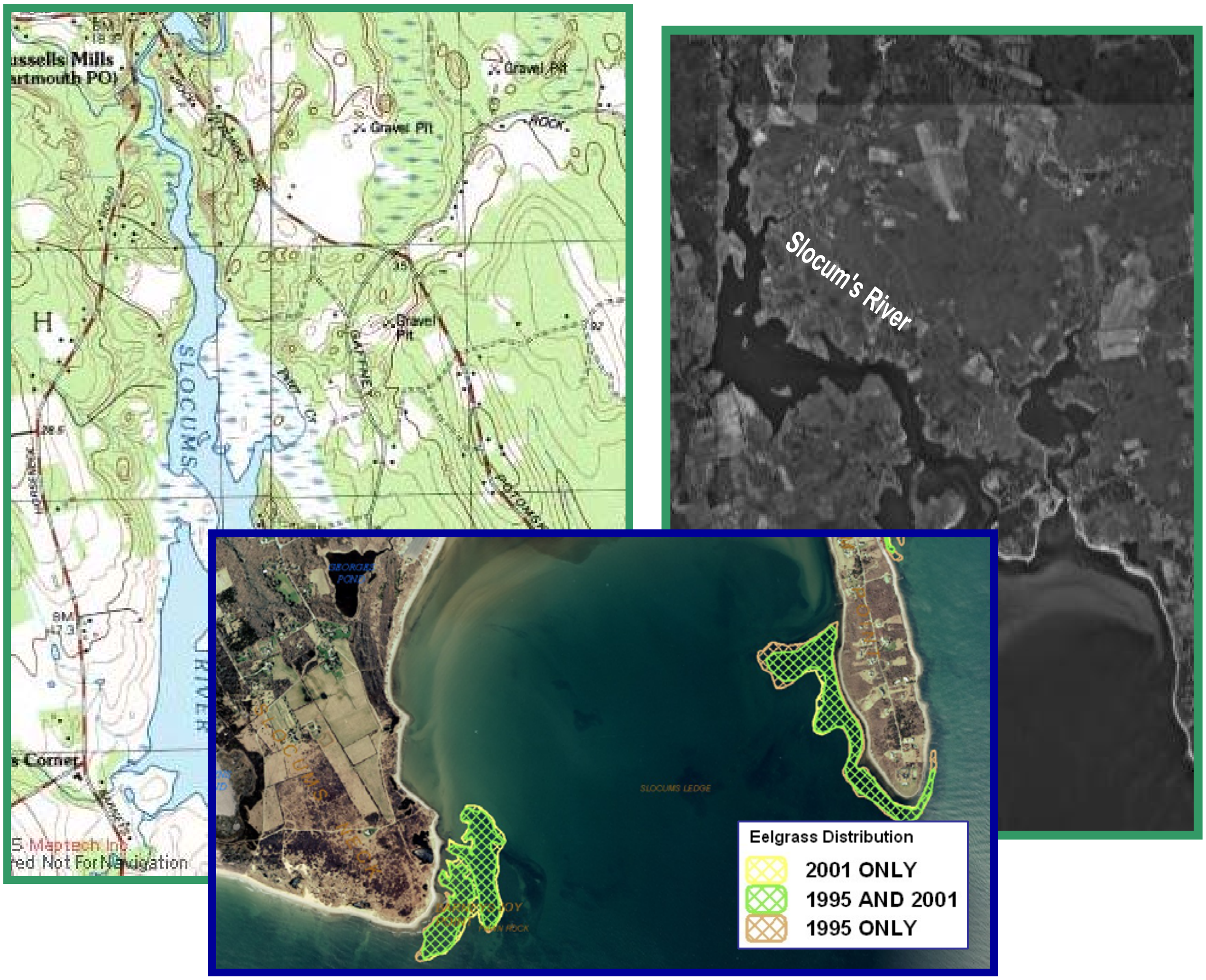
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Slocum's and Little River Estuaries, Dartmouth, MA



University of Massachusetts Dartmouth
School of Marine Science and Technology

Massachusetts Department of
Environmental Protection

FINAL REPORT – December 2008

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Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Slocum's and Little River Estuaries, Dartmouth, MA

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The Massachusetts Estuaries Project Technical Team would like to acknowledge the contributions of the many individuals who have worked tirelessly for the restoration and protection of the critical coastal resources of the Slocum's and Little River Estuaries and supported the application of the Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for these systems. Without these stewards and their efforts, this project would not have been possible.

First and foremost we would like to recognize and applaud the significant time and effort in data collection and discussion spent by members of the Coalition for Buzzards Bay's BayWatcher, Water Quality Monitoring Program. These individuals gave of their time to consistent and sound nutrient related water quality from this system for over a decade. These data were enhanced by short-term intensive water quality monitoring efforts by the Lloyd Center Staff and interns participating in the Turn the Tide Project. These multiple efforts have resulted in a solid water quality database for these estuaries, without which the present analysis would not have been possible. Of particular note has been the effort of the Coalition for Buzzards Bay's Monitoring Coordinator, Tony Williams, who has spent countless hours ensuring a scientifically defensible monitoring program and reviewing data and information with MEP Technical Team members.

The present MEP Technical Report was developed as part of the on-going partnership project to restore the Town of Dartmouth's estuaries, known as Turn-The-Tide. This program is a partnership between the Town of Dartmouth, the Coalition for Buzzards Bay, the Lloyd Center for the Environment and the Coastal Systems Program at the School for Marine Science and Technology - University of Massachusetts Dartmouth. The goal is to restore water quality and living resources in Dartmouth's three major estuarine systems. Much of the present effort was conducted under this partnership, which greatly enhanced information and data transfers with the Town and its Departments. The Town of Dartmouth and its citizens have expended "extra" effort in the stewardship of these critical coastal systems and are to be commended.

Departments and staff from the Town of Dartmouth have provided essential insights toward this effort, particularly the Department of Public Works and its commissioners who oversaw the Turn-The-Tide Project and specifically the help provided by David Hickox; Water and Sewer Division, Steve Sullivan; Animal Control, Sandra Gosselin and Wendy Henderson Board of Health. The technical team would like to specifically acknowledge the efforts of Mike O'Reilly, Dartmouth's Environmental Affairs Coordinator, who worked tirelessly as the Town interface with the Turn-The-Tide Project and was key in facilitating the overall effort. Other individuals of particular note include Mark Rasmussen, Executive Director CBB and Darcy McMahon Director of the Lloyd Center, who helped to guide and disseminate the information from the Turn-The-Tide effort.

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Support for this project was provided by the Town of Dartmouth through the Turn the Tide Project, private donations from citizens of the Town of Dartmouth, the MassDEP, and the USEPA.

This Nutrient Threshold Technical Report to be used by the Town of Dartmouth in the restoration of two of its key estuarine systems is dedicated to Don Tucker former Director of the Lloyd Center, who helped to establish the Turn the Tide partnership project but passed away suddenly before its completion.

CITATION

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I. INTRODUCTION

The Slocum's River and Little River Estuaries are located within the Town of Dartmouth, Massachusetts. Both have tidal inlets to the south into Buzzards Bay. The watershed for the Slocum's River is located mostly within the Town of Dartmouth, with substantial areas of the northern watershed within the City of New Bedford, and very small portions of the western watershed are in the Town of Westport, while Little River is solely within the Town of Dartmouth. While these two estuaries have separate and independent tidal basins, they both receive tidal waters from Buzzards Bay though a common basin bounded by Barneys Joy Point and Mishaum Point. As such, it was important to assess them in concert and the assessment and modeling presented in this MEP Nutrient Threshold Technical Report is based upon an integrated modeling and assessment approach of the Slocum's and Little River Complex.

Slocums River: The present-day configuration of the Slocum's River embayment results from the drowning by rising sea level of an old river valley formed by long-term erosion of the underlying bedrock fabric and modified by glaciation. At present, the Slocum's River is a tidal embayment with a number of streams, which flow into it. The principal stream is the Paskamanset River, which discharges into the northern headwaters and accounts for >80% of the surface water inflows. Other streams that discharge to the embayment include, in order of diminishing freshwater contribution: Destruction Brook; two streams crossing Barneys Joy Road and entering the estuary on the southwestern shore; and several relatively small, seasonal streams along both shores of the embayment. The watershed boundaries are defined primarily by a bedrock morphology of several low ridges and valleys running roughly in a northward and northeastward direction (Zen, 1983). The mouth of the Slocum's River embayment is defined by bedrock outcrops on the east at Potomska Point and by outcrops on the west in Lloyd State Park. In addition to the bedrock morphology, large amounts of sand occur within the lower embayment and within and beyond the mouth of the estuary. The sand results from coastal processes, occurring as a dynamic and variable spit and bar system, which has strongly influenced the configuration and efficiency of the tidal inlet over at least the past 70 years (Fitzgerald, et al, 1993). At present, the main tidal channel flows to the east around Potomska Point and along the shore of Mishaum Point where it enters Buzzards Bay (Figure I-1). Prior to about 1980, the tidal channel flowed directly southward between Potomska Point and Lloyd State Park into Buzzards Bay.

The Slocum's River is a typical drown river valley estuary and is the mixing zone for terrestrial fresh water, primarily from the Paskamanset River and saline tidal flow from Buzzards Bay. With a relatively large watershed and consequent substantial fresh surface water inputs, the Slocum's River estuary has a variable salinity gradient that is strongly influenced by both short-term and seasonal rainfall patterns.

The Slocum's River estuary and its watershed constitute one of the most important natural and cultural components of Dartmouth and encompass the largest fraction of the town's land area of all of its coastal watersheds. The Paskamanset River and the Slocum's River together effectively divide the town roughly in half and provide a natural riparian and marine corridor through the Town. A few physical facts about the watershed and estuary are useful to an understanding of the present health of the system. The long axis of the watershed is nearly 15 miles from the northern boundary near Freetown to the mouth at Potomska Point, while the tidewater length of the Slocum's River from Potomska Point to Russells Mills village is about 3.75 miles. Of the 23,771 acre watershed, more that 80% is north of the tidal reach of the estuary and supports the Paskamanset River inflow.

As an estuary in a populous region, the Slocum's River brings two opposing elements to bear: as protected marine shoreline it is a popular region for boating, recreation and land-development; as enclosed body of water the Slocum's River may not be readily flushed of the pollutants that it receives from the watershed. With 54 acres of land area contributing nutrients to each acre of the Slocum's River Estuary, activities occurring on the land area have a strong influence on the estuary health. As a result, the Slocum's River, like many shallow coastal embayments in the region, has become nutrient enriched as a result of changing land-use from forest and fields to agricultural uses over the past centuries and more recently the increase in residential and commercial development. Current nitrogen loading to Slocum's River is from three principal sources: onsite disposal of wastewater; fertilizer use; and atmospheric deposition of nitrogen compounds on the land and water surface. Loading of the critical nutrient (nitrogen) to the embayment has increased over the last four decades with further increases certain unless nitrogen management is implemented. Presently, habitat degradation resulting from nutrient enrichment is the single major ecological threat to the Slocum's River.

Regular documentation of a decline in ecological health of the Slocum's River began in 1993 with the start of the Baywatchers Program in Dartmouth and other Buzzards Bay community's coastal waters by the Coalition for Buzzards Bay. The Baywatchers data from 1993 to 2006 shows the upper Slocum's River to be among the poorest in nutrient related habitat quality (bottom 20%) of the more than 65 embayment segments surveyed throughout Buzzards Bay (Coalition for Buzzards Bay 2007). In 2000, the water quality of the Slocum's River and other Dartmouth estuaries was consistent with a land-use analyses performed by the Buzzards Bay Project National Estuary Program in 1994 and revised in 1999, based primarily upon land-use analysis and generic Buzzards Bay water quality standards. This survey study suggested that the Slocum's River was receiving nitrogen pollution inputs 3 fold higher than what it could tolerate without significant habitat decline (Buzzards Bay Project 1999). The measured water quality data, absence of eelgrass beds and low shellfish populations (even without harvest) were consistent with this preliminary analysis. However, nitrogen management required a more quantitative site-specific analysis and restoration threshold, which lead to the Town's support for and participation in the present application of the MEP Linked Assessment and Modeling Approach to the Slocum's River Estuarine System.

