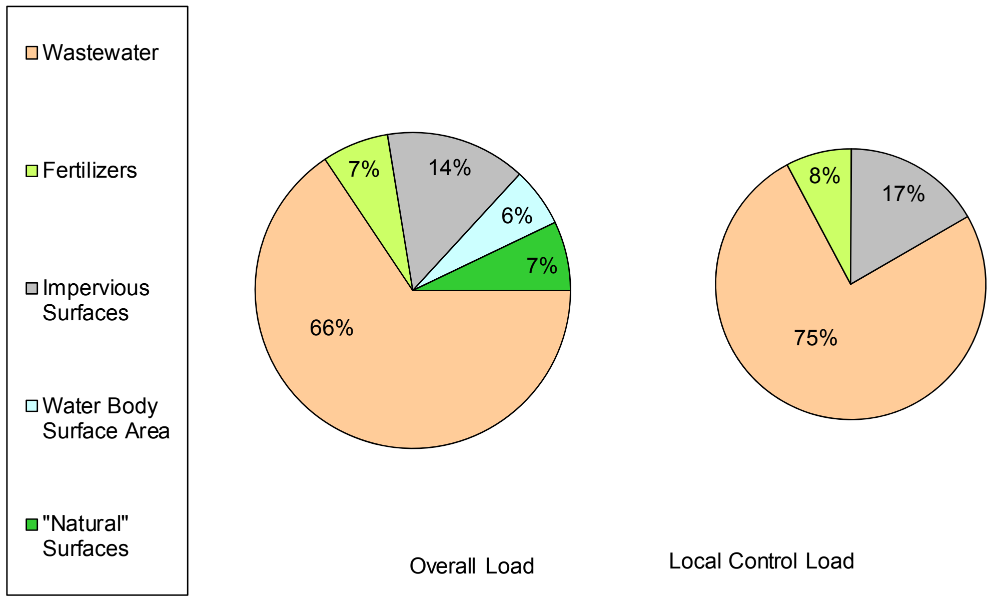
Table IV-3. Rands Harbor and Fiddlers Cove Watershed Nitrogen Loads. Attenuated nitrogen loads shown below are based on measured and assigned attenuation factors assigned to up-gradient streams and freshwater ponds. Stream attenuation factors are based on measured loads (see Section IV.2), while pond attenuation factors are assigned a standard MEP nitrogen attenuation rate of 50% based on water quality monitoring from the Cape Cod Pond and Lake Stewards program or a modified factor if sufficient monitoring data is available. All nitrogen loads are kg N yr^{-1}.

		Rands Harbor N Loads by Input (kg/y):							***Present N Loads***			***Buildout N Loads***		
Watershed Name	**Watershed ID#**	**Wastewater**	**Fertilizers**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**% of Pond Outflow**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Rands Harbor System		1,652	172	363	153	178	2,066		2,519		2,269	4,585		4,233
Rands Harbor Inlet		3	0	0	8	0	-		13		13	13		13
Rands Harbor LT10 Inlet	15	3	0	0	-	0	-		5		5	5	-	5
Rands Harbor Inlet Estuary Surface					8				8		8	8	-	8
Rands Harbor North Arm		745	50	159	83	80	384		1,116		922	1,500		1,248
Rands Harbor GT10N	4	5	-	28	-	23	77		57		57	133	-	133
Rands Harbor LT10N	14	64	6	5	-	2	7		77		77	84	-	84
Bay Road Gauge		676	43	126	71	55	301		971		777	1,272	-	1,019
Rands Harbor North Estuary Surface					12				12		12	12	-	12
Rands Harbor South Arm		904	122	204	62	98	1,682		1,390		1,334	3,072		2,973
Rands Harbor LT10S	5	512	38	53	-	25	593		629		629	1,221	-	1,221
Rands Harbor GT10S	10	22	32	83	-	29	-		167		167	167	-	167
Rands Beach Road Gauge Total		316	44	59	19	39	1,084		477		463	1,561	-	1,507
Trout Pond	TP	54	7	9	11	5	5	73%	86	50%	43	91	50%	46
Rands Harbor South Estuary Surface					32				32		32	32	-	32

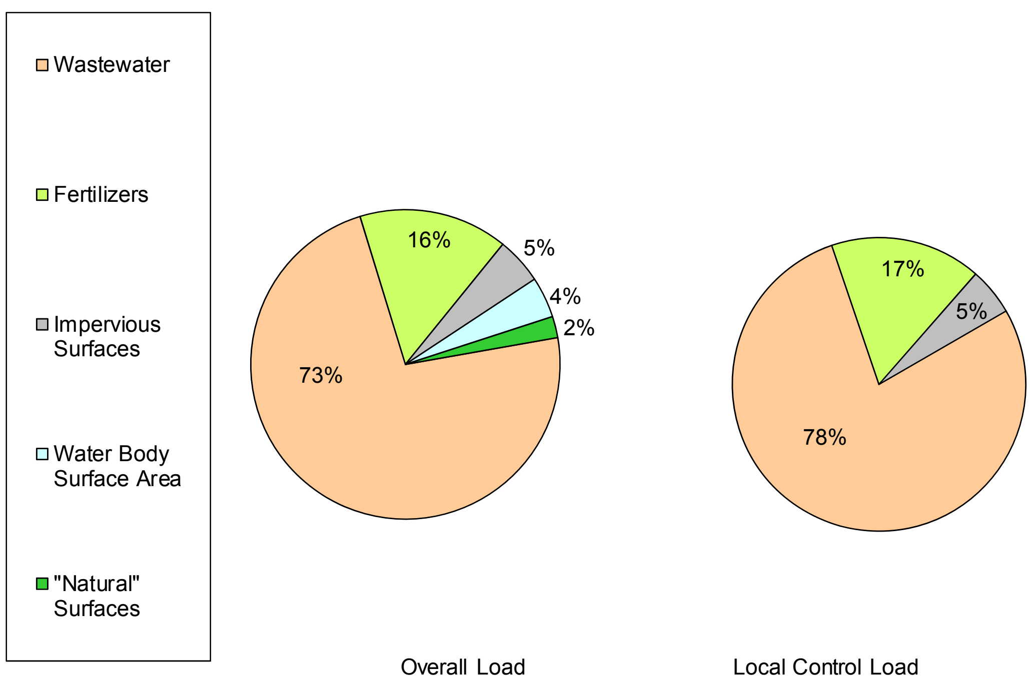
		Fiddlers Cove N Loads by Input (kg/y):							***Present N Loads***			***Buildout N Loads***		
Watershed Name	**Watershed ID#**	**Wastewater**	**Fertilizers**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**% of Pond Outflow**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Fiddlers Cove System		1,215	259	81	71	37	413		1,664		1,648	2,077		2,060
Fiddlers Cove Inlet		291	15	16	25	3	-		350		350	350		350
Fiddlers Cove LT10 Inlet	17	291	15	16	-	3			325		325	325	-	325
Fiddlers Cove East Estuary Surface					25				25		25	25	-	25
Fiddlers Cove East		925	245	65	46	34	413		1,314		1,298	1,727		1,710
Fiddlers Cove GT10	11	116	199	14	-	12	49		341		341	390	-	390
Fiddlers Cove LT10E	12	789	43	48	-	20	363		899		899	1,261	-	1,261
Trout Pond	TP	20	3	3	4	2	2	27%	32	50%	16	34	50%	17
Fiddlers Cove West Estuary Surface					42				42		42	42	-	42

Table IV-3 cont'd. Rands Harbor and Fiddlers Cove Watershed Nitrogen Loads. Attenuated nitrogen loads shown below are based on measured and assigned attenuation factors assigned to up-gradient streams and freshwater ponds. Stream attenuation factors are based on measured loads (see Section IV.2), while pond attenuation factors are assigned a standard MEP nitrogen attenuation rate of 50% based on water quality monitoring from the Cape Cod Pond and Lake Stewards program or a modified factor if sufficient monitoring data is available. All nitrogen loads are kg N yr^{-1}.

		Stream and Pon N Loads by Input (kg/y)						% of Pond Outflow	***Present N Loads***			***Buildout N Loads***		
Watershed 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**
streams														
Bay Road Gauge Total		676	43	126	71	55	301		971		777	1,272	-	1,019
Bay Road Gauge	3	76	5	16	-	2	7		99		99	106	-	106
Cedar Lake Total	CL	600	38	110	71	53	294	54%	872	20%	678	1,165	20%	913
Rands Beach Road Gauge Total		316	44	59	19	39	1,084		477		463	1,561	-	1,507
Rands Beach Rd Gauge GT10	8	7	19	14	-	17	565		57		57	622	-	622
Rands Beach Rd Gauge LT10	9	228	16	29	-	11	114		285		285	399	-	399
Flax Pond Total	FP	81	9	16	19	11	405	100%	134	10%	121	539	10%	485
ponds														
Cedar Lake Total	CL	1,120	71	205	132	99	548		1,627	20%	1,266	2,175	20%	1,704
Cedar Lake GT10	1	-	-	30	-	30	0		60		60	60	-	60
Cedar Lake LT10	2	1,120	71	131	99	55	548		1,477		1,477	2,025	-	2,025
Edmunds Pond	13	-	-	44	33	13	0		90	50%	45	90	50%	45
Flax Pond Total	FP	81	9	16	19	11	405		134	10%	121	539	10%	485
Flax Pond GT10	6	-	-	1	-	3	230		4		4	234	-	234
Flax Pond LT10	7	81	9	14	19	8	174		131		131	305	-	305
Trout Pond	16	74	10	12	15	7	7		118	50%	59	125	50%	63



Whole System: Rands Canal



Whole System: Fiddlers Cove

Figure IV-4. Land use-specific unattenuated nitrogen loads (by percent) to the whole Rands Harbor and whole Fiddlers Cove watersheds. “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.

completely contained within the Cedar Lake watershed. The other ponds (Flax Pond and Cedar Lake) have outflow to gauged streams and their outflow and attenuated nitrogen load is divided between the gauges and groundwater discharge to down gradient watersheds.

Freshwater Pond Nitrogen Loads

Freshwater ponds on Cape Cod are generally watershed sites of natural nitrogen reduction (or attenuation) prior to the watershed nitrogen reaching an estuary. These ponds are generally kettle hole depressions of the land surface that intercept the surrounding groundwater table revealing what some call “windows on the aquifer.” Groundwater typically flows into the pond along the up-gradient shoreline, then lake water flows back into the groundwater system along the down gradient shoreline. Occasionally a Cape Cod pond will also have a stream outlet, which is often a herring run, that also acts as a discharge point. Since the nitrogen loads usually flow into a 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 in the pond watershed is removed from the estuary watershed system, mostly through burial in pond sediments and denitrification that returns it to the atmosphere. Following these reductions, the remaining (attenuated) loads flow back into the groundwater system along the down gradient side of the pond and eventual discharge into the down gradient embayment or through a stream outlet directly to the estuary. The nitrogen load summary in Table IV-3 includes both the unattenuated (nitrogen load to each sub-watershed) and attenuated nitrogen loads.

Nitrogen attenuation in freshwater ponds has generally been found to be at least 50% in MEP analyses, so a conservative attenuation rate of 50% is generally assigned to all nitrogen from freshwater pond watersheds in the watershed model unless more detailed pond monitoring or studies are available. 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 as a reasonable, somewhat conservative rate. However, in some cases, if sufficient monitoring information is available, a pond-specific attenuation rate is incorporated into the watershed nitrogen loading modeling (e.g., 87%, Mystic Lake; 40%, Middle Pond; and 52%, Hamblin Pond in the Three Bays MEP Report, Howes, *et al*., 2006). In order to review whether a pond-specific nitrogen attenuation rate other than 50% should be used, the MEP Technical Team reviews the available data on each pond, including available nitrogen concentrations, impacts of sediment regeneration, temperature profiles, and bathymetric information.

Bathymetric information is generally a prerequisite for determining enhanced attenuation, since it provides the volume of the pond and, with appropriate pond total nitrogen concentrations, a measure of the nitrogen mass in the water column. Combined with the watershed recharge, this information can provide a residence or turnover time that is necessary to gauge nitrogen attenuation.

In addition to bathymetry, temperature profiles are useful to help understand whether temperature stratification is occurring in a pond. If the pond has an epilimnion (*i.e.*, a well-mixed, relatively isothermic, warm, upper portion of the water column) and a hypolimnion (*i.e.*, a deeper, colder layer), the stability and volume of these two layers must be accounted for in the nitrogen attenuation calculations. In these stratified lakes, the upper epilimnion is usually the primary discharge for watershed nitrogen loads; the deeper hypolimnion generally does not interact with the upper layer. However, deep lakes with hypolimnions often also have significant sediment regeneration of nitrogen and in lakes with impaired water quality this regenerated nitrogen can impact measured nitrogen concentrations in the upper epilimnion and this impact should also be considered when estimating nitrogen attenuation.

Many ponds on Cape Cod have been sampled through the regional Cape Cod Pond and Lake Stewards (PALS) Snapshots and the initiative of local volunteer pond sampling programs. The PALS Snapshots are regional volunteer one-time pond sampling that happens each year and was initiated and is supported for the last nine years by SMAST and the Cape Cod Commission, with free laboratory services provided by the Coastal Systems Program Laboratory at SMAST. Sampling protocols developed through the PALS program (Eichner *et al*., 2003) have been used for more extensive pond sampling programs in many communities on Cape Cod. Sampling under these protocols has included field collection of temperature and dissolved oxygen profiles and sampling has generally occurred at standardized depths that provide some evaluation of potential sediment nutrient regeneration. PALS water samples are analyzed at the SMAST laboratory for total nitrogen, total phosphorus, chlorophyll *a*, alkalinity, and pH. In some cases town programs have generated sufficient sampling data that modified MEP nitrogen attenuation rates can be reliably assigned to freshwater ponds.

Within the Rands Harbor and Fiddlers Cove watersheds, there are four freshwater ponds with delineated watersheds: Cedar Lake, Edmunds Pond, Flax Pond, and Trout Pond. None of the ponds has available pond-wide bathymetric data (Eichner *et al*., 2003) or sufficient water quality data collection outside of the MEP to provide a basis for an alternative nitrogen attenuation rate. Cedar Lake and Trout Pond have been sampled six times during the nine years of PALS Snapshots and Flax Pond and Edmunds Pond have not been sampled through the PALS Program.

None of the freshwater ponds has sufficient in-pond sampling or adequate bathymetry to assign an alternative MEP nitrogen attenuation rate. However, MEP staff did have two stream gauges that measured freshwater discharge and nitrogen outflow from Cedar Lake and Flax Pond. Using the information collected from these gauges (see Section IV.2), MEP staff assigned a 20% nitrogen attenuation rate to Cedar Lake and a 10% nitrogen attenuation rate to Flax Pond. These attenuation rates balance the measured flow and load leaving the pond through the stream gauge and the likely discharge of a portion of the flow and load from the pond through its down gradient shoreline. More refined evaluation of these ponds would offer the opportunity to refine these attenuation rates and evaluation of management options to increase the attenuation rates and naturally remove additional nitrogen. Edmunds and Trout Ponds are assigned the standard 50% nitrogen attenuation rate that has been determined to be a reasonably conservative attenuation rate for freshwater ponds in the MEP study area that are lacking sufficient pond-specific data.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development and accompanying nitrogen loads within the study area watersheds. The MEP buildout is relatively straightforward and is generally completed in four steps: 1) each residential parcel classified by the town assessor as developable is identified and divided by minimum lot sizes specified in town zoning and the resulting number of new residential units is rounded down, 2) parcels classified as developable commercial and industrial parcels by the town assessor are identified, 3) residential, commercial and industrial parcels with existing development and areas greater than twice zoning's minimum lot size are identified, divided by the minimum lot size and the resulting number of new units is rounded down, and 4) results are discussed with town staff and/or planning board members and the analysis results are modified based on local knowledge.

It should be noted that the initial buildout approach is relatively simple and does not include any modifications/refinements for lot line setbacks, wetlands, road construction, frontage requirements, parcel shape requirements, or other more detailed zoning provisions. The MEP buildout approach also does not include potential impacts associated with the higher densities usually associated with 40B affordable housing projects. The fourth step, including the discussions with town planners, and, occasionally, town planning boards and wastewater consultants, usually leads to additional insights on developments that are planned, especially developments planned on government or public service parcels, and updates to assessor classifications, including lands purchased by the town as open space. This final step may lead to removal and/or additions to the number of parcels initially identified as developable and application of more detailed zoning provisions.

As an example of how the MEP approach might apply, assume an 81,000 square foot lot is classified by the town assessor as a developable residential lot (land use code 130). This lot is divided by the 40,000 square foot minimum lot size specified in town zoning and the result is rounded down to two. As a result, two additional residential lots would be added to the sub-watershed in the MEP buildout scenario.

Other provisions of the MEP buildout assessment include differentiated treatment of undevelopable lots, commercial and industrial properties, and lots less than the minimum areas specified by zoning. Properties classified by the Town of Falmouth assessors as "undevelopable" (*e.g.*, MassDOR codes 132, 392, and 442) are not assigned any development at buildout (unless revised by the town review). Commercial and industrial properties classified as developable are not subdivided; the area of each parcel and the factors in Table IV-2 are used to determine a building size and wastewater flow for these properties. Pre-existing lots classified by the town assessor as developable are also treated as developable even if they are less than the minimum lot size specified in zoning. As an example, a 10,000 square foot lot classified by the town assessor as 130 land use code will be assigned an additional residential dwelling in the MEP buildout scenario even though the minimum lot size in the area is 40,000 square feet. Most town zoning bylaws have a lower minimum lot size for pre-existing lots (usually 5,000 square feet) that will minimize instances of regulatory takings. Existing developed residential properties that are larger than zoning's minimum lot sizes are also assigned additional development potential only if enough area is available to accommodate at least one additional lot as specified by the zoning minimum.

Following the completion of the initial buildout assessment for the Rands Harbor and Fiddlers Cove watersheds, MEP staff reviewed and modified the initial results with Brian Currie, Falmouth Town Planner in April 2011. Suggested changes from town staff review were incorporated into the final buildout for Rands Harbor and Fiddlers Cove.

All the parcels with additional buildout potential within the Rands Harbor and Fiddlers Cove watershed are shown in Figure IV-4. Each additional residential, commercial, or industrial property added at buildout is assigned nitrogen loads for wastewater and impervious surfaces. Residential additions also include lawn fertilizer nitrogen additions. All wastewater loads are assumed to come from standard on-site septic systems. Cumulative unattenuated buildout loads from all sub-watersheds are indicated in a separate column in Table IV-3. Increases in nitrogen loads to the watershed at buildout of the Rands Harbor watershed will increase the unattenuated system-wide nitrogen loading rate by 82%. In contrast, buildout of the Fiddlers Cove watershed will increase the unattenuated system-wide nitrogen loading rate by only 25%. These increases are predominantly due to high density development (8 units per acre) that is allowed within portions of both watersheds.

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 Fiddlers Cove and Rands Harbor Embayment Systems 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 regions of the Fiddlers Cove and Rands Harbor watersheds). 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 watershed for the Rands Harbor embayment system, a portion of the freshwater flow and transported nitrogen passes through two main surface water systems (e.g. un-named creek discharging into the head of the east branch of the Rands Harbor system from Cedar Lake, un-named creek discharging into the head of the west branch of the Rands Harbor system from Flax Pond) prior to entering the estuary, producing the opportunity for reductions in nutrient loading, primarily through nitrogen attenuation (Figure IV-5). There are no significant surface water discharges (creeks, streams, rivers) associated with the Fiddlers Cove embayment system therefore an analysis of nitrogen attenuation in streams was not undertaken. Nitrogen attenuation in ponds within the watershed to Fiddlers Cove was taken into consideration in the analysis of nitrogen loading from the watershed based on land use.

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 2000). 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.

Figure IV-5. Location of stream flow gauge and nitrogen load measurements (red symbol) associated with the Rands Harbor Embayment System.

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 in the Rands Harbor embayment system. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the perimeter of the embayment system in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). These additional site-specific studies were conducted in the 2 major surface water flow systems in the Rands Harbor watershed, 1) Un-named Creek discharging to the east branch of Rands Harbor from Cedar Lake and 2) Un-named Creek discharging to the west branch of Rands Harbor from Flax Pond. Both branches join near the inlet to form the main tidal channel of the Rands Harbor system.

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 stream discharging to the estuary provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up gradient from the various gaging sites. Flow and nitrogen load were determined at two gauge locations for 16 months of record (Figures IV-6 and IV-7). During the study period, a velocity profile was completed at each gauge positioned in each of the creeks every month to two months. The summation of the products of creek subsection areas of the channel cross-section and the respective measured velocities represent the computation of instantaneous flow (Q) through a given creek.

Determination of flow at the gauges on the two un-named Creeks discharging to Rands Harbor was calculated and based on the measured values obtained for cross sectional area of each creek as well as creek specific velocity. Freshwater discharge was represented by the summation of individual discharge calculations for each channel subsection for which a cross sectional area and velocity measurement were obtained. Velocity measurements across the entire channel cross section were not averaged and then applied to the total creek 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.

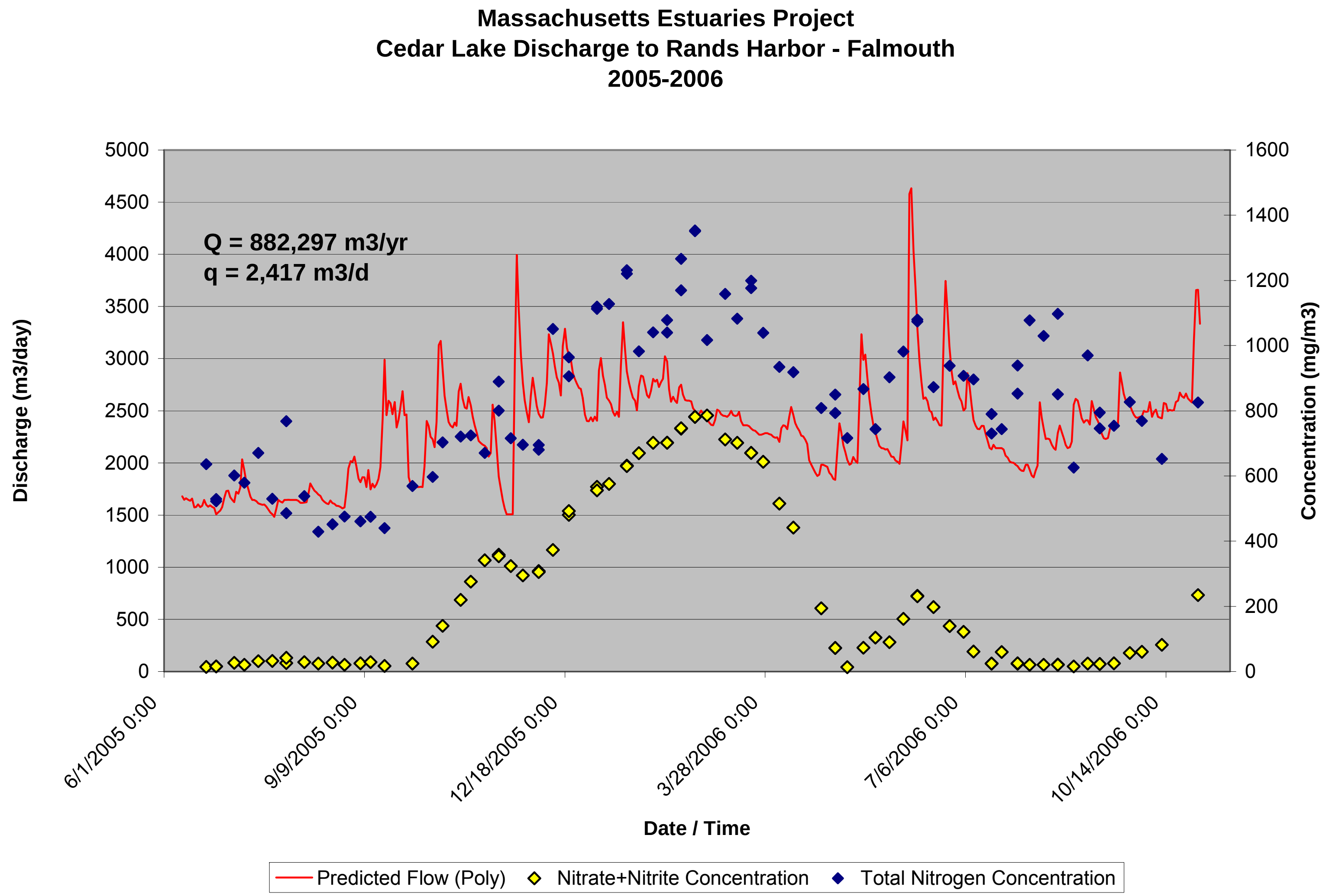


Figure IV-6. Un-named Creek flowing under Bay Road and discharging directly into the head of the East Branch of Rands Harbor (solid red line), nitrate+nitrite (yellow triangle) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Rands Harbor (Table IV-4).

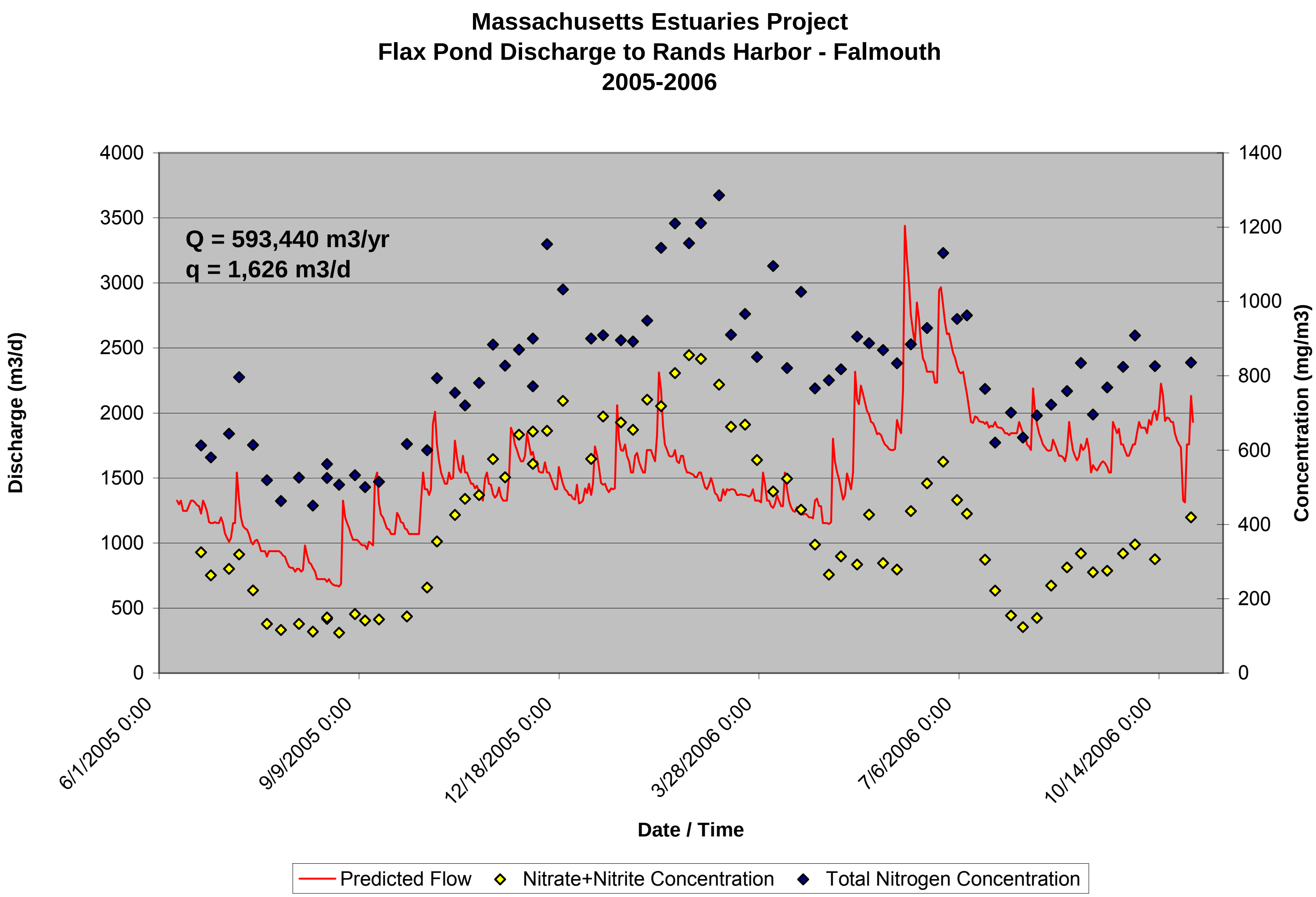


Figure IV-7. Un-named Creek flowing from Flax Pond and discharging directly into the head of west branch of Rands Harbor (solid blue line), nitrate+nitrite (yellow triangle) and total nitrogen (blue square) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Rands Harbor (Table IV-4).

Table IV-4. Comparison of water flow and nitrogen discharges from the two un-named Creeks (freshwater) discharging to the east and west branches of the Rands Harbor system from Cedar Lake and Flax Pond respectively. The "Stream" data is from the MEP stream gaging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	Cedar Lake Discharge[a] East Branch Rands	Flax Pond Discharge[a] West Branch Rands	Data Source
Total Days of Record	365[b]	365[c]	(1)
Flow Characteristics			
Stream Average Discharge (m3/day) **	2,417	1,626	(1)
Contributing Area Average Discharge (m3/day)	2,477	1,646	(2)
Discharge Stream 2005-06 vs. Long-term Discharge	2%	1%	
Nitrogen Characteristics			
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.314	0.462	(1)
Stream Average Total N Concentration (mg N/L)	0.895	0.875	(1)
Nitrate + Nitrite as Percent of Total N (%)	35%	53%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	2.16	1.42	(1)
TN Average Contributing UN-attenuated Load (kg/day)	2.66	1.31	(3)
Attenuation of Nitrogen in Pond/Stream (%)	19%	-8%	(4)

(a) Flow and N load to creeks discharging to the East and West Branches of Rands Harbor and includes apportionments of Pond contributing areas.
(b) September 1, 2005 to August 31, 2006.
(c) September 1, 2005 to August 31, 2006.
** Flow is an average of annual flow for 2005-2006 in both creeks

(1) MEP gage site data
(2) Calculated from MEP watershed delineations to ponds upgradient of specific gages;
the fractional flow path from each sub-watershed which contribute to the flow in the creeks to Rands Harbor;
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. Flax Pond attenuation (-) is effectively zero as the difference is artifical and driven by the variation inherent to measuring flow in very small streams.

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 creek. 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. A complete annual record of flow in the creeks (365 days) was generated for the surface water discharge flowing into the head of each of the branches of the Rands Harbor embayment system and emanating from Cedar Lake and Flax Pond.

The annual flow record for the surface water flow at the gauge was merged with the nutrient data set generated through the weekly water quality sampling performed at the gauge location to determine nitrogen loading rates to the head of each branch of the Rands Harbor system. Nitrogen discharge from the two small creeks was calculated using the paired daily discharge and daily nitrogen concentration data to determine the mass flux of nitrogen through the specific gaging sites. For each of the creek gauge locations, weekly water samples were collected (at low tide for a tidally influenced stage, creek from Flax Pond to west branch) 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 flow in the creeks 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 the gauged creeks currently reduces (percent attenuation) nitrogen loading to the overall embayment system.

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Fiddlers Cove

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 or sewering analysis) 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 watershed of the Fiddlers Cove System were 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 is through groundwater in sandy outwash aquifers without passing through large freshwater ponds or streams during transport. The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification. This is the case for the Fiddlers Cove watershed. Unlike most watersheds in southeastern Massachusetts, nitrogen does not pass through a surface water ecosystem on its path to the adjacent embayment. It is in these surface water systems that the needed conditions for nitrogen retention and denitrification exist. As there were no streams discharging from ponds within the Fiddlers Cove watershed, the watershed loading approach considered that nitrogen reaching the water table was transported without attenuation in the groundwater system until discharge to the estuary. In the case of nitrogen load entering Trout Pond, a pond attenuation factor was applied to the load prior to the load entering the groundwater flow along the pond's down gradient shore line.

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Creek flowing into Rands Harbor East Branch from Cedar Lake

Located up-gradient of the stream gauge on the un-named creek discharging into the east branch of Rands Harbor is a small freshwater pond, Cedar Lake. Cedar Lake, unlike many of the freshwater ponds on Cape Cod, has a surface water discharge rather than draining solely to the aquifer along its down-gradient shore. This outflow through the un-named Creek, 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 occurs within associated wetland areas, riparian zones and streambed associated with the Creek. 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 Creek above the stream gauge and the measured annual discharge of nitrogen to the tidally influenced north (east) branch of the Rands Harbor system, Figure IV-5.