The present effort arose directly from the efforts of concerned citizens, municipal officials and staff and local advocates to restore the health of all of Dartmouth's estuaries (Slocum's River, Little River, Apponagansett Bay). That partnership effort became Turn the Tide: Restore Dartmouth's Estuaries, and includes active participation by the Town of Dartmouth, the Coalition for Buzzards Bay, the Lloyd Center for the Environment and the University of Massachusetts School for Marine Science and Technology (SMAST),

Little River: The watershed for Little River is located entirely within the Town of Dartmouth. Similar to the adjacent Slocum's River, the Little River Estuary is the result of the drowning by rising sea level of a small, shallow valley formed by long-term erosion of the underlying bedrock fabric and modified by glaciation. The Little River embayment has a small watershed relative to its size, with 16.5 acres of land for each acre of estuary. There are a few short intermittent streams and large areas of salt marsh. The mouth of Little River is defined and controlled on the west by the bedrock outcrop of Potomska Point and on the east by both buried and partially exposed bedrock. Today, abutments of the Little River Road bridge further structure the embayment's inlet channel. North of the Little River bridge, the tidal channel is shallow and tortuous with sand and gravel bars extending up into the central portion of the embayment (Figure I-1). A shoal area of sand, gravel and boulders lies to the south of the bridge with no well defined tidal channel. Tidal waters flowing out of Little River mouth flow southward across the shoals and into the Slocum's River tidal channel which tracks eastward across the shoal area. Therefore, tidal exchange and thus potentially water quality of the Little River Estuary is presently linked in part to that of the Slocum's River, whereas prior to about 1980 when the Slocum's River tidal channel still flowed southward directly to Buzzards Bay, it is likely that Little River had a more discrete tidal interchange with Buzzards Bay.

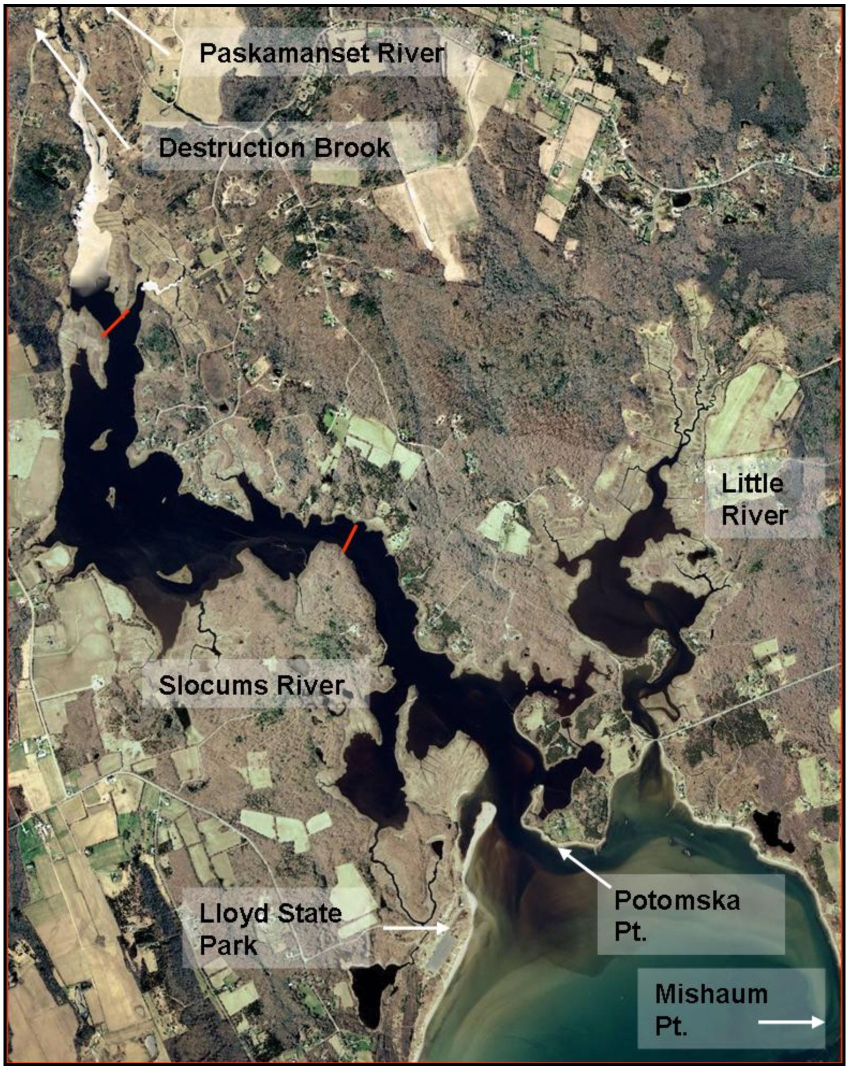


Figure I-1. Study region proximal to the Slocum's River and Little River embayment system for the Massachusetts Estuaries Project nutrient analysis. Tidal waters enter the outer bay between Potomska Point and Lloyd State Park, then the tidal channel swings to the east and discharges to Buzzards Bay along Mishaum Point. Freshwater enters the Slocum's River primarily from the north via discharge from the Paskamanset River and Destruction Brook, with smaller streams entering along the east and west shores of the Slocum's River. (Photo date: 2002; Source: MA GIS).

Little River is a moderately nutrient enriched estuary. However, as to the extent that it is functioning as primarily a salt marsh basin, it's level of impairment has been unclear. The present MEP analysis takes into account the much lower sensitivity of salt marshes to nutrient inputs compared to tidal embayments, so as to establish the proper nutrient threshold for restoration/protection of this estuarine system.

The watershed to Little River is defined to its southern, eastern, northwestern and western boundaries by low bedrock ridges. The boundary to the northeast has limited bedrock and topographic control and is an area of glacially-derived permeable sediments that stretch northward beneath the Dike Marsh portion of Apponagansett Bay (Williams and Tasker, 1978). The soils on the northwestern and eastern upland slopes are principally of glacial basal and ablation till, while lowlands to the northeast include permeable sands and gravels of glacial outwash and ice-contact deposits. Surface water inflow to the estuary is from two short intermittent streams that drain the low uplands to the northwest, while groundwater discharge is primarily to the extensive northern and eastern saltmarsh areas. As a result of the small amount of freshwater inflow, due to the small watershed relative to the surface area of estuary, and the relative "open" tidal exchange, Little River shows little dilution of the salinity from the incoming Buzzards Bay waters and lower nutrient levels compared to the adjacent Slocum's River waters.

Development within the Little River watershed is limited but has steadily continued to alter open land over the past decade. The preliminary nitrogen loading figures developed by the Buzzards Bay Project (1999) indicate that the estuary was well below its nitrogen loading tolerance limit, based primarily upon land-use analysis and generic Buzzards Bay water quality standards. Despite these positive projected nitrogen loading estimates, Baywatchers Program water quality sampling data from the period between 1993 and 2006 shows that Inner Little River may be impaired, based upon embayment metrics. However, as stated above, It is also possible (as also noted by BayWatchers 1999) that some of the disparity arises from Little River functioning more as a salt marsh basin, than a traditional tidal embayment. It is this disparity between predicted health and the measured nutrient-impaired water quality that underscore the need for a site-specific analysis and restoration threshold and which has led to the Town's support for the present quantitative analysis and modeling effort for the Little River estuary.

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. 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 declining 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 use. Similar to nutrients, bacterial contamination is related to changes in land-use as watersheds become more developed. Regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to culture, economy, and tax base of Massachusetts's coastal communities.

As a result of documented bacterial contamination and shellfish closures within the Slocum's River estuary and its impacts on the citizens of the Town of Dartmouth, Turn-The-Tide conducted a full bacterial analysis of the Slocum's River and Little River Estuaries (White et al. 2007). The results are presented in a separate MEP Bacterial Technical Report and will not be discussed herein. The result of this effort are being used to craft best management approaches to further reduce bacterial inputs, hence bacterial levels in the receiving estuarine waters.

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 Dartmouth) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries. Fortunately, the Town of Dartmouth has already moved significantly along its CWMP development and implementation. The Town presently operates a WWTF with a capacity of 4.2 mgd and a Buzzards Bay outfall, servicing over half of the Town, distributed within watersheds to the Slocum's River, Little River, Apponagansett Bay and Westport River 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 (MA DEP), the University of Massachusetts – Dartmouth School of Marine Science and Technology (SMAST), and others including the Cape Cod Commission (CCC) have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts.

The Massachusetts Estuary Project is founded upon science-based management. The Project is using a consistent, state-of-the-art approach throughout the region's coastal waters and providing technical expertise and guidance to the municipalities and regulatory agencies tasked with their management, protection, and restoration. The overall goal of the Massachusetts Estuaries Project is to provide the DEP 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 that are protective of embayment health.

The major Project goals are to:

- develop a coastal TMDL working group for coordination and rapid transfer of results,
- determine the nutrient sensitivity of each of the 89 embayments in Southeastern MA
- provide necessary data collection and analysis required for quantitative modeling,
- conduct quantitative TMDL analysis, outreach, and planning,
- keep each embayment's model "alive" 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 (Figure I-2). 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. 23 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.

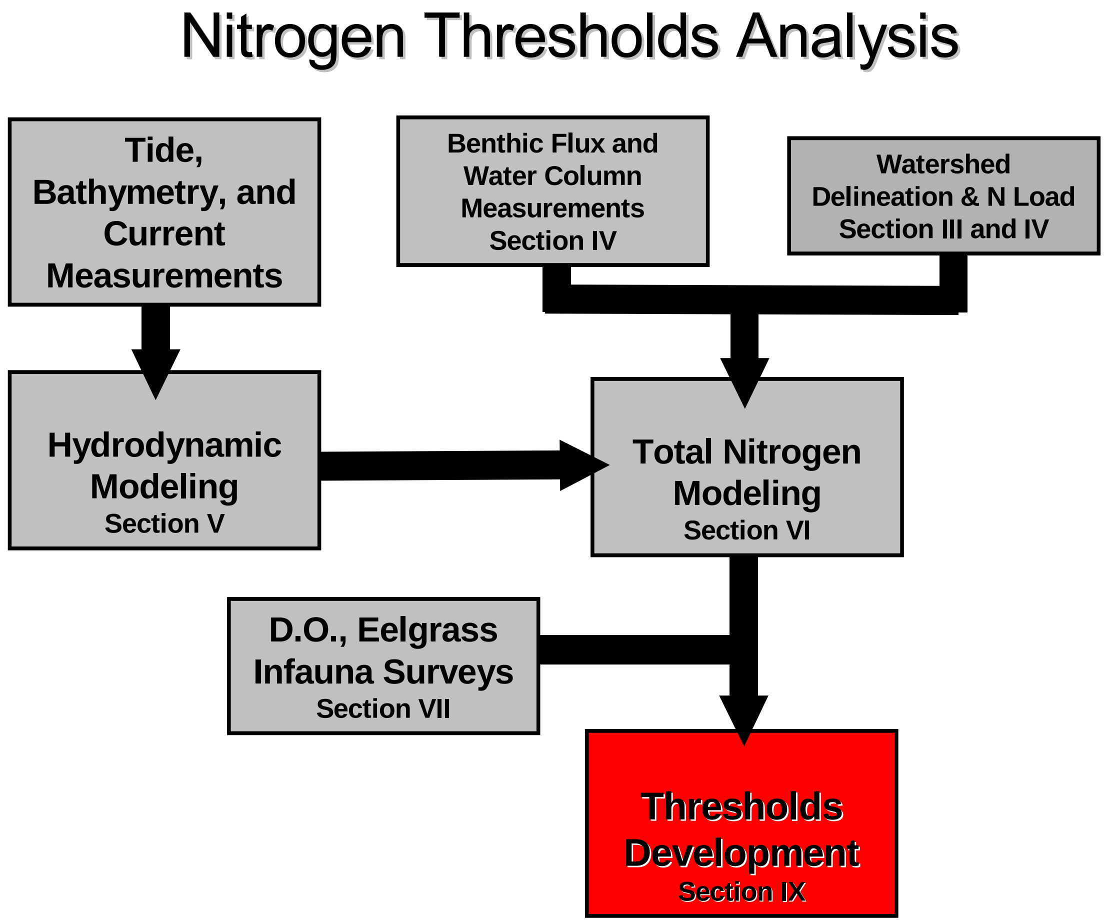


Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach. Section numbers refer to sections in this MEP Nutrient Technical Report where the specified information is provided.

Linked Watershed-Embayment Model Overview: The Model provides a quantitative approach for determining an embayment's: (1) nitrogen sensitivity, (2) nitrogen threshold loading levels (TMDL) and (3) response to changes in loading rate. The approach is fully field validated and unlike many approaches, accounts for nutrient sources, attenuation, and recycling and variations in tidal hydrodynamics (Figure I-2). This methodology integrates a variety of field data and models, specifically:

- Monitoring - multi-year embayment nutrient sampling
- Hydrodynamics -
  - embayment bathymetry
  - site specific tidal record
  - current records (in complex systems only)
  - hydrodynamic model
- Watershed Nitrogen Loading
  - watershed delineation
  - stream flow (Q) and nitrogen load
  - land-use analysis (GIS)

- watershed N model
- Embayment TMDL - Synthesis
  - linked Watershed-Embayment N Model
  - salinity surveys (for linked model validation)
  - rate of N recycling within embayment
  - D.O record
  - Macrophyte survey
  - Infaunal survey

I.2 SITE DESCRIPTION

The Slocum's and Little River embayments are oriented roughly north to south and both are open to Buzzards Bay on the south via single tidal inlets. The configuration of the two embayments results from post-glacial sea-level rise drowning of shallow valleys formed by both long-term and short-term processes. Long-term processes include erosion of the bedrock by chemical and physical weathering of the bedrock over the past 30 million years or more, which maintained a drainage network in the region. The bedrock underlying the soils of the region is crystalline bedrock of about 600 million years age (Zen, 1983). The bedrock types include granite, gneiss, schist and other rocks (Murray 1990). Over the past 600,000 years a series of repeated continental glaciations have advanced and retreated across the region, with the most recent ending about 16,000 years ago. The glaciations lowered the local bedrock erosional surfaces by small amounts, leaving smoothed upland bedrock surfaces and a variety of glacial sediments covering much of the underlying bedrock structure. Bedrock outcrops occur throughout the watersheds and the exposed and buried bedrock topography is the primary control upon the local topography. The watershed shape and length is defined by a framework of roughly north-northeastward trending, low bedrock ridges with shallow intervening valleys (Figs. I-3 and I.4). Where the low valleys meet the sea, the locations of the Slocum's River and Little River mouths are anchored by the configuration of the low bedrock ridges, outcrops and submarine reefs (FitzGerald et al, 1993). The Slocum's River embayment is about 6 km from south to north along the center line of the estuary and the embayment width varies from a about 10 meters to about 600 m at the widest point about halfway between the mouth and the northern limit of the embayment at Russells Mills village. The watershed of the Slocum's River is about 24 km long from south to north and varies in width from about 1.7 km near the embayment mouth in the south to more than 5 km in the central and northern watershed areas. The definition of the watershed basin predominantly by bedrock creates the crenulated margins, as opposed to the smooth watershed borders seen in sand outwash aquifers, like on Cape Cod. This difference in geology allows for the use of topographic techniques as part of delineating the contributing areas to these estuaries.

The soils and sediments of the two watersheds consist of a variable fabric of low permeability basal till which has been compressed by the weight of ice of a thickness of several hundred feet and by more permeable ablation or melt-out till that drapes the bedrock ridges and ridge slopes. Basal till usually forms the bottom-most sediment in the valley floors (Williams and Tasker, 1978; Larson, 1982). The area bedrock has a very low permeability, while the basal tills (locally known as hardpan) and ablation tills have low to moderately low permeability. The shallow valleys and lower elevations have a variety of glacial sediments in them usually described as stratified drift, which have substantially higher permeabilities than the glacial tills. The total thickness of soils mantling the bedrock structure is variable from zero at outcrops and ridges and to about 25 meters depth in the floor of the Acushnet Cedar Swamp at the northern end of the Slocum's River watershed (Williams and Tasker, 1978).

The combination of exposed and shallowly buried bedrock and generally low permeability glacial tills affects the upland hydrology of the two watersheds. The regions' bedrock and low permeability upland soils form a surface-water dominated regime where rainfall and snow melt tend to flow over the ground surface in a greater proportion than they percolate into the soils to become groundwater (Williams and Tasker, 1978; Bent 1995). The upland stream network is therefore well-developed and most upland groundwater flow is local, that is to the nearest stream.

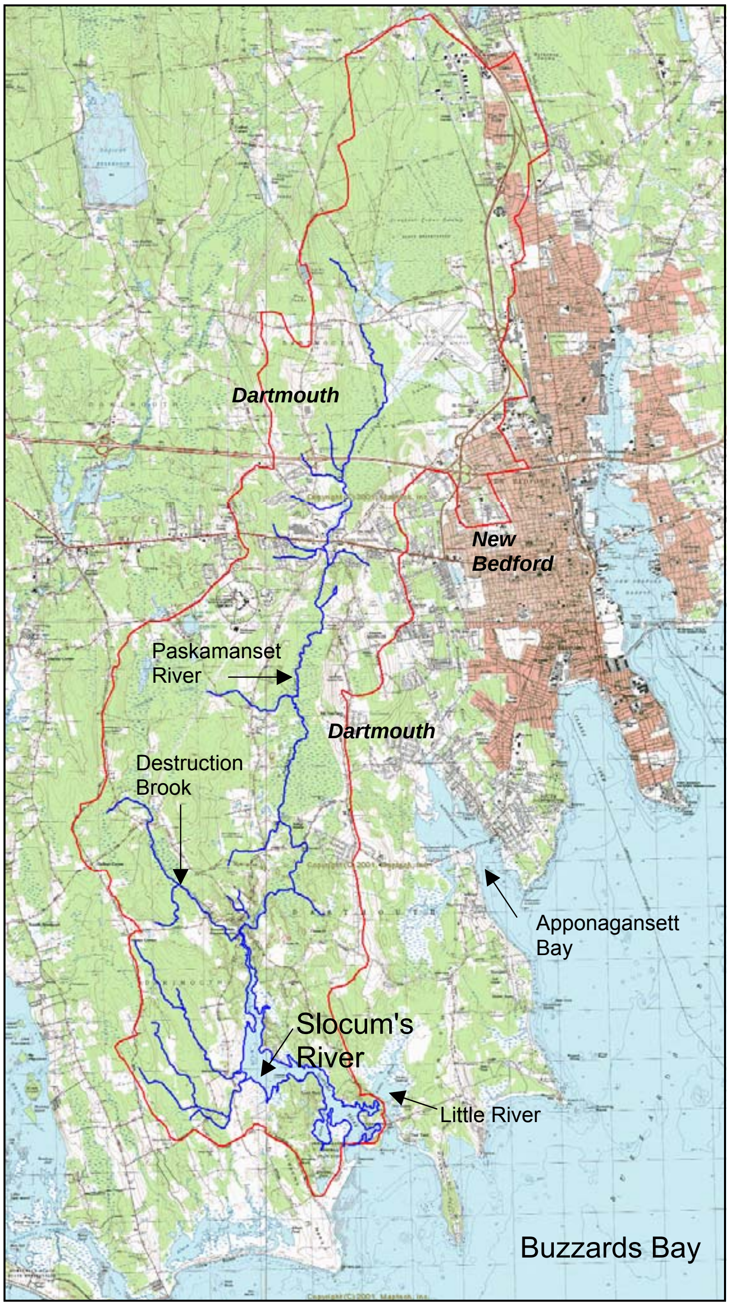


Figure I-3. Topographic map showing the Slocum's River watershed boundaries (red line) and principal streams in the Town of Dartmouth and City of New Bedford.

In the shallow valleys with more permeable soils, the proportion of runoff in “undisturbed” settings is reduced and the role of groundwater in the valleys is proportionately more substantial. Streams that flow in till-dominated watersheds are likely to have “flashy” flow characteristics. That is the streams display both rapid rise and fall in amount of flow in response to rainfall or snowmelt. In the smaller tributary watersheds till-dominated streams will seasonally cease flowing for a week or more during late summer during a typical summer. Streams that flow in stratified drift dominated watersheds display more moderate flow characteristics and typically will flow year round even in dry summers. The largest stream, the Paskamanset River drains more than three-quarters of the total Slocum's River embayment watershed. The main stream channel flows across valley sediments which are generally stratified drift and very permeable, while its short tributaries flow generally from till-dominated sub-watersheds (Williams and Tasker, 1978; Bent 1995).

The lower Paskamanset River basin is one source of public water supply for Dartmouth from wells located near the stream. Destruction Brook, the next largest stream with about 8 per cent of the embayment watershed has a stratified drift dominated watershed and flows year round. These two major streams have large proportions of stratified drift in their watersheds, so that groundwater flow is important to maintaining stream flow and stream ecological health during drought. Despite the strong groundwater component in the local flow of these two streams, at their points of discharge to the embayment, bedrock outcrops limit the role of direct groundwater flow to the Slocum's River Estuary. As a result, most of the freshwater inflow to the estuary is via the stream network,, while groundwater transports a relatively small and localized amount directly to the shore.

The Little River watershed differs from that of Slocum's River in its configuration. While the Slocum's River watershed is about 5 times longer than it is wide, Little River has a watershed nearly the same in length and width. The watershed is about 3.2 km long from south to north and about 2.5 km wide. The Little River embayment water surface is about 1.8 km long along the centerline from the highway bridge to the northern extremity and about 300 meters wide at its widest point. Two short, seasonal streams drain parts of Little Rivers’ northern watershed and with areas stratified drift in the embayments northern watershed limits, groundwater may be more important in the water budget of the embayment watershed.

As mentioned above the soils within the two estuaries reflect a mixture of two hydrologic regimes: the uplands are dominated by the bedrock and glacial till distribution; and the valleys and low areas reflect the sediments deposited during glacial ice margin retreat, still-stand and ablation. The sediments that fill the shallow valleys usually include uppermost layers of sand, silt, clay and peat that comprise the most recent (<13,000 years ago) alluvial and lake bottom deposits. Surface glacial deposits along the valley sides and floors include highly permeable ice-contact deposits of outwash fans, moraines, kames and eskers. In the valley floors, the glacial sediments fall under the generalized term “stratified drift”, which describes variable sequences of moderate to highly permeable glacial-fluvial (stream-laid) outwash deposits, both exposed and buried and glacial lake-bottom deposits of sand, silt, clay and peat (Williams and Tasker, 1978). As noted above, the valley floor sediment strata are often underlain by a basal till that lies upon the bedrock surface (Williams and Tasker, 1978; Larson, 1982). The valley sediments with the exception of clay and peat are more permeable than the upland till deposits and where they occur in areas of greater depth and extent in the Slocum's River basin, they provide water resources for a portion of the municipal water supply for the Town of Dartmouth. Estimates of the percentage of stratified drift areas in the Slocum's River watershed based upon soils, well borings and exposures in gravel pits vary from 44% for the upper and middle Paskamanset River basin, to about 55% for the Destruction Brook basin (Bent 1995).

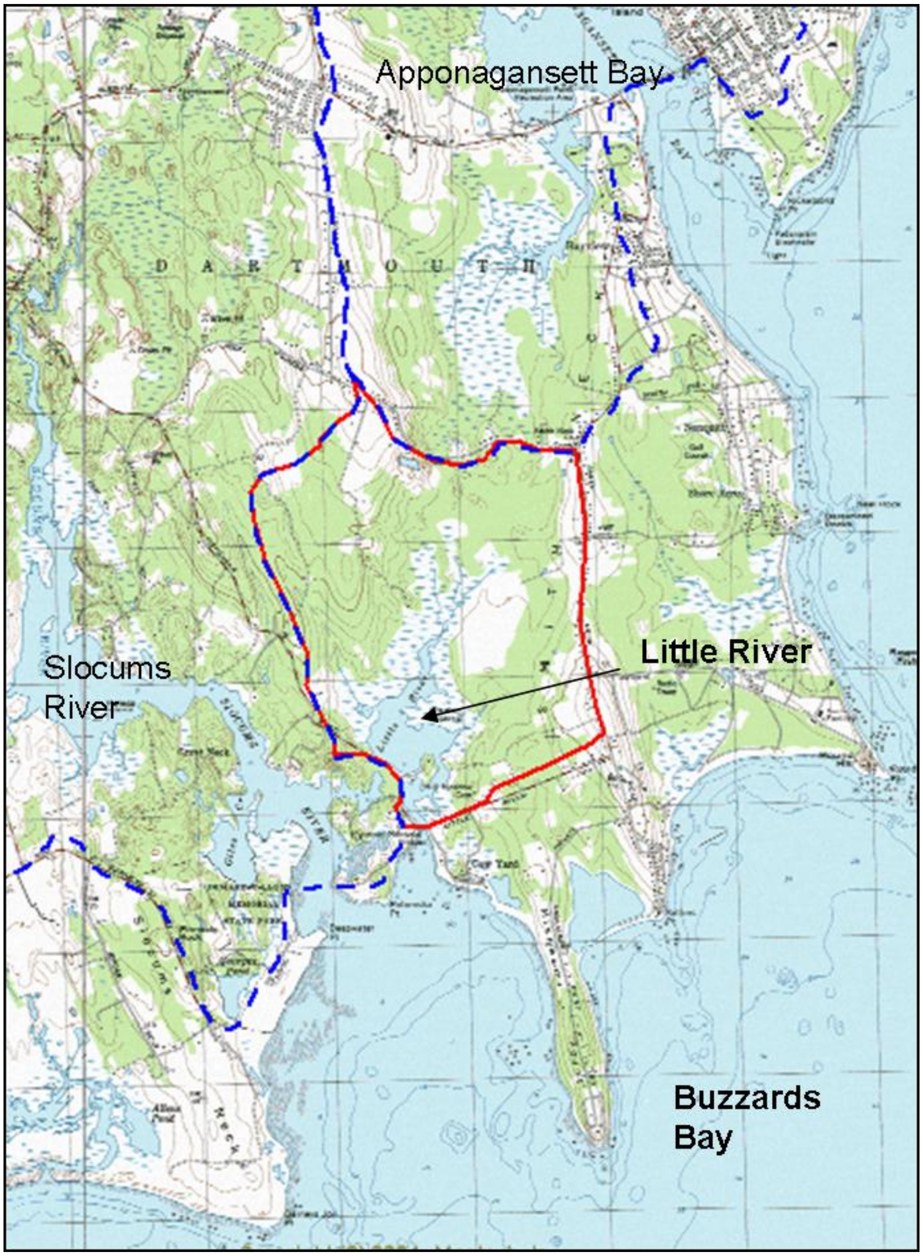


Figure I-4. Little River embayment watershed boundary (solid red line) and the constraining watershed boundaries of Slocum's River and Apponagansett Bay (dashed lines).