At the Creek gauge site (situated immediately up-gradient of Bay Road), a continuously recording vented calibrated water level gauge was installed to yield the level of water in the freshwater creek discharging from Cedar Lake and which carries the flows and associated nitrogen load to the head of the east branch of the Rands Harbor embayment. As both branches of the system are tidally influenced, the gauge was located as far down gradient along the Creek reach such that freshwater flow could be measured at low tide. Based on the stage record, however, the location of this specific gauge did not appear to be tidally influenced. To confirm the lack of tidal influence as observed in the stage record, salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average salinity for all the water samples collected over the entire gauge deployment period was determined to be 0.1 ppt. Therefore, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked approximately monthly each time the site was visited and a flow measurement obtained. The gauge on the Creek was installed on June 9, 2005 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 October 30, 2006 for a total deployment of 16 months.

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 un-named Creek 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 head of the east branch and subsequently, the main tidal channel of the Rands Harbor system. This measured attenuated mass discharge is reflective of the biological processes occurring in Cedar Lake as well as the stream channel and riparian zone contributing to nitrogen attenuation (Figure IV-6 and Table IV-4). 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 the gauge site.

The annual freshwater flow record for the Creek flowing under Bay Road and into the east branch as 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 Creek was only 2% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for one hydrologic year beginning September and ending in August (low flow to low flow) was 2,417 m^3/day compared to the long term average flows determined by the USGS modeling effort (2,477 m^3/day).

The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Creek was considered to be negligible given the relatively small flow and associated load. The negligible difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Creek discharging from Cedar Lake would indicate that the Creek is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Creek outflow were moderate, 0.895 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 2.16 kg/day and a measured total annual TN load of 790 kg/yr. In the Creek (freshwater), nitrate was significantly less than half of the total form of nitrogen (35%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was largely taken up by plants within the small up-gradient pond (Cedar Lake) or stream ecosystems. This is further supported when considering that dissolved and particulate organic nitrogen constitute 61 percent of the total nitrogen load discharging to the East Branch portion of the Rands Harbor system. However, the nitrate level (0.314 mg N L^{-1}) in the outflowing stream water suggests the possibility for some additional uptake by freshwater systems up-gradient from the gauge location. Inorganic nitrogen appears significantly attenuated already. Opportunities for enhancing nitrogen attenuation elsewhere in the overall sub-watershed to the East Branch of the Rands Harbor system could be considered, however there is not likely to be much more natural attenuation to be gained from the Creek-Cedar Lake sub-watersheds.

From the measured nitrogen load discharged by the Creek to the east branch of the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that nitrogen attenuation is occurring during transport of upper watershed derived nitrogen during transport to the estuary. Based upon lower total nitrogen load (790 kg yr^{-1}) discharged from the freshwater Creek compared to that added by the various land-uses to the associated watershed (971 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 19% (i.e. 19% of nitrogen input to watershed does not reach the estuary). This level of attenuation compared to other streams evaluated under the MEP is expected given the hydrologic and biogeochemical characteristics of the up-gradient pond(s) capable of attenuating nitrogen. The directly measured nitrogen loads and attenuation rate from the Creek were used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

IV.2.4 Surface water Discharge and Attenuation of Watershed Nitrogen: Creek flowing into Rands Harbor West Branch from Flax Pond

Located up gradient of the gauge site on the un-named creek discharging into the south (west) branch of the Rands Harbor system is a small freshwater pond (Flax Pond) and unlike many of the freshwater ponds on Cape Cod, this small pond has a surface water discharge rather than draining solely to the aquifer along its down-gradient shore. This outflow through the un-named Creek, 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 associated wetland areas, riparian zones and streambed associated with the

Creek. 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 Creek above the gauge site and the measured annual discharge of nitrogen to the tidally influenced west branch of the Rands Harbor system, Figure IV-5.

At the stream gauge site (situated immediately up-gradient of Rand Beach Road), a continuously recording vented calibrated water level recorder was installed to measure the level of water in the freshwater creek discharging from Flax Pond and support determination of the associated nitrogen load to the head of the west branch of the Rands Harbor embayment. As the west branch is tidally influenced, the gauge was located as far down gradient along the Creek reach such that freshwater flow could be measured at low tide. To confirm that freshwater was being measured the stage record was analyzed for any semi-diurnal variations indicative of tidal influence and salinity measurements were conducted on the weekly water quality samples collected from the gauge site. Average low tide salinity was determined to be 0.1 ppt. Therefore, the gauge location was deemed acceptable for making freshwater flow measurements. Calibration of the gauge was checked approximately monthly each time the site was visited and a flow measurement obtained. The gauge on the Creek was installed on June 22, 2005 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 October 30, 2006 for a total deployment of 16 months.

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 un-named Creek 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 head of the west branch and subsequently, the main tidal channel of the Rands Harbor system. This measured attenuated mass discharge is reflective of the biological processes occurring in Flax Pond as well as the stream channel and riparian zone contributing to nitrogen attenuation (Figure IV-7 and Table IV-4). 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 the gauge site.

The annual freshwater flow record for the Creek discharging from Flax Pond as 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 Creek was only 1% below the long-term average modeled flows. The average daily flow based on the MEP measured flow data for one hydrologic year beginning September and ending in August (low flow to low flow) was 1,626 m^3/day compared to the long term average flows determined by the USGS modeling effort (1,646 m^3/day).

The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Creek was considered to be negligible given the relatively small flow and associated load. The good agreement between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Creek discharging to the west branch of Rands Harbor would indicate that the Creek is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Creek outflow were moderate, 0.875 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 1.42 kg/day and a measured total annual TN load of 519 kg/yr. In the Creek (freshwater), nitrate was slightly more than half of the total form of nitrogen (53%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was partially taken up by plants within the small up-gradient pond or stream ecosystems. This is further supported when considering that dissolved and particulate organic nitrogen constitute 45 percent of the total nitrogen load discharging to the west branch portion of the Rands Harbor system. The higher concentration of inorganic nitrogen (0.482 mg N L^{-1}) in the out flowing creek waters also suggests the possibility of enhancing uptake by biologic activity within the up gradient freshwater ecosystems compared to Cedar Lake (inorganic nitrogen of 0.348 mg N L^{-1} in outflowing water). In addition, the moderate nitrate level (0.462 mg N L^{-1}) suggests that additional uptake by freshwater systems up-gradient from the gauge location is possible in this system. Inorganic nitrogen appears only moderately attenuated by Flax Pond. Opportunities for enhancing nitrogen attenuation in Flax Pond could be considered as there may be additional natural attenuation to be gained from the Creek-Flax Pond systems. This would not be the case if nitrate levels were lower as observed in Cedar Lake.

From the measured nitrogen load discharged by the Creek to the west branch of the Rands Harbor estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is no nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. In the case of Flax Pond, the measured nitrogen load determined at the stream gauge was slightly higher compared to that added by the various land-uses to the associated watershed (519 kg yr^{-1} vs. 477 kg yr^{-1}). While this 42 kg difference in Total Nitrogen might suggest that Flax Pond is a producer of nitrogen that would not be consistent with theory. The difference is more likely artificial and a function of variations in the measurement of stream flow inherent to very small streams. That the measured nitrogen load and the land-use based load are essentially the same, suggesting no attenuation in Flax Pond, does not raise concern for several reasons. Most importantly, the structure of Flax Pond, a small very shallow pond that is more like a bog, does not tend to generate significant attenuation. This has been seen in other systems gauged by the MEP such as Hurley Bog in Orleans (19% attenuation), Bumps River in Barnstable (22% attenuation), Carding Machine Brook in Harwich (21%) and similarly situated Cedar Lake discharge (19% attenuation) adjacent Flax Pond. Unlike these example systems, Flax Pond represents even less of a pond system then those just mentioned. As such, it is not surprising to see no attenuation in Flax Pond. This presents a unique opportunity for the Town of Falmouth to consider a restoration program for Flax Pond in order to potentially enhance the natural attenuation capability of the pond in order to further lower total nitrogen load to Rands Harbor. The directly measured nitrogen loads from the Creek was used in the Linked Watershed-Embayment Modeling of water quality (see Section VI, below).

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 throughout the Fiddlers Cove and Rands Harbor Systems. The mass exchange of nitrogen between water column 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.

Table IV-5. Summary of annual volumetric discharge and nitrogen load from the two un-named Creeks discharging to the east and west branches of the Rands Harbor system from Cedar Lake and Flax Pond respectively. Flows and loads based upon the data presented in Figures IV-6 and 7 and Table IV-4.

EMBAYMENT SYSTEM	PERIOD OF RECORD	DISCHARGE (m3/year)	ATTENUATED LOAD (Kg/yr)	
			Nox	TN
Rands Harbor (East Branch) Creek discharge from Cedar Lake (MEP)	**September 1, 2005 to August 31, 2006**	**882,297**	**277**	**790**
Rands Harbor (East Branch) Creek discharge from Cedar Lake (CCC)	Based on Watershed Area and Recharge	**904,105**	--	--
Rands Harbor (West Branch) Creek discharge from Flax Pond (MEP)	**September 1, 2005 to August 31, 2006**	**593,440**	**274**	**519**
Rands Harbor (West Branch) Creek discharge from Flax Pond (CCC)	Based on Watershed Area and Recharge	**600,790**	--	--

IV.3.1 Sediment-Water column Exchange of Nitrogen

As stated in the above section, 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 Fiddlers Cove and Rands Harbor systems predominantly in highly bio-available forms from the surrounding upland watersheds and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the water column (once it entered) then predicting water column 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 bio-available form nitrate. This nitrate and other bio-available 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 water column for sufficient time to be flushed out to a down gradient larger water body (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 embayments.

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. 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 bio-available nitrogen is returned to the embayment water column 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 (e.g. Mashapaquit Creek Salt Marsh, West Falmouth Harbor; Centerville River Salt Marsh or Sesachacha Pond on the Island of Nantucket). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, for example in the margins of the main basin to Lewis Bay (Town of Barnstable, Cape Cod). In contrast, most embayments show low rates of nitrogen release throughout much of a basins area and, in regions of high deposition, typically support anoxic sediments with high release rates during summer months. The consequence of high deposition rates is that the basin sediments are unconsolidated, organic rich and sulfidic nature (MEP field observations).

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading to both the Fiddlers Cove and Rands Harbor systems. 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-Water column Nitrogen Exchange

For the Fiddlers Cove and Rands Harbor Embayment Systems, 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. In the Fiddlers Cove system, sediment samples (8 cores) were collected from 8 sites (Figure IV-8) in July-August 2006, focusing on obtaining an areal distribution that would be representative of nutrient fluxes throughout the system but also considering tributary “basins” such as the narrow channel that extends landward off the main embayment basin. In the Rands Harbor system, sediment samples (8 cores) were collected from 7 sites (Figure IV-9), also in July-August 2006. Duplicate cores were taken at one site. 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 sampling locations and numbers of cores collected are listed below. The spatial distribution of the stations is presented in Figures IV-8 and IV-9.

Fiddlers Cove System Benthic Nutrient Regeneration Cores

- FC-1 1 core (Canal)
- FC-2 1 core (Canal)
- FC-3 1 core (Canal)
- FC-4 1 core (Canal)
- FC-5 1 core (Main Basin)
- FC-6 1 core (Main Basin)
- FC-7 1 core (Main Basin)
- FC-8 1 core (Main Basin)

Rands Harbor System Benthic Nutrient Regeneration Cores

- RH-1 1 core (East Branch)
- RH-2 1 core (East Branch)
- RH-3 1 core (West Branch)
- RH-4/5 1 core (West Branch)
- RH-6 1 core (West Branch)
- RH-7 1 core (Inlet Basin)
- RH-8 1 core (Inlet Basin)

Sampling was distributed throughout the pond such that the results for each site could be combined to calculate the net nitrogen regeneration rates for the water quality modeling effort.

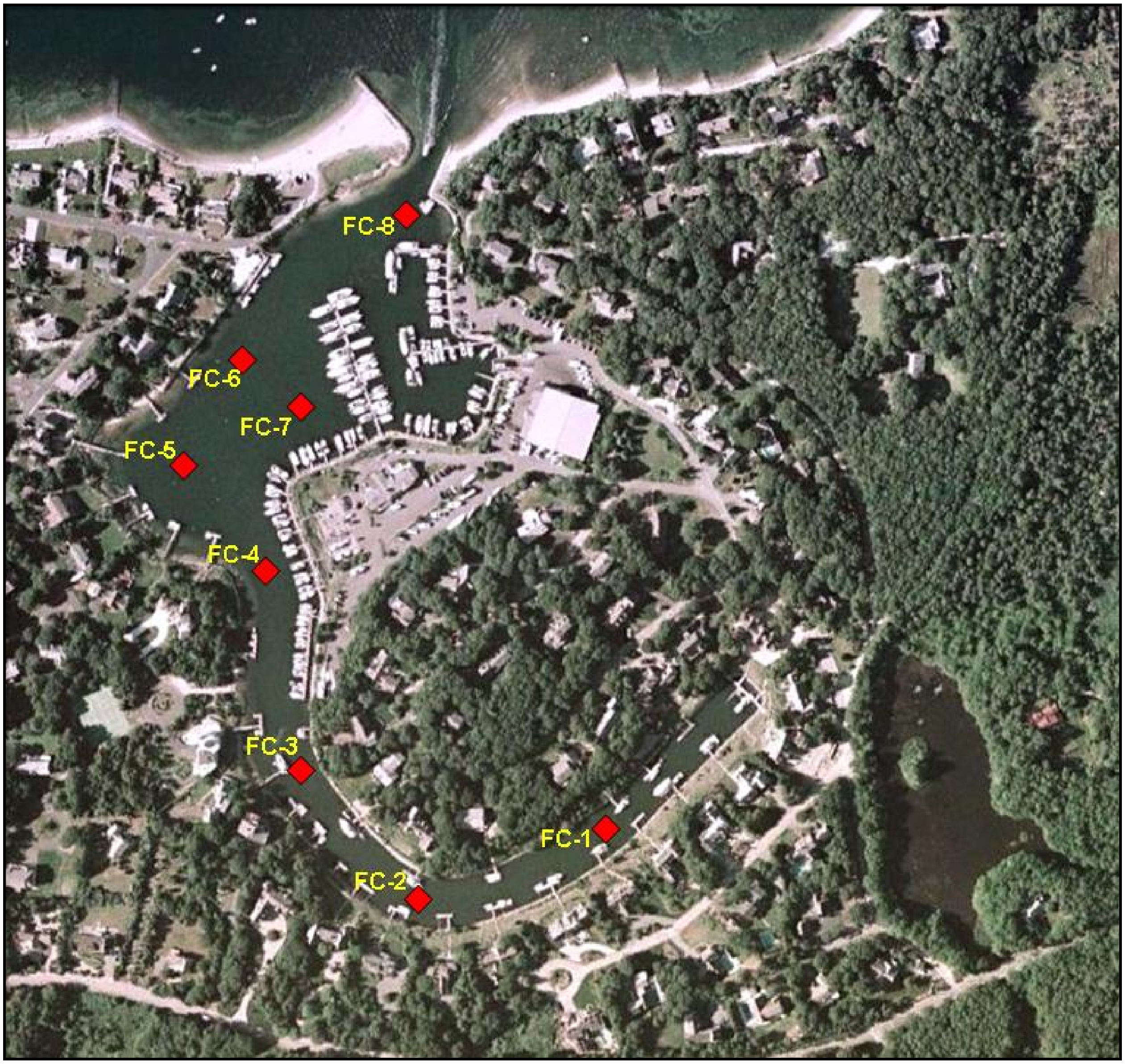


Figure IV-8. Fiddlers Cove System locations (red symbols) of sediment sample collection for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-6.

Sediment-water column exchange follows the methods of Jorgensen (1977), Klump and Martens (1983), and Howes *et al.* (1998) for nutrients and metabolism. Upon return to the field laboratory (Brewer Fiddlers Cove Marina), 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 orthophosphate (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.

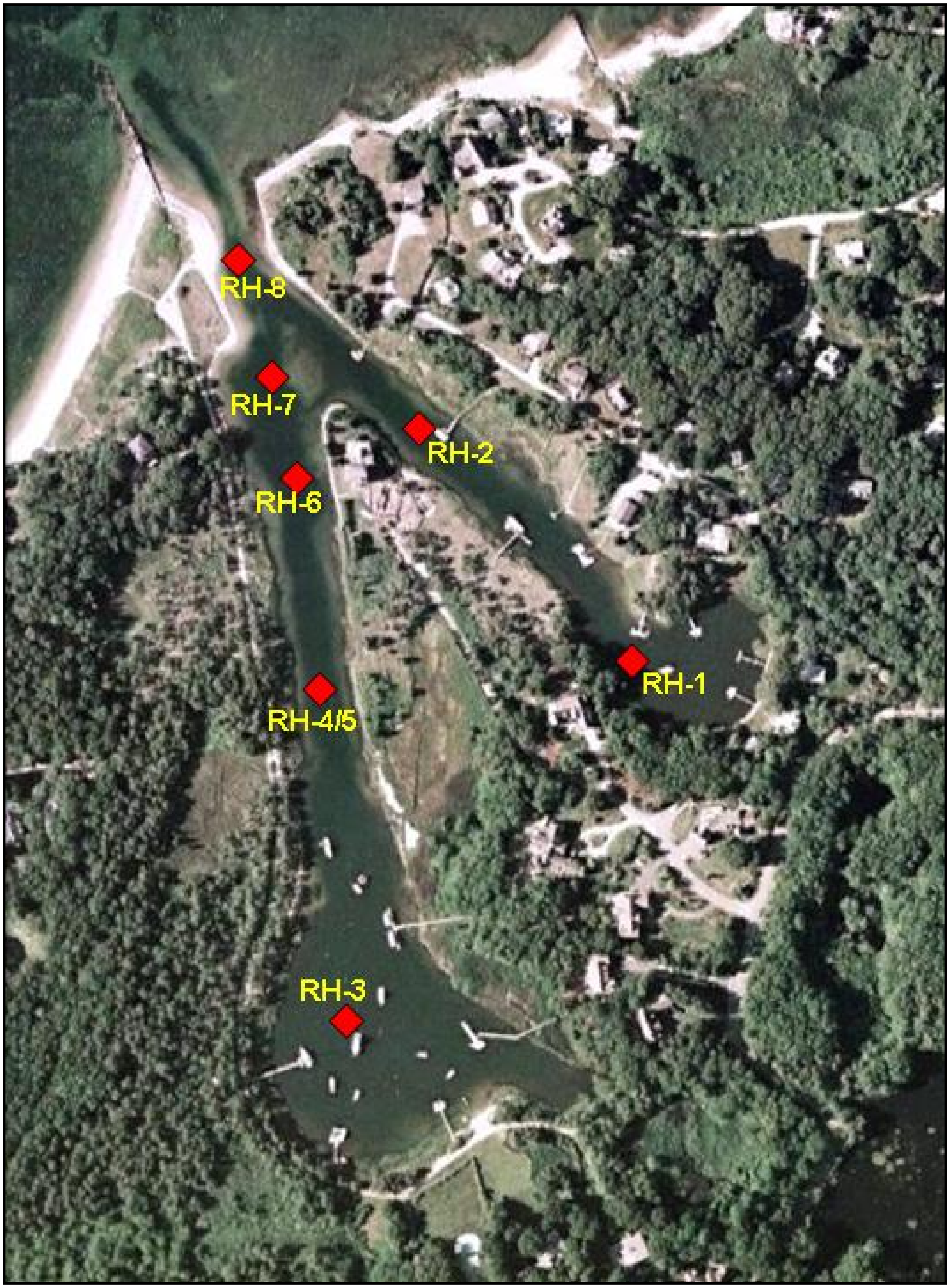


Figure IV-9. Rands Harbor System locations (red symbols) of sediment sample collection for determination of nitrogen regeneration rates. Numbers are for reference in Table IV-7.

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 [*508-910-6325*]. The laboratory follows standard methods for saltwater analysis and sediment geochemistry.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

Water column nitrogen levels are the balance of inputs from direct sources (land, rain etc), losses (denitrification, burial), regeneration (water column 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 water column 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 water column 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 water column oxygen status. However, for the modeling of nitrogen within an embayment it is the relative balance of nitrogen input from water column 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 levels of organic matter within the sediments, whether the sediments are oxic or 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-10).

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 water column 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.

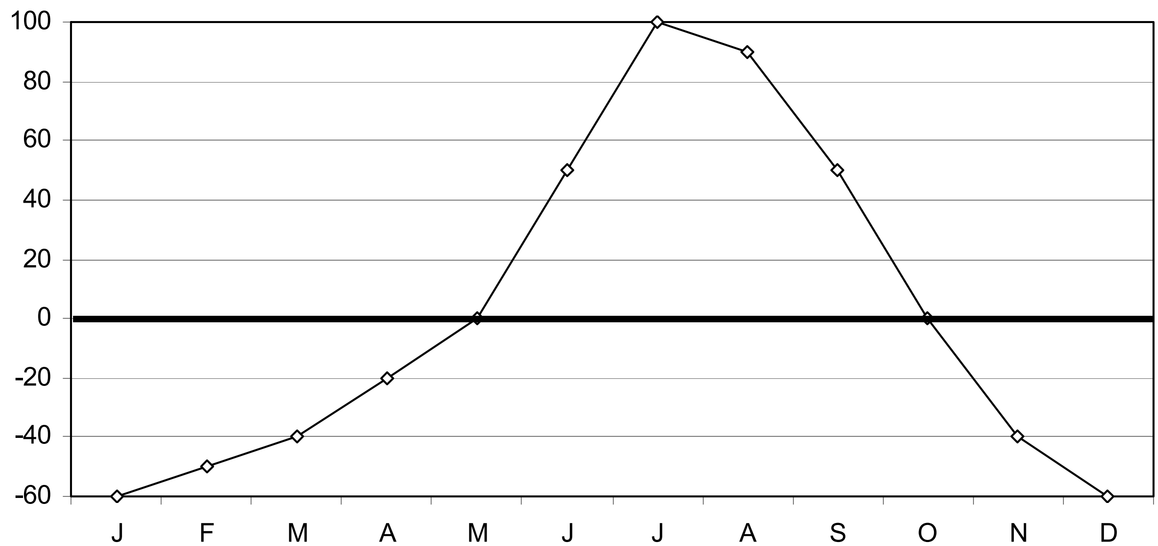


Figure IV-10. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

Sediment Nitrogen Release by Standard Core Approach: Sediment sampling was conducted throughout the embayment basins of each of the two estuaries. In Fiddlers Cove, samples were collected in the main basin that constitutes the marina area as well as along the narrow canal that extends landward off the main basin and has mostly armored banks and is bordered by residential parcels. In the Rands Harbor system, samples were collected from both the north (east) and south (west) branches of the system as well as at the confluence of the branches and at the mouth (inlet basin). 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, as well as sediment type and an analysis of each site's tidal flow velocities. As expected flow velocities are generally low throughout both the Fiddlers Cove and Rands Harbor systems with the exception of the area in the immediate vicinity of the tidal inlets. 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 (Section V). Based upon the low velocities, a water column particle residence time of ~8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins). Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas that are net nitrogen sinks for the aquatic system. This approach has been previously validated in outer Cape Cod embayments (Town of Chatham) 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 other 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.

Rates of net nitrogen release or uptake from the sediments within the Fiddlers Cove and Rands Harbor Embayment Systems generally showed only slightly lower rates in the lower versus upper basins and overall the rates were also similar between the 2 estuaries. The spatial pattern of sediment-watercolumn exchange is consistent with basin morphology, sediment type and water depth. Similarly the net nitrogen release rates throughout Fiddlers Cove and Rands Harbor were comparable to other embayments of similar depth and configuration in southeastern Massachusetts. A similar Buzzards Bay embayment, the inner basin of Quissett Harbor has similar sediments. Like much of Rands Harbor and Fiddlers Cove the sediments consist mainly of organic enriched mud. Summertime nitrogen exchange between sediments and overlying water in the inner basin of Quissett Harbor was similar to that presented here (Tables IV-6, IV-7) with a net release of nitrogen to the waters of 32.0 mg N m^{-2} d^{-1}. A similarly configured estuary, Lagoon Pond (Martha's Vineyard) also supported net nitrogen release rates in its enclosed inner depositional basins of 8.4 and 31.8 mg N m^{-2} d^{-1}, while the enclosed basins of Polpis Harbor (Nantucket Harbor System) showed net nitrogen release (East Polpis, 14.6 mg N m^{-1} d^{-1}; West Polpis 65.9 mg N m^{-1} d^{-1}). Overall, the summer sediment nitrogen release from the sediments within the component basins of the Fiddlers Cove and Rands Harbor Systems are comparable to other similarly configured enclosed basins, appear to be in balance with the overlying waters and are consistent with the level of nitrogen loading to this system, the basin morphology and tidal exchange. Net nitrogen flux rates for use in the water quality modeling effort for the component sub-basins of the Fiddlers Cove and Rands Harbor Systems (Section VI) are presented in Tables IV-6 and IV-7.

Table IV-6. Rates of net nitrogen return from sediments to the overlying waters of the Fiddlers Cove Embayment System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Section VI). Measurements represent July - August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			i.d. *
	Mean	S.E.	N	
Fiddlers Cove Embayment System				
Main Basin	14.7	9.0	4	FC-5, 6,7, 8
Canal	35.6	13.8	4	FC-1, 2, 3, 4

* Station numbers refer to Figures IV-8.

Table IV-7. Rates of net nitrogen return from sediments to the overlying waters of the Rands Harbor Embayment System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Section VI). Measurements represent July - August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			i.d. *
	Mean	S.E.	N	
Rands Harbor Embayment System				
Rands Harbor – North Branch	27.0	6.8	2	RH-1, 2
Rands Harbor – South Branch	19.8	19.9	4	RH-3, 4, 5, 6
Inlet Basin	21.3	39.4	2	RH-7,8

* Station numbers refer to Figures IV-9.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This section summarizes the field data collection efforts and the development of hydrodynamic models for the Fiddlers Cove and Rands Harbor estuary systems (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 water quality, as well as a tool for later determining nitrogen loading “thresholds”. Tidal flushing information is utilized as the basis for a quantitative evaluation of water quality. Nutrient loading data combined with measured environmental parameters within the Fiddlers Cove and Rands Harbor area 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 residence to understand how pollutant loadings into the estuary will affect the biochemical environment and its ability to sustain a healthy marine habitat.

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. Megansett Harbor). Several embayment-specific parameters influence tidal flushing and the associated residence time of water within an estuary. For the Fiddlers Cove and Rands Harbor system, the most important parameters are the tide range along with the shape, length and depth of the estuary.

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 of the surrounding area 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.

The Fiddlers Cove and Rands Harbor system (Figure V-1) is a pair of tidally dominated embayments, each with a northern opening to Megansett Harbor on the north side of North Falmouth, MA. Fiddlers Cove is located about 2000 feet further west than Rands Harbor. Both systems are lined with docks and private piers for the mooring and protection of small boats. Fiddlers Cove is roughly 14 acres in size and Rands Harbor is roughly 9 acres in size.

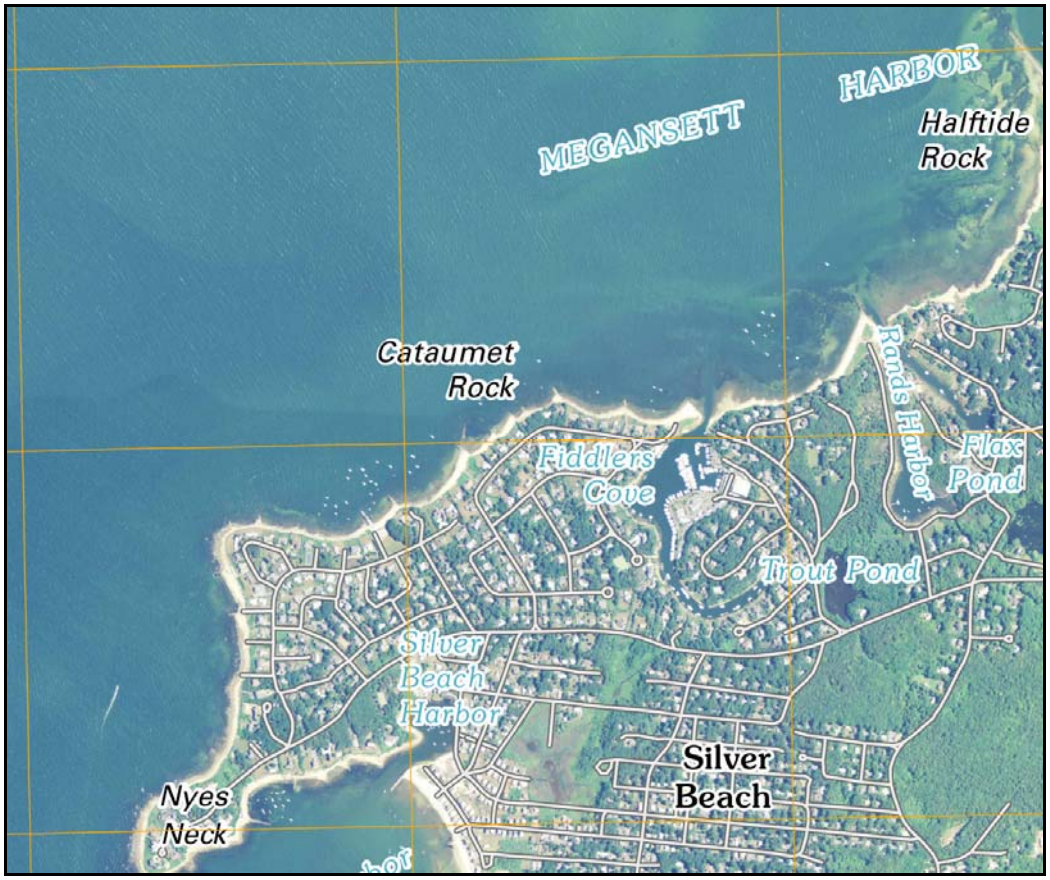


Figure V-1. Map of the Fiddlers Cove and Rands Harbor estuary system (from United States Geological Survey topographic maps).

Since the water elevation difference between Megansett Harbor and the estuarine system is the primary driving force for tidal exchange of Fiddlers Cove and Rands Harbor systems, the local tide range limits the volume of water flushed during a tidal cycle. Tidal damping (reduction in tidal amplitude) along the length of Fiddlers Cove and Rands Canal is negligible, indicating systems that flush efficiently. Any issues with water quality, therefore, would likely be due to other factors including nutrient loading conditions from the system's watersheds, and the tide range in Megansett Harbor.

Circulation in the Fiddlers Cove and Rands Harbor estuarine system was simulated using the RMA-2 numerical hydrodynamic model. To calibrate the model, field measurements of water elevations and bathymetry were required. Tide data were acquired for the system at a gage station installed in Megansett Bay and at two stations located within each system (Figure V-2). All temperature-depth recorders (TDRs or tide gages) were installed for a 36-day period to measure tidal variations through two bi-monthly spring-to-neap tidal cycles. In this manner, attenuation of the tidal signal as it propagates through the harbor and into the embayments was evaluated accurately.

Figure V-2. Map of the study region identifying locations of the tide gauges used to measure water level variations throughout the system. The three (3) gages were deployed for a 36-day period between March 23, and April 28, 2005. Each yellow dot represents the approximate locations of the tide gauges: (S-1) represents the Megansett Harbor gage (Offshore), (S-2) the Fiddlers Cove gage, and (S-3) the Rands Harbor gage.

V.2 FIELD DATA COLLECTION AND ANALYSIS

Accurate modeling of system hydrodynamics is dependent upon measured conditions within the estuary for two important reasons:

- To define accurately the system geometry and boundary conditions for the numerical model
- To provide 'real' observations of hydrodynamic behavior to calibrate and verify the model results

System geometry is defined by the shoreline of the system, including all coves, creeks, and marshes, as well as accompanying depth (or bathymetric) information. The three-dimensional surface of the estuary is mapped as accurately as possible, since the resulting hydrodynamic behavior is strongly dependent upon features such as channel widths and depths, sills, marsh elevations, and inter-tidal flats. Hence, this study included an effort to collect bathymetric information in the field.

Boundary conditions for the numerical model consist of variations of water surface elevations measured in Megansett Harbor. These variations result principally from tides, and provide the dominant hydraulic forcing for the system, and are the principal forcing function applied to the model. Additional pressure sensors were installed at selected interior locations to measure variations of water surface elevation along the length of the system (gage locations are shown in Figure V-2). These measurements were used to calibrate and verify the model results, and to assure that the dynamic of the physical system were properly simulated.

V.2.1 Bathymetry

Bathymetry data (i.e., depth measurements) for the hydrodynamic model of the Fiddlers Cove and Rands Harbor system was assembled from a hydrographic survey performed specifically for this study, conducted in early May 2007. Survey transects were densest in the vicinity of the inlets, were the greatest variability in bottom bathymetry was expected. Bathymetry in the inlet is important from the standpoint that it has the most influence on tidal circulation in and out of the estuary. The first survey was conducted from a shoal draft outboard boat with a precision fathometer installed (with a depth resolution of approximately 0.1 foot), coupled together with a differential GPS to provide position measurements accurate to approximately 1-3 feet. Digital data output from both the echo sounder (fathometer) and GPS were logged to a laptop computer, which integrated the data to produce a single data set consisting of water depth as a function of geographic position (latitude/longitude).

The raw measured water depths were merged with water surface elevation measurements to determine bathymetric elevations relative to the North American Vertical Datum of 1988 (NAVD88) vertical datum in feet. Once rectified, the finished, processed data were archived as ‘xyz’ files containing x-y horizontal position (in Massachusetts Mainland State Plan 1983 coordinates) and vertical elevation of the bottom (z). These xyz files were then interpolated into the finite element mesh used for the hydrodynamic simulations. The final processed bathymetric data from the survey are presented in Figure V-3. The maximum depth was 16 feet at the southwestern lobe of Rands Harbor and 11 feet in the harbor area of Fiddlers Cove. The average depth of Fiddlers Cove and Rands Harbor were 7.7 feet and 6.8 feet respectively.

V.2.2 Tide Data Collection and Analysis

Variations in water surface elevation were measured at stations in two locations in the Fiddlers Cove and Rands Harbor estuary and at a station in Megansett Harbor. The offshore station (S-1) is located in Megansett Harbor. The Fiddlers Cove station (S-2) is located at the southernmost section of the creek. The Rands Harbor station (S-3) is located at the furthest point from the inlet along the western branch. TDRs were deployed at each gage station from the beginning of March 23th through April 28th 2005. The duration of the TDR deployment allowed time to conduct the bathymetric surveys, as well as sufficient data to perform a thorough analysis of the tides in the system.

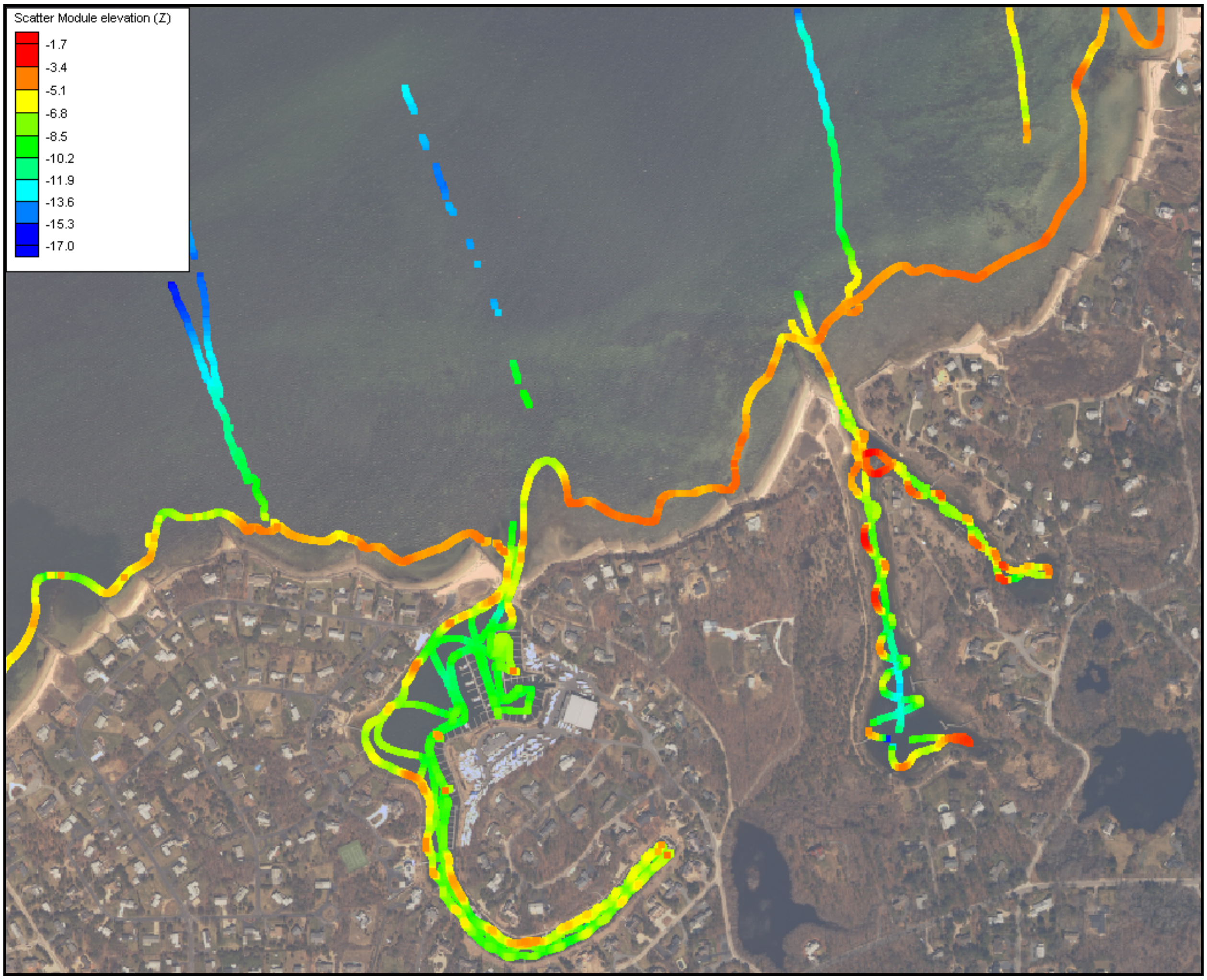


Figure V-3. Bathymetric data interpolated to the finite element mesh of hydrodynamic model.

The tide records from Fiddlers Cove and Rands Harbor were corrected for atmospheric pressure variations and then rectified to the NAVD88 vertical datum. Atmospheric pressure data, available in one-hour intervals from the NDBC Buzzards Bay C-MAN platform, were used to pressure correct the raw tide data. Final processed tide data from the stations used for this study are presented in Figure V-4, for the complete 36-day period of the TDR deployment.

Tide records longer than 29.5 days are necessary for a complete evaluation of tidal dynamics within the estuarine system. Although a one-month record likely does not include extreme high or low tides, it does provide an accurate basis for typical tidal conditions governed by both lunar and solar motion. For numerical modeling of hydrodynamics, the typical tide conditions associated with a one-month record are appropriate for driving tidal flows within the estuarine system.

The loss of amplitude together with increasing phase delay with increasing distance from the inlet is described as tidal attenuation. Tide attenuation can be a useful indicator of flushing efficiency in an estuary. Attenuation of the tidal signal is caused by the geomorphology of the near-shore region, where channel restrictions (e.g., bridge abutments) and also the depth of an estuary are the primary factors which influence tidal damping in estuaries. A visual comparison of the three stations throughout the Fiddlers Cove and Rands Harbor estuary systems (Figure V-5), demonstrates no discernable attenuation in the system.

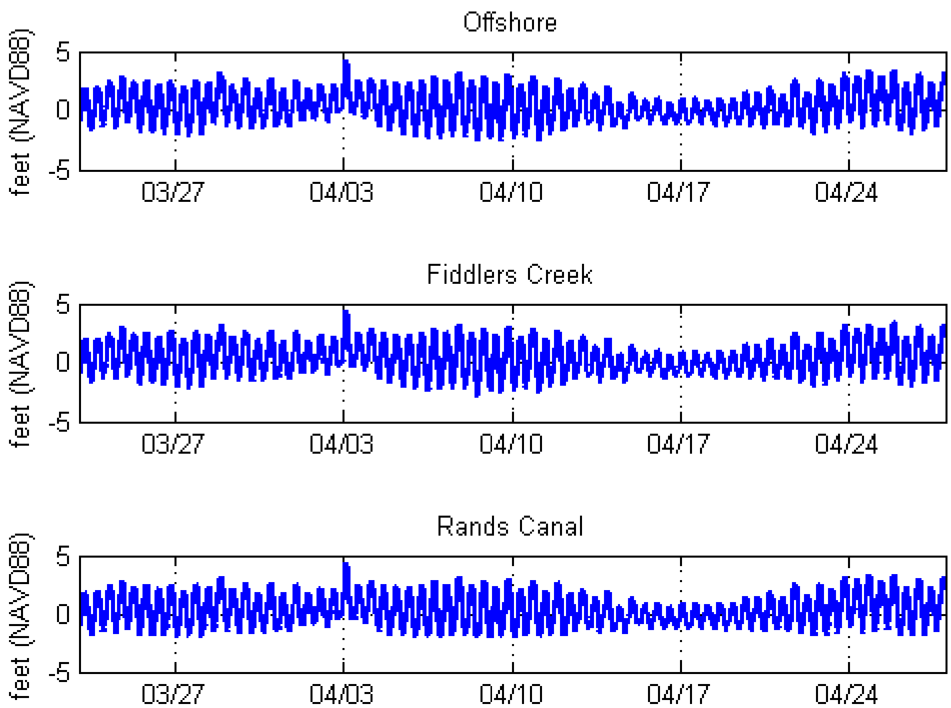


Figure V-4. Water elevation variations as measured at the three locations of the Fiddlers Cove and Rands Harbor system, from March 23rd to April 28th 2005.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 36-day records. These datums are presented in Table V-1. The Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels represent the mean of the daily highest and lowest water levels, respectively. 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. The tides in Megansett Harbor 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

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. From the computed datums, it further apparent that there is negligible damping occurring between Megansett Harbor and either Fiddlers Cove or Rands Harbor.

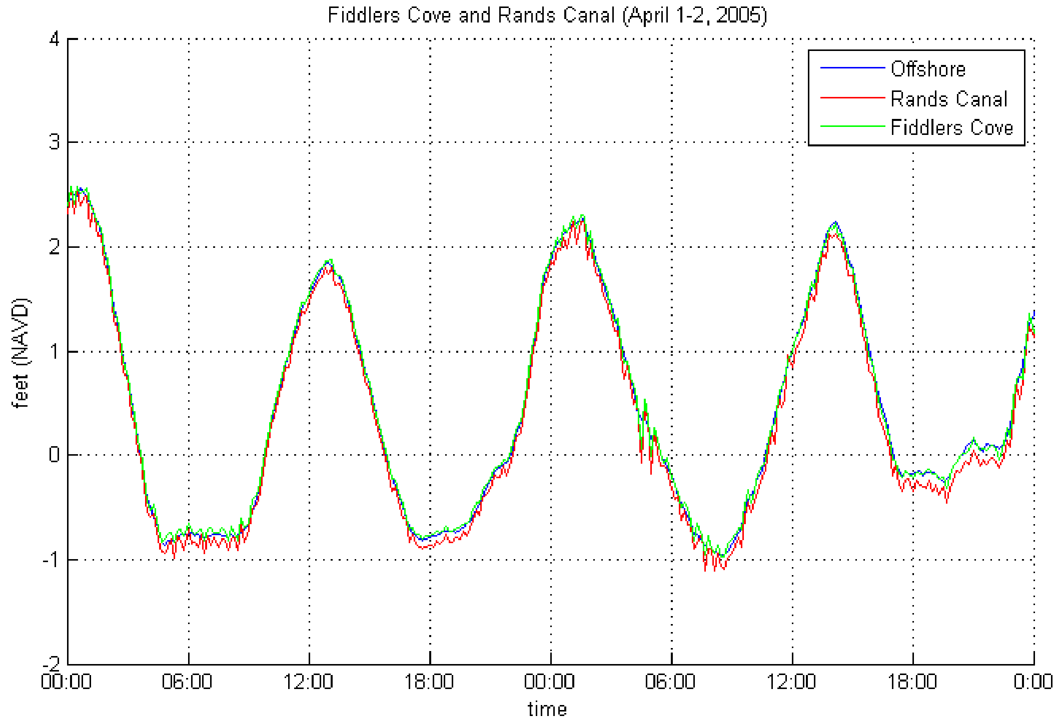


Figure V-5 Plot showing two tide cycles tides at three stations in the Fiddlers Cove and Rands Harbor system plotted together. Demonstrated in this plot is lack of attenuation in the tidal signal.

Table V-1. Tide datums computed from records collected in the Fiddlers Cove and Rands Harbor Estuarine system March 23 - April 28, 2005. Datum elevations are given relative to NAVD88.

Tide Datum	Offshore	Fiddlers Cove	Rands Harbor
Maximum Tide	4.245	4.372	4.464
MHHW	2.546	2.553	2.524
MHW	2.246	2.254	2.220
MTL	0.340	0.340	0.340
MLW	-1.565	-1.573	-1.539
MLLW	-1.703	-1.707	-1.643
Minimum Tide	-2.787	-2.798	-1.981

A more thorough harmonic analysis was also performed on the time series data from each gage station in an effort to separate the various component signals which make up the observed tide. The analysis allows an understanding of the relative contribution that diverse physical processes (i.e. tides, winds, etc.) have on water level variations within the estuary. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 tidal constituents, with periods between 4 hours and 2 weeks, result from this procedure. The observed tide is therefore the sum of an astronomical tide component and a residual atmospheric component. The astronomical tide in turn is 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-6.

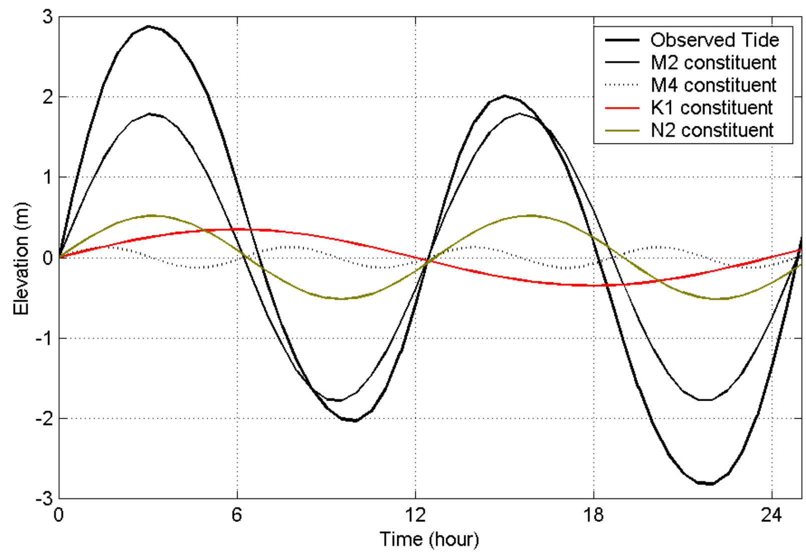


Figure V-6. Example of observed astronomical tide as the sum of its primary constituents. In this example the observed tide signal is the sum of individual constituents (M2, M4, K1, N2), with varying amplitude and frequency.

Table V-2 presents the amplitudes of seven significant tidal constituents. The M_2, or the familiar twice-a-day lunar, semi-diurnal, tide is the strongest contributor to the signal for the entire system. The M2 amplitude fluctuation is an order of magnitude smaller than the resolution of the bathymetry survey, implying almost no attenuation of the tide in the entire system. The range of the M_2 tide is twice the amplitude, or about 3.4 feet. The diurnal (once daily) tide constituents, K_1 (solar) and O_1 (lunar) possess amplitudes of approximately 0.51 feet and 0.39 feet respectively. These constituents account for the semi-diurnal variance one high/low tide to the next, as seen in figure V-5. The M_4 tide, a higher frequency harmonic of the M_2 lunar tide (twice the frequency of the M_2), results from frictional dissipation of the M_2 tide in shallow water.

Table V-2. Tidal Constituents for the Fiddlers Cove and Rands Harbor System. Data collected March 23 - April 28, 2005.

	AMPLITUDE (feet)						
	M2	M4	M6	K1	S2	N2	O1
Period (hours)	12.42	6.21	4.14	23.93	12.00	12.66	25.82
Offshore	1.724	0.291	0.019	0.259	0.518	0.364	0.198
Fiddlers Cove	1.717	0.289	0.018	0.256	0.517	0.362	0.198
Rands Harbor	1.687	0.307	0.014	0.251	0.493	0.348	0.203

Table V-3 presents the phase delay (in other words, the travel time required for the tidal wave to propagate throughout the system) of the M_2 tide at all tide gauge locations inside the system. This confirms no appreciable attenuation in this system.

Table V-3. M2 Tidal Attenuation, Fiddlers Cove and Rands Harbor Estuary System, March 23 - April 28, 2005 (Delay in minutes relative to Offshore).	
Location	Delay (minutes)
Fiddlers Cove	12
Rands Harbor	4

The tide data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. Non-tidal 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 two river systems is presented in Table V-4 compared to the energy content of 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 are relative to hydrodynamic circulation within the estuary. Figure V-7 shows the comparison of the measured tide from the offshore gage, with the predicted tide resulting from the harmonic analysis, and the resulting non-tidal residual.

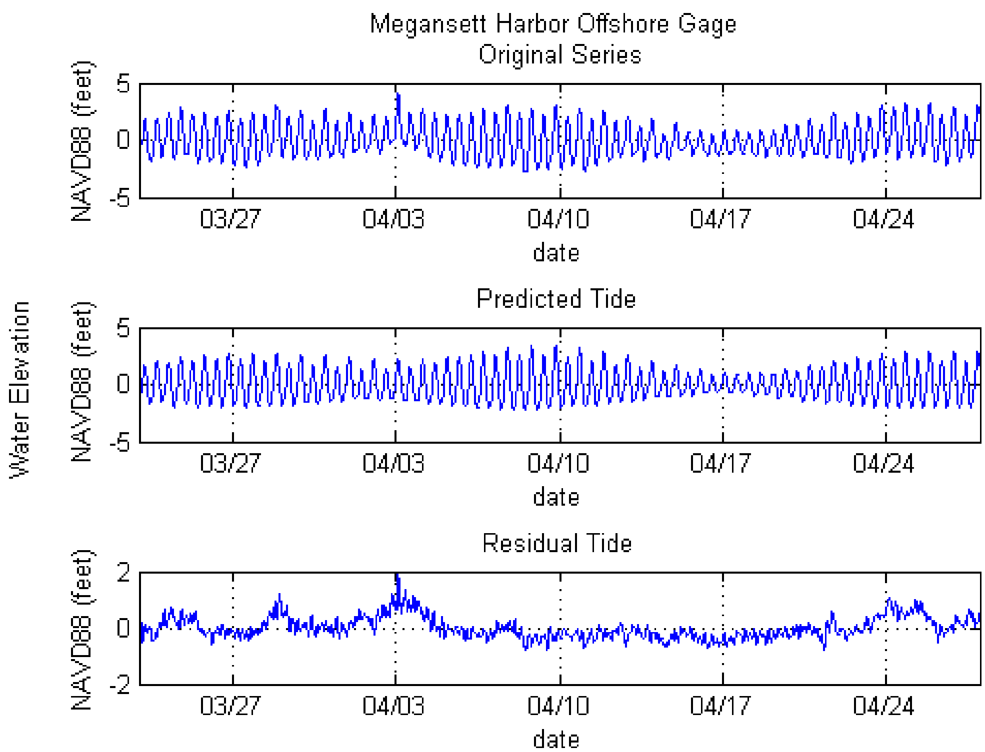


Figure V-7. Results of the harmonic analysis and the separation of the tidal from the non-tidal, or residual, signal measured at the Offshore Gage (S-1).

Table V-4 shows that the percentage contribution of tidal energy was the driving force of the observed tidal signal in the Fiddlers Cove and Rands Harbor Estuarine Systems. The analysis also shows that tides are responsible for 92% of the water level changes in the system. The remaining 8% was the result of atmospheric forcing, due to winds, or barometric pressure gradients acting upon the collective water surface of the system. The total energy content of the tide signal should carry over from one embayment to the next unless tidal flow is inhibited, which is clearly demonstrated in the consistency of the total variance and the percent of non-tidal factors influencing the tidal signal.

Table V-4. Percentages of Tidal versus Non-Tidal Energy, Fiddlers Cove and Rands Harbor, 2005

Location	Total Variance (ft^2)	Total (%)	Tidal (%)	Non-tidal (%)
Offshore	2.022	100	92.70	7.30
Fiddlers Cove	2.004	100	92.50	7.50
Rands Harbor	1.936	100	93.10	6.90

The results from Table V-4 indicate that hydrodynamic circulation throughout the Fiddlers Cove and Rands Harbor Estuarine System is primarily dependent upon tidal processes. While wind and other non-tidal effects can be a less significant portion of the total variance, the residual signal should not be ignored. Therefore, for the hydrodynamic modeling effort described below, the actual tide signal from the offshore gage was used to force the model so that the effects of non-tidal energy are included in the modeling analysis.

V.3 HYDRODYNAMIC MODELING

The focus of this study was the development of a numerical model capable of accurately simulating hydrodynamic circulation within the Fiddlers Cove and Rands Harbor estuary systems. Once calibrated, the model was used to calculate water volumes for selected sub-embayments (e.g., Fiddlers Cove and Rands Harbor) as well as determine the volumes of water exchanged during each tidal cycle. These parameters are used to calculate system residence times, or flushing rates. The ultimate utility of the hydrodynamic model is to supply required input data for the water quality modeling effort described in Chapter VI.

V.3.1 Model Theory

This study of Fiddlers Cove and Rands Harbor utilized a state-of-the-art computer model to evaluate tidal circulation and flushing. 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 for estuary systems in southeast Massachusetts, including systems in Chatham, Falmouth’s ‘finger’ ponds, and Popponesset Bay.

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 Brigham Young University through a package called the Surfacewater Modeling System or SMS (BYU, 1998). SMS is a front- and back-end software package that allows the user to easily modify model parameters (such as geometry, element coefficients, and boundary conditions), as well as view the model results and download specific data types. While the RMA model is essentially used without cost or constraint, the SMS software package requires site licensing for use.

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 criterion 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 the finite element grid was generated using 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 the system based on the tide gauge data collected at the offshore gage location. 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 (5+) 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 for the model was assisted through the use of the SMS package. The digital shoreline and bathymetry data were imported to SMS, and a finite element grid was generated to represent the estuary with 1881 elements and 5688 nodes (Figure V-8). All regions in the system were represented by two-dimensional (depth-averaged) elements. The finite element grid for the system provided the detail necessary to evaluate accurately the variation in hydrodynamic properties within the estuary. Fine resolution was required to simulate the numerous channel constrictions (e.g., at the culverts in Madaket Ditch) that significantly impact the estuarine hydrodynamics. The completed grid is made up of quadrilateral and triangular two-dimensional elements. Reference water depths at each node of the model were interpreted from bathymetry data obtained in the recent field surveys and the NOAA data archive. The final interpolated grid bathymetry is shown in Figure V-9. The model computed water elevation and velocity at each node in the model domain.

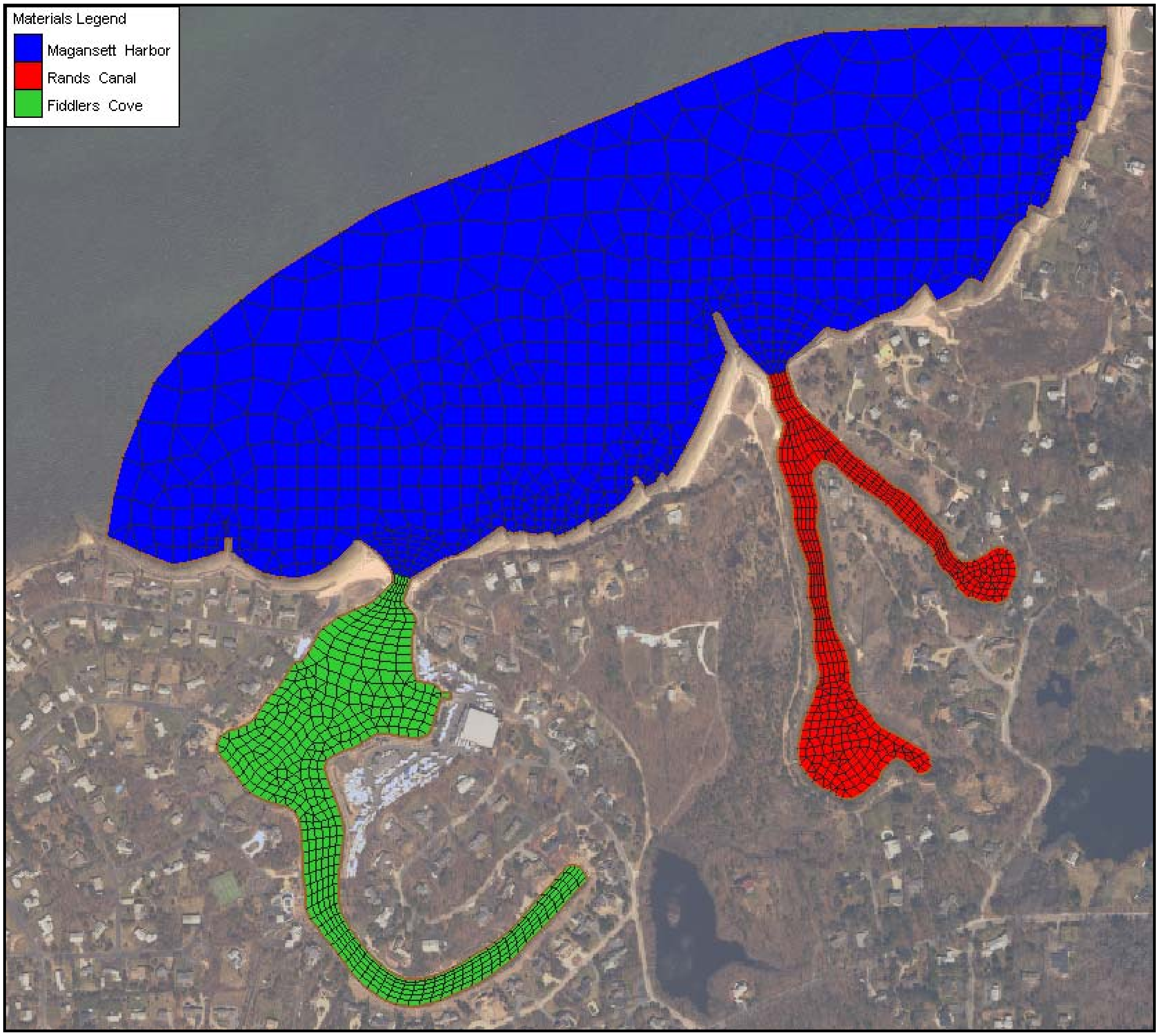


Figure V-8. The model finite element mesh developed for Fiddlers Cove and Rands Harbor estuary system. The model seaward boundary was specified with a forcing function consisting of water elevation measurements obtained at the Offshore Gage (S-1).

Grid resolution is governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability in each region. Smaller cross channel node spacing in the river channels was designed to provide a more detailed analysis in these regions of rapidly varying velocities and bathymetry. Widely spaced nodes were utilized in areas where velocity gradients were likely to be less acute; for example, in broad, deep channel sections in the model domain. Appropriate implementation of wider node spacing and larger elements reduces computer run time with no sacrifice of accuracy.

V.3.2.2 Boundary Condition Specification

Two types of boundary conditions were employed for the RMA-2 model: 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.

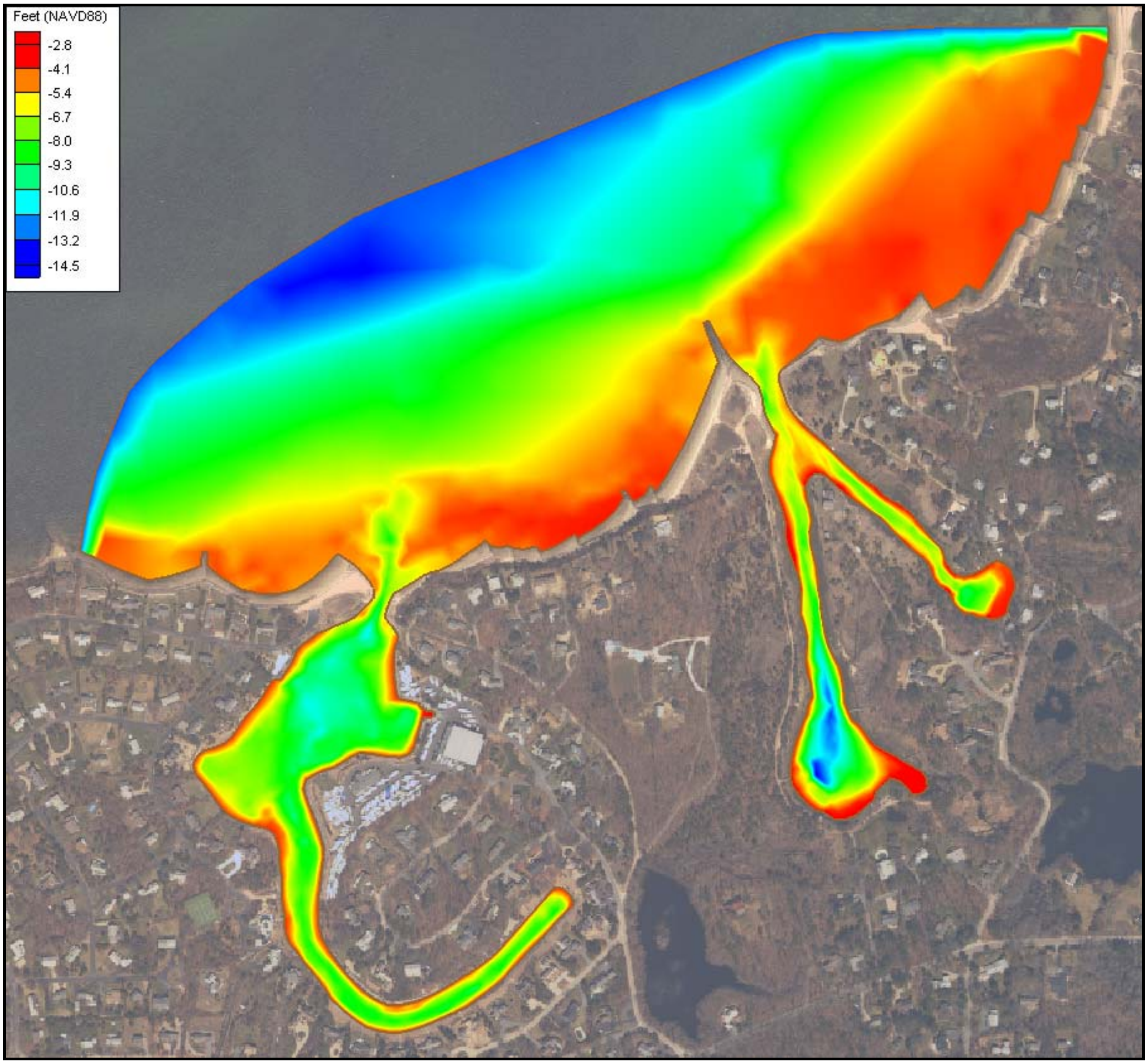


Figure V-9. Depth contours of the completed Fiddlers Cove and Rands Harbor finite element mesh.

The model was forced at the open boundary using water elevations measurements obtained in Megansett Harbor (described in section V.2.2). This measured time series consists of all physical processes affecting variations of water level: tides, winds, and other non-tidal oscillations of the sea surface. The rise and fall of the tide in Megansett Harbor is the primary driving force for the estuarine circulation. Dynamic (time-varying) model simulations specified a new water surface elevation at the offshore boundary every 10 minutes. The model specifies the water elevation at the offshore boundary, and uses this value to calculate water elevations at every nodal point within the system, adjusting each value according to solutions of the model equations. Changing water levels in Megansett Harbor produce variations in surface slopes within the estuary; these slopes drive water either into the system (if water is higher offshore) or out of the system (if water levels are higher in the Canal or Cove).

V.3.3 Calibration

After developing the finite element grid and specifying boundary conditions, the model was calibrated. Calibration ensured the model predicts accurately what was observed during the field measurement program. Numerous model simulations were required to calibrate the model, with each run varying specific parameters such as friction coefficients, turbulent exchange coefficients, fresh water inflow, and subtle modifications to the system bathymetry to achieve a best fit to the data.

Calibration of the flushing model required a close match between the modeled and measured tides at each gage station. Initially, the model was calibrated by the visual agreement between modeled and measured tides. To refine the calibration procedure, water elevations were output from the model at the same locations in the estuary where tide gauges were installed, and the data were processed to calculate standard error as well harmonic constituents (of both measured and modeled data) over the seven-day calibration period. The amplitude and phase of five constituents (M_2, M_4, K_1, S_2, and N_2) were compared and the corresponding errors for each were calculated. The intent of the calibration procedure is to minimize the error in amplitude and phase of the individual constituents. In general, minimization of the M_2 amplitude and phase becomes the highest priority, since this is the dominant constituent. Emphasis is also placed on the M_4 constituent, as this constituent has the greatest impact on the degree of tidal distortion within the system, and provides the unique shape of the modified tide wave at various points in the system.