Because of the layout of the two embayments, both are mixing zones for watershed freshwater and marine waters. However, the similarity between embayment physical and chemical environments is only very general. Because of the large length and area of the Slocum's River watershed, the tidal waters exhibit strong contrasts in salinity both temporally, between headwaters and tidal inlet. At the northern reach of the estuary there is a highly variable but usually low salinity, which is maintained by average flows from the Paskamanset River and Destruction Brook. Southward down the embayment salinity increases during average stream flow conditions, reflecting mixing with Buzzards Bay tidal flows. During periods of high stream discharge the salinity of the embayment is diluted more and the brackish water zone can extend southward to include much of the upper half of the estuary. Generally in summer, the brackish zone shrinks northward as the freshwater flow into the embayment diminishes. Thus, the salinity regime of the upper half of the embayment is very dynamic and sensitive to recent rainfall patterns.

Little River embayment is also a mixing zone between fresh and salt waters but has a relatively small watershed area, absence of major streams, and short embayment length. As a result, Little River is tidally dominated and supports a higher average salinity than does the Slocum's River (even the lower portion) and the pattern of salinity distribution is more stable seasonally.

Historical Change: Both the Slocum's River and Little River are relatively recent (<16,000 years) ecological systems due to the effects of recent glacial erosion "planing" off older soils and plant cover. After the wasting of the last glacier about 16,000 years ago, the present day watersheds were occupied by a freshwater stream system that continued southward out of the mouths of the two future embayments and into a larger stream in the middle of Buzzards Bay. Drainage of the combined local waters of the Buzzards Bay basin continued southwestward to the edge of the continental shelf where the shoreline of the lowered Atlantic Ocean was at that time (O'Hara and Oldale, 1980).

As sea level rose rapidly after deglaciation, the shoreline migrated shoreward and entered Buzzards Bay. As sea level continued to rise more slowly over the past 6,000 years shoreline processes of the advancing sea altered the glacial sediments of the area just south of the present day mouths of the two embayments, eroding the till from the proto-headlands of Barneys Joy and Mishaum Points. It is likely that these basins became "enclosed" and took on estuarine characteristics about 4,500 years ago. Beginning about 2,500 years ago, shoreline process began to modify the southern portions of the Slocum's River embayment. This process formed successive small barrier spits that migrated shoreward and attached to the western shore of the mouth of the embayment (Fitzgerald et al 1993). For most of the last 2,500 years it is likely that the tidal channel of the Slocum's River inlet flowed more or less due southward into Buzzards Bay. Up until about 70 years ago, this channel remained marginally navigable directly southward to the open waters of Buzzards Bay, with a shallow bar across the southern end of the channel (Figure I–5). Anecdotal evidence from local residents and from marine charts place names (Deepwater Point) suggests that vessels were able to enter the lower Slocum's River in the 19th century. By 1911 navigation into and out of the Slocum's River even at high tide would have been difficult, especially during a southeast wind. It is also clear from the 1911 chart that the shoals south of both the Slocum's River and Little River were similar in layout but smaller in extent than at present and were between 1 and 3 feet below mean low water. Today much of the same area is exposed during low tide. Both the increase in extent and the net shoaling of these areas indicate a large increase in sediment within the Barneys Joy - Mishaum Point embayment in the past 95 years.

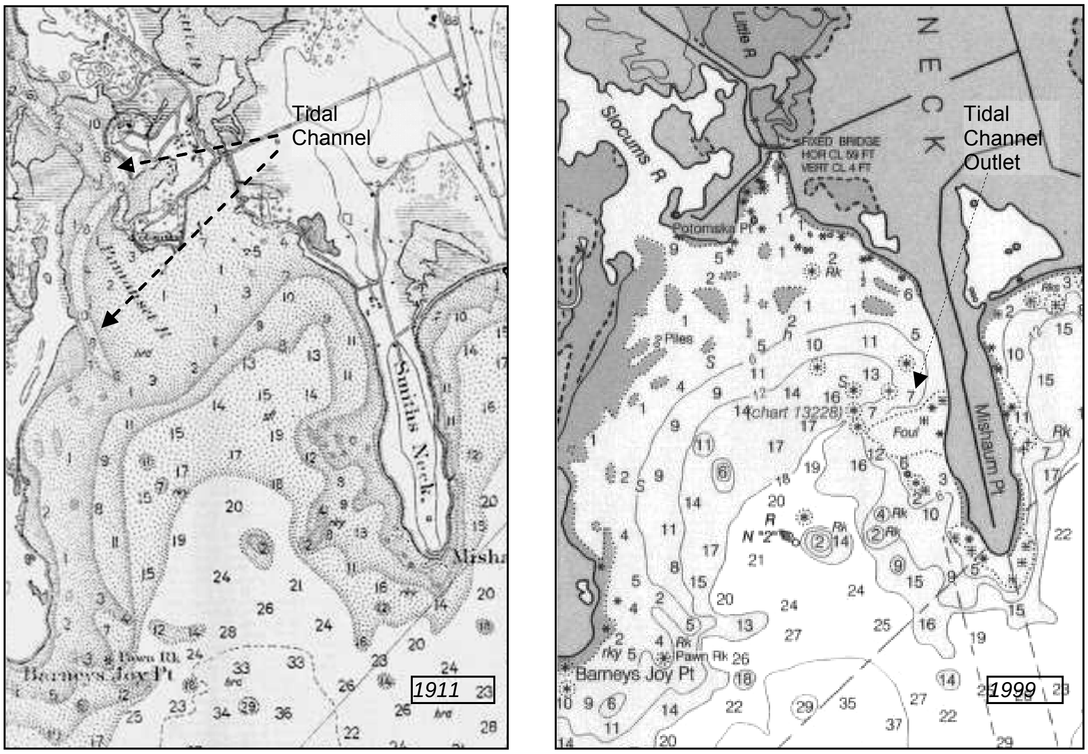


Figure I-5. Slocum's River bathymetry from 1911 (left panel) and 1999 (right panel) charts. The 1991 chart shows a tidal channel along the west side of the Slocum's River mouth with depths of between 6 to 10 feet ending in a shoal of 1 foot depth along what is now Lloyd State Beach. The right hand panel at similar scale shows the decrease in depth of the shoal area and an increase in the extent of the shoals, particularly on the northeastern side of the embayment. (Soundings in feet at mean low water; Source: NOAA Historic Map and Chart Project).

About 70 years ago, perhaps as a result of the 1938 hurricane, the amount of sand present in the bay formed by Barneys Joy and Mishaum Points increased and began moving shoreward during subsequent major storms (FitzGerald, 1993). As this process continued the tidal inlet for the Slocum's River, which previously had flowed southward into Buzzards Bay began to be deflected to the east by the shoaling and by the emergence of the formerly subtidal sand flats and bars anchored on the east at Lloyd State Park. These shoals extend southward from Potomska Point in an arc between 0.5 km and 1 km wide into Buzzards Bay. With a large supply of sand within the bay, the inlet mouth shoaling continued to move shoreward (to the north and east), forcing the Slocum's River tidal inlet to migrate eastward, and in doing so influencing the Little River tidal, as well. Today the combined Slocum's River and Little River tidal flows discharge into deeper Buzzards Bay waters about two thirds of the way southward along the west shore of Mishaum Point (Fig. I-6). The inlet migration process has tripled the distance the Slocum's River waters flow to reach Buzzards Bay from about 0.8 km to about 2.4 km. As the sand moved shoreward, it also moved into the lower Slocum's River embayment forming flood tidal shoals that now are nearly continuous from shore to shore across the lower embayment between Potomska Point and Pine Island.

Figure I-6. The Slocum's River and Little Rivers from a 2002 aerial photograph showing the present day outlet near Mishaum Point at the lower right of the picture (Source: MA GIS).

The effects of this continuing sedimentation process upon the ecological health of the Slocum's River embayment are likely to be mostly negative, by increasing the time of tidal flushing with cleaner Buzzards Bay waters or in other words by increasing the proportion of Slocum's River waters that are returned to the embayment with each flood tide. One tangible result of this process may be the closure of all of the Slocum's River embayment to all shell fishing starting around 1992, possibly related to alterations in tidal exchange brought on by Hurricane Bob in 1991.

From the 1911 chart information it seems unlikely that Little River had a tidal channel south of the highway bridge and this is consistent with the much smaller tidal volume that moves in and out of the Little River embayment. North of the bridge, during the same 70 year period since 1938, shoaling from sand and gravel moving northward into the embayment during severe storms also has affected the bathymetry and tidal regime. The migration of the Slocum's River tidal channel across the outer Little River embayment area has meant that ebbing Slocum's River waters are mixed with Buzzards Bay waters that enter the Little River embayment with each flood tidal cycle, reducing the dilution effects of the cleaner Buzzards Bay water on Little River waters.

Tidal damping (reduction in tidal amplitude) through an embayment can range from negligible indicating “well-flushed” conditions or show tidal attenuation caused by constricted channels and marsh plains indicating a “restrictive” system, where tidal flow and the associated flushing are inhibited. MEP tidal data indicate slight tidal damping of the 1.8 meter Buzzards Bay tide, through the Slocum's River inlet and moderate damping through the Little River inlet. It is possible that dredging a more direct inlet channel to Buzzards Bay for the Slocum's River would increase flushing in the Slocum's River and the relative merits of this management tool are a part of the MEP analysis described in this report. For Little River, as a salt marsh basin with a much smaller tidal prism, the dredging of a channel south of the highway bridge does not appear to be warranted at this time (see Chapter 5).

As noted above, the Slocum's River is an estuary with greatest freshwater inputs at the northern headwaters of the system and tidal exchange of marine waters from Buzzards Bay (tide range of approximately 1.8 m) at its southern inlet. The Slocum's River estuarine system was partitioned into 3 regions: an 1) upper narrow northern portion, which receives discharge from the two major streams and is characterized by moderate salinity (brackish); 2) a central portion characterized by broad shallows surrounding a somewhat deeper channel and where mixing of brackish and marine waters is a predominant characteristic; 3) a lower, or southern portion that includes small, shallow side bays and the tidal inlet (Figure I-7). The Slocum's River is a classic drown river valley estuary, acting as the mixing zone of terrestrial freshwater inflow and saline tidal waters from Buzzards Bay. Salinity in the system ranges from approximately 30 ppt. at the Buzzards Bay inlet to less than 10 ppt at the northern end.

The Little River embayment, as noted above has a relatively small watershed with two small, short streams flowing from the northern watershed. The salinity gradient in the embayment is therefore dominated by the tidal exchange with Buzzards Bay (tide range of approximately 1.8 m) at its southern inlet. The small size of the Little River embayment, its general absence of water quality gradients and its functioning as a single salt marsh basin lead to it being addressed as a single basin for the purposes of the MEP analysis. However, Little River is also considered an estuary, being semi-enclosed, and serving as the mixing zone of terrestrial freshwater inflow (direct groundwater discharge) from its watershed and saline tidal waters from Buzzards Bay.

Given the present hydrodynamic characteristics of the Slocum's River embayment system, it appears that estuarine habitat quality is dependent on both the level of nutrient loading to embayment waters and the tidal characteristics. In Slocum's River, some enhancements to tidal flushing may be achieved via inlet or channel modification resulting in some mediation of the nutrient loading impacts from the Slocum's River watershed. The details of such are a part of the MEP analysis described in this report.

Nutrients:

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.

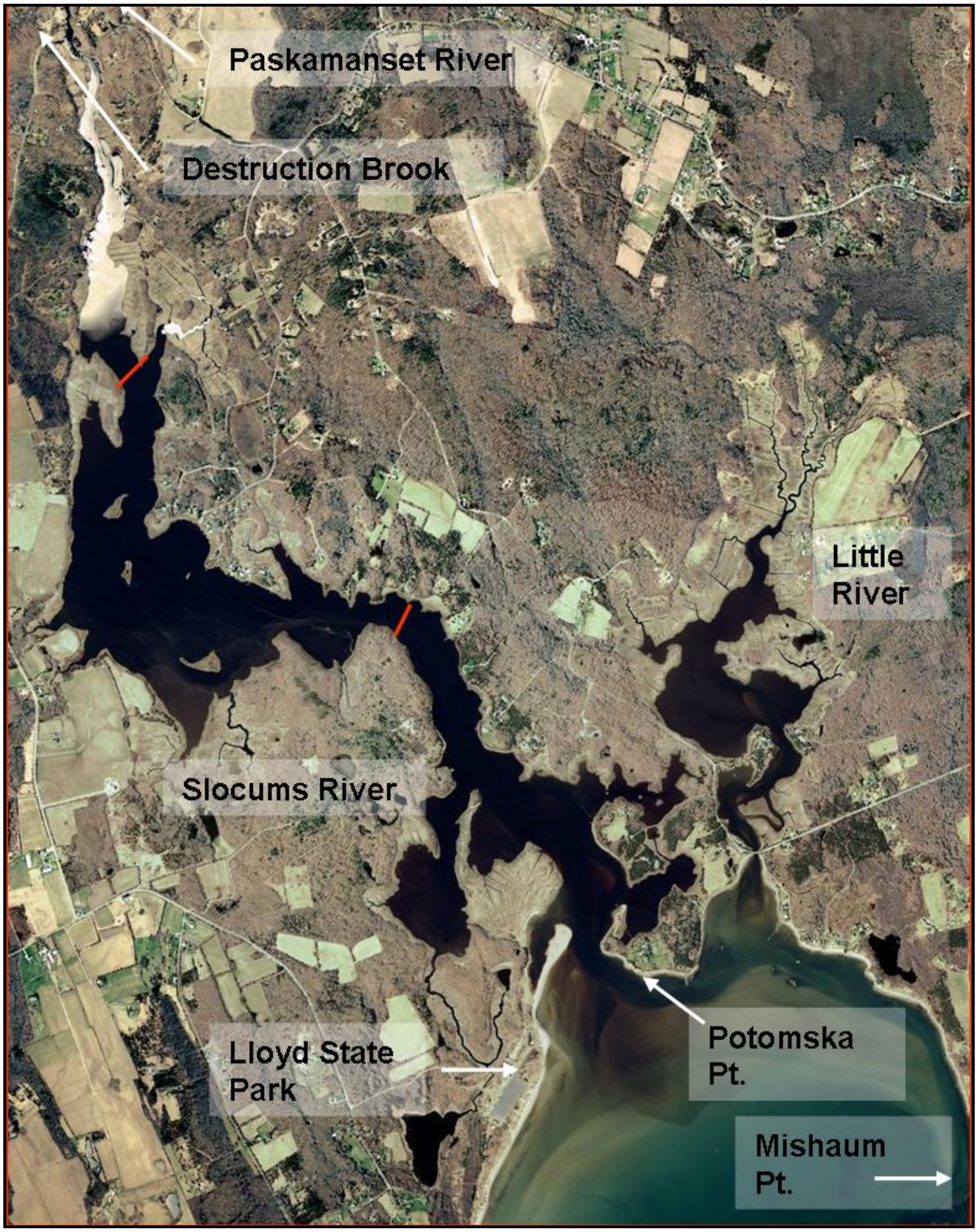


Figure I-7. Partitioning of the Slocum's River system into three sub-units for analysis of the ecological health of the embayment (Photo date: 2002; Source: MA GIS).

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). 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 River system monitored by the SMAST staff with site-specific habitat quality data (D.O., eelgrass, phytoplankton blooms, benthic animals; macroalgae; and finfish) to "tune" general nitrogen thresholds typically used by the Cape Cod Commission, Buzzards Bay Project, and Massachusetts State Regulatory Agencies.

Nitrogen loading to the Slocum's River embayment system was determined relative to the upper, central and lower portions of the estuary as depicted in Figure I-7. The watershed of the Slocum's River includes areas in three towns: about 74% is within the Town of Dartmouth; about 26 % lies in the City of New Bedford; and about 0.35% is within the Town of Westport. Based upon land-use and the watershed being predominantly within Dartmouth, it appears that substantial nitrogen management for the Slocum's River restoration may be formulated and implemented through Town of Dartmouth actions. Cooperation with the City of New Bedford on planning and management will still be critical to the long-term success of a restoration plan, although much of the watershed area in New Bedford is presently tied into the municipal wastewater system. However, as management alternatives are being developed and evaluated, it is important to note that moderate gradients define the nutrient characteristics in the Slocum's River and also control the associated habitat impacts. There is a moderate gradient in nitrogen levels and health in Slocum's River, with highest nitrogen and lowest environmental health in the headwaters of the system and lowest nitrogen and greatest health near the inlet to Buzzards Bay. The upper and middle reaches of the Slocum's River are presently showing poor water quality and "Eutrophic" conditions. Large areas of macroalgae cover the bottom in the middle portion of the Slocum's River, eelgrass is absent, and a fish kill has been reported, resulting from oxygen depletion.

Nitrogen loading to the Little River embayment system was determined relative to the whole embayment north of the highway bridge as depicted in Figure I-7. The watershed of Little River lies entirely within the Town of Dartmouth, making management of the embayment dependent only upon the Town residents. As management alternatives are being developed and evaluated, it is important to note that only modest gradients define the nutrient characteristics of Little River.

I.3 NITROGEN LOADING

Surface and groundwater flows are pathways for the transfer of land-sourced nutrients to coastal waters. Fluxes of primary ecosystem structuring nutrients, nitrogen and phosphorus, differ significantly as a result of their hydrologic transport pathway (i.e. streams versus groundwater). In mixed stratified drift and glacial till watershed, such as in the watershed to the Slocum's River and the Little River embayment systems, phosphorus is highly retained during groundwater transport as a result of sorption to aquifer mineral (Weiskel and Howes 1992). Since stream baseflow (flow provided by groundwater rather than surface water runoff) for the principal streams in the Slocum's River and Little River watersheds is provided by groundwater (Bent, 1995), much of the phosphorous generated in the watershed is retained by the soils and the watershed tends to release relatively moderate amounts of phosphorus to the Slocum's River and Little River. In contrast, nitrogen, primarily as plant available nitrate, is readily transported through the stratified drift in the watershed valleys, both during surface flow and through groundwater systems (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 Slocum's River and Little River follow this general pattern, where the primary nutrient of eutrophication in these systems is nitrogen.

Unfortunately, as noted above, almost all of the estuarine reach within Slocum's River is beyond its ability to assimilate additional nutrients without impacting ecological health. The result is that nitrogen management of the primary sub-embayments is aimed at restoration, not protection or maintenance of existing conditions. In general, nutrient over-fertilization is termed "eutrophication" and when the nutrient loading is primarily from human activities, "cultural eutrophication". Although the influence of human-induced changes has increased nitrogen loading to the system and contributed to the degradation in ecological health, it is sometimes possible that eutrophication within the Slocum's River could potentially occur, wholly or in part, without human influence. It is critical to separate human induced versus natural processes in the nutrient threshold analysis. While this partitioning 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.

Conditions in Little River are different than those in the Slocum's River in that nutrient loading is lower, nitrogen levels are lower, and the system functions primarily as a salt marsh basin. However, Little River's water quality appears to be poorer than previous nutrient loading studies (BBP, 1999). The extent to which this is a concern or results from mixing of the Slocum's River ebb waters with Little River flood waters is one of the focal points of the present MEP analysis. Achieving Little River's target water quality classification as an Outstanding Resource Water may depend not only upon management of its watershed and inlet, but upon the restoration of the Slocum's River System.

I.4 WATER QUALITY MODELING

Evaluation of upland nitrogen loading provides important "boundary conditions" for water quality modeling of the Slocum's River and Little River 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 Slocum's River and in Little River. A two-dimensional depth-averaged hydrodynamic model based upon the tidal currents and water elevations was employed for the system. Once the hydrodynamic properties of the estuarine system were computed, two-dimensional water quality model simulations were used to predict the dispersion of the nitrogen at current loading rates.

Using standard dispersion relationships for estuarine systems of this type, the water quality model and the hydrodynamic models were then integrated in order to generate estimates regarding the spread of total nitrogen from the site-specific hydrodynamic properties. The distributions of nitrogen loads from watershed sources were determined from land-use analysis, based upon watershed delineations by SMAST and Lloyd Center staff for watershed and sub-watershed areas designated by MEP. Almost all nitrogen entering the Slocum's River embayment is transported by surface water (streams) while in the Little River embayment groundwater may provide an equal portion of nutrients delivered to that embayment. Concentrations of total nitrogen and salinity of Buzzards Bay source waters and throughout the Slocum's River and Little River systems were measured over two summers during 2004-2005 and integrated with the Coalition for Buzzards Bay's BayWatch data (2000-2006). Measurements of current salinity and nitrogen and salinity distributions throughout estuarine waters of the system were used to calibrate and validate the water quality model (under existing loading conditions).

I.5 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Massachusetts Estuaries Project linked watershed-embayment approach to the Slocum's River and Little River systems for the Town of Dartmouth. 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 Southeastern Regional Planning and Economic Development District (SRPEDD) data and offshore water column nitrogen values were derived from an analysis of a monitoring station 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 and other bioassays (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 receiving estuarine system. This latter assessment represents only one of many solutions and is produced to assist the Town in developing a variety of alternative nitrogen management options for the Slocum's River and Little River systems, although future management alternatives are anticipated as part of the Town's restoration effort. Finally, analyses of the Slocum's River and Little River systems was relative to potential alterations of circulation and flushing, including an analysis to identify hydrodynamic restrictions and an examination of dredging options to improve nitrogen related water quality. The results of the nitrogen modeling for each scenario have been presented (Section IX).

II. PREVIOUS STUDIES RELATED TO NITROGEN MANAGEMENT

In most marine and estuarine systems, such as the Slocums River and Little River embayments the limiting nutrient, and thus the nutrient of primary concern, is nitrogen. In large part, if nitrogen addition is managed, then eutrophication is controlled. This approach has been formalized through the development of tools for predicting nitrogen loads from watersheds and the concentrations of water column nitrogen that may result. Additional development of the eutrophication management approaches via the reduction of nitrogen loads has also 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. 2003).

Until recently, these tools for predicting loads and concentrations tended to be generic in nature, and overlooked some of the site-specific characteristics associated with a given water body. The present Massachusetts Estuaries Project (MEP) study focuses on linking water quality model predictions, based upon watershed nitrogen loading and embayment recycling and system hydrodynamics, to actual measured values for specific nutrient species. The linked watershed-embayment model is built using embayment specific measurements, thus enabling calibration of the prediction process for specific conditions in each of the coastal embayments of southeastern Massachusetts, including the Slocums River and Little River systems.

Beginning in 1990, nutrient loading evaluations for all Dartmouth embayments were included in the initial and then subsequently updated nitrogen loading and management strategy plans for all Buzzards Bay embayments (Buzzards Bay Comprehensive Conservation and Management Plan (CCMP) issued by the Buzzards Bay National Estuary Program (BBNEP 1991). The 1991 CCMP used embayment–specific hydrodynamic data and available land-use data to characterize the Total Maximum Annual Nitrogen Load (TMAL) for a given embayment. The 1991 tiered nitrogen loading model assigned values for nitrogen generation and transport within a watershed using: watershed delineations; land usage characterizations (e.g., forest, water, cropland and pasture, commercial, residential, industrial, marsh, transportation, etc.); their respective land-use area measurements using GIS (Geographical Information Systems); and the hydrodynamic characteristics of the embayment (bathymetry, volume, estuary turn-over time) to calculate the nitrogen loading to each embayment. The TMAL was a measure of each embayments ability to meet one of several regulatory water quality classifications. For the Slocums River, a classification of SA, the second highest marine waters classification, has been set by MA Department of Environmental Protection, while Little River has been classified as the highest level, an Outstanding Resource Water (ORW). The 1991 CCMP loading model calculated a recommended load limit of 29,600 kg of nitrogen per year while the calculated 1991 existing nitrogen load to the Slocums River at was 97,000 kg nitrogen per year, or more than three times the recommended limit.

The CCMP Nitrogen loading model data was used as a starting point for the nitrogen management portion of the CCMP. The Buzzards Bay Action Plan outlined measures that Town could adopt to manage nitrogen inputs to the regions embayments. The recommendations the Action Plan provided to municipalities included conducting parcel by parcel build-out analysis of the watersheds; sewering when appropriate; adoption of nitrogen–loading bylaws for sensitive embayments; reduction of agricultural fertilizer use by cranberry growers (there are two bogs in the Slocums River watershed); and the implementation of agricultural best-management practices for fertilizers and manure.

Since the late 1980's the Town of Dartmouth has instituted many of the recommendations of the CCMP in order to improve ground and surface water quality in the Town. Many of these measures resulted in some reduction in nitrogen transport to the embayments. The Planning Board adopted stormwater regulations that required constructed wetlands and other stormwater management tools to treat parking lot and roof runoff for new commercial and residential projects. When older commercial developments are remodeled or increased in scale, the Planning Board negotiates improvements in stormwater management infrastructure that tend to improve stream water quality. The Town has adopted several Aquifer Protection Zones that limit the intensity and type of development which can occur within the protection zones and the rules indirectly limit the increase in nitrogen in the Slocums River watershed. The Board of Health provides oversight and collaboration on best management practices for manure, fertilizer and composting with farmers to lessen runoff of contaminants to town streams. The Department of Public Works has worked to improve stormwater runoff by installing several stormwater treatment units and has recently purchased storm drain maintenance equipment to improve the performance of the existing infrastructure. The Department of Public Works has extended the sewer network along Route 6 and northward along Reed Road, thereby reducing the nitrogen load in the Westport River watershed. Additionally, planning is underway for an extension of sewer lines to serve the Bay View neighborhood on Smith Neck Road, and when completed will reduce the nitrogen inputs to Outer Apponagansett Bay. Since the mid-1980's the Town has increased protected open space through land purchases and conservation easements for substantial parcels of land throughout the Town, thereby substantially limiting the amount of future buildout-related nitrogen. It is likely that these combined efforts have and will continue to contribute to a slowing in the rate of increase of nitrogen loading to the Town embayments.