The calibration was performed for an approximate seven-day period, beginning 2030 hours EDT March 26, 2005 and ending 2130 hours EDT April 2, 2005. This time period included a 24-hour model spin-up period, and a 12-tide cycle period used for calibration. This representative time period was selected because it included tidal conditions where the wind-induced portion of the signals (i.e. the residual) was minimal, hence more typical of tidal circulation within the estuary. The selected time period also spanned the transition from spring (bi-monthly maximum) to neap (bi-monthly minimum) tide ranges, which is representative of average tidal conditions in the embayment system. Throughout the selected 6 day period after the spin-up, the tide ranged approximately 5.5 feet from minimum low to maximum high tides. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. Modeled tides were evaluated for time (phase) lag and height damping of dominant tidal constituents. The calibrated model was used to analyze existing detailed flow patterns and compute residence times.

V.3.3.1 Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where water depths can become shallow and velocities relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude attenuation and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient. First, Manning's friction coefficient values of 0.025 were specified for all elements (Table V-5). These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels with pools and shoals with higher friction (Henderson, 1966). Small changes in these values did not change the accuracy of the calibration.

Table V-5. Manning's Roughness coefficients used in simulations of modeled embayments.	
Embayment	Bottom Friction
Offshore	0.025
Fiddlers Cove	0.025
Rands Harbor	0.025

V.3.3.2 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 swift, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). Small changes in these values did not change the accuracy of the calibration. Typically, model turbulence coefficients (D) are set between 10 and 100 lb-sec/ft^2 (as listed in Table V-6).

Table V-6. Turbulence exchange coefficients (D) used in simulations of modeled embayment system.	
Embayment	D (lb-sec/ft$^{2)}$
Offshore	20
Fiddlers Cove	20
Rands Harbor	20

V.3.3.3 Comparison of Modeled Tides and Measured Tide Data

Several calibration model runs were performed to determine how changes to various parameters (e.g. friction and turbulent exchange coefficients) affected the model results. These trial runs achieved excellent agreement between the model simulations and the field data. Comparison plots of modeled versus measured water levels at the four gauge locations are presented in Figures V-10 through V-12. RMS errors were roughly 0.1 ft (<1.2 inches) and computed R^2 correlation was 0.99 for every station. Errors between the model and observed tide constituents were less than 0.03 feet for all locations, suggesting the model accurately predicts tidal hydrodynamics within the system. Measured tidal constituent amplitudes and time lags (ϕ_{lag}) for the calibration time period are shown in Table V-7. The constituent values for the calibration time period differ from those in Tables V-2 because constituents were computed for only 6 days, rather than the entire 36-day period represented in Table V-2. Errors associated with tidal constituent height were on the order of hundredths of feet, which was an order of magnitude better than the accuracy of the tide gage gauges ($\pm$0.12 ft). Time lag errors were close to the time increment resolved by the model and measured tide data (1/6 hours or 10 minutes) for every gage, indicating good agreement between the model and data.

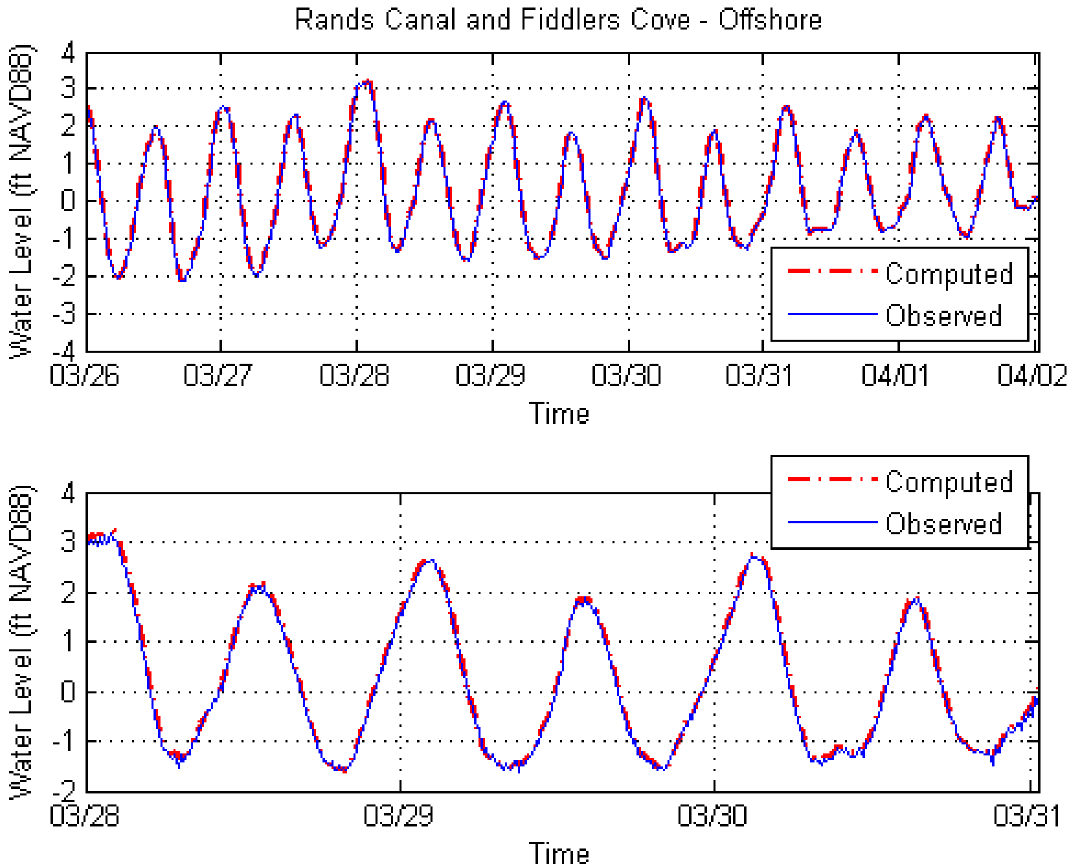


Figure V-10. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Offshore Gage Station. The top plot shows the entire record with the bottom plot showing a 3-day segment.

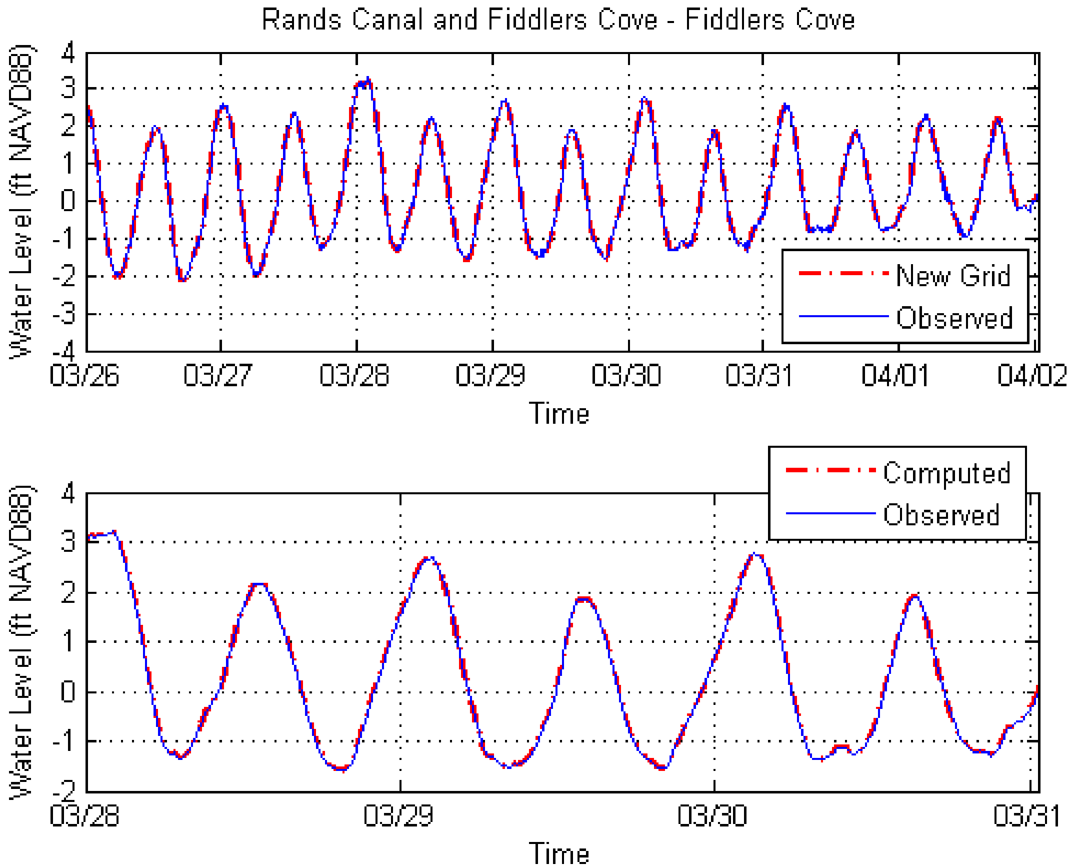


Figure V-11. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Fiddlers Cove Gage Station. The top plot shows the entire record with the bottom plot showing a 3-day segment.

V.3.4 Model Circulation Characteristics

The final calibrated and validated model serves as a useful tool for investigating the circulation characteristics of the Fiddlers Cove and Rands Harbor estuary 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 estuary system, maximum flood velocities at both inlets are the same as maximum ebb velocities. Maximum depth-averaged velocities in the model are approximately 0.66 feet/sec for flooding tides, and 0.55 ft/sec for ebbing tides. An example of the model output is presented in Figure V-13, which shows contours of flow velocity, along with velocity vectors which indicate the direction and magnitude of flow, for a single model time-step, at the portion of the tide where maximum ebb velocities occur at the inlets.

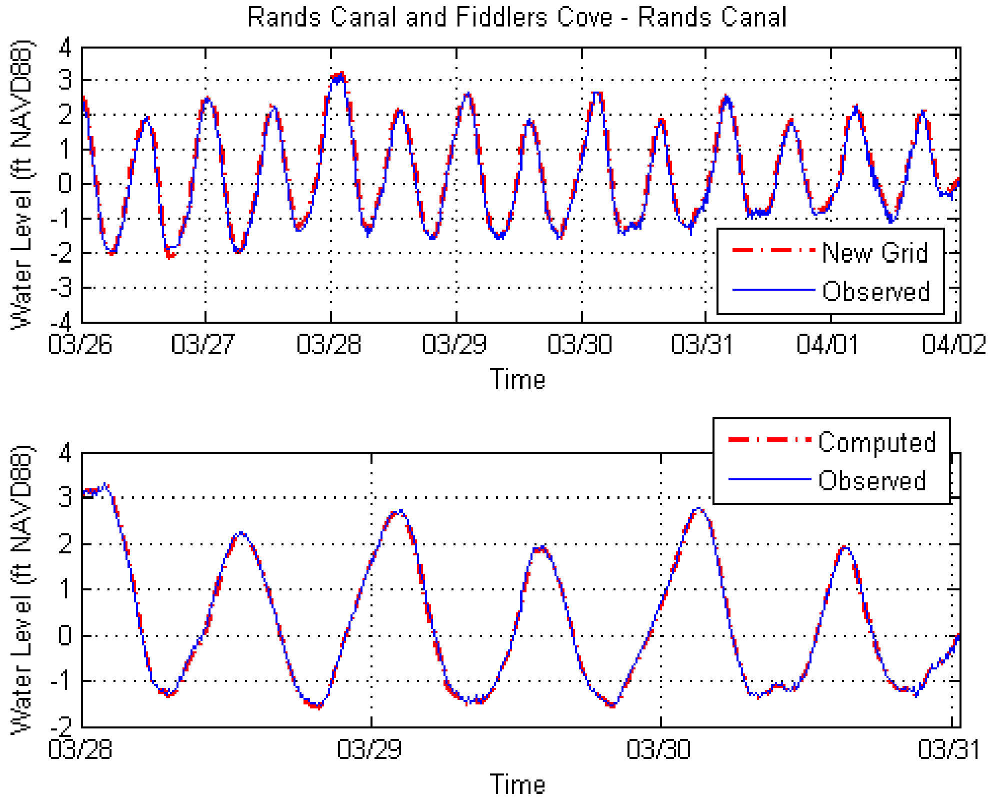


Figure V-12. Comparison of water surface variations simulated by the model (dashed red line) to those measured within the system (solid blue line) for the calibration time period, for the Rands Canal Gage Station. The top plot shows the entire record with the bottom plot showing a 3-day segment.

Table V-7. Comparison of Tidal Constituents calibrated RMA2 model versus measured tidal data for the period March 26 to April 2, 2007.

Model Verification Run						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	N_2	K_1	ΦM_2	ΦM_4
Offshore	1.815	0.245	0.452	0.164	67.7	144.7
Fiddlers Cove	1.817	0.245	0.452	0.164	67.9	144.8
Rands Harbor	1.816	0.245	0.452	0.164	67.8	144.7
Measured Tidal Data						
Location	Constituent Amplitude (ft)				Phase (degrees)	
	M_2	M_4	N_2	K_1	ΦM_2	ΦM_4
Offshore	1.845	0.244	0.469	0.166	70.5	150.4
Fiddlers Cove	1.843	0.245	0.475	0.163	70.4	149.9
Rands Harbor	1.842	0.246	0.480	0.158	73.2	154.9
Error						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	N_2	K_1	ΦM_2	ΦM_4
Offshore	-0.027	-0.002	-0.017	-0.001	5.8	6.2
Fiddlers Cove	-0.027	0.000	-0.023	0.002	5.1	5.3
Rands Harbor	-0.029	0.001	-0.028	0.007	11.1	10.6

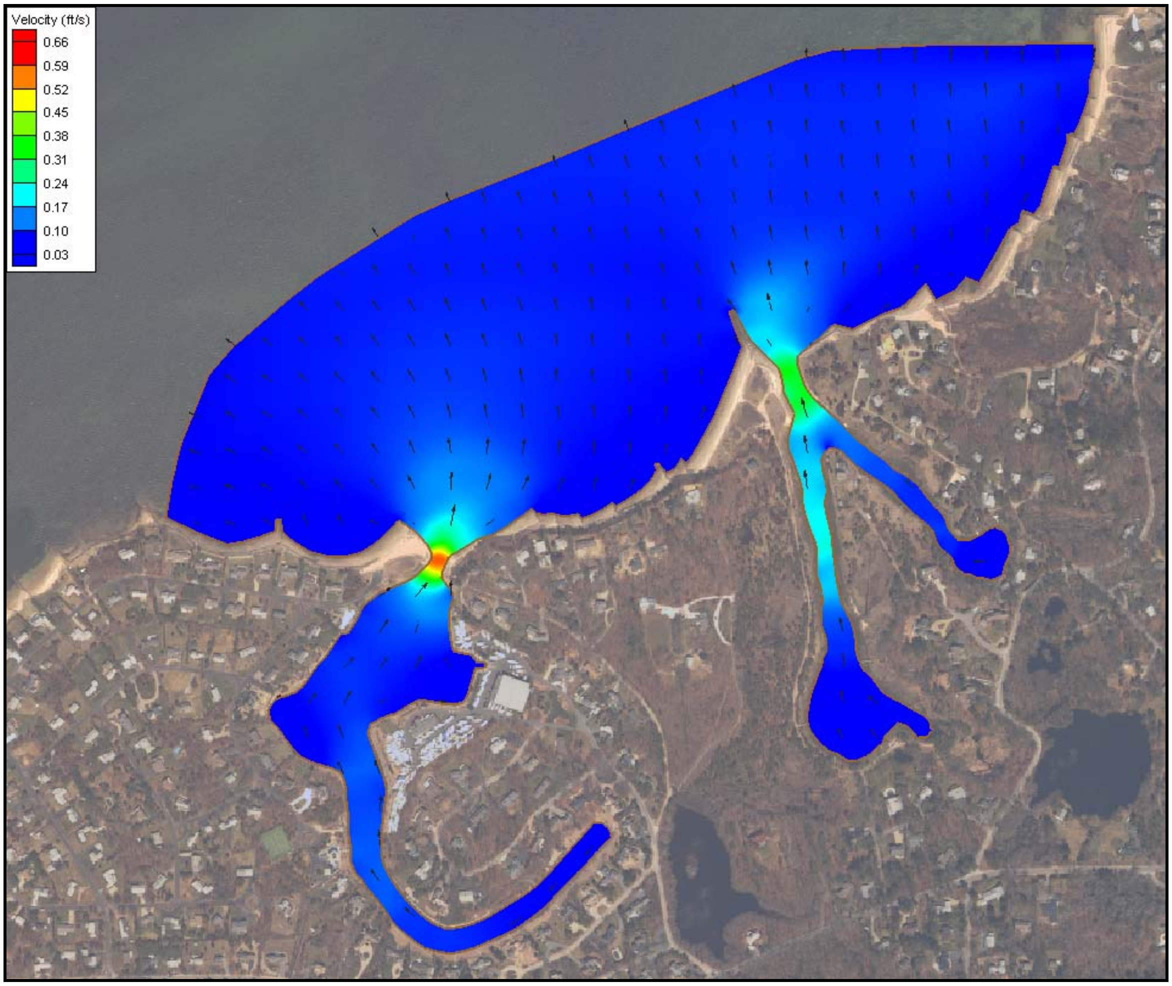


Figure V-13. Example of hydrodynamic model output for a single time step where maximum ebb velocities occur for this tide cycle. Color contours indicate flow velocity, and vectors indicate the direction and magnitude of flow.

In addition to depth averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs through the Fiddlers Cove and Rands Harbor Estuarine system is seen in Figure V-14. During the simulation time period, maximum modeled flood tide flow rates through the Fiddlers Cove inlet were 296 ft^3/sec and ebb tide flow rates were 297 ft^3/sec. The maximum modeled flood tide flow rates through the Rands Harbor inlet were 196 ft^3/sec and ebb tide flow rates were 197 ft^3/sec.

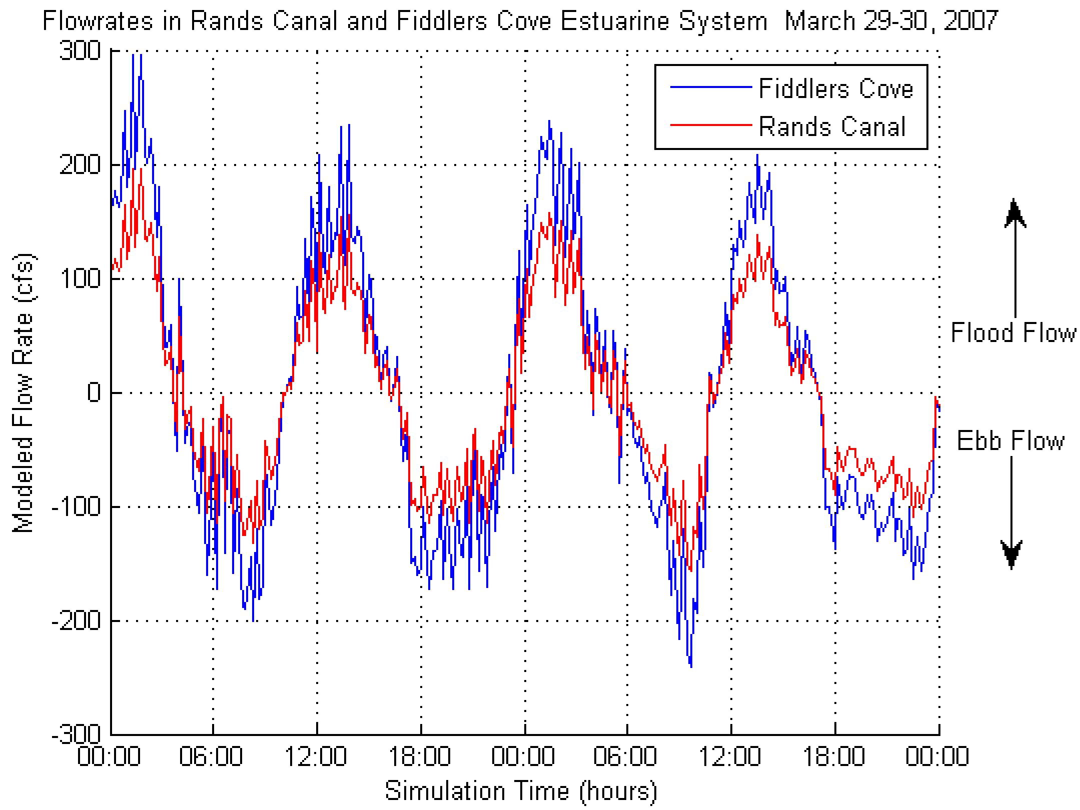


Figure V-14. Time variation of computed flow rates for transects across Fiddlers Cove inlet and Rands Harbor inlet. Model period shown corresponds to spring tide conditions, where the tide range is the largest, and resulting flow rates are likewise large compared to neap tide conditions. Positive flow indicates 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 the inlet, the primary mechanism controlling estuarine water quality within Fiddlers Cove and Rands Harbor is tidal exchange. A rising tide offshore in Megansett Harbor creates a slope in water surface from the ocean into the modeled systems. Consequently, water flows into (floods) the system. Similarly, the estuary drains into the open waters of the Sound 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 the head of Fiddlers Cove as an example, the system residence time is the average time required for water to migrate from the head of Fiddlers Cove, through the lower portions of the Cove, and finally into Megansett Harbor, where the local residence time is the average time required for water to migrate from the head of the Harbor to just the mid portion of the Harbor (not all the way to the inlet and out of the system). 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 modeled system, this approach is applicable, since it assumes the main system has relatively low quality water relative to Megansett Harbor.

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 a total nitrogen dispersion model (Section VI). The water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Fiddlers Cove and Rands Harbor and it's sub-embayments.

The volume of each sub-embayment, as well as their respective tidal prisms, was computed in cubic feet (Table V-8). Model divisions used to define the system sub-embayments for the two systems include 1) Fiddlers Cove and 2) Rands Harbor The model computed total volume of each sub-embayment at every time step, and this output was used to calculate mean sub-embayment volume and average tide prism. Since the 6-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.

Table V-8. Mean volumes and average tidal prism of the Fiddlers Cove and Rands Harbor estuary system during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Fiddlers Cove	4,835,000	2,246,000
Rands Harbor	2,686,000	1,433,000

Residence times were averaged for the tidal cycles comprising a representative 6 day period (11 tide cycles), and are listed in Table V-9. Residence times were computed for each estuary. 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 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 moderate local residence time (roughly 1 day) of the whole Fiddlers Cove and Rands Harbor estuary system shows that both systems most likely flush reasonably well.

Table V-9. Computed System and Local residence times for sub-embayments of the Fiddlers Cove and Rands Harbor estuary system.

Embayment	Local Residence Time (days)	System Residence Time (days)
Fiddlers Cove	1.1	1.1
Rands Harbor	1.0	1.0

Based on our knowledge of estuarine processes, we estimate that the combined errors associated with the method applied to compute residence times are within 10% to 15% of "true" residence times, for the Fiddlers Cove and Rands Harbor estuary system. 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 in some of the smaller sub-embayments of the system.

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 Megansett Harbor is typically strong because of the effects of the local winds and tidal induced mixing, the "strong littoral drift" assumption should cause only minor errors in residence time calculations.

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 Fiddlers Cove and Rands Harbor estuary systems. 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 embayments 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 systems. 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 15-tidal cycle period in April 2005. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 40-hour spin-up period, to allow the model to reach 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 the 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 the Fiddlers Cove and Rands Harbor estuary systems, consisting of the background concentrations of total nitrogen in the waters entering from Buzzard’s 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. Due to the location of threshold stations upstream of measured water quality stations, all concentration values were derived directly from the calibrated model. 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. Ten years of data (collected between 2000 and 2009) were available for stations monitored by SMAST in the Fiddlers Cove and Rands Harbor estuary systems.

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 Fiddlers Cove and Rands Harbor estuary systems. 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 Fiddlers Cove and Rands Harbor estuary systems. 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).

Table VI-1. Town of Falmouth water quality monitoring data, and modeled Nitrogen concentrations for the Fiddler's Cove and Rand's Canal estuary systems used in the model calibration plots of Figure VI-2. "Data mean" values are calculated as the average of the entire data set. All concentrations are given in mg/L N.

Sub-Embayment	Monitoring station	Mean	s.d. all data	N	model min	model max	model average
Rand's Canal	RH1	0.436	0.092	38	0.326	0.545	0.447
Fiddler's Cove	FC1	0.414	0.098	38	0.356	0.416	0.389

Rand's Canal Annual TN means									
2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
0.374	0.416	0.423	0.451	0.374	0.382	0.540	0.499	0.544	0.403

Fiddler's Cove Annual TN means									
2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
0.335	0.537	0.391	0.493	0.366	0.437	0.388	0.441	0.444	0.322

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.

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.

Figure VI-1. Estuarine water quality monitoring station locations in the Fiddlers Cove and Rands Harbor estuary systems. Station labels correspond to those provided in Table VI-1. Threshold stations are shown by the red symbols.

The model is therefore used to compute spatially and temporally varying concentrations 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 Fiddlers Cove and Rands Harbor estuary systems.

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 Fiddlers Cove and Rands Harbor estuary systems was used for the water quality constituent modeling portion of this study. Based on groundwater recharge rates from the USGS the overall groundwater flow rate into the system is 4.07 ft^3/sec (9,704 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 spin-up period of just 16 days. At the end of the spin-up period, the model was run for an additional 14 tidal-cycle (174 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 Fiddlers Cove and Rands Harbor estuary systems.

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, and 3) summer benthic regeneration. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed and direct atmospheric deposition load for the main basin of Fiddlers Cove was evenly distributed at grid cells along the edge 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 Fiddlers Cove and Rands 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, 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 a significant portion of the total loading rate from benthic regeneration as from watershed loads. For other sub-embayments, the benthic flux is relatively low 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 Buzzard’s Bay was set at 0.301 mg/L, based on SMAST data from Buzzard’s Bay. The open boundary total nitrogen concentration represents long-term average summer concentrations found within this region of Buzzard’s Bay.

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 Figure VI-2. Observed values of *E* (Fischer, *et al.*, 1979) vary between order 10 and order 1000 m^2/sec for riverine estuarine systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent areas of Fiddlers Cove and Rands Harbor 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; following the recommendations provided by the US Army Corps of Engineers (USACE, 2001) 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.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Fiddlers Cove and Rands Harbor estuary systems , 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)
Rand Inlet	0.014	0.022	0.103
Rand North	2.496	0.033	0.228
Rand South	3.564	0.088	0.345
Fiddler Main	0.890	0.068	0.863
Fiddler Upper	3.441	0.115	0.391

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for Fiddlers Cove and Rands Harbor estuary systems.

Embayment Division	E m^2/sec
Buzzards Bay	2.0
Lower Rands Harbor	0.5
Lower Fiddlers Cove	0.3
Upper Fiddlers Cove	0.75
Rands Harbor North Arm	1.0
Rands Harbor South Arm	1.0
Middle Fiddlers Cove	0.5
Fiddler's Inlet	0.15
Rand's Inlet	0.5

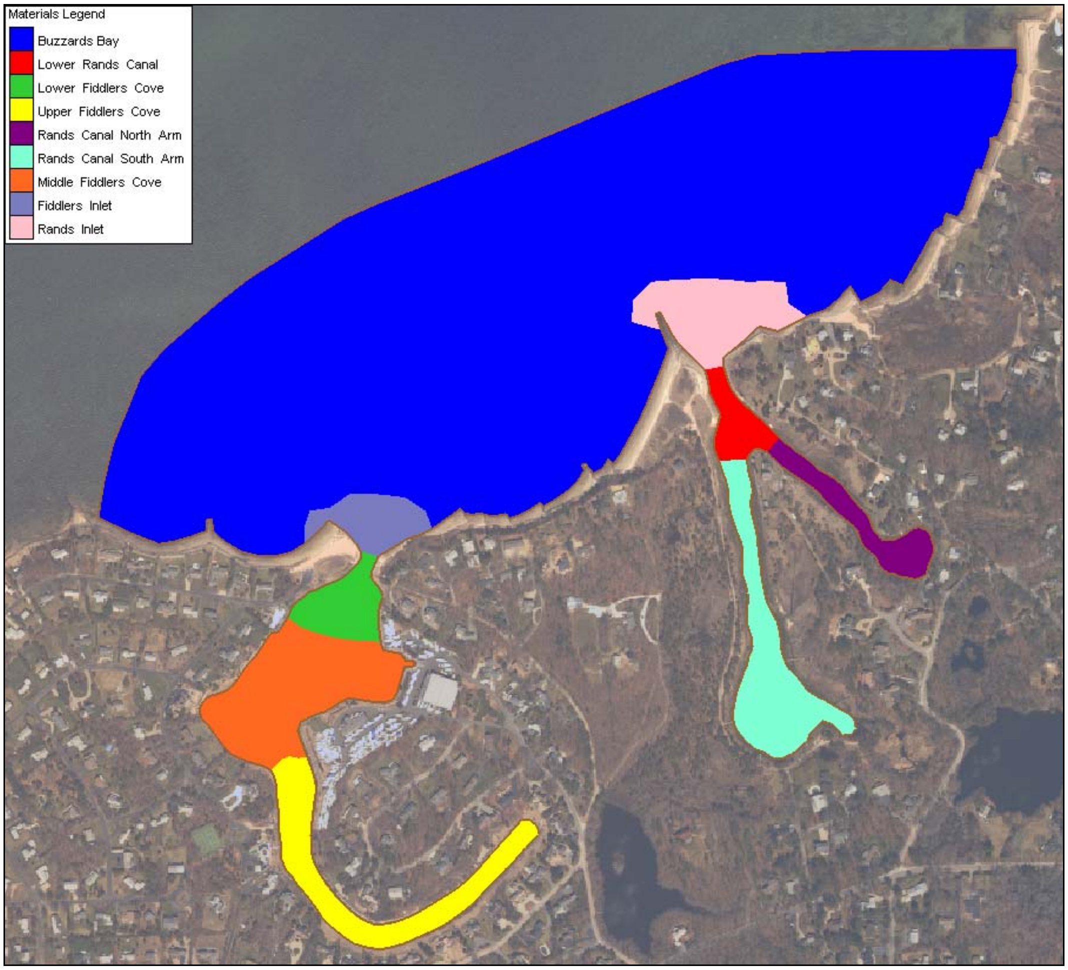


Figure VI-2. Map of the Fiddlers Cove and Rands Harbor water quality model longitudinal dispersion coefficients. Color patterns designate the different areas used to vary model dispersion coefficient values.

Comparisons between model output and measured nitrogen concentrations are shown in Figure VI-3. In this figure, means of the water column data and a range of one 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.

For model calibration, the mid-point between maximum modeled TN and average modeled TN was compared to mean measured TN data values, at each 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. Because there is only a single monitoring station for each system, there is no way to calculate a meaningful correlation coefficient. The rms error is 0.019.

A contour plot of calibrated model output is shown in Figure VI-4 for Fiddlers Cove and Rands Harbor estuary systems. 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 7-tidal-day model simulation output period.

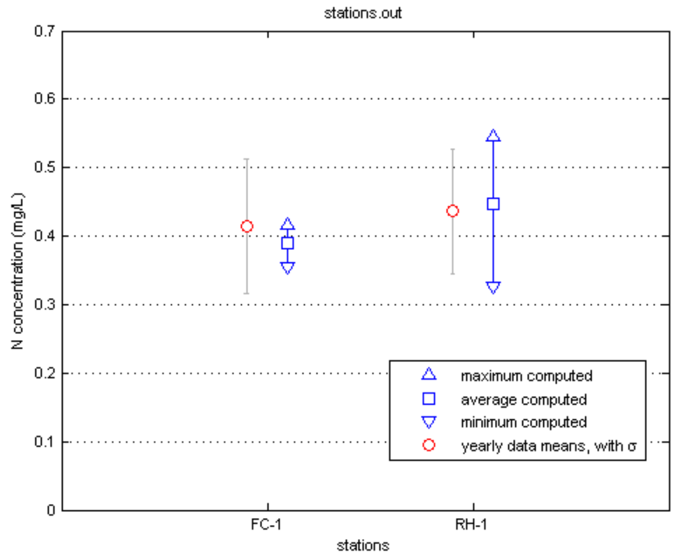


Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Fiddlers Cove and Rands Harbor estuary systems. Station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed 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.

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 Fiddlers Cove and Rands Harbor estuary systems 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 30.29 ppt, based upon offshore measurements. For groundwater inputs, salinities were set at 0 ppt. Groundwater input used for the model was 4.07 ft^3/sec (9,704 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed evenly in each model through the use of several rainwater element input points positioned along each model's land boundary.

Comparisons of modeled and measured salinities are presented in Figure VI-5, with contour plots of model output shown in Figure VI-6. Though model dispersion coefficients were not changed from those values selected through the nitrogen model calibration process, the model skillfully represents salinity gradients in Fiddlers Cove and Rands Harbor estuary systems. The rms error of the models was 0.226 ppt. Again, a meaningful correlation cannot be calculated, since only one monitoring station exists for each estuarine system. 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.

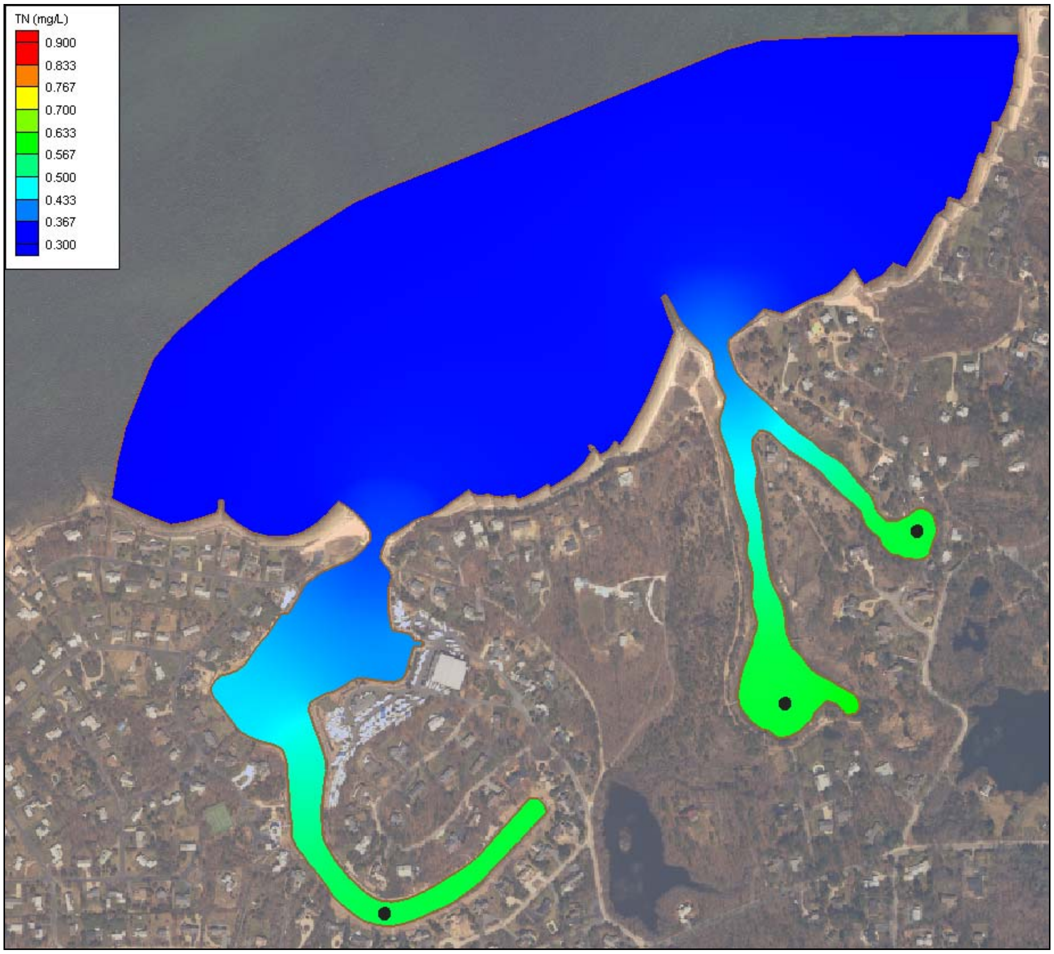


Figure VI-4. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for Fiddlers Cove and Rands Harbor estuary systems. The approximate location of the sentinel threshold stations for Fiddlers Cove and Rands Harbor estuary systems are shown by the black symbols.

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.

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be a 88% total increase in watershed nitrogen load to all Rand's Canal watersheds as a result of potential future development, with an increase of 26% for the all Fiddler's Cove watersheds combined. For the no load scenario, a majority of the load entering the watershed is removed; therefore, the combined load of all watersheds is lower than existing conditions by over 96% for Fiddler's Cove and 88% for Rand's Canal.

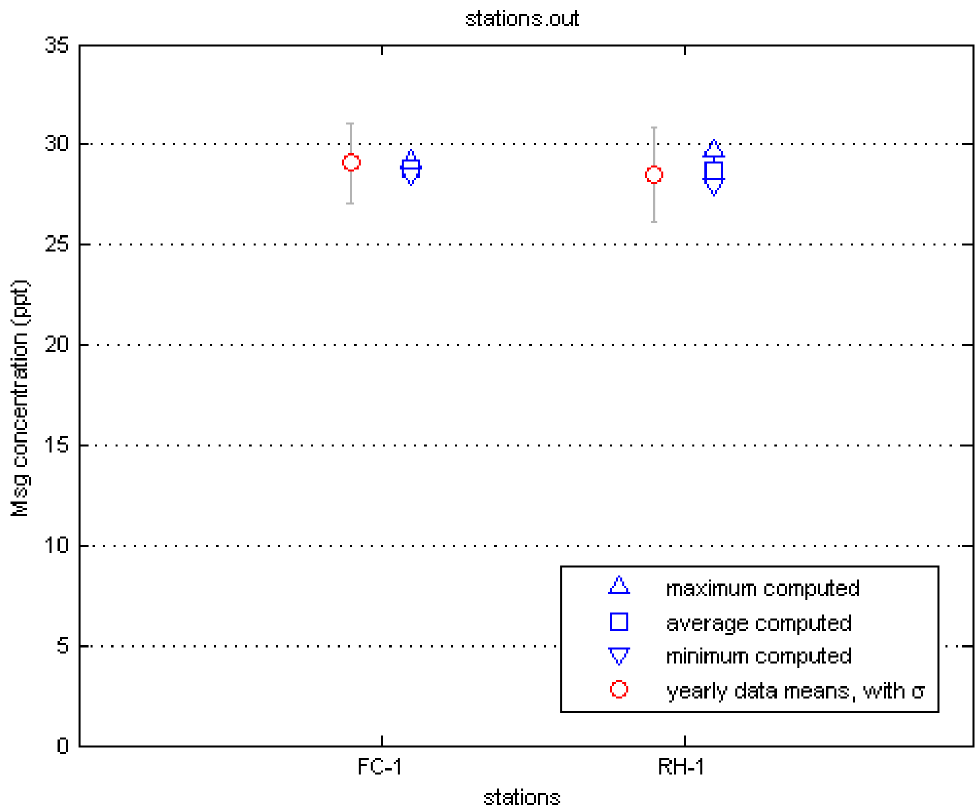


Figure VI-5. Comparison of measured and calibrated model output at stations in Fiddlers Cove and Rands Harbor estuary systems. Stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (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.

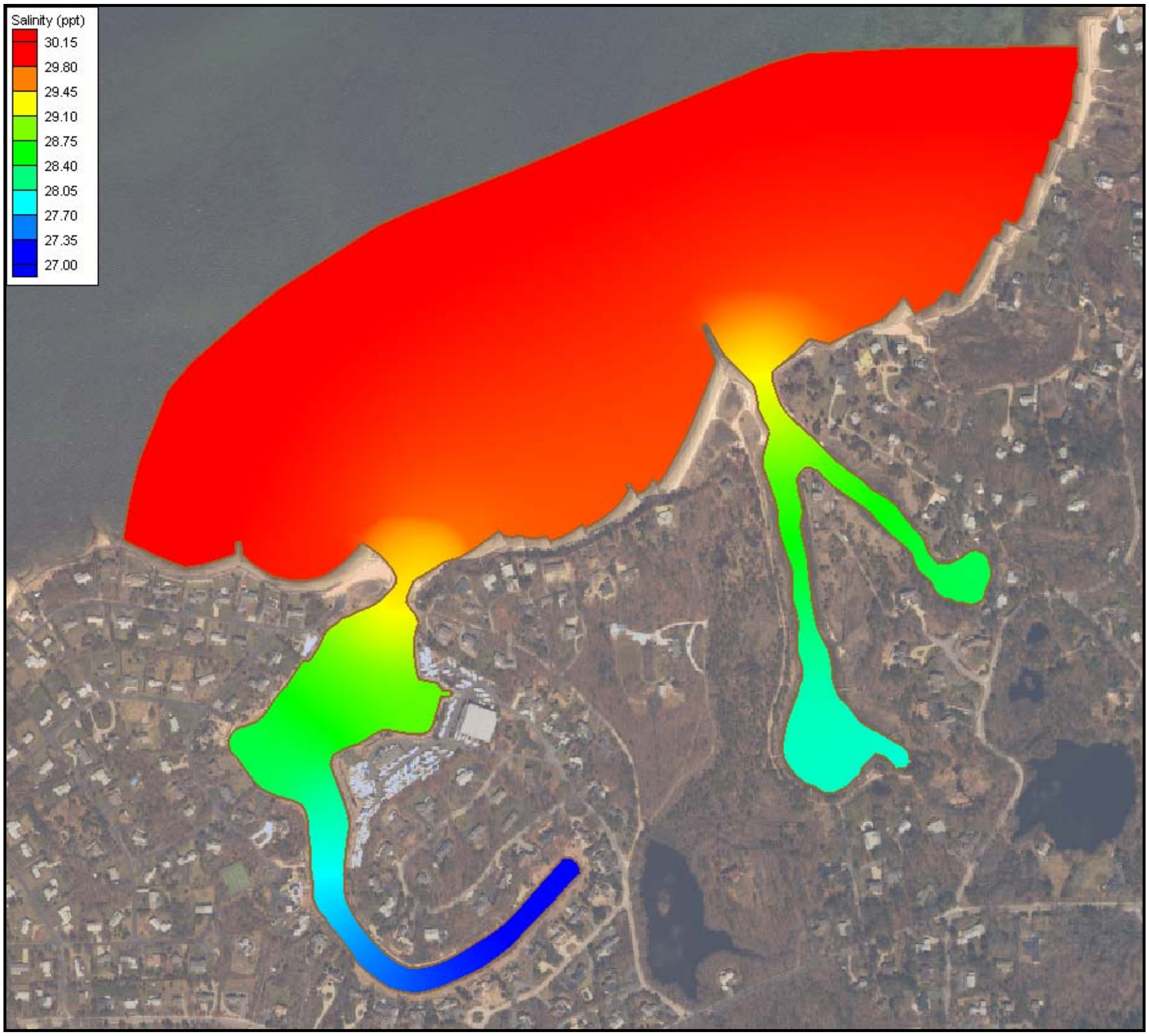


Figure VI-6. Contour plots of modeled salinity (ppt) in Fiddlers Cove and Rands Harbor estuary systems.

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 Fiddlers Cove and Rands Harbor estuary systems. 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
Rand Inlet	0.014	0.014	0.0%	0.003	-78.6%
Rand North	2.496	3.386	35.7%	0.342	-86.3%
Rand South	3.564	8.055	126.0%	0.362	-89.8%
Fiddler Main	0.890	0.890	0.0%	0.068	-92.4%
Fiddler Upper	3.441	4.570	32.8%	0.115	-96.7%

VI.2.6.1 Build-Out

For the build-out scenario, a breakdown of the total nitrogen load entering the Fiddler's Cove and Rand's Canal estuary systems 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:

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

where the projected PON concentration is calculated by,

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

using the watershed load ratio,

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

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 Fiddlers Cove and Rands Harbor estuary systems, 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)
Rand Inlet	0.014	0.022	0.148
Rand North	3.386	0.033	0.328
Rand South	8.055	0.088	0.497
Fiddler Main	0.890	0.068	0.936
Fiddler Upper	4.570	0.115	0.422

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of the Fiddlers Cove and Rands Harbor estuary systems was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Buzzard's Bay) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most in the Rands Harbor system (29%), while the change in the Fiddlers Cove system was not as drastic (5%). Color contours of model output for the build-out scenario are present in Figure VI-7. The range of nitrogen concentrations shown are the same as for the plot of present conditions in Figure VI-4, which allows direct comparison of nitrogen concentrations between loading scenarios. For typical systems, a total nitrogen concentration greater than 0.5 mg/L leads to negative impacts in benthic fauna.

Table VI-6. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Fiddlers Cove and Rands Harbor estuary systems. The sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Fiddlers Cove	FC1	0.3891	0.4073	4.6%
Fiddlers Canal	**Sentinel**	**0.5579**	**0.6207**	**11.3%**
Rands Harbor	RH1	0.4469	0.5749	28.6%
Rands North Arm	**Sentinel**	**0.5696**	**0.7095**	**24.6%**
Rands South Arm	**Sentinel**	**0.5705**	**0.8356**	**46.5%**

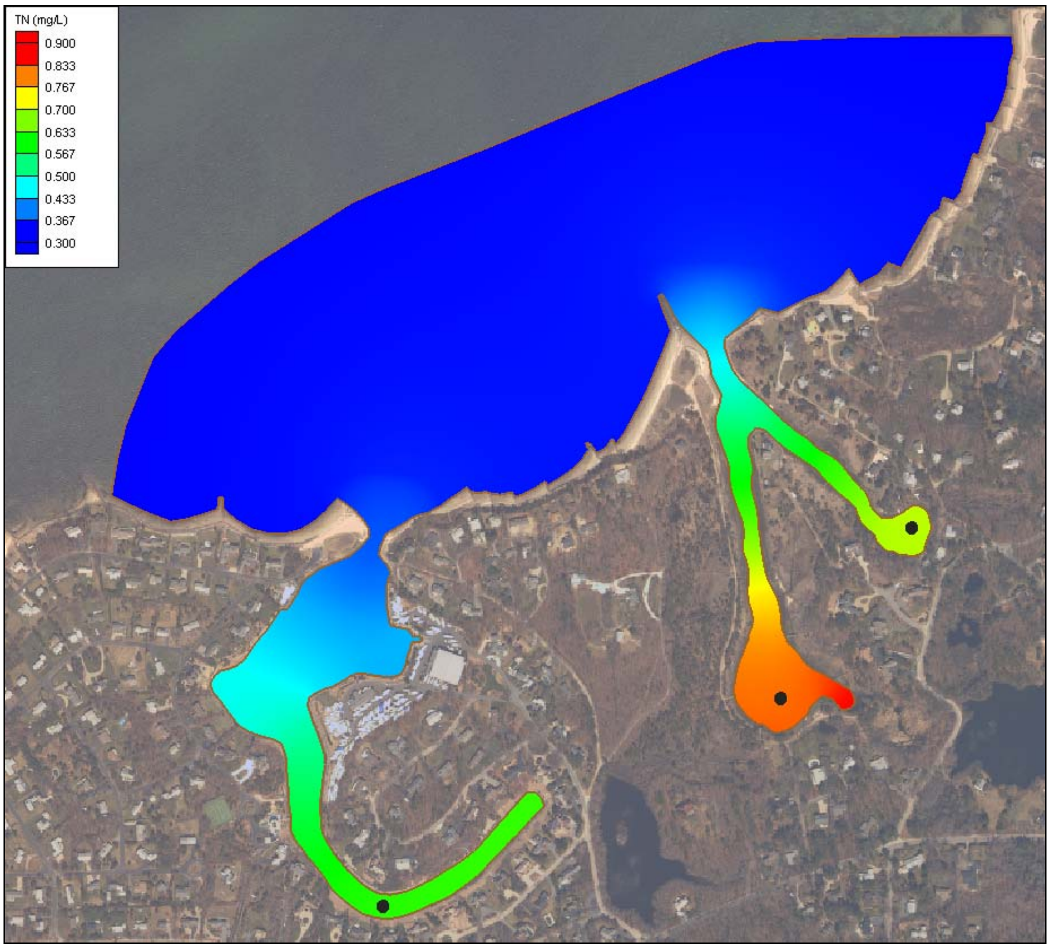


Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in Fiddlers Cove and Rands Harbor estuary systems, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold stations for Fiddlers Cove and Rands Harbor estuary systems are shown by the black symbols.

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.

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., Buzzard's Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was significant as shown in Table VI-8, with reductions of over 16% in both systems. Results for the system are shown pictorially in Figure VI-8.

Table VI-7. "No anthropogenic loading" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of Fiddlers Cove and Rands Harbor estuary systems , 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)
Rand Inlet	0.003	0.022	0.058
Rand North	0.342	0.033	0.128
Rand South	0.362	0.088	0.194
Fiddler Main	0.068	0.068	0.597
Fiddler Upper	0.115	0.115	0.269

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 Fiddlers Cove and Rands Harbor estuary systems. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). The sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Fiddlers Cove	FC1	0.3891	0.3243	-16.7%
Fiddlers Cove	**Sentinel**	**0.5579**	**0.3610**	**-35.3%**
Rands Harbor	RH1	0.4469	0.3324	-25.6%
Rand's North Arm	**Sentinel**	**0.5696**	**0.3581**	**-37.1%**
Rand's South Arm	**Sentinel**	**0.5705**	**0.3549**	**-37.8%**

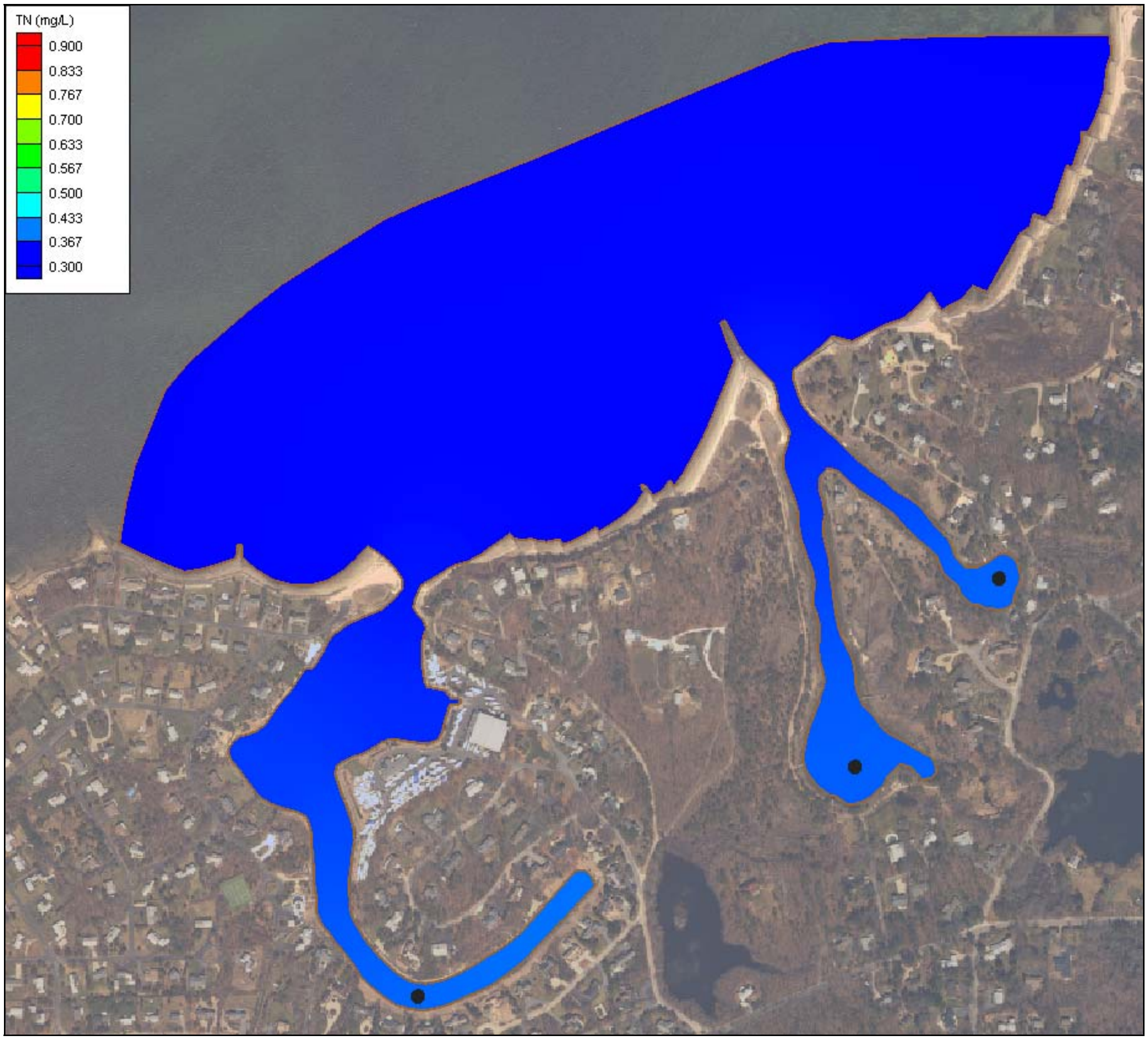


Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in Fiddlers Cove and Rands Harbor estuary systems, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold stations for Fiddlers Cove and Rands Harbor estuary systems are shown by the black symbols.

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 Fiddlers Cove and Rands Harbor embayment systems in the Town of Falmouth, MA, our assessment is based upon data from the water quality monitoring database (1999-2009) developed by the Coalition for Buzzards Bay, surveys of eelgrass distribution (1951, 1995, 2001), benthic animal communities (fall 2006), sediment characteristics (summer 2006), and dissolved oxygen records (summer 2006). 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 both of these systems (Section VIII). It should be noted that nitrogen enrichment occurs through 2 primary mechanisms, high rates of nitrogen entering from the surrounding watershed and/or low rates of flushing due to restriction of tidal exchange with the low nitrogen waters of Buzzards Bay. Fiddlers Cove and Rands Harbor have increasing nitrogen loading from the associated watersheds from shifting land-uses and Rands Harbor periodically may become restricted due to sediment deposition within its inlet. Fundamentally, restrictions of tidal exchange increase the sensitivity of an estuary to nitrogen inputs.

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 threshold 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 autonomous dissolved oxygen sensors in both Fiddlers Cove and Rands Harbor at locations that would be representative of the dissolved oxygen conditions at critical locations in each of the systems. Sensors (2) were deployed to capture oxygen conditions within an upper location in Fiddlers Cove (i.e. the Canal), furthest removed from the influence of inflowing waters from Buzzards Bay, and within the lower main basin. Sensors (2) were placed in Rands Harbor within the terminal basins of the North (East) and South (West) Branches. The dissolved oxygen moorings were deployed 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 both the Fiddlers Cove and Rands Harbor systems 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. It appears that neither Fiddlers Cove nor Rands Harbor presently or historically supported significant eelgrass beds. It is likely that this is due in part to the artificial nature of these open water embayments that were formed by excavating wetlands to create protected harbors for boats over the past 90 years (initial construction followed by modifications into the 1970's). Therefore, eelgrass habitat was not used as an indicator in the MEP assessment for these systems.

Analysis of inorganic N/P molar ratios within the watercolumn of Fiddlers Cove and Rands Harbor supports the contention that nitrogen is the nutrient to be managed, as the ratio in Fiddlers Cove (3.6) and Rands Harbor (7.0) is clearly below the Redfield Ratio value (16) indicating that nitrogen additions will increase phytoplankton production in these systems. Within the Fiddlers Cove and Rands Harbor systems, since temporal changes in eelgrass distribution could not provide a basis for evaluating nutrient related habitat quality, nutrient threshold determination was based on results from the dissolved oxygen and chlorophyll mooring and water quality monitoring data, macroalgae surveys, and the benthic infaunal community characterization.

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 4 mg L-1. Massachusetts State Water Quality Classification indicates that SA (high quality) waters be able to maintain oxygen levels above 6 mg L-1. The tidal waters of the Fiddlers Cove and Rands Harbor embayments 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 and that it is the designated water quality that is the target of TMDL's generated under the U.S. Clean Water Act. It is through the MEP and TMDL processes that site specific management targets are developed and under the Town's CWMP that management alternatives are designed 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 bottom of the two embayments within key regions of the Fiddlers Cove and Rands Harbor systems (Figure VII-2 and VII-3). The dissolved oxygen sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployments. In addition periodic calibration samples were collected at the depth of each sensor 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 25-30 days within the interval from July through mid-September. All of the mooring data from the Fiddlers Cove and Rands Harbor systems were collected during the summer of 2006.

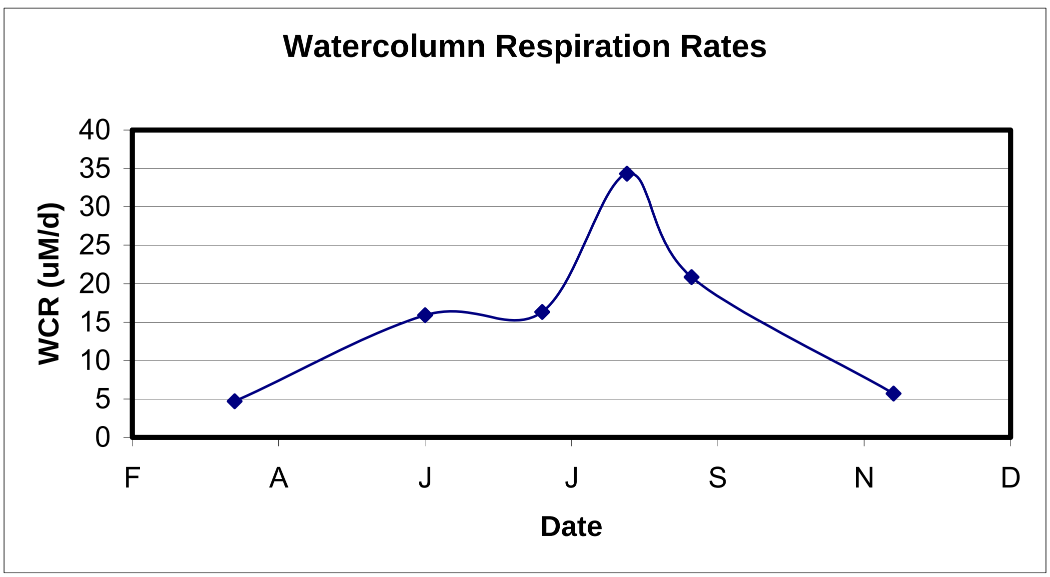


Figure VII-1. Example of typical average water column respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System, Cape Cod (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter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

Similar to other embayments in southeastern Massachusetts, the Fiddlers Cove and Rands Harbor systems 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 40 day and 26 day deployment periods (Fiddlers Cove and Rands Harbor respectively) that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2, VII-3, VII-4). 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.

Figure VII-2. Aerial Photograph of the Fiddlers Cove system in the Town of Falmouth showing the location of the continuously recording Dissolved Oxygen / Chlorophyll-a sensors deployed during the Summer of 2006.

Figure VII-3. Aerial Photograph of the Rands Harbor system in the Town of Falmouth showing the location of the continuously recording Dissolved Oxygen / Chlorophyll-a sensors deployed during the Summer of 2006.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a levels indicate moderately nutrient enriched waters within the lower basin and upper Canal region of Fiddlers Cove. The dissolved oxygen data is further described below and depicted in Figures VII-4 and VII-6. The oxygen data is consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-a. The measured levels of oxygen depletion and enhanced chlorophyll-a levels follows the spatial pattern of total nitrogen levels in this system (Section VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of the Fiddlers Cove estuarine system. Similarly in Rands Harbor, the level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a levels also indicate moderately nutrient enriched waters with similar chlorophyll levels, but a slightly lower extent of oxygen depletion when compared to Fiddlers Cove. Oxygen excursions and depletions were not significantly different between the west branch of Rands Harbor and the east branch, although the oxygen condition in the west branch may be slightly less stressful to benthic animal communities. The dissolved oxygen data is further described below and depicted in Figures VII-8 and VII-10). As in Fiddlers Cove, the oxygen data collected from Rands Harbor is consistent with organic matter enrichment, primarily from phytoplankton production as seen from the parallel measurements of chlorophyll-a. The measured levels of oxygen depletion and enhanced chlorophyll-a levels follows the spatial pattern of total nitrogen levels in this system (Section VI), and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment of the Rands Harbor estuarine system.

The oxygen record for both Fiddlers Cove and Rands Harbor show levels of oxygen depletion and daily oxygen excursions and chlorophyll-a levels indicative of nitrogen enrichment. Oxygen records from both harbors coupled with the multi-year monitoring by BayWatchers indicates that oxygen levels are generally lower than atmospheric equilibration but only infrequently decline to <4 mg L^{-1}. 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). The clear evidence of oxygen levels above atmospheric equilibration indicates that the innermost reaches of both these systems are nitrogen enriched. Measured dissolved oxygen depletion indicates that portions of both the Fiddlers Cove and the Rands Harbor systems present oxygen stress to benthic animal communities. The embayment specific results are as follows:

Fiddlers Cove outer DO/CHLA Mooring (Figures VII-4 and VII-5):

Two moorings were deployed in the Fiddlers Cove system. One of the two instrument moorings was located in the main basin of Fiddlers Cove at the farther end of the basin away from the inlet connecting the estuary to lower nutrient water from Buzzards Bay. The second instrument was placed in the upper reach (Canal) of this system (discussed below). The mooring in the main basin was centrally located and approximately 100 meters from where the main basin joins the "canal". Moderate daily excursions in oxygen levels were observed at this location, ranging from levels at or just above air equilibration to slightly hypoxic conditions where levels decline to 4 mg L^{-1} (Figure VII-4, Table VII-1). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The organic enrichment of the system is also demonstrated by the algal blooms that were observed during the meter deployment period as well as the high rates of photosynthesis (carbon fixation) and the rapid declines in oxygen after sunset stemming from respiration.

Oxygen levels regularly exceeded 6 mg L^{-1} and periodically exceeded 8 mg L^{-1}. These moderately high oxygen levels are primarily the result of photosynthesis by high phytoplankton biomass and relatively quiescent waters. Over the 44 day deployment there appear to be multiple moderately intense phytoplankton blooms where chlorophyll-a increased to 10-15 ug L^{-1} and a few periods of bloom activity where chlorophyll-a concentrations peaked at just over 20 ug L^{-1}. The periodic low levels of oxygen observed in this system is indicative of moderate habitat impairment which is also consistent with the somewhat elevated chlorophyll-a levels, also indicative of nitrogen enrichment (average chlorophyll-a by mooring, 10.5 ug L^{-1}; water quality monitoring program, 6.1 ug L^{-1}). In the portion of the main basin of the Fiddlers Cove system close to where the narrow channel meets the main basin, chlorophyll-a exceeded the 10 ug L^{-1} benchmark 44 percent of the time (Table VII-2, Figure VII-5). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

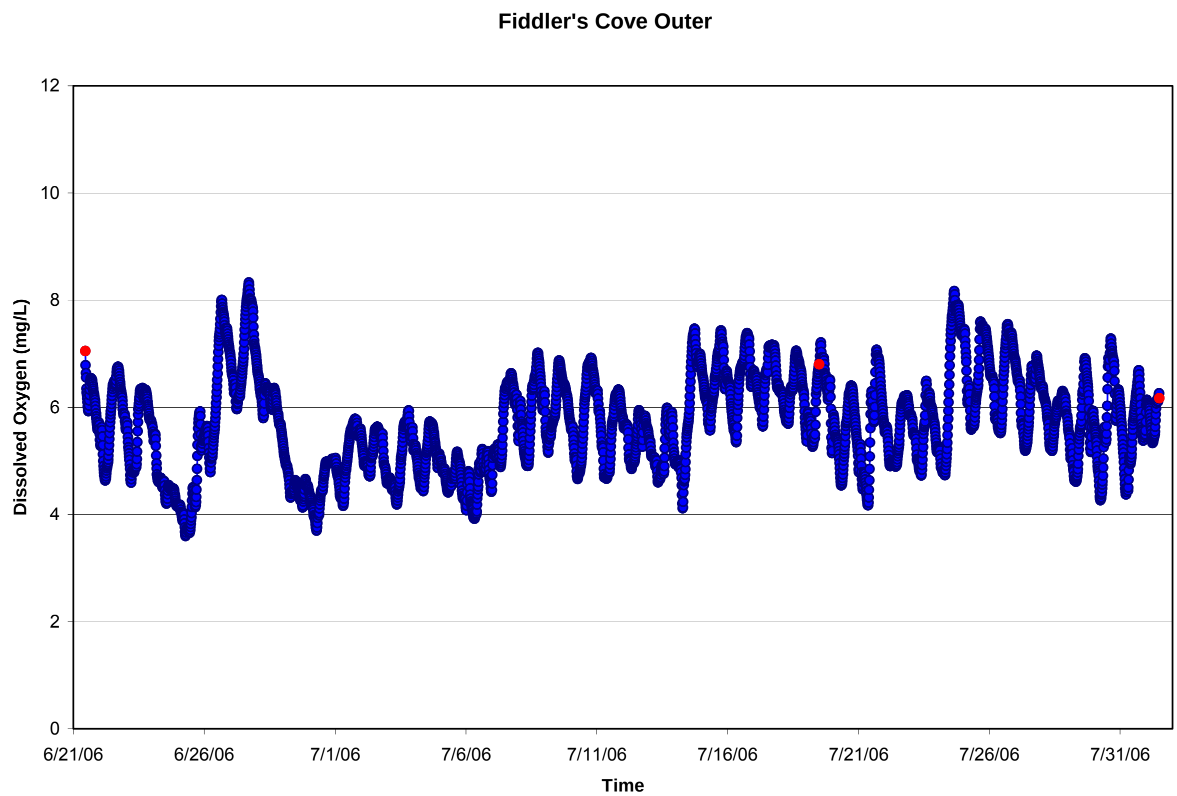


Figure VII-4. Bottom water record of dissolved oxygen at the Fiddlers Cove outer station, Summer 2006. Calibration samples represented as red dots.