Beginning in 1993, summer measurement of nutrient levels (dissolved and particulate nitrogen; phosphorus); and other water quality indicators, (chlorophyll; secchi depth, dissolved oxygen and temperature) was begun in the Slocums and Little River embayments by the Baywatchers program instituted by the Coalition for Buzzards Bay for most Buzzards Bay estuaries. The Coalition's BayWatcher Program has collected the principal baseline water quality data necessary for ecological management of each of Dartmouth's embayments and harbors. The BayWatcher is a citizen-based water quality monitoring program that is run by the Coalition for Buzzards Bay (T. Williams, Project Coordination) with technical and analytical assistance from the Coastal Systems Program at SMAST-UMD.

The common focus of the Coalition for Buzzards Bay BayWatcher Water Quality Monitoring Program effort has been to gather site-specific data on the current nitrogen related water quality throughout all the embayments tributary to Buzzards Bay. The program was tailored to the gathering of data specifically to support evaluations relating observed water quality to habitat health. The BayWatcher Water Quality Monitoring Program in the Slocums River Embayment System developed a data set that elucidated the long-term water quality of this system. The BayWatcher Program provided the quantitative watercolumn nitrogen data (1999-2006) required for the implementation of the MEP's Linked Watershed-Embayment Approach. The MEP effort also builds upon the previous watershed delineation and land-use analyses, river transport and attenuation data, and embayment water quality and eelgrass surveys. This information is integrated with MEP collected higher order biogeochemical analyses and water quality modeling necessary to develop critical nitrogen targets for the Slocums River System. The MEP has incorporated all appropriate data from all previous studies to enhance the determination of nitrogen thresholds for the Slocums River System and to reduce costs to the Town of Dartmouth.

In 1999 the first 7 years of embayment data from 30 embayments monitored by the Baywatchers Program was compared with the 1991 BBNEP Buzzards Bay nitrogen loading model results (Costa et al, 1999). The 1999 study undertook a comparative analysis of previous studies of nitrogen loading and ecosystem responses and compared those analyses with the BayWatchers results, using the BayWatchers data as a yardstick for CCMP model evaluation. Costa et al. found that the revised loading methodology yielded somewhat lower existing loading levels to the Slocums River at 93,541 kg of nitrogen per year and at the same time revising the TMAL limit downward from 29,600 kg of nitrogen annually to 12,000 kg of nitrogen per year. The 1999 change in nitrogen load recommendation underscores the seven-fold imbalance that exists between the Slocums River recommended nitrogen "carrying capacity" and the 1999 estimate of nitrogen load (Costa et al. 1999).

For Little River the BBNEP estimated existing nitrogen loading for 1999 was 51% of the recommended TMAL for that embayment, or 2,608 kg n/y of the 5,000 kg/y total nitrogen recommended threshold (BBNEP,1999)

After the first ten years of monitoring, the BayWatchers data set was reviewed in 2001 by the Coalition for Buzzards Bay and summarized in a report for the first period, 1992-2001 (CBB 2002). For Inner Slocums River the Baywatchers data indicated finding consistently poor/eutrophic water quality in seven of nine years of samples from Inner Slocums River; fair water quality in seven of 9 years of samples at Outer Slocums River with one season (1999) having good summer water quality. In Little River the 2002 report indicated that Inner Little River had poor/eutrophic water quality during five of the nine seasons sampled; Outer Little River had fair water quality during six of the nine seasons, with one season, 1999 showing good to excellent water quality (CBB 2003). More recent 5-year running averages of the health indexes for the Slocums River and Little River through the summer of 2005 show no improvement in the water quality of both Inner and Outer Slocums River and Outer Little River sites. The health index for Inner Little River showed some small improvement, with 5 of the past 6 years of data falling in the lowest range of fair to good water quality (CBB, 2006). In comparison to other Buzzards Bay embayments sampled by the BayWatchers program, the Slocums River and Little River "Health Index" ratings were consistently in the lowest third of all 29 embayments.

In addition to the BayWatcher's data, other data collected relative to nutrient levels in the Slocums River began in the mid-1960's with a two-year hydrographic study by Hoff et al. (1968). Hoff measured nitrate and phosphorus concentrations at four locations within the Slocums River and one station at Barneys Joy Point in Buzzards Bay and found a nitrate gradient between "extremely high levels" at the head of the Slocums River at Russells Mills and "very low levels" of nitrate at the mouth of the Slocums River. Hoff proposed that the nitrate gradient was likely due to the freshwater origin of the nitrogen inputs in the Upper Slocums River, tidal dilution with cleaner Buzzards Bay water and cyclical uptake by diatom species. Hoff did not measure the other species of nitrogen, ammonium, dissolved organic nitrogen and particulate nitrogen that when summed give a more complete picture of the nitrogen levels in the estuary. Thus, it is difficult to evaluate the level of total nitrogen in the estuary during the period using Hoff's data.

Between 1995 and 1997 nitrogen levels were measured in the Slocums River, Paskamanset River and Destruction Brook by the U.S. Environmental Protection Agency as part of a comparative study of anthropogenic impacts upon the Slocums River, the Westport River and New Bedford Harbor-Acushnet River (Johnson, et al, US EPA 2000). For the Paskamanset River and Destruction Brook watersheds combined, together representing about 86 % of the land watershed of the Slocums River, EPA calculated the average daily dissolved inorganic nitrogen (DIN) load (ammonium + nitrate + nitrite) at 44.45 kg DIN per day or 16,225 kg DIN annually. The total nitrogen load for the streams is larger because DIN values are a variable fraction of the stream total nitrogen load and dissolved organic and particulate nitrogen are not included in the EPA measured DIN carried by those two streams. To estimate the total nitrogen using the EPA 1995-1997 data, we can use the average DIN and total nitrogen data from 346 samples collected between 2003 and 2005 at the mouths of the Paskamanset River and Destruction Brook for this study (we must assume that no substantial changes in stream nitrogen species fractions in these streams has occurred in the interim). After normalizing for the relative stream watershed area of the Paskamanset River and Destruction Brook, the average DIN fraction of total nitrogen in the samples is 0.39. When applied to the EPA average, estimated total nitrogen is about 114 kg TN per day or about 41,600 kg total nitrogen per year from the upper Slocums River watershed, or about one-half (44%) of the BBNEP estimated nitrogen load delivered from the upper 86% of the Slocums River watershed. Even so, this TN estimate based on the 1995 EPA DIN data indicates that the Slocums River TN input was about 3.5 times greater than the BBNEP loading threshold of 12,000 kg TN per year. The EPA nitrogen loading also exceeded that of two other nearby estuaries in 1995. Johnson (2000) normalized the DIN load to each of the three estuaries by factoring in the estuary volume and the estuary flushing time, an adjustment that reduces the effects of the physical differences between the estuaries. Using the normalized DIN values, Johnson concluded that compared to the West Branch of the Westport River and New Bedford Harbor, the Slocums River DIN loading was about two times greater than the other two estuaries.

Considering all the historical nitrogen loading data sets: 1) the BayWatchers nitrogen and other water quality indicator measurements, 2) the US EPA data from 1996, 3) the 1999 revised BBNEP embayment loading model current land use estimate, the Slocums River appears beyond its assimilative capacity for nitrogen. The data also indicates that the Slocums River probably was excessively loaded with nitrogen before 1991. Estimates of the overload vary between c.a. three times (US EPA data) to more than seven times the assimilative capacity as determined in the past by the BBNEP in 1999. The MEP is a refinement of all the above loading estimates factoring refinement of the watershed delineations, detailed land use analysis on a parcel by parcel basis (including water use data) and measured stream flow and nitrogen loading at all the surface water inflows to the overall Slocums River System.

In Little River the BBNEP estimated existing nitrogen loading for 1999 was 2,608 kg n/y, or 51% of the recommended TMAL for that embayment of 5,000 kg/y total nitrogen (BBNEP,1999). This level would appear to indicate that Little River is comfortably below the level at which eutrophication and habitat degradation will begin. However, the BayWatchers Little River monitoring data for the same time period indicated a disagreement between the BayWatchers' measured water quality, which has been generally poor to fair for Inner Little River and the 1999 BBNEP loading estimates which indicate otherwise. It seems likely given the monitoring data, that some other factors may be affecting the water quality in Little River. The MEP has generated a refined watershed and hydrodynamic analysis of the Little River system in order to clarify the historical discrepancy.

III. DELINEATION OF WATERSHEDS

III.1 BACKGROUND

In the Slocums River and Little River watersheds, the regional surficial geology controls the way rainwater and snow melt are transported from the limits of the watershed to the estuaries. Underlying the soils of the region is crystalline bedrock of about 600 million years age (Zen, 1983). The underlying bedrock types include granite, gneiss, schist and other rocks (Murray 1990). Bedrock outcrops occur throughout the watersheds and the exposed and buried bedrock surface is the primary control upon the local topography. The watershed topography is defined by a framework of roughly north-northeastward trending, low bedrock ridges with shallow intervening valleys. Along the local coastline the locations of the Slocums and Little River embayments are determined by and anchored by the locations of low bedrock ridges and submarine reefs (Fitzgerald et al, 1987). The present-day bedrock ridge and valley morphology is the result of both long-term and short-term processes. Long-term processes include chemical and physical weathering of the bedrock and the physical and chemical transport of the eroded materials by the drainage network of streams and rivers into the sea. More recently, a series of repeated continental glaciations have advanced and retreated across the region over the past 600,000 years, with the most recent ending about 15,000 years ago. The glaciations lowered the local bedrock surface by small amounts, leaving smoothed bedrock surfaces and a variety of glacial sediments covering much of the underlying bedrock structure.

The soils and sediments of the two watersheds consist of a variable fabric of low permeability basal till and more permeable ablation till that drapes the bedrock ridges and ridge slopes and usually forms the bottom-most sediment in the valley floors (Williams and Tasker, 1978; Larson, 1982). The shallow valleys and lower areas have a variety of glacial sediments in them usually described as stratified drift. The area bedrock has a very low permeability, while the basal tills (locally known as hardpan) and ablation tills have low to moderately low permeability. The combination of exposed and shallowly buried bedrock and generally low permeability glacial tills affects the hydrology of the two watersheds. The regions' bedrock and low permeability upland soils form a surface-water dominated regime where rainfall and snow melt tend to flow over the ground surface in a greater proportion than percolate into the soils to become groundwater (Bent 1995). The stream network is therefore well-developed and most upland groundwater flow is local, to the nearest stream. Bedrock also controls the area around the mouths of the two largest streams, the Paskamanset River and Destruction Brook in the Slocums River watershed. This bedrock control reduces the likely hood of substantial groundwater underflow and discharge directly into the estuary. As a result, of the total amount of freshwater falling across the watersheds and entering the estuaries, the stream network transports a high proportion of the freshwater flow into the Slocums River estuary, while groundwater transports a relatively small amount of freshwater to the shore.

The watershed soils within the two estuaries reflect a mixture of the two hydrologic regimes: the uplands are dominated by the bedrock and glacial till distribution; and the valleys and low areas reflect the sediments deposited during glacial ice margin retreat, stillstand and ablation. The sediments that fill the shallow valleys usually include uppermost layers of sand, silt, clay and peat that comprise the most recent (<13,000 years ago) alluvial and lake bottom deposits. Surface glacial deposits along the valley sides and floors include highly permeable ice-contact deposits of outwash fans, moraines, kames and eskers. In the valley floors, the glacial sediments fall under the generalized term "stratified drift", which describes variable sequences of moderate to highly permeable glacial-fluvial (stream-laid) outwash deposits, both exposed and buried and glacial lake-bottom deposits of sand, silt, clay and peat (Williams and

Tasker, 1978). As noted above, the valley floor sediment strata are often underlain by a basal till that lies upon the bedrock surface (Williams and Tasker, 1978; Larson, 1982). The valley sediments with the exception of clays and peats are more permeable than the upland till deposits and where they occur in areas of greater depth and extent in the Slocums River basin, they provide water resources for a portion of the municipal water supply for the Town of Dartmouth. Estimates of the percentage of stratified drift areas in the Slocums River watershed based upon soils, well borings and exposures in gravel pits vary from 44% for the upper and middle Paskamanset River basin, to about 55% for the Destruction Brook basin (Bent 1995).

This local hydrologic regime is one that prevails over much of the glaciated Northeastern United States but is a marked contrast to the hydrology that prevails eastward from Mattapoisett to the tip of Cape Cod where more deeply buried bedrock covered with relatively high permeability glacial sediments combine to produce a groundwater-dominated freshwater regime. In those areas, watershed divides are determined primarily by the shape of the groundwater surface as determined by the recorded levels in groundwater wells and from pond and stream elevation records. This data is processed in computer models to produce the maps of the groundwater surface elevation and groundwater flow paths that are used to delineate the watersheds.