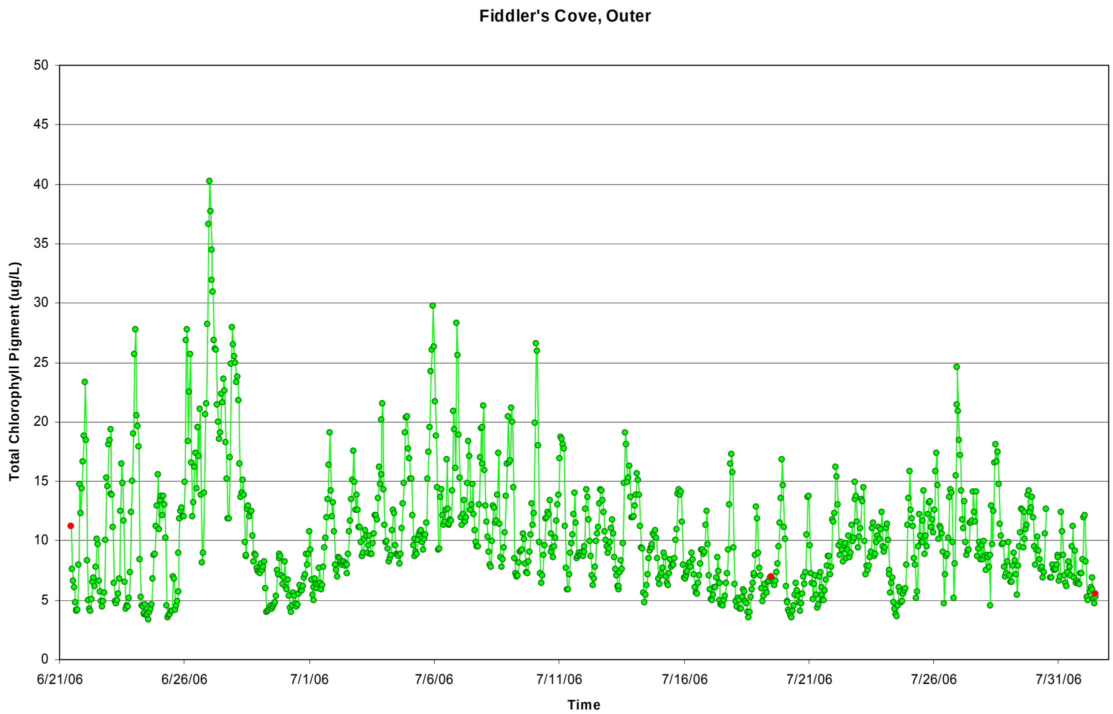


Figure VII-5. Bottom water record of Chlorophyll-*a* in the Fiddlers Cove outer station, Summer 2006. Calibration samples represented as red dots.

Fiddlers Cove inner DO/CHLA Mooring (Figures VII-6 and VII-7):

The second of the two instrument moorings (Fiddlers Cove-inner) deployed in the Fiddlers Cove system was located approximately midway along the narrow Canal that extends landward from the main Fiddlers Cove basin, well away from the inlet connecting the estuary to lower nutrient water from Buzzards Bay. The mooring was centrally located in the channel. Oxygen conditions at this location were similar to the main basin, but with larger daily excursions in oxygen levels. Oxygen concentrations ranged from levels clearly above (over 8 mg L^{-1}) air equilibration to slightly hypoxic conditions where levels decline to 4 mg L^{-1} (Figure VII-6, Table VII-1). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The organic enrichment of the system is demonstrated by the several large algal blooms that were observed during the deployment period, as well as the high rates of photosynthesis (carbon fixation) and the rapid declines in oxygen after sunset stemming from respiration.

Oxygen levels periodically exceeded 8 mg L^{-1} and even 10 mg L^{-1}. These high oxygen levels are likely the result of the combined effects of photosynthesis by the high phytoplankton biomass measured in this basin (average chlorophyll-a, 15.2 ug L^{-1}). Over the 26 day deployment there appear to be multiple phytoplankton blooms where chlorophyll-a regularly increased to 15-20 ug L^{-1} and in a few blooms, to between 25 and 35 ug L^{-1} for nearly a ten day period. The periodic low levels of oxygen observed in this system is indicative of moderate habitat impairment, consistent with the elevated chlorophyll-a levels. Phytoplankton blooms were common in the Fiddlers Cove Canal, with chlorophyll-a exceeding the 10 ug L^{-1} benchmark 74 percent of the time (Table VII-2, Figure VII-7) and a mooring average chlorophyll-a of 15.2 ug L^{-1}. Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

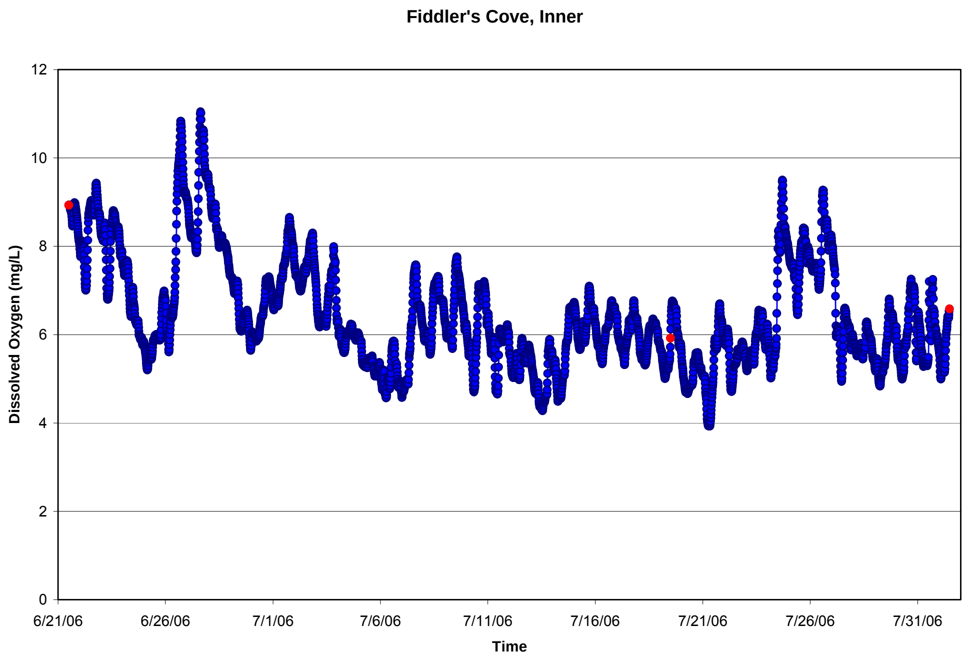


Figure VII-6. Bottom water record of dissolved oxygen at the Fiddlers Cove inner station, Summer 2006. Calibration samples represented as red dots.

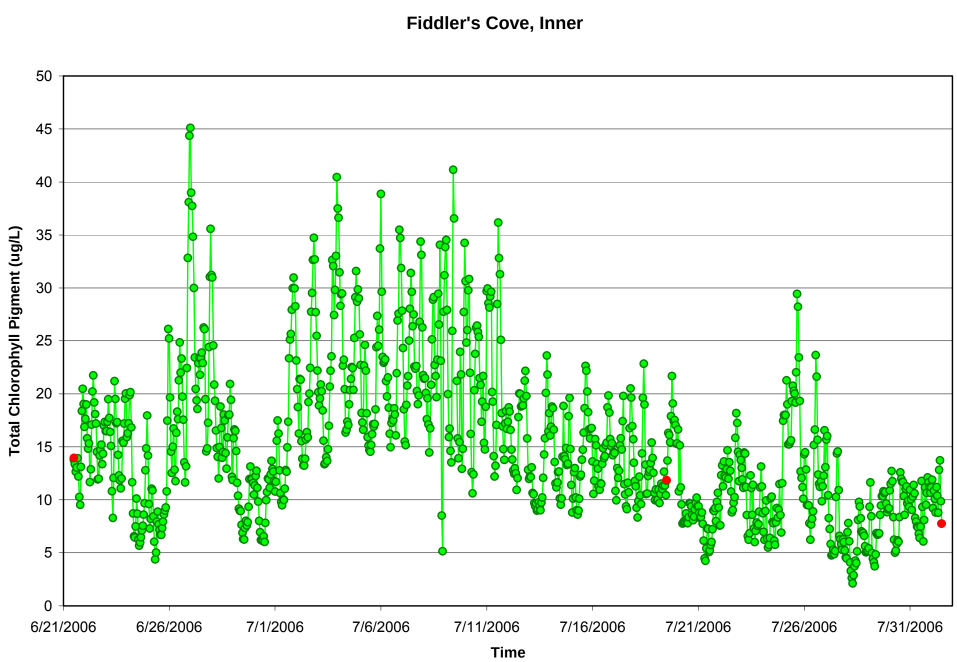


Figure VII-7. Bottom water record of Chlorophyll-*a* in the Fiddlers Cove inner station, Summer 2006. Calibration samples represented as red dots.

Rands Harbor East DO/CHLA Mooring (Figures VII-8 and VII-9):

Two dissolved oxygen moorings were deployed in the Rands Harbor embayment system. One mooring was deployed within the central region of the terminal basin of each of the two branches, farthest from the inlet connecting the estuary to waters from Buzzards Bay. Moderate daily excursions in oxygen levels were observed at these locations, ranging from levels at and slightly above air equilibration to ~ 5 mg L^{-1}. Oxygen depletion, although clearly occurring did not reach 4 mg L^{-1} (Figure VII-8, Table VII-3). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The moderate level of organic enrichment of the system is demonstrated by a ten day phytoplankton bloom measured during the deployment period, as well as the high rates of photosynthesis (carbon fixation) and the rapid declines in oxygen after sunset stemming from respiration.

Oxygen levels regularly exceeded 8 mg L^{-1} and periodically exceeded 9 mg L^{-1} with a peak exceeding 10 mg L^{-1}. These high oxygen levels are likely the result of the combined effects of photosynthesis by macroalgae and high phytoplankton biomass and relatively quiescent waters. Over the 26 day deployment there appears to be an extended period (~10 days) of phytoplankton blooms where chlorophyll-a increased to 10-15 ug L^{-1} and several instances of increased bloom activity where chlorophyll-a concentrations rose to between 15-20 ug L^{-1}. The periodic low oxygen concentrations observed in the east branch of this system is indicative of some habitat impairment which is also consistent with the moderate chlorophyll-a levels, also indicative of nitrogen enrichment (average chlorophyll-a levels measured by the mooring, 6.2 ug L^{-1}). In the east branch of the Rands Harbor system, chlorophyll-a exceeded the 10 ug L^{-1} benchmark 15 percent of the time (Table VII-4, Figure VII-9). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

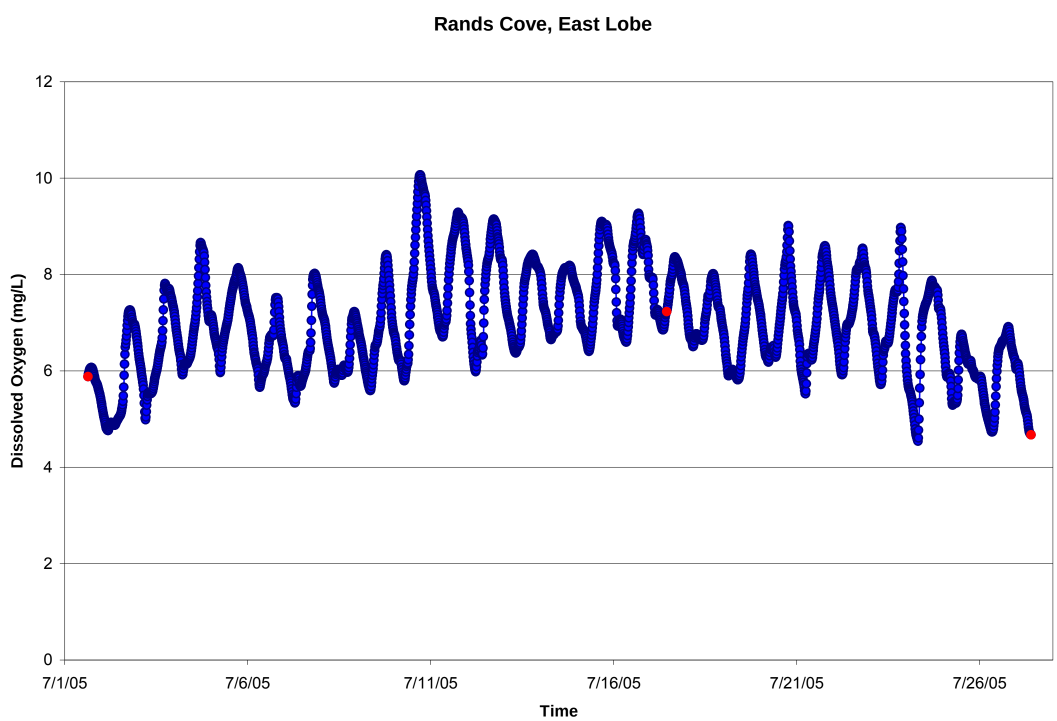


Figure VII-8. Bottom water record of dissolved oxygen at the Rands Harbor East station, Summer 2006. Calibration samples represented as red dots.

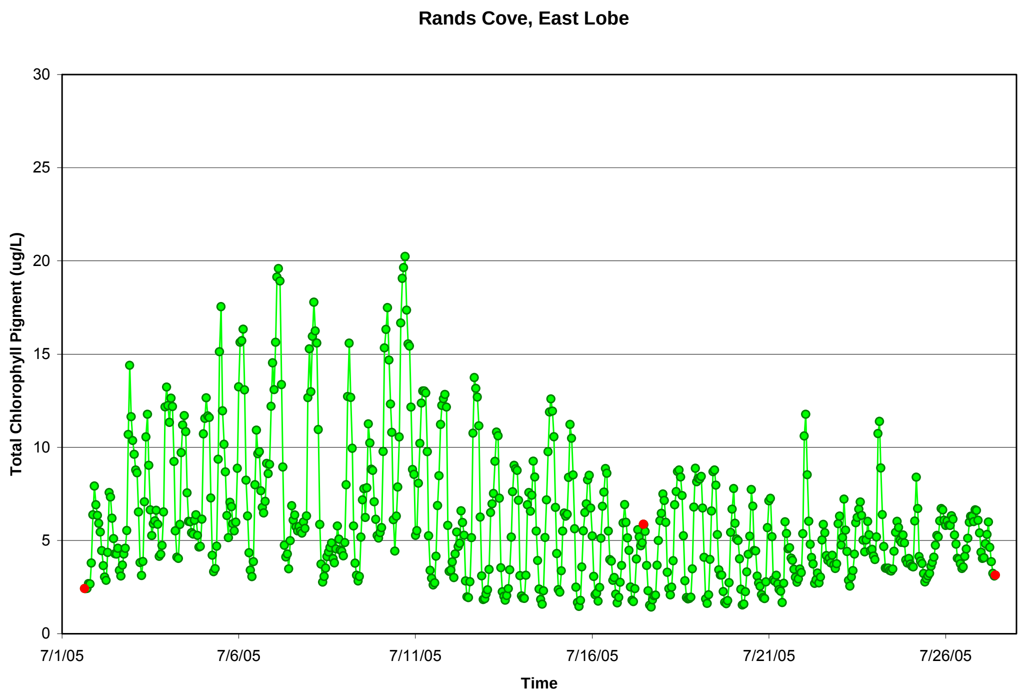


Figure VII-9. Bottom water record of Chlorophyll-*a* in the Rands Harbor East station, Summer 2006. Calibration samples represented as red dots.

Rands Harbor West DO/CHLA Mooring (Figures VII-10 and VII-11):

The second moorings deployed in the Rands Harbor system was located in the central region of the terminal basin of the west branch. Like in the east branch, the mooring was located well away from the inlet connecting the estuary to waters from Buzzards Bay. Oxygen conditions in the west branch were generally similar to conditions observed in the east branch, although oxygen levels showed slightly less depletion and less of a daily excursion. Oxygen levels in both branches were almost always >5 mg L^{-1}. Moderate daily excursions in oxygen levels were observed at this location, ranging from levels at and slightly above air equilibration to moderately low conditions where levels approached 4 mg L^{-1} (Figure VII-10, Table VII-3). Similarly, the water quality monitoring results showed oxygen levels only periodically declining to below 5 mg L^{-1} (5% of 195 samples). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The moderate level of organic enrichment of the system is demonstrated by a ten day period of algal bloom activity that was measured during the deployment period as well as the high rates of photosynthesis (carbon fixation) and the rapid declines in oxygen after sunset stemming from respiration.

Oxygen levels occasionally exceeded 8 mg L^{-1} and periodically approached 9 mg L^{-1} with a peak exceeding 10 mg L^{-1}. These high oxygen levels are likely the result of the combined effects of photosynthesis by macroalgae (and any associated epiphytes) and high phytoplankton biomass and relatively quiescent waters. Over the 26 day deployment there appears to be an extended period (~10 days) of moderately intense phytoplankton blooms where chlorophyll-a increased to 10-15 ug L^{-1} and several instances of increased bloom activity where chlorophyll-a concentrations rose to between 15-20 ug L^{-1} and peaked as high as between 20-25 ug L^{-1}. The periodic low oxygen concentrations and chlorophyll blooms observed in the west branch of this system is indicative of a low level of habitat impairment which is also consistent with the elevated chlorophyll-a levels, also indicative of nitrogen enrichment (average chlorophyll-a levels measured by the mooring, 8.3 ug L^{-1} and by the multi-year monitoring program, 8.8 ug L^{-1}). In the west branch of the Rands Harbor system, chlorophyll-a exceeded the 10 ug L^{-1} benchmark 80 percent of the time (Table VII-4, Figure VII-11). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

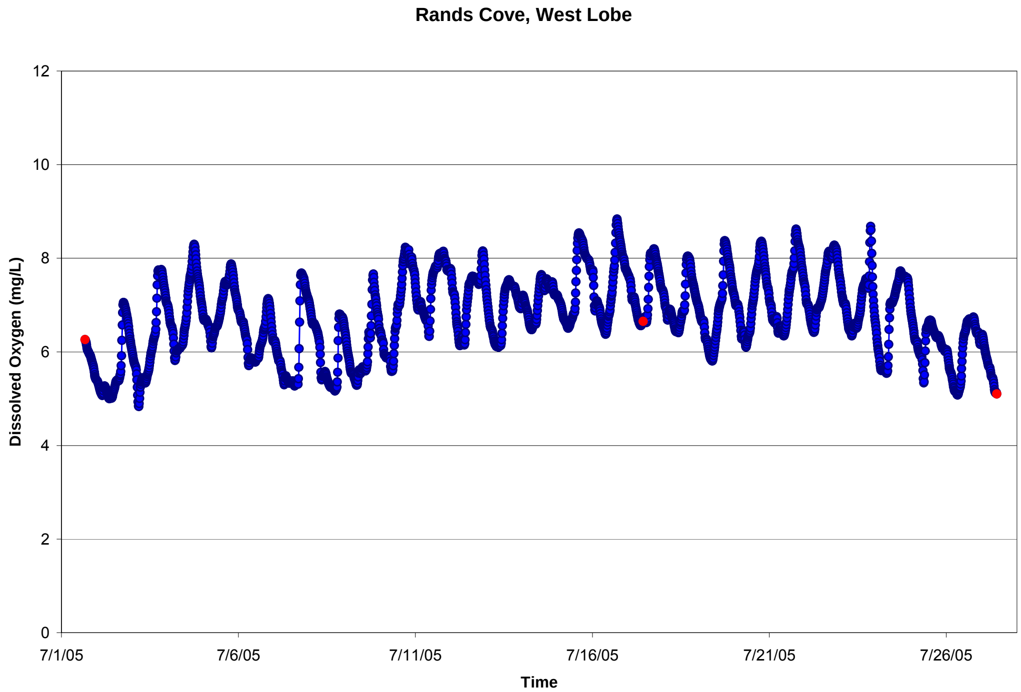


Figure VII-10. Bottom water record of dissolved oxygen at the Rands Harbor West station, Summer 2006. Calibration samples represented as red dots.

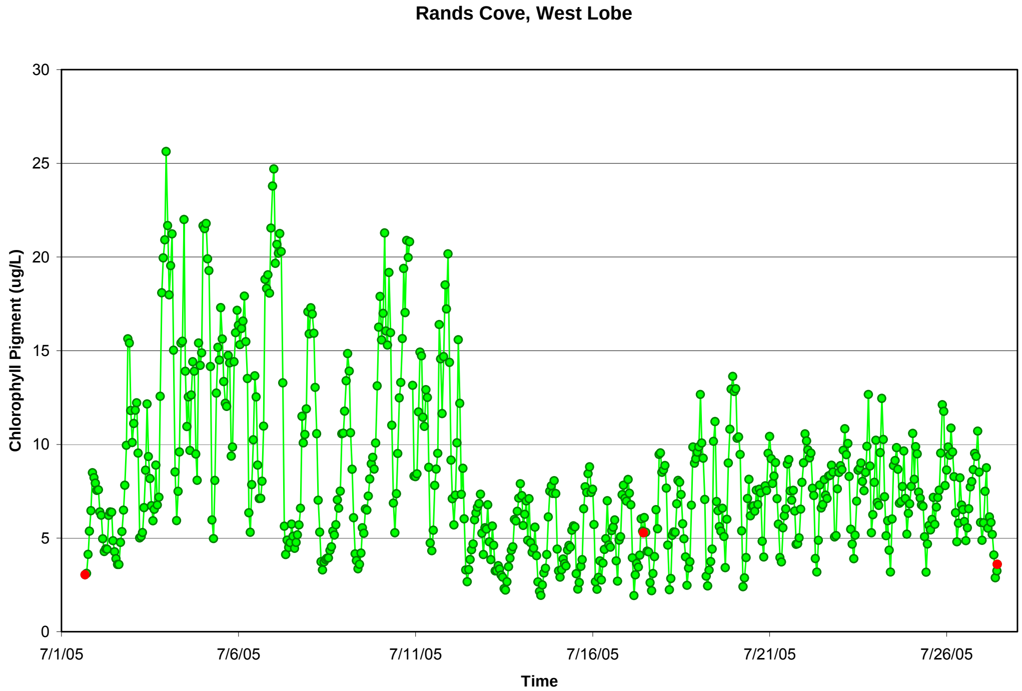


Figure VII-11. Bottom water record of Chlorophyll-*a* in the Rands Harbor West station, Summer 2006. Calibration samples represented as red dots.

Table VII-1. Days and percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels within the Fiddlers Cove embayment system. Data collected by the Coastal Systems Program, SMAST.

Mooring Location	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)
Fiddler's Cove Inner	**6/21/2006**	**8/1/2006**	**40.99**	**44%**	**8%**	**0%**	**0%**
			Mean	0.43	0.20	0.13	N/A
			Min	0.01	0.01	0.13	0.00
			Max	2.76	0.65	0.13	0.00
			S.D.	0.61	0.20	N/A	N/A
Fiddler's Cove Outer	**6/21/2006**	**8/1/2006**	**40.96**	**63%**	**26%**	**2%**	**0%**
			Mean	0.69	0.29	0.11	N/A
			Min	0.03	0.01	0.01	0.00
			Max	8.68	1.76	0.29	0.00
			S.D.	1.46	0.38	0.10	N/A

Table VII-2. Duration (days and % of deployment time) that chlorophyll a levels exceed various benchmark levels within the Fiddlers Cove 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.

Mooring Location	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)
Fiddler's Cove Inner	**6/21/2006**	**8/1/2006**	**40.99**	**98%**	**74%**	**43%**	**22%**	**11%**
Mean Chl Value = 15.2 ug/L			**Mean**	5.01	0.62	0.35	0.20	0.19
			Min	0.04	0.04	0.04	0.04	0.04
			Max	25.83	7.42	1.92	0.75	0.50
			S.D.	8.67	1.27	0.39	0.17	0.10
Fiddler's Cove Outer	**6/21/2006**	**8/1/2006**	**40.96**	**90%**	**44%**	**14%**	**6%**	**3%**
Mean Chl Value = 10.5 ug/L			**Mean**	1.32	0.27	0.16	0.13	0.13
			Min	0.04	0.04	0.04	0.04	0.04
			Max	13.83	1.63	0.92	0.58	0.42
			S.D.	2.69	0.28	0.16	0.14	0.12

Table VII-3. Days and percent of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels within the Rands Harbor embayment system. Data collected by the Coastal Systems Program, SMAST.

Mooring Location	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)
Rands Cove West	**7/1/2005**	**7/27/2005**	**25.8**	**20%**	**0%**	**0%**	**0%**
			Mean	0.40	0.03	N/A	N/A
			Min	0.05	0.02	0.00	0.00
			Max	0.94	0.04	0.00	0.00
			S.D.	0.24	0.01	N/A	N/A
Rands Cove East	**7/1/2005**	**7/27/2005**	**25.8**	**26%**	**3%**	**0%**	**0%**
			Mean	0.27	0.11	0.13	0.13
			Min	0.01	0.02	0.13	0.13
			Max	0.71	0.22	0.13	0.13
			S.D.	0.20	0.08	N/A	N/A

Table VII-4. Duration (days and % of deployment time) that chlorophyll a levels exceed various benchmark levels within the Rands Harbor 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.

Mooring Location	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)
Rands Cove West	**7/1/2005**	**7/27/2005**	**25.8**	**76%**	**80%**	**25%**	**19%**	**11%**
Mean Chl Value = 8.3 ug/L			**Mean**	0.52	0.67	0.21	0.33	0.19
			Min	0.04	0.04	0.04	0.04	0.04
			Max	2.58	1.29	0.58	0.63	0.50
			S.D.	0.56	0.38	0.17	0.19	0.15
Rands Cove East	**7/1/2005**	**7/27/2005**	**25.8**	**56%**	**41%**	**15%**	**6%**	**4%**
Mean Chl Value = 6.2 ug/L			**Mean**	0.30	0.48	0.18	0.19	0.13
			Min	0.04	0.04	0.04	0.04	0.04
			Max	0.96	0.92	0.38	0.33	0.29
			S.D.	0.23	0.27	0.09	0.10	0.08

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass distribution and analysis of historical data was conducted for the Fiddlers Cove and Rands Harbor Embayment Systems by the MassDEP Eelgrass Mapping Program as part of the MEP technical effort. Field surveys of the two harbors were conducted in 1995 and 2001 by MassDEP, as part of this program, with additional observations during summer and fall 2006 by the SMAST/MEP Technical Team. Analysis of available aerial photography from 1951 was conducted to reconstruct the eelgrass distribution prior to the present level of development of the watershed. The primary use of the eelgrass data within the MEP approach is to indicate (a) if eelgrass once or currently colonizes a basin and (b) any large-scale system-wide shifts in distribution. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 (Figure VII-12). These data were also compared with an eelgrass survey in the mid 1980's (Costa 1988), thus increasing the validity of the overall assessment of eelgrass trends in Megansett Harbor (inclusive of Fiddlers Cove and Rands Harbor). This temporal information can be used to determine the stability of the eelgrass community in many systems.

Field surveys in 1995 and 2001 by MassDEP and in the mid 1980's of these two heavily man-altered harbor systems indicates that these embayments have not supported eelgrass over the past half century and likely have not supported eelgrass for over a century. The MEP Technical Team confirmed the lack of eelgrass within Fiddlers Cove and Rands Harbor basins while undertaking field surveys as part of the benthic regeneration and infauna studies and during the deployment and recovery of the instrument moorings. Part of this effort included SMAST research divers conducting visual surveys throughout the harbor basins for the presence of eelgrass (and macroalgae).

The key underlying cause of the absence of historic eelgrass coverage in both Fiddlers Cove and Rands Harbor stems from the fact that they are artificial embayments significantly altered by human activity over the past approximately 100 years. Fiddlers Cove and Rands Harbor were formed primarily as salt marshes with associated tidal creeks as seen in historical maps (1880 and 1916). Human activity gradually transformed these salt marsh dominated tidal creeks into more open water systems resembling embayments. The tidal wetlands were functionally removed to increase the navigability of the systems, though portions of the upper reaches of Fiddlers Cove still supported bordering saltmarsh into the 1970’s. At present almost all of the tidal wetlands along the shoreline of Fiddlers Cove have been removed and replaced with hard coastal structures (e.g. riprap). Although Rands Harbor was also constructed from tidal creeks, it still maintains fringing salt marsh areas, particularly in the western branch. Based on the history of both these systems, it is clear they likely have not historically supported eelgrass given that they have been open water embayments for <100 years.

It should be noted that while no eelgrass habitat could be documented within either of the two estuaries, the adjacent nearshore waters of Buzzards Bay do support extensive eelgrass beds (Figure VII-12). Based on the 1995 and 2001 eelgrass survey conducted by the DEP Eelgrass Mapping Program offshore, there was evidence of a potential decline in the coverage of the offshore beds. However, it is not possible at this time to determine if this represents a decline or natural variation at this site. Additional temporal sampling is planned to address this issue.

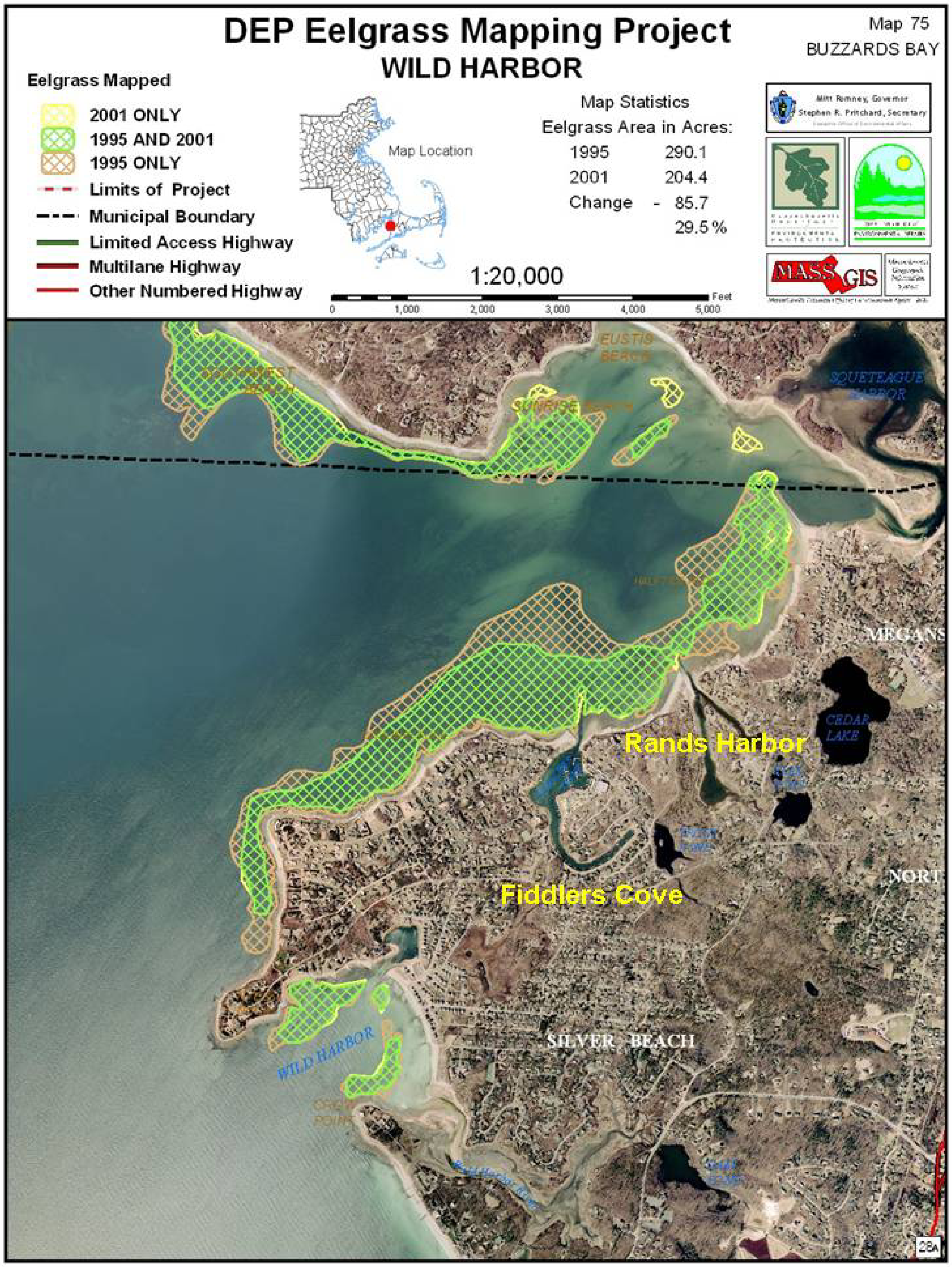


Figure VII-12. Eelgrass bed distribution offshore of Fiddlers Cove and Rands Harbor. Beds delineated in 1995 are circumscribed by the brown outline with a composite of 1995 and 2001 outlined in green (map from the MassDEP Eelgrass Mapping Program). No eelgrass was observed in Fiddlers Cove or Rands Harbor in 1995, 2001 or by SMAST-MEP surveys conducted in 2006.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 8 and 6 locations respectively within the Fiddlers Cove and Rands Harbor Embayment Systems (Figure VII-13 and VII-14 respectively), with replicate assays at each 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 while it does not appear that the Fiddlers Cove or Rands Harbor systems have ever supported significant eelgrass beds and do show signs based on DO and chlorophyll-a levels of moderate impairment from nutrient enrichment, it is possible to improve habitat conditions to be supportive of healthy benthic communities. To the extent that these two systems can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded) and what nutrient concentrations would be supportive of healthy habitat. 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.

Fiddlers Cove Infaunal Characteristics:

Overall, the infauna survey indicated that the main basin and the “canal” which comprise the Fiddlers Cove Embayment System are presently supporting low to moderately impaired benthic infaunal habitat (Table VII-5). It appears that organic deposition in these areas is the cause of the stress, consistent with the bottom water oxygen levels and phytoplankton biomass (Table VII-4). There is a gradient in benthic animal habitat impairment with low to moderate impairment nearest the tidal inlet increasing into the Canal. Animal communities colonizing sediments within the main basin and Canal are moderately diverse (21 and 19 species, respectively) and moderately productive (~300 individuals per sample). The main basin general ranked better based upon the key community indices, the Weiner Diversity Index (H') and Evenness, which had values of 3.4 and 0.77, respectively. The more enriched nature of the Canal can be seen in the slightly lower Index values of 2.8 (H') and 0.67 (E). Equally important the species dominating the communities were generally representative of low to moderate stress environments, with some patches of amphipods and some areas with deep burrowers. High numbers of organic enrichment indicators (tubificids, capitellids) were not observed. In general the Canal was dominated by a mixture of species indicative of low and moderate levels of enrichment (amphipods, and a variety of crustaceans, mollusks and polychaete worms), while the main basin (particularly near the inlet) supported slightly more diverse communities of polychaetes, molluscs and crustaceans. This pattern of higher organic enrichment and lower habitat quality in the inner versus outer regions is common to estuaries in general. The small size of the Fiddlers Cove estuary, will tend to minimized the magnitude of this spatial differences compared to other larger systems.

Figure VII-13. Aerial photograph of the Fiddlers Cove system showing location of benthic infaunal sampling stations (green symbols).

The benthic animal communities were compared to high quality environments, such as the Outer Basin of Quissett Harbor, which also indicated a level of impairment throughout Fiddlers Cove. The Outer Basin of Quissett Harbor supports benthic animal communities with $\geq$28 species, >400 individuals with high diversity (H' $\geq$3.7) and Evenness (E $\geq$0.77). Similarly, outer stations within Lewis Bay in Barnstable currently support similarly high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Eveness (0.74). Equally important these communities are not consistent with nutrient enrichment being composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms.

Figure VII-14. Aerial photograph of the Rands Harbor system showing location of benthic infaunal sampling stations (green symbols).

Classification of habitat quality necessarily included the structure of the estuarine basin, specifically that it is fully representative of a tidal embayment, as opposed to a tidal river or salt marsh basin. Integration of all of the metrics clearly indicates that the main basin and Canal of the Fiddlers Cove System are generally supporting benthic animal habitat that is moderately impaired. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the upper reach of the Canal present are 0.558 mg TN L^{-1}, a level generally found associated with a low to moderate level of impairment of benthic animal habitat in southeastern Massachusetts estuaries.

Table VII-5. Benthic infaunal community data for the Rands Harbor and Fiddlers Cove embayment systems. 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). Stations refer to map in Figure VII-13 and VII-14.

	Station	Total Species	Total Individuals	#Species Calc @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Rands Harbor						
West Branch	3,4/5	24	231	18	3.73	0.82
East Branch	1	8	256	8	2.34	0.78
Lower Basin	2,6,7	6	188	5	2.07	0.81
Inlet	8	24	414	12	2.63	0.58
Fiddlers Cove						
Main Basin	5,6,8	21	292	15	3.37	0.77
Upper Channel	2,3,4	19	316	13	2.79	0.67
Station numbers refer to ID's on maps presented above.						

Rands Harbor Infaunal Characteristics:

Overall, the Infauna Survey indicated that both the east and west branches of the Rands Harbor system are presently supporting impaired benthic infaunal habitat (Table VII-5). Infaunal habitat within the east branch is more impaired that than west branch, based upon the lower numbers of species and diversity and stress indicator organisms. It appears that organic deposition in these areas is the cause of the stress, consistent with the bottom water oxygen levels and phytoplankton biomass (Table VII-4). The highest quality habitat within the Rands Harbor System is presently at the tidal inlet, as found for nearby Fiddlers Cove and many other estuaries in the region. However, even this region of the embayment is slightly impaired as can be seen from its moderate to high number of species (24), individuals (414) but only moderate diversity and Evenness (H'= 2.6; E= 0.58). Equally important, even the closest station to the inlet had 23% of the community comprised of organic enrichment tolerant species (tubificids, spionids, capitellids).

There is a clear difference between the 2 branches with the West Branch (also called the South Branch) presently supporting higher quality habitat than the East Branch. This is seen in almost every community metric for the west versus east branches, number of species (24 versus 8), diversity (H'= 3.7 versus 2.3), Evenness (E- 0.82 versus 0.81), only the number of individuals was similar (231 versus 256). Benthic species indicative of organic enrichment were evident in both branches as well (tubificids, spionids, capitellids), with some patches of transitional species (amphipods). These organic enrichment species generally accounted for between 25% and 40% of the community within each branch.

The benthic animal communities were compared to high quality environments, such as the Outer Basin of Quissett Harbor, which also indicated a level of impairment throughout Fiddlers Cove. The Outer Basin of Quissett Harbor supports benthic animal communities with $\geq$28 species, >400 individuals with high diversity (H' $\geq$3.7) and Evenness (E $\geq$0.77). Similarly, outer stations within Lewis Bay in Barnstable currently support similarly high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Eveness (0.74). Equally important these communities are not consistent with nutrient enrichment being composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms.

Classification of habitat quality necessarily included the structure of the estuarine basin, specifically, that it is fully representative of a tidal embayment, as opposed to a tidal river or salt marsh basin. Integration of all of the metrics clearly indicates that the main basin and Canal of the Rands Harbor System are generally supporting benthic animal habitat that is moderately impaired. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the upper terminal basins of each branch of the harbor are presently 0.57 mg TN L^{-1}, a level generally found associated with a low to moderate level of impairment of benthic animal habitat in southeastern Massachusetts estuaries.

Other Resource Characteristics:

In addition to benthic infaunal community characterization undertaken as part of the MEP field data collection, other biological resources assessments were integrated into the habitat assessment portion of the MEP nutrient threshold development process as developed by the Commonwealth and as available to the MEP Technical Team. The Massachusetts Division of Marine Fisheries has an extensive library of shellfish resources maps which indicate the current status of shellfish areas closed to harvest as well as the suitability of a system for the propagation of shellfish (Figure VII-15). As is the case with some systems on Cape Cod, all of the enclosed waters of Fiddlers Cove and Rands Harbor are classified as conditionally approved for the taking of shellfish during specific portions of the year, indicating the system is moderately impaired relative to the taking of shellfish. This could be due to bacterial concerns which would be a result of both human activity (septic systems in the watershed) as well as natural fauna, however, it may also be related to the historic oil spill that occurred in Buzzards Bay and significantly affected Wild Harbor. Moreover, the status of conditionally approved in Fiddlers Cove is also likely related to the fact that it support an active marina with associated impacts to sediments. Nevertheless, the Fiddlers Cove and Rands Harbor systems have also been classified as supportive of specific shellfish communities (Figure VII-16 and VII-17). The major shellfish species with potential habitat within the Fiddlers Cove Estuary are soft shell clams (*Mya*) and quahogs (*Mercenaria*). Habitat theoretically suitable to *Mercenaria* and the American oyster can be found throughout the main basin of Fiddlers Cove extending slightly into the narrow channel that constitutes the upper part of the system. Theoretically suitable habitat for *Mya* is essentially along the shallow waters at the upper edge of the main basin of Fiddlers Cove relatively close to the inlet. In Rands Harbor, theoretically suitable habitat for shellfish extends only into the west branch of the system. Accordingly, that area was identified as theoretically supportive of mostly American oyster with limited areas close to the inlet that would be supportive of both soft shell clams (*Mya*) and quahogs (*Mercenaria*). It should be noted that the observed pattern of shellfish growing area is consistent with the observed organic rich sediments within the basins of both these systems. Improving benthic animal habitat quality should also expand the shellfish growing area within these systems.

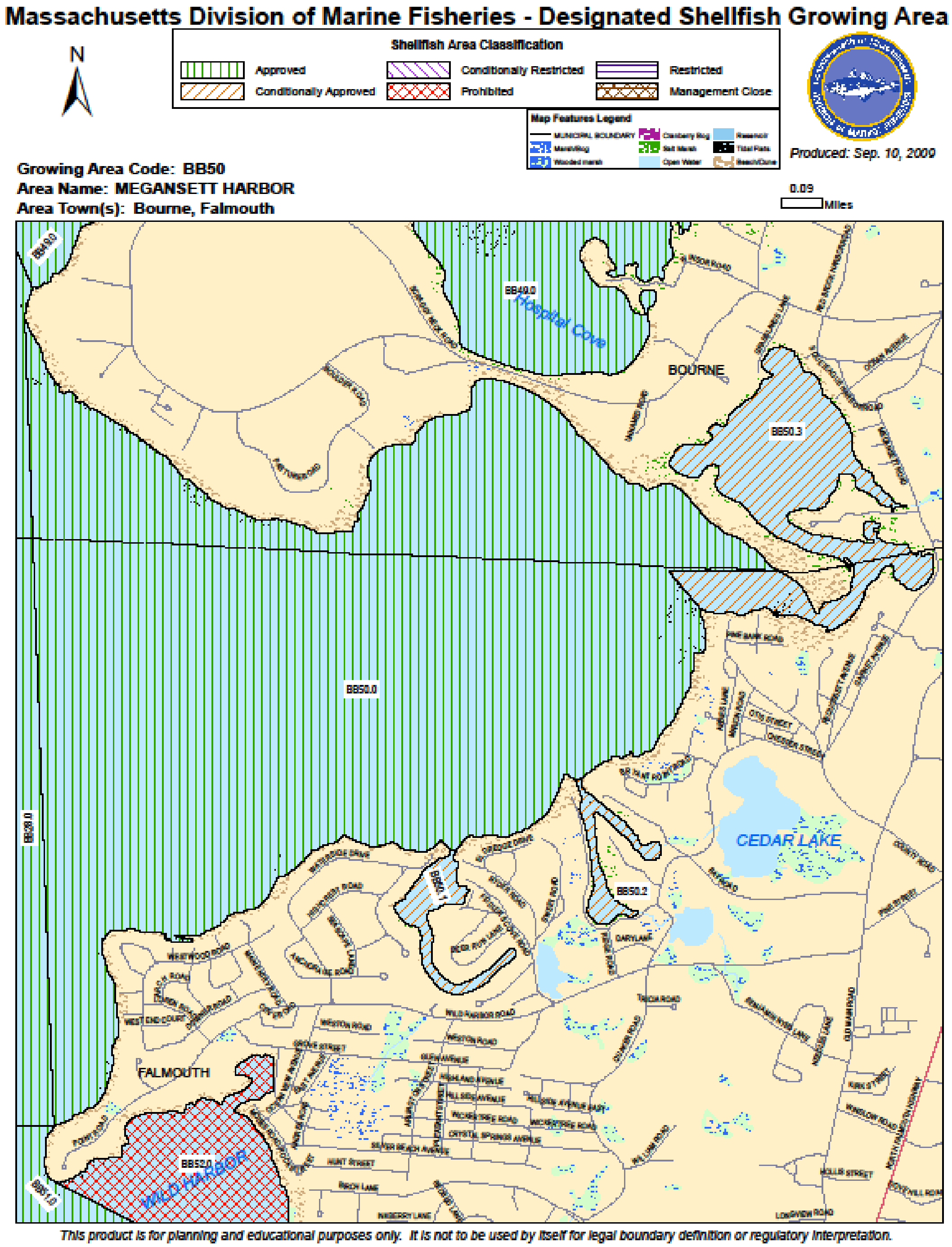


Figure VII-15. Location of shellfish growing areas in the Fiddlers Cove and Rands Harbor embayment systems and the status relative to shellfish harvesting as determined by Mass Division of Marine Fisheries. Closures are generally related to bacterial contamination or "activities", such as the location of marinas.

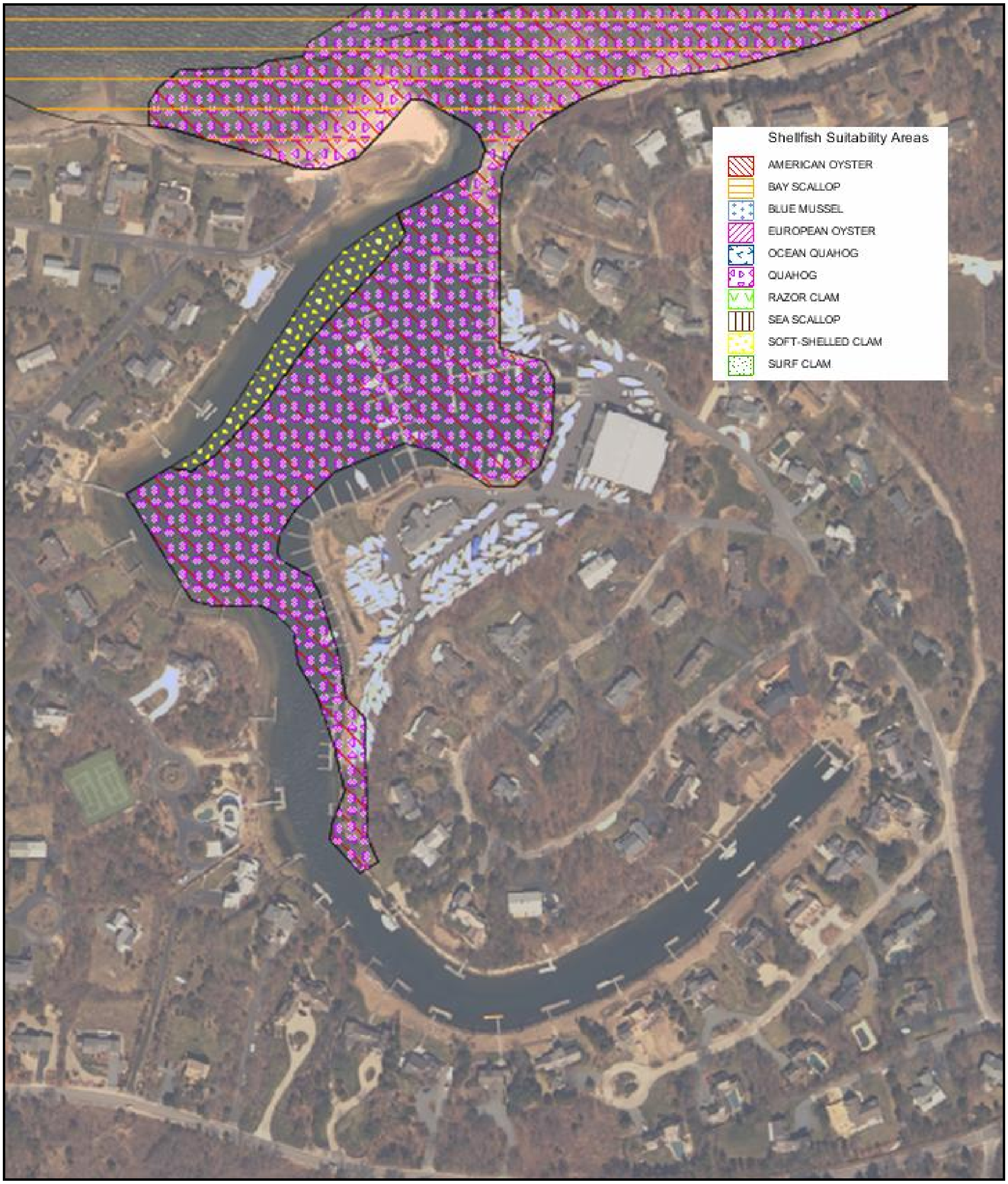


Figure VII-16. Location of shellfish suitability areas within the Fiddlers Cove Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

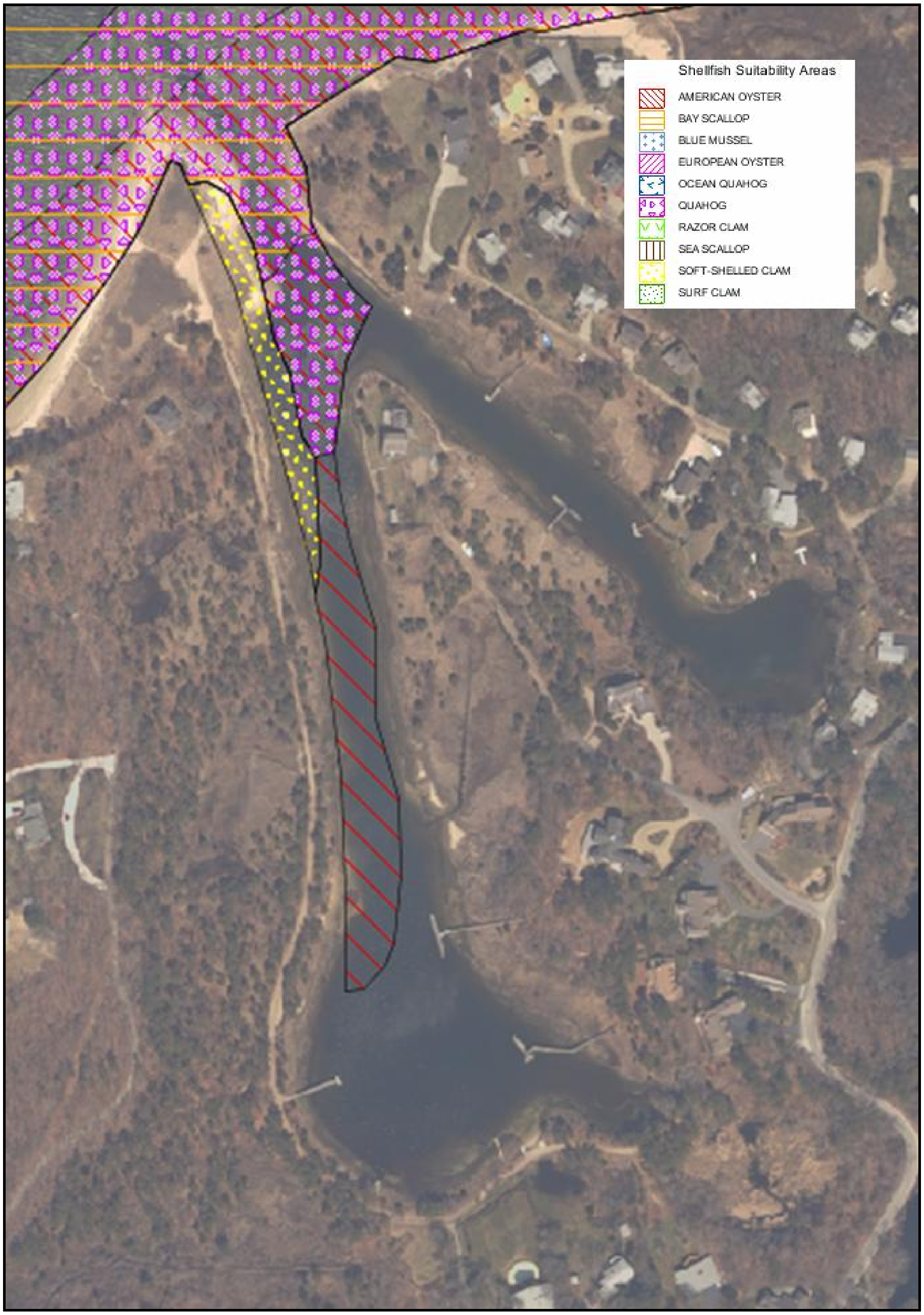


Figure VII-17. Location of shellfish suitability areas within the Rands Harbor Estuary as determined by Mass Division of Marine Fisheries. Suitability does not necessarily mean "presence".

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). Additional information on temporal changes within each sub-embayment of an estuary, its associated watershed nitrogen load and geomorphological considerations of basin depth, stratification and functional type further strengthen the analysis. These data were collected to support threshold development for the Fiddlers Cove and Rands Harbor Embayment Systems by the MEP and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels from the baseline Water Quality Monitoring Program conducted by the Coalition for Buzzards Bay's BayWatchers with analytical support from the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth through 2008.

The Fiddlers Cove and Rands Harbor Systems are artificial open water embayments significantly altered by human activity over the past approximately 100 years. Both estuaries were formed primarily as tidal salt marshes associated tidal creeks. Human activity gradually transformed these salt marsh dominated tidal creeks into more open water systems resembling embayments. The tidal wetlands were removed to increase the navigability of the systems and to create protected harbors, though portions of the upper reaches of Fiddlers Cove still supported bordering saltmarsh into the 1970's. At present almost all of the tidal wetlands along the shoreline of Fiddlers Cove have been removed and replaced with hard coastal structures (e.g. riprap). Although Rands Harbor was also constructed from tidal creeks, it still maintains significant fringing salt marsh areas, particularly in the western branch. Regardless of their formation, both estuaries are now functioning as tributary embayments to Buzzards Bay and must be managed as such. However, based on the history of both these systems, they likely have not supported eelgrass over the past 60 years.

The Fiddlers Cove and Rands Harbor systems are presently relatively simple estuarine systems with Rands Harbor being the more complex of the two given that it has two distinct branches. Both Fiddlers Cove and Rands Harbor are part of the larger complex Megansett Harbor / Squeteague Harbor Estuary. The present inlet to Fiddlers Cove is armored and leads into a main basin that serves as a small mooring area for boats and supports a large marina. The main basin of the Fiddlers Cove system leads into a narrow terminal canal. The Canal, is fully armored and is an artificial feature of the system. The inlet to Rands Harbor is armored to the east and leads to the confluence of two narrow branches, an east branch and a west branch, both of which have dredged channels and end in small terminal basins. Management of ecological changes and impairments of these semi-enclosed systems must be considered not only relative to nutrient enrichment from an increasingly developed coastal watershed but also the structural changes that have occurred over the during the last century.

Each type of functional component to an estuary (salt marsh basin, embayment, tidal river, deep basin (sometimes drown kettles), shallow basin, etc.) has a different natural sensitivity to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of the specific basin and its ability to support eelgrass beds and infaunal communities. Fiddlers Cove and Rands Harbor have not supported eelgrass over the past half century and likely have not supported eelgrass for over a century. The key underlying cause of the absence of historic eelgrass coverage in both Fiddlers Cove and Rands Harbor stems from the fact that they are artificial embayments significantly altered by human activity over the past 100 years. As eelgrass beds could not be documented to exist, either historically or presently, the thresholds analysis for these systems is necessarily focused on restoration of their impaired infaunal animal habitats resulting in part from oxygen depletion and organic matter enrichment. At present, the Fiddlers Cove/Rands Canal Estuarine System is beyond its ability to assimilate nitrogen without impairment and is showing a moderate level of nitrogen enrichment, with generally moderate impairment of infaunal habitats (Table VIII-1). However, it is likely that nitrogen management within these two embayments will improve eelgrass and infaunal habitat within the down-gradient near shore waters of Buzzards Bay.

Key water quality parameters, oxygen and chlorophyll, supported the contention that the basins of Fiddlers Cove and Rands Harbor are impaired by nitrogen enrichment. Within Fiddlers Cove the level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate moderately nutrient enriched waters within the lower basin and upper Canal region. The main basin of Fiddlers Cove showed moderate daily excursions in oxygen levels. Oxygen regularly exceeded 6 mg L^{-1} and periodically exceeded 8 mg L^{-1}. These moderately high oxygen levels are primarily the result of the combined effects of photosynthesis by the high phytoplankton biomass and relatively quiescent waters. Over the 44 day deployment there appear to be multiple moderately intense phytoplankton blooms where chlorophyll a increased to 10-15 ug L^{-1} and a few periods of bloom activity where chlorophyll-a concentrations peaked at just over 20 ug L^{-1}. The periodic low levels of oxygen observed in this system is indicative of moderate habitat impairment which is also consistent with the elevated chlorophyll a levels, also indicative of nitrogen enrichment (average chlorophyll a by mooring, 10.5 ug L-1; water quality monitoring program, 6.1 ug L-1). In the portion of the main basin of the Fiddlers Cove system close to where the narrow channel meets the main basin, chlorophyll-a exceeded the 10 ug L^{-1} benchmark 44 percent of the time. Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

Oxygen conditions within the Canal reach of Fiddlers Cove were similar to the main basin, but did exhibit larger daily excursions in oxygen levels. Oxygen levels periodically regularly exceeded 8 mg L^{-1} and periodically exceeded 10 mg L^{-1}. These high oxygen levels are the result of the combined effects of high phytoplankton biomass (photosynthesis) and high rates of respiration. Average chlorophyll a levels were higher than the main basin, 15.2 ug L^{-1} versus 10.5 ug L^{-1}. The Canal, like the attached main basin has periodic (but more intense) phytoplankton blooms where chlorophyll a regularly increased to 15-20 ug L^{-1} and sometimes to 25 and 35 ug L^{-1} (once for nearly a ten day period). Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments. The periodic low levels of oxygen observed in this system is indicative of moderate to significant habitat impairment, consistent with the elevated chlorophyll a levels, also indicative of nitrogen enrichment.

Table VIII-1. Summary of nutrient related habitat quality within the Fiddlers Cove and Rands Harbor Embayment Systems tributary to outer Megansett Harbor in the Town of Falmouth, MA, based upon assessments detailed in Section VII. Rands Harbor North and South Branches, also sometimes named East and West Branches, respectively.

Health Indicator	Fiddlers Cove		Rands Harbor	
	Main Basin	Canal	North Branch	South Branch
Dissolved Oxygen	MI[1]	MI[2]	H/MI[3]	H/MI[3]
Chlorophyll	MI[4]	MI/SI[5]	H/MI[6]	MI[7]
Macroalgae	H[8]	H[8]	H/MI[9]	H[10]
Eelgrass	--[11]	--[11]	--[11]	--[12]
Infaunal Animals	H/MI[13]	MI[14]	MI/SI[15]	MI[15,16]
Overall:	**H/MI[17]**	**MI[18]**	**MI[19]**	**MI[20]**

1- mooring oxygen <5mg/L 26%, <4mg/L 2% of time, generally 4-7 mg/L, daily excursion ~2.5 mg/L WQMP: >5 mg/L 100%, >6 mg/L 94%of 158 samples
2- mooring oxygen <6mg/L 44%, <5mg/L 8% of time, periodically to 4mg/L, daily excursion ~2.5 mg/L
3-mooring oxygen >6mg/L >75, periodically to 5mg/L, daily excursion ~2.5 mg/L; WQMP South Branch: >5mg/L 95%, >6mg/L 81%, 4-5 mg/L 4%, 3.5-4mg/L 1%, of 195 samples, minimum = 3.5 mg/L
4- levels moderate for a coastal basin, mooring average 10.5 ug L^{-1}, >10ug L^{-1} 44% of record; blooms 20-30 ug L^{-1}; WQMP long-term average 6.1 ug L^{-1}, <10 ug L^{-1} 89% of 40 samples.
5- levels moderate/high, mooring average 15.2 ug L^{-1}, >10ug L^{-1} 74% of record; blooms >20 ug L^{-1};
6 - levels low/moderate for a coastal basin, averaging 6.2 ug L^{-1}, <5 ug L^{-1} 44% and <10 ug L^{-1} 85% of record; blooms ~15 ug L^{-1}.
7- levels moderate for a coastal basin, mooring average 8.3 ug L^{-1}, >5 ug L^{-1} 75%, >10ug L^{-1} 25% of record; blooms 15-20 ug L^{-1}; WQMP long-term average 8.8 ug L^{-1}
8- drift algae generally absent, some small patches of attached Codium.
9- drift algae sparse to medium density patches over very soft organic rich muds
10- sparse filamentous green algae with some attached *Codium*, sands and mud.
11-artificial open water basin, no historical evidence of eelgrass beds within this basin
12-artificial open water basin, no historical evidence of eelgrass beds, but possibly some patches ca. 1950
13- moderate numbers of individuals, species (21), high diversity (>3) and Evenness (>0.7), dominated by non-stress indicator species with crustaceans and mollusks, some deep burrowers; gradient in habitat quality: highest near inlet lowest near mouth of Canal
14- moderate numbers of individuals, species (19), diversity (2.8) and Evenness (~0.7), some stress indicator species but with crustaceans and mollusks, some deep burrowers
15- low numbers of species, moderate number of individuals, low diversity (H':2.3) consistent with the organic rich sediments and periodic D.O. depletion to <4 mg/L.
16- Upper reach: moderate numbers of individuals, moderate to high species (24), diversity (3.7) and Evenness (>0.7), with crustaceans and mollusks, some deep burrowers. Lower reach: see #15 above.
17- benthic infaunal animal communities are moderately diverse and productive with non-stress indicator species and some deep burrowers, but lower quality in the inner region. The level of impairment is consistent with infauna indicators, moderate chlorophyll & periodic DO to 4 mg/L, habitat quality gradient from inlet to mouth of Canal
18-benthic infaunal animal communities are moderately diverse and productive with non-stress indicator species and some deep burrowers, but increased impairment over main basin. Moderate Impairment is consistent with infauna indicators, moderate/high chlorophyll & periodic DO to 4 mg/L and organic enrichment of the sediments.
19- Moderate to Significantly impaired benthic communities throughout branch, low number of species with moderate numbers of individuals and diversity, generally high oxygen but depletions to 4 mg/L in WQMP and moderate levels of chlorophyll, depositional environment has resulted in sediments consisting of soft organically enriched muds.
20- generally high quality benthic habitat in the upper reach but impaired habitat in the lower reach (which resembles the north branch). Animal communities consistent with the generally high DO with periodic depletion and moderate chlorophyll levels, sediments are sand in the upper reach and soft organic enriched muds in the lower reach.

H = High quality habitat conditions; MI = Moderate Impairment; SI = Significant Impairment;
SD = Severely Degraded; -- = not applicable to this estuarine reach
WQMP: Water Quality Monitoring Program

Rands Harbor, like Fiddlers Cove, appears to have moderate impairment of benthic habitat through oxygen depletion and periodic phytoplankton blooms, but a slightly lower extent of oxygen depletion when compared to Fiddlers Cove. Oxygen conditions in the west branch were generally similar to conditions observed in the east branch, although oxygen levels in the terminal basin of the west branch showed slightly less depletion and less of a daily excursion. Oxygen levels in both branches were almost always >5 mg L^{-1}. Moderate daily excursions in oxygen levels were observed at this location, ranging from levels at and slightly above air equilibration to moderately low conditions where levels approached 4 mg L^{-1}. Similarly, the water quality monitoring results showed oxygen levels only periodically declining below 5 mg L^{-1} (5% of 195 samples). Instantaneous oxygen levels that drop below 4 mg L^{-1} are indicative of oxygen stress. The moderate level of organic enrichment of the system is demonstrated by a ten day period of algal bloom activity that was measured during the deployment period as well as the high rates of photosynthesis (carbon fixation) and the rapid declines in oxygen after sunset stemming from respiration.

Both branches of the Harbor have periodic phytoplankton blooms, with the more intense blooms in the western (northern) branch. During the continuous record, there was an extended period (~10 days) of moderately intense phytoplankton blooms where chlorophyll a increased to 10-15 ug L^{-1} and several instances of increased bloom activity where chlorophyll-a concentrations rose to between 15-20 ug L^{-1} and peaked as high as between 20-25 ug L^{-1}. The periodic low oxygen concentrations and chlorophyll blooms observed in the west branch of this system is indicative of low to moderate habitat impairment which is also consistent with the elevated chlorophyll a levels, also indicative of nitrogen enrichment (average chlorophyll a levels measured by the mooring, 8.3 ug L-1 and by the multi-year monitoring program, 8.8 ug L-1). In the west branch of the Rands Harbor system, chlorophyll a exceeded the 10 ug L-1 benchmark 25 percent of the time. Similarly, chlorophyll a levels in the east branch were also elevated, with periodic blooms where chlorophyll a increased to 10-15 ug L^{-1} and 15-20 ug L^{-1}. The periodic low oxygen concentrations observed in the east branch of this system is indicative of some moderate habitat impairment which is also consistent with the moderate elevated chlorophyll a levels, also indicative of nitrogen enrichment (average chlorophyll a levels measured by the mooring, 6.2). In the east branch of the Rands Harbor system, chlorophyll a exceeded the 10 ug L-1 benchmark 15 percent of the time. Average chlorophyll levels over 10 ug L-1 have been used to indicate eutrophic conditions in embayments.