III.2 WATERSHED DELINEATION APPROACH

A watershed divide or boundary can be described as the line from which rainwater or snowmelt flows on the surface and the groundwater beneath flow towards one stream, river or estuary while rainfall and groundwater just across the divide flow away to an adjacent water body. Underground, the upper portion of saturated sediments or the groundwater table also tends to reflect the changes in surface elevation within a bedrock and till landscape. The technique of topographic inspection analyzes the pattern of lines of local maximum elevation upon a US Geological Survey 1:25,000 topographic map and draws watershed divides based upon the tendency of surface water and groundwater to flow straight downhill or perpendicularly to the topographic contour lines. Due to the occasional bedrock outcrops along ridges, the combination of ablation and basal tills and the often shallow depth-to-bedrock distances, the lines of maximum elevation along the low ridges of the local region are usually the locations of water divides. Divides tentatively drawn upon topographic maps by inspection of the topography are usually confirmed by visiting the areas of the boundaries and observing water flow on the ground surface during rainfall or during snow melt, by observing the flow of water in small streams, in drainage ditches and in culverts. In zones where the watershed divide crosses low areas, the visual confirmation of small-scale, local flow is important to the accuracy of the boundary.

Watershed delineations were drawn in 1991 for all the Buzzard Bay estuary sub-basins by the Buzzards Bay Project, now the Buzzards Bay National Estuary Program (BBNEP), in partnership with the US Geological Survey (BBP, 1991). These boundaries were determined by the method of topographic inspection. For this MEP review, the 1991 watersheds to Slocums River and Little River were field-verified by Lloyd Center and SMAST technical staff. In some areas, the boundaries were altered based upon the field observations or by examination of the storm drain network as outlined in the following section. As a result of the adjustments, the MEP Slocums River (Figure III-1) and Little River (Figure III-2) watershed boundaries and resultant areas differ somewhat from the BBNEP published watershed areas (Table III-1). Sub-basin boundaries were determined using the estuary watershed boundaries as a framework and topographic inspection was used to delineate the separate stream watershed sub-basins and then the boundaries were field verified.

Storm Drain and Sewer Networks

In more urbanized areas much of the precipitation falls on low permeability soils or impervious surfaces and flows into storm drain networks. In Dartmouth these storm drain systems discharge both to the streams and directly to the estuaries. In New Bedford, much of the surface flow is into a drainage system that combines storm drain and sewer networks. For the areas of the Slocums River watershed served by storm drains in both municipalities, the flow of surface drainage may not agree with the watershed boundaries determined by topographic inspection. Storm drain and sewer networks are often delimited by town boundaries, or by the locations of lift stations in the case of combined storm drain and sewer systems. For the purposes of this project, the existing BBNEP watershed boundaries were adjusted to reflect the pattern of the storm drain networks in one area, the divide along the eastern, common divide between the Slocums River-Paskamanset River basin and the Acushnet River-New Bedford harbor watershed (previously delineated in 2004 during the initial years of the MEP). The original BBNEP watershed boundary in this area was shifted to reflect the New Bedford storm drain-sewer network. The net effect of the boundary adjustments for storm drains in the Slocums River watershed was a 310 acre decrease in the Slocums River basin area or a change of -1.3% of total area.

Divides Crossing Permeable Sediments

In a two areas where the watershed boundaries cross topographic lows in an east-west direction, a degree of uncertainty exists as to the location of the divide due to the higher permeability of the stratified drift that underlies the two boundary areas and the lack of clear bedrock or till surface control. In both the cases where surface and subsurface water flow tendency is not clear, the length of the uncertain boundary is relatively short. First, the northern boundary between Little River estuary watershed and that of Apponagansett Bay crosses permeable outwash sediments and ice contact deposits in an area of bedrock outcrops. A definitive determination of the divide would require suitably located groundwater wells and water table measurements taken from the wells over an extended period of time, however the potential uncertainty of the divide between Little River and Apponagansett Bay using the method of topographic inspection is about 0.4%, small relative to the size of the total watershed.

At the northern extremity of the Slocums River watershed, a short portion of the boundary crosses the triangle formed by Braley Road, Quanapoag Road and the northern end of the New Bedford Industrial Park. The potential uncertainty of divide placement in this area is also on the order of 0.4%, and also insignificant relative to the size of the total watershed. Within the Slocums River watershed a stretch of the northern sub-basin boundary of Destruction Brook along with the Paskamanset River in Deerfield Swamp crosses stratified drift. In this case the uncertainty is difficult to estimate, but the divide location does not affect the Slocums River watershed basin area, only the relative size of the Destruction Brook and Paskamanset River drainages within it.

Based on the details presented above, the MEP Technical Team concurred that the watershed delineations, as presented in Figures III-1 and III-2 for the Slocums and Little Rivers, respectively, were suitable for the nutrient threshold analysis.

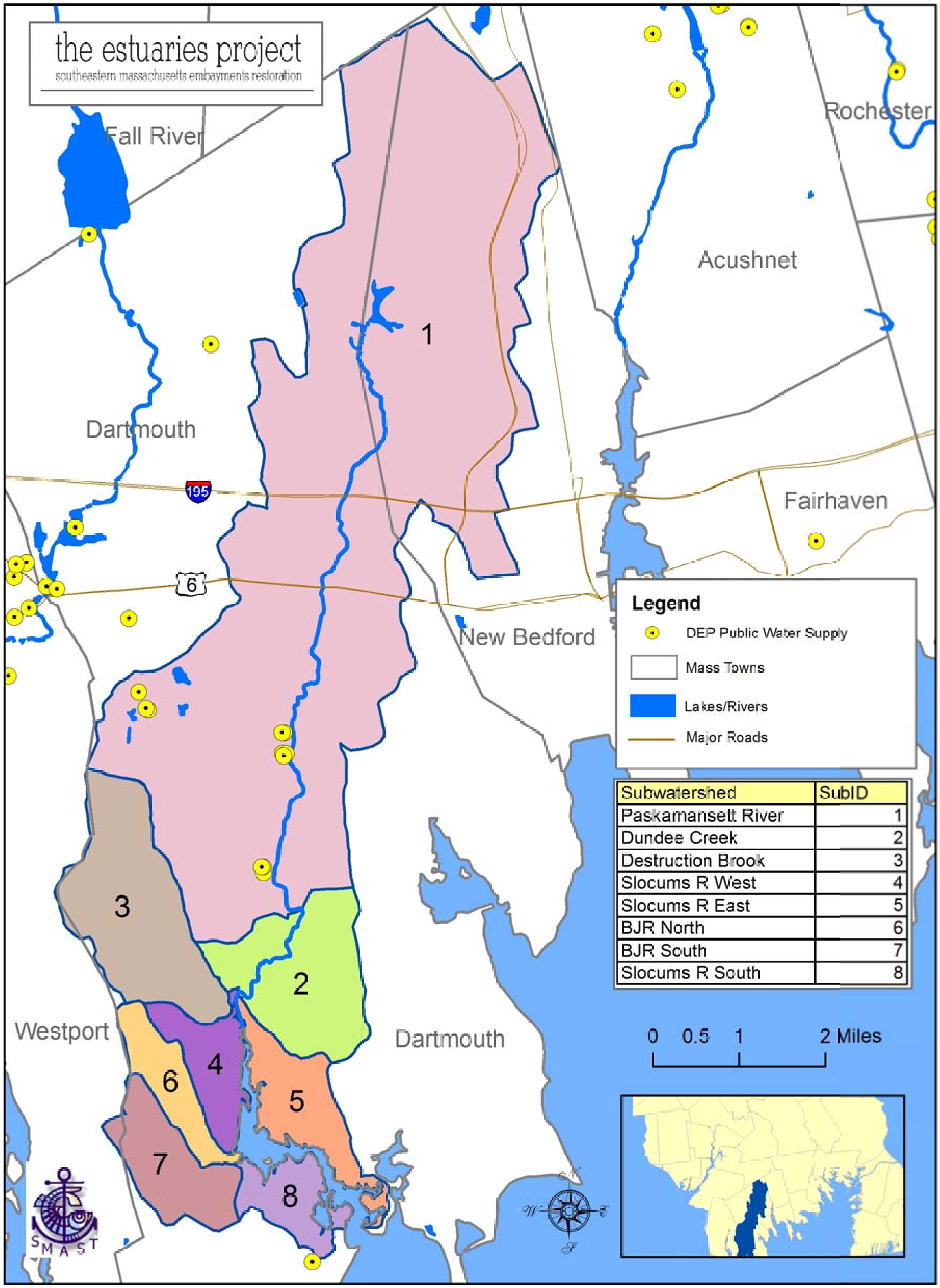


Figure III-1. Slocums River estuary watershed and sub-watershed delineation.

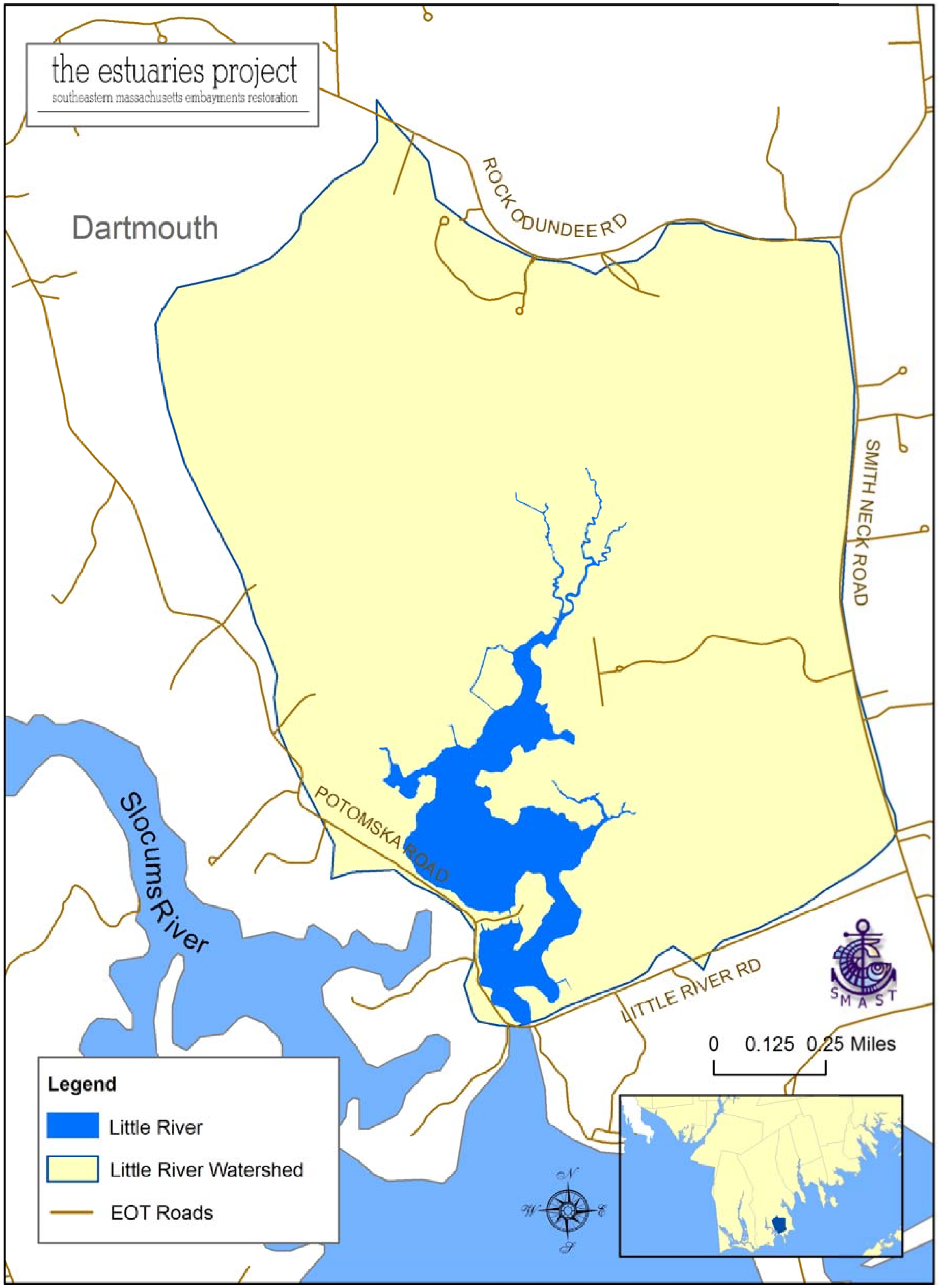


Figure III-2. Little River estuary watershed delineation.

Table III-1. Slocums River and Little River Watershed Areas.

Watershed Name	Watershed #	Area (acres)
Paskamanset River	1	16,700
Dundee Creek	2	1,598
Destruction Brook	3	1,927
Slocums R West	4	642
Slocums R East	5	902
BJR N	6	571
BJR S	7	881
Slocums R South	8	551
Slocum River TOTAL		23,771
Little River TOTAL		1,320

Note: Watershed areas and numbers based on delineations shown in Figures III-1 and III-2

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 Slocums River and the Little River. 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 the transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes. This latter natural attenuation process results from biological processes that naturally occur within ecosystems. Failure to account for attenuation of nitrogen during transport results in an over-estimate of nitrogen inputs to an estuary and an underestimate of the sensitivity of a system to new inputs (or removals). In addition to the nitrogen transport from land to sea, the amount of direct atmospheric deposition on each embayment surface must be determined as well as the amount of nitrogen recycling within the embayment, specifically nitrogen regeneration from sediments. Sediment nitrogen recycling results primarily from the settling and decay of phytoplankton and macroalgae (and eelgrass when present). During decay, organic nitrogen is transformed to inorganic forms, which may be released to the overlying waters or lost to denitrification within the sediments. Burial of nitrogen is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source of nitrogen to embayment waters or in some cases a sink for nitrogen reaching the bottom. Failure to include the nitrogen balance of estuarine sediments generally leads to errors in predicting water quality, particularly in determination of summertime nitrogen load to embayment waters.

The MEP Technical Team includes technical staff from the Cape Cod Commission (CCC). In coordination with other MEP Technical Team members and staff from the Southeastern Regional Planning & Economic Development District (SRPEDD), CCC staff developed nitrogen-loading rates (Section IV.1) to the Slocums River estuary system (Section III). The Slocums River watershed was sub-divided to define contributing areas to each of the major inland freshwater systems and to each major sub-estuary. A total of eight sub-watersheds were delineated for the Slocums River estuary watershed (Figure IV-1). Because of its comparatively small size, the Little River estuary does not have any sub-watersheds (Figure IV-2). The nitrogen loading effort for each system also involved further refinement of watershed delineations to accurately reflect shoreline areas to each embayment/estuary (see Chapter III).

The initial task in the MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the estuary. This generally involves a temporal review of land use changes, review of data at natural collections points (streams and ponds), and in groundwater dominated systems, the time of groundwater travel provided by the USGS watershed model. The Slocums River and Little River watershed systems are stream-dominated systems because of the underlying geology, so this portion of the review focused on land use development and data from stream gauges. In the Slocums River, most of the watershed area is within a mile or less of the sub-watershed stream or a tributary. In the Little River, the outer boundaries of the entire watershed are approximately 0.5 miles from the Little River. Recharge with nitrogen loads from these watersheds would take approximately 14 years for flow to reach the river with a flow rate of 1 ft/d if groundwater were the primary flow to the river and no tributaries existed. Since most of these areas are lined with extensive tributary networks to the main stream or river, flow to the main streams must be 10 years or less from the outer edges of the watershed. Other MEP analyses in groundwater-dominated systems have shown that if most development is within 10 years or less, then the watershed and nitrogen loads are in relative balance with the estuary nitrogen concentrations. Given the hydrogeologic characteristics of the Slocums and Little River watersheds, the MEP has a high level of confidence that the present watershed nitrogen loads appears to accurately reflect the present nitrogen sources to the estuaries (after accounting for natural attenuation, see below).

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data is used for some portion of the loads, while information developed from other detailed studies is applied to other fractions of the watershed loads. 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. For the Slocums River estuary system, the model used town land use data from Dartmouth and as well as land use data from the City of New Bedford. For the Little River estuary, the model used town land use data form Dartmouth only. All land use data was provided by SRPEDD. This land-use data was transformed to nitrogen loads using both regional nitrogen loading factors and local watershed specific data (such as average water use from Dartmouth). Determination of the nitrogen loads required obtaining watershed specific information regarding wastewater, fertilizers, runoff from impervious surfaces and atmospheric deposition. The primary regional factors were derived for southeastern Massachusetts from direct measurements. The resulting nitrogen loads represent the “potential” or unattenuated nitrogen load to each receiving embayment, since attenuation during transport has not yet been included.

Natural attenuation of nitrogen during transport from land-to-sea (Section IV.2) within the Slocums River watershed was determined based upon a site-specific study of stream flow from the Paskamanset River, Destruction Brook, BJR North, and BJR South. Little River did not have a gauged location. Generally, the MEP analysis also includes attenuation in ponds and lakes, but the river-dominated nature of this system did not include any significant ponds or lakes. Delineating the sub-watershed to the stream, however, allowed comparisons between field collected data from the stream and estimates from the nitrogen-loading sub-model. Stream flow attenuation is included in the MEP’s nitrogen attenuation and freshwater flow investigation, presented in Section IV.2.

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 (~10%) overestimated given the distribution of nitrogen sources within the watershed. Based upon these considerations, the MEP Technical Team used the Nitrogen Loading Sub-Model estimate of nitrogen loading for the three Slocum River sub-watersheds and the whole Little River watershed that directly discharge groundwater to the estuary without flowing through a gauged stream or river. Internal nitrogen recycling was also determined throughout the tidal reaches of the Slocums and Little River estuarine 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 critical season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

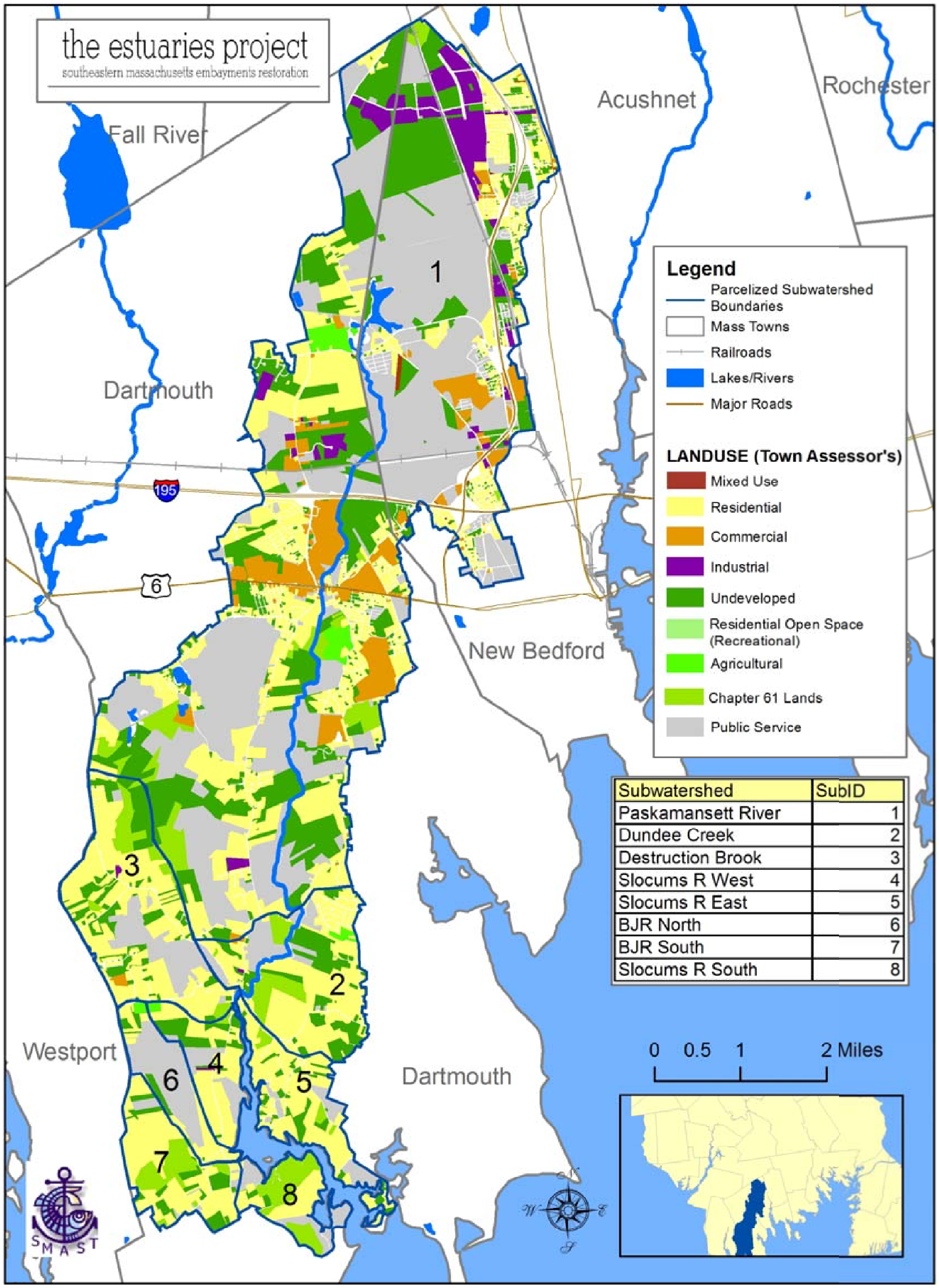


Figure IV-1. Land-use in the Slocums River watershed. The watershed is split between the Town of Dartmouth and the City of New Bedford. Land use classifications are based on town assessors' records provided by the SRPEDD.

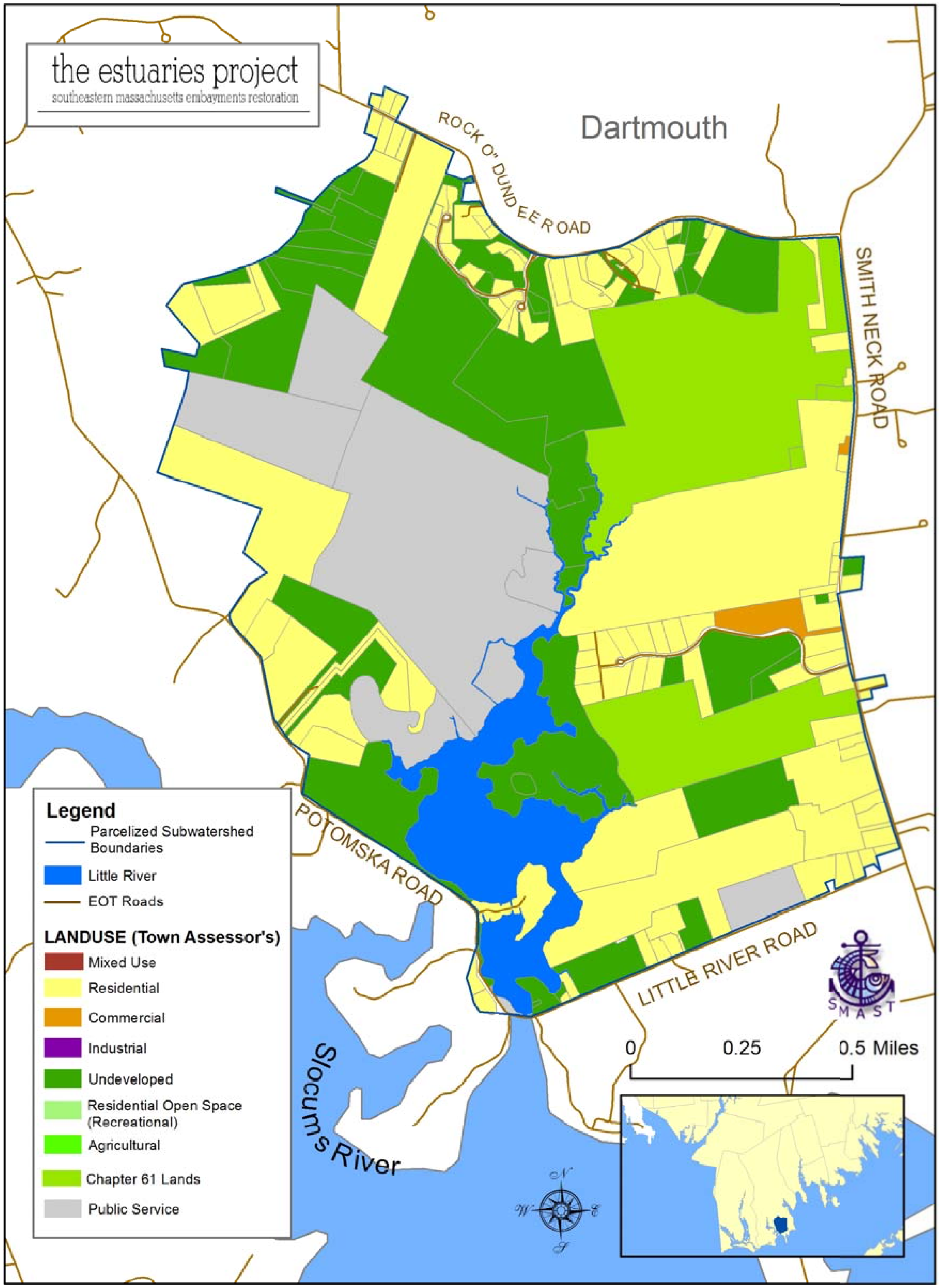


Figure IV-2. Land-use in the Little River watershed. The watershed is only within the Town of Dartmouth; it does not cross any town boundaries. Land use classifications are based on town assessors' records provided by the SRPEDD.

IV.1.1 Land Use and Water Use Database Preparation

Estuaries Project staff obtained available City of New Bedford and Town of Dartmouth