The oxygen data is consistent with organic matter enrichment within the Fiddlers Cove and Rands Harbor Systems, as seen from the parallel measurements of chlorophyll a. The measured levels of oxygen depletion and enhanced chlorophyll a levels follows the spatial pattern of total nitrogen levels, and the parallel variation in these water quality parameters is consistent with watershed based nitrogen enrichment. At present, both the Fiddlers Cove and Rands Harbor Systems are beyond their ability to assimilate nitrogen without impairment and are showing a moderate level of nitrogen enrichment, with moderate impairment of infaunal habitats.

Overall, the Infauna Survey indicated that the main basin and the Canal which comprise the Fiddlers Cove Embayment System presently support low to moderately impaired benthic infaunal habitat. It appears that organic deposition in these areas is the cause of the stress, consistent with the bottom water oxygen levels and phytoplankton biomass. There is a gradient in benthic animal habitat impairment with low to moderate impairment nearest the tidal inlet increasing into the Canal. Animal communities colonizing sediments within the main basin and Canal are moderately diverse (21 and 19 species, respectively) and moderately productive (~300 individuals per sample). The main basin general ranked better based upon the key community indices, the Weiner Diversity Index (H') and Evenness, which had values of 3.4 and 0.77, respectively. The more enriched nature of the Canal can be seen in the slightly lower Index values of 2.8 (H') and 0.67 (E). Equally important the species dominating the communities were generally representative of low to moderate stress environments, with some patches of amphipods and some areas with deep burrowers. High numbers of organic enrichment indicators (tubificids, capitellids) were not observed. In general the Canal was dominated by a mixture of species indicative of low and moderate levels of enrichment (amphipods, and a variety of crustaceans, mollusks and polychaete worms), while the main basin (particularly near the inlet) supported slightly more diverse communities of polychaetes, mollusks and crustaceans.

Overall, the Infauna Survey indicated that both the east and west branches of the Rands Harbor system are presently supporting impaired benthic infaunal habitat, with the east branch more impaired than the west branch. It appears that organic deposition in these areas is the cause of the stress, consistent with the bottom water oxygen levels and phytoplankton biomass. The highest quality habitat is presently at the tidal inlet, a pattern also found for nearby Fiddlers Cove and many other estuaries in the region. However, even this region of Rands Harbor is slightly impaired as seen from its moderate to high number of species (24), individuals (414) but only moderate diversity and Evenness (H'= 2.6; E= 0.58) and that 23% of the community is comprised of organic enrichment tolerant species. There is a clear difference between the 2 branches with the West Branch (also called the South Branch) presently supporting higher quality habitat than the East Branch. This is seen in almost every community metric for the west versus east branches, number of species (24 versus 8), diversity (H'= 3.7 versus 2.3), Evenness (E- 0.82 versus 0.81), only the number of individuals was similar (231 versus 256). Benthic species indicative of organic enrichment were evident in both branches (tubificids, spionids, capitellids), with some patches of transitional species (amphipods).

The benthic animal communities were compared to high quality environments, such as the Outer Basin of Quissett Harbor, which by comparison indicated a level of impairment throughout Fiddlers Cove and Rands Harbor. The Outer Basin of Quissett Harbor supports benthic animal communities with $\geq$28 species, >400 individuals with high diversity (H' $\geq$3.7) and Evenness (E $\geq$0.77). Similarly, outer stations within Lewis Bay in Barnstable currently support similarly high quality benthic habitat as seen in the numbers of individuals (502 per sample), number of species (32), diversity (3.69) and Eveness (0.74). Equally important these communities are not consistent with nutrient enrichment being composed of a variety of polychaete, crustacean and mollusk species, as opposed to stress tolerant small opportunistic oligochaete worms.

Classification of habitat quality necessarily included the structure of the estuarine basin, specifically that it is fully representative of a tidal embayment, as opposed to a tidal river or salt marsh basin. Integration of all of the metrics clearly indicates that the basins of Fiddlers Cove and Rands Harbor are generally supporting benthic animal habitat that is moderately impaired. The proximate cause of impairment is organic matter enrichment and oxygen depletion, stemming ultimately from nitrogen enrichment. Total nitrogen levels within the upper reach of the Fiddlers Cove Canal and within the upper terminal basins of Rands Harbor are presently 0.558 mg TN L^{-1} and 0.57 mg TN L^{-1}, respectively, levels generally found associated with a low to moderate level of impairment of benthic animal habitat in southeastern Massachusetts estuaries.

VIII.2 THRESHOLD NITROGEN CONCENTRATIONS

The approach for determining nitrogen loading rates that will support acceptable habitat quality throughout an embayment system is to first identify a sentinel location within the embayment and secondly, to determine the nitrogen concentration within the water column that will restore the 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 (Section VIII.2), the Linked Watershed-Embayment Model is used to sequentially adjust nitrogen loads until the targeted nitrogen concentration is achieved (Section VIII.3).

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Fiddlers Cove and Rands Harbor Embayment Systems is based primarily upon the nutrient and oxygen levels and current benthic community indicators, as there is no history of eelgrass colonization of these basins. Given the information on a variety of key habitat characteristics, it is possible to develop a site-specific threshold, which is a refinement upon more generalized threshold analyses frequently employed.

Both the Fiddlers Cove and Rands Harbor Embayment Systems presently show a moderate level of impairment of benthic animal habitat and both systems are beyond their nitrogen thresholds (i.e. the level of nitrogen a system can tolerate without impairment). Both systems show similar indications of impairment to infaunal animal habitat, supported by the observed levels of oxygen depletion and clearly enhanced chlorophyll a levels throughout their tidal reaches. The spatial distribution of habitat quality and associated oxygen and chlorophyll a levels also parallels the gradient in water column total nitrogen levels within these estuaries and indicate a greater impairment in the upper versus lower reaches.

Sentinel stations were established within each estuary for development of nitrogen threshold targets that when met will restore benthic animal habitat throughout the tidal reaches. Since nitrogen levels are highest in the upper reaches of each system the Sentinel Station for Fiddlers Cove was placed within the upper reach of the Canal and in Rands Harbor in the terminal basins of each branch. Rands Harbor requires 2 sentinel stations, since the branches have different watersheds, stream inputs and sediment characteristics. As there are no long-term water quality monitoring stations in each of these basins the water quality model was used to determine the present total nitrogen levels at each one under present loading conditions, in order to refine nitrogen threshold development (Section VI). Using this approach, total nitrogen levels within the upper reach of the Fiddlers Cove Canal and within the upper terminal basins of Rands Harbor are presently 0.56 mgTN L^{-1} and 0.57 mgTN L^{-1}, respectively. These TN levels are comparable to other estuarine basins throughout the region that show similar levels of oxygen depletion, organic enrichment and moderately impaired benthic animal habitat. Given that in numerous estuaries it has been previously determined that 0.500 mg TN L-1 is the upper limit to sustain unimpaired benthic animal habitat (Eel Pond, Parkers River, upper Bass River, upper Great Pond, upper Three Bays) this level is deemed most appropriate for restoration of the basins comprising Fiddlers Cove and Rands Harbor. Watershed management to meet these restoration thresholds for benthic animal habitat is the focus of the nitrogen management threshold analysis (Section VIII.3).

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 infaunal habitats in the Fiddlers Cove and Rands Harbor 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 lowered by reductions in septic effluent discharges, until the nitrogen levels reached the threshold level at the sentinel station chosen for Fiddlers Cove and Rands Harbor. It is important to note that load reductions can be produced by reduction of any or all sources. 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. A comparison between present septic and total watershed loading and the loadings for the two modeled threshold scenarios is provided in Tables VIII-2 and VIII-3.

As shown in Table VIII-2, the nitrogen load reductions within the system necessary to achieve the threshold nitrogen concentrations required 33% removal of septic load (associated with direct groundwater discharge to the embayment) for the entire system. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

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. For example, removal of 33% of the septic load from the North Rands Harbor watershed results in a 27% reduction in total watershed nitrogen load within the North Rands Harbor. 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.

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, reductions in TN total watershed load of 25% are required in the system.

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.

Table VIII-2. Comparison of sub-embayment watershed septic loads (attenuated) used for modeling of present and threshold loading scenarios of the Fiddlers Cove and Rands Harbor 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
Rands Inlet	0.008	0.008	0.0%
Rands North	2.041	1.368	33.0%
Rands South	2.477	1.486	40.0%
Fiddlers Main	0.797	0.797	0.0%
Fiddlers Upper	2.534	1.571	38.0%
System Total	7.857	5.230	-33.4%

Table VIII-3. Comparison of sub-embayment ***total watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Fiddlers Cove and Rands Harbor 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
Rands Inlet	0.014	0.014	-0.0%
Rands North	2.496	1.822	-27.0%
Rands South	3.564	2.574	-27.8%
Fiddlers Main	0.890	0.890	-0.0%
Fiddlers Upper	3.441	2.478	-28.0%
System Total	10.405	7.778	-25.2%

Table VIII-4. Threshold sub-embayment loads used for total nitrogen modeling of the Fiddlers Cove and Rands Harbor 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)
Rands Inlet	0.014	0.022	0.103
Rands North	1.822	0.033	0.195
Rands South	2.574	0.088	0.285
Fiddlers Main	0.890	0.068	0.863
Fiddlers Upper	2.478	0.115	0.345
System Total	7.778	0.326	1.791

Table VIII-5. Comparison of model average total N concentrations from present loading and the threshold scenario, with percent change, for the Fiddlers Cove and Rands Harbor System. The threshold is 0.50 mg/L for stations in the upper reaches of each subembayment within both Fiddlers Cove and Rands Harbor, as shown in Figure VIII-1.				
Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Fiddlers Cove	FC1	0.3891	0.3731	-4.1%
Fiddlers Cove	Sentinel	0.5579	0.4998	-10.4%
Rands Harbor	RH1	0.4469	0.4090	-8.5%
Rands North Arm	Sentinel	0.5696	0.4995	-12.3%
Rands South Arm	Sentinel	0.5705	0.4996	-12.4%

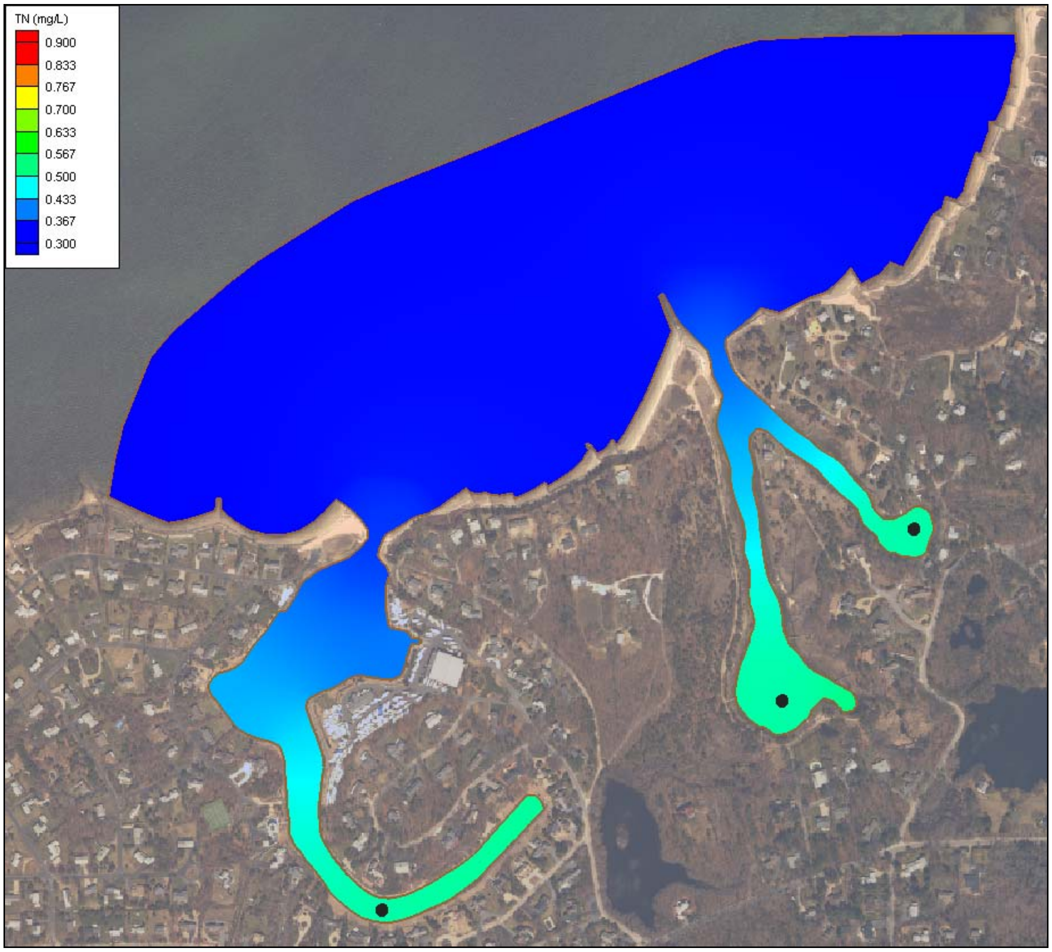


Figure VIII-1. Contour plot of modeled total nitrogen concentrations (mg/L) in the Fiddlers Cove and Rands Harbor estuary, for threshold conditions. Threshold station is shown (0.5 mg/L at the black symbols).

IX. REFERENCES

AFCEE (with Howes, B.L. & Jacobs Engineering). 2000. Ashumet Pond Trophic Health Technical Memorandum. AFCEE/MMR Installation Restoration Program, AFC-J23-35S18402-M17-0005, 210pp.

Anders, F.J., and M.R. Byrnes. 1991 Accuracy of Shoreline Change Rates as Determined from Maps and Aerial Photographs. Shore and Beach 16:17-26.

Aravena, R. and W.D. Robertson. 1998. Use of Multiple Isotope Tracers to Evaluate Denitrification in Ground Water: Study of Nitrate from a Large-Flux Septic System Plume. Ground Water, 36(6):975-982.

Brawley, J.W., G. Collins, J.N. Kremer, C.H. Sham, and I. Valiela, 2000. A time-dependent model of nitrogen loading to estuaries form coastal watersheds. Journal of Environmental Quality 29:1448-1461.

Brigham Young University, 1998. "User's Manual, Surfacewater Modeling System."

Burns, K., M. Ehrhardt, B. Howes and C. Taylor., 1993. Subtidal benthic community respiration and production rates near the heavily oiled coast of Saudi Arabia. Marine Pollution Bull. 27:199-205.

Cambareri, T.C. and E.M. Eichner, 1998. Watershed Delineation and Ground Water Discharge to a Coastal Embayment. *Ground Water*; 36(4): 626-634.

Cape Cod Commission, 1998. "Cape Cod Coastal Embayment Project." Barnstable, MA.

Cape Cod Commission Water Resources Office, 1991. Technical Bulletin 91-001, Nitrogen Loading.

Cape Cod Commission Water Resources Office, 1998. Cape Cod Coastal Embayment Project Interim Final Report.

Cape Cod Commission, 1998. Cape Cod Coastal Embayment Project: A Nitrogen Loading Analysis of Popponesset Bay. Cape Cod Commission Technical Report.

Cape Cod Commission. 1996. Regional Policy Plan. Cape Cod Commission, Barnstable, MA.

Cape Cod Commission. 2001. Regional Policy Plan. Cape Cod Commission, Barnstable, MA.

Chow, V. T. (1959). Open Channel Hydraulics, McGraw-Hill, NY.

Conover, J.T., 1958. Seasonal Growth of Benthic Marine Plants as Related to Environmental Factors in an Estuary. *Institute of Marine Science*, 5:97-147.

Costa, J.E., B.L. Howes, I. Valiela and A.E. Giblin. 1992. Monitoring nitrogen and indicators of nitrogen loading to support management action in Buzzards Bay. In: McKenzie et al. (eds.) Ecological Indicators Chapter. 6, pp. 497-529.

Costa, J.E., G. Heufelder, S. Foss, N.P. Millham, B.L. Howes, 2002. Nitrogen Removal Efficiencies of Three Alternative Septic System Technologies and a Conventional Septic System. Environment Cape Cod 5(1): 15-24.

Costello, Charles. Section Chief, Wetlands Conservancy Program. Director, Eelgrass Mapping Program 617-292-5907.

Crowell, M., S.P. Leatherman, M.K. Buckley. 1991. Historical Shoreline Change: Error Analysis and Mapping Accuracy. Journal of Coastal Research 7(3):839-852.

D'Elia, C.F, P.A. Steudler and N. Corwin. 1977. Determination of total nitrogen in aqueous samples using persulfate digestion. Limnology and Oceanography 22:760-764.

DeSimone, L.A. and B.L. Howes. 1996. Denitrification and nitrogen transport in a coastal aquifer receiving wastewater discharge. *Environmental Science and Technology* 30:1152-1162.

Dyer, K.R., 1997. Estuaries, A Physical Introduction, 2nd Edition, John Wiley & Sons, NY, 195 pp.

Eichner, E.M. and T.C. Cambareri, 1992. Technical Bulletin 91-001: Nitrogen Loading. Cape Cod Commission, Water Resources Office, Barnstable, MA. Available at:

http://www.capecodcommission.org/regulatory/NitrogenLoadTechbulletin.pdf

Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith, 2003. Cape Cod Pond and Lake Atlas. Cape Cod Commission. Barnstable, MA.

Eichner, E.M., T.C. Cambareri, K. Livingston, C. Lawrence, B. Smith, and G. Prahm, 1998. Cape Coastal Embayment Project: Interim Final Report. Cape Cod Commission, Barnstable, MA.

Ellis, M.Y., 1978. Coastal Mapping Handbook, Department of the Interior, U.S. Geological Survey and U.S. Department of Commerce, National Ocean Service and Office of Coastal Zone Management, U.S. GPO, Washington, D.C.

Fischer, H. B., List, J. E., Koh, R. C. Y., Imberger, J., and Brooks, N. H. (1979). *Mixing in inland and coastal waters*. Academic. San Diego.

FitzGerald, D.M., 1993. "Origin and Stability of Tidal Inlets in Massachusetts." In: Coastal and Estuarine Studies: Formation and Evolution of Multiple Tidal Inlets, Volume 29, Symposium on Hydrodynamics and Sediment Dynamics of Tidal Inlets (D. G. Aubrey and G.S. Geise, eds.). American Geophysical Union, Washington, D.C. pp. 1-61.

Frimpter, M.H., J.J. Donohue, M.V. Rapacz. 1990. A mass-balance nitrate model for predicting the effects of land use on groundwater quality. U.S. Geological Survey Open File Report 88:493.

Geise, G.S., 1988. "Cyclical Behavior of the Tidal Inlet at Nauset Beach, Massachusetts: Application to Coastal Resource Management." In: Lecture Notes on Coastal and Estuarine Studies, Volume 29, Symposium on Hydrodynamics and Sediment Dynamics of Tidal Inlets (D. Aubrey and L. Weishar, eds.), Springer-Verlag, NY, pp. 269-283.

Hamersley, R.M. and B. Howes, 2004. Nitrogen Fluxes and Mitigation Strategies in the Audubon Skunknett River Wildlife Sanctuary. Report to the Town of Barnstable

Hampson, G.R., E.T. Moul. 1978. No. 2 Fuel Oil Spill in Bourne, Massachusetts: Immediate Assessment of the Effects on Marine Invertebrates and a 3-Year Study of Growth and Recovery of a Salt Marsh. Journal of Fisheries Research Bd. Canada 35(5):731-744

Hampson, G.R. 1989. A REMOTS Survey of Buzzards Bay with Ground Truth Verification, EPA Report Region I Water Management Division, CR-8142976-01

Harbaugh, A.W. and McDonald, M.G., 1996. User's Documentation for MODFLOW-96, an update to the U.S. Geological Survey Modular Finite-Difference Ground-Water Flow Model: U.S. Geological Survey Open-File Report 96-485, 56p.

Henderson, F. M., 1966. *Open Channel Flow*. Macmillan Publishing Company, New York. pp. 96-101.

Howes, D.L, D.D. Goehringer, 1996. Water Quality Monitoring of Falmouth's Coastal Ponds: Results from the 1994 and 1995 Seasons

Howes, B.L., D.D. Goehringer, N.P. Millham, D.R. Schlezinger, G.R. Hampson, C.D. Taylor and D.G. Aubrey. 1997. Nantucket Harbor Study: A quantitative assessment of the environmental health of Nantucket Harbor for the development of a nutrient management plan. Technical Report to the Town of Nantucket, pp. 110.

Howes, B.L., J.S. Ramsey and S.W. Kelley, 2000. Nitrogen modeling to support watershed management: comparison of approaches and sensitivity analysis. Final Report to MA Department of Environmental Protection and USEPA, 94 pp. Published by MADEP.

Howes, B.L., R.I. Samimy and B. Dudley, 2003. Massachusetts Estuaries Project, Site-Specific Nitrogen Thresholds for Southeastern Massachusetts Embayments: Critical Indicators Interim Report

Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2003). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Stage Harbor, Sulphur Springs, Taylors Pond, Bassing Harbor, and Muddy Creek, Chatham, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes, B., Kelley, S., Ramsey, J., Samimy, R., Eichner, E., Schlezinger, D., and Wood, J., 2004. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Popponesset Bay, Mashpee and Barnstable, Massachusetts. Commonwealth of Massachusetts, Department of Environmental Protection, Massachusetts Estuaries Project, 138 pp. + Executive Summary, 10 pp.

Howes, B.L., R.I. Samimy, D.R. Schlezinger, S. Kelley, J. Ramsey, T. Ruthven, and E. Eichner, 2004. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Quashnet River, Hamblin Pond, and Jehu Pond, in the Waquoit Bay System of the Towns of Mashpee and Falmouth, MA. Massachusetts Estuaries Project Final Report, pp. 147.

Howes B.L., J. Ramsey, E.M. Eichner, R.I. Samimy, S. W. Kelley, D.R. Schlezinger (2005).

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Oyster Pond System, Falmouth, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes B.L., J. Ramsey, E.M. Eichner, R.I. Samimy, S. W. Kelley, D.R. Schlezinger (2005).

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Three Bays System, Barnstable, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes, B.L., H.E. Ruthven, E.M. Eichner, J.S. Ramsey, R.I. Samimy, D.R. Schlezinger. 2008. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Lewis Bay System, Towns of Barnstable and Yarmouth, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA

Howes B., S. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2009). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Parkers River Embayment System, Yarmouth, Massachusetts, Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA.

Howes, B.L. and J.M. Teal. 1995. Nitrogen balance in a Massachusetts cranberry bog and its relation to coastal eutrophication. Environmental Science and Technology 29:960-974.

Jorgensen, B.B. 1977. The sulfur cycle of a coastal marine sediment (Limfjorden, Denmark). Limnology Oceanography, 22:814-832.

King, Ian P. (1996). "Users Guide to RMA2 Version 4.2." US Army Corps of Engineers – Waterways Experiment Station Hydraulics Laboratory.

Kelley, S.W., Ramsey, J.R., Côté, J.M., Wood, J.D. (2001). "Tidal Flushing Analysis of Coastal Embayments in Chatham, MA" Applied Coastal Research and Engineering, Inc. report prepared for the Town of Chatham. 115 pp.

King, Ian P., 1990. "Program Documentation - RMA2 - A Two Dimensional Finite Element Model for Flow in Estuaries and Streams." Resource Management Associates, Lafayette, CA.

Klump, J. and C. Martens. 1983. Benthic nitrogen regeneration. In: Nitrogen in the Marine Environment, (Carpenter & Capone, eds.). Academic Press.

Koppelman, L.E. (Ed.). 1978. The Long Island comprehensive waste treatment management plan. Vol II. Summary documentation report, Long Island Regional Planning Board, Hauppage, N.Y.

Lindeburg, Michael R., 1992. *Civil Engineering Reference Manual, Sixth Edition*. Professional Publications, Inc., Belmont, CA.

Massachusetts Department of Environmental Protection, 1999. DEP Nitrogen Loading Computer Model Guidance. Bureau of Resource Protection. Boston, MA. Available at:

http://www.state.ma.us/dep/brp/dws/techtool.htm

Massachusetts Department of Revenue. November, 2002. Property Type Classification Codes.

Massachusetts Water Resources Authority, 1983. Water supply study and environmental impact statement for the year 2020, Task I: Water demand projections. MWRA Report, Boston.

Masterson, J.P., Walter, D.A., Savoie, J., 1996, Use of particle tracking to improve numerical model calibration and to analyze ground-water flow and contaminant migration, Massachusetts Military Reservation, western Cape Cod, Massachusetts: U.S. Geological Survey Open-File Report 96-214, 50 p.

Millham, N.P. and B.L. Howes, 1994a. Freshwater flow into a coastal embayment: groundwater and surface water inputs. Limnology and Oceanography 39: 1928-1944.

Millham, N.P. and B.L. Howes, 1994b. Patterns of groundwater discharge to a shallow coastal embayment. Marine Ecology Progress Series 112:155-167.

Millham, N.P. and B.L. Howes. 1994. Nutrient balance of a shallow coastal embayment: I. Patterns of groundwater discharge. Marine Ecology Progress Series 112:115-167.

Millham, N.P. and B.L. Howes. 1994. A comparison of methods to determine K in a shallow coastal aquifer. Groundwater. 33:49-57.

Murphy, J. and J.P. Reilly, 1962. A Modified Single Solution Method for the Determination of Phosphate in Natural Waters. Analytica Chemica Acta, v. 27, p. 31-36

Nelson, M.E., S.W. Horsley, T.C. Cambareri, M.D. Giggey and J.R. Pinnette. 1998. Predicting nitrogen concentrations in groundwater- An analytical model. Focus Conference on Eastern Groundwater Issues, National Water Well Association, Stamford, CT.

Norton, W.R., I.P. King and G.T. Orlob, 1973. "A Finite Element Model for Lower Granite Reservoir", prepared for the Walla Walla District, U.S. Army Corps of Engineers, Walla Walla, WA.

O'Hara, C.J., Oldale, R.N., 1987. Geology, Shallow Structure, and Bedform Morphology, Nantucket Sound, Massachusetts. 1:125,000. United States Geological Survey Miscellaneous Field Studies Map MF 1911.

Oldale, R. N., 1992, Cape Cod and the Islands: The geologic history: East Orleans, MA, Parnassus Imprints, 208 p.

Oldale, R.N. 1974a. Geologic Map of the Hyannis Quadrangle, Barnstable County, Cape Cod, Massachusetts. US Geological Survey Map GQ-1158. US Geological Survey, Reston, VA.

Oldale, R.N. 1974b. Geologic Quadrangle Maps of the United States, Geologic Map of the Dennis Quadrangle, Barnstable County, Cape Cod, Massachusetts. US Geological Survey Map GQ-1114. US Geological Survey, Washington, DC.

Pleasant Bay Technical Advisory Committee, and Ridley & Associates, Inc., 1998. Pleasant Bay resource management plan. Report to the Pleasant Bay Steering Committee, 158 pp + app.

Pollock, D.W., 1994. User's Guide to MODPATH/MODPATH_PLOT, version 3 – A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey modular three dimensional finite-difference ground-water-flow-model: U.S. Geological Survey Open-File Report 94-464, [variously paged].

Ramsey, J.S., B.L. Howes, S.W. Kelley, and F. Li (2000). "Water Quality Analysis and Implications of Future Nitrogen Loading Management for Great, Green, and Bournes Ponds, Falmouth, Massachusetts." Environment Cape Cod, Volume 3, Number 1. Barnstable County, Barnstable, MA. pp. 1-20.

Ramsey, John S., Jon D. Wood, and Sean W. Kelley, 1999. "Two Dimensional Hydrodynamic Modeling of Great, Green, and Bournes Ponds, Falmouth, MA." Applied Coastal Research and Engineering, Inc. report prepared for the Town of Falmouth and Horsley & Witten, Inc. 41 pp.

Ramsey, J.S., B.L. Howes, N.P. Millham, and D. Bourne. 1995. Hydrodynamic and water quality study of West Falmouth Harbor, Falmouth MA. Aubrey Consulting Inc. Technical Report for Town of Falmouth, pp. 81.

Rhoads, D.C. and J.D. Germano. 1986. Interpreting long-term changes in benthic community structure: a new protocol. Hydrobiologia 142:291-308

Robertson, W.D., S.L. Schiff, and C.J. Ptacek. 1998. Review of Phosphate Mobility and Persistence in 10 Septic System Plumes. Ground Water, 36(6):1000-1010.

Ryther, J.H., and W.M. Dunstan. 1971. Nitrogen, phosphorous and eutrophication in the coastal marine environment. Science, 171:1008-1012.

Scheiner, D. 1976. Determination of ammonia and Kjeldahl nitrogen by indophenol method. Water Resources 10: 31-36.

Shalowitz, A.L., 1964. Shore and Sea Boundaries--with special reference to the interpretation and use of Coast and Geodetic Survey Data. U.S. Department of Commerce Publication 10-1, Two Volumes, U.S. GPO, Washington, D.C.

Smith, K. 1999. Salt Marsh Uptake of Watershed Nitrate, Mashapaquit Creek Marsh, West Falmouth Harbor, Falmouth, Cape Cod, Massachusetts. Masters Thesis, Boston University Department of Earth Sciences, Boston, pp. 1-76.

Smith, K.N. and B.L. Howes. Manuscript. Attenuation of watershed nitrogen by a New England salt marsh: a buffer for cultural eutrophication of coastal waters.

Smith, R.L., B.L. Howes and J.H. Duff. 1991. Denitrification in nitrate-contaminated groundwater: occurrence in steep vertical geochemical gradients. Geochimica Cosmochimica Acta 55:1815-1825.

Stearns and Wheler. 2001. Wastewater Facilities Plan and Final Environmental Impact Report for the Town of Falmouth, Massachusetts. Hyannis, MA.

Taylor, C.D. and B.L. Howes, 1994. Effect of sampling frequency on measurements of seasonal primary production and oxygen status in near-shore coastal ecosystems. Marine Ecology Progress Series 108: 193-203.

Thieler, E.R., J.F. O'Connell, C.A. Schupp, 2001. The Massachusetts Shoreline Change Project: 1800s to 1994. Technical Report, 60 p.

U.S. Army Corps of Engineers (1964). "Beach Erosion Control Report on Cooperative Study of Falmouth, Massachusetts." Headquarters, Department of the Army, Office of the Chief of Engineers, Washington, D.C.

U.S. Army Corps of Engineers, New England Division, Tidal Flood Profiles, New England Coastline, September 1988.

US Army, Engineer Research and Development Center, Waterways Experiment

Station, Coastal and Hydraulics Laboratory, Users Guide To RMA4 WES Version 4.5, June 05, 2001.

USGS web site for groundwater data for Massachusetts and Rhode Island:

http://ma.water.usgs.gov/ground_water/ground-water_data.htm

Van de Kreeke, J., 1988. "Chapter 3: Dispersion in Shallow Estuaries." In: Hydrodynamics of Estuaries, Volume I, Estuarine Physics, (B.J. Kjerfve, ed.). CRC Press, Inc. pp. 27-39.

Walter, D.A. and Whealan, A.T. 2005. Simulated Water Sources and Effects of Pumping on Surface and Ground Water, Sagamore and Monomoy Flow Lenses, Cape Cod, Massachusetts. US Geological Survey Scientific Investigations Report 2004-5181, 85 p.

Weiskel, P.K. and B.L. Howes, 1991. Quantifying Dissolved Nitrogen Flux Through a Coastal Watershed. Water Resources Research, Volume 27, Number 11, Pages 2929-2939.

Weiskel, P.K. and B.L. Howes, 1992, Differential Transport of Sewage Derived Nitrogen and Phosphorous through a Coastal Watershed. Environmental Science and Technology, Volume 26, No. 2, pp. 352 - 360

Wilhelm, S.R., S.L. Schiff, and W.D. Robertson. 1996. Biogeochemical Evolution of Domestic Waste Water in Septic Systems: 2. Application of Conceptual Model in Sandy Aquifers. Ground Water, 34(5):853-864.

Wood, J.D., J.S. Ramsey, and S. W. Kelley, 1999. "Two-Dimensional Hydrodynamic Modeling of Barnstable Harbor and Great Marsh, Barnstable, MA." Applied Coastal Research and Engineering, Inc. report prepared for the Town of Barnstable. 28 pp.

Zimmerman, J.T.F., 1988. "Chapter 6: Estuarine Residence Times." In: Hydrodynamics of Estuaries, Volume I, Estuarine Physics, (B.J. Kjerfve, ed.). CRC Press, Inc. pp. 75-84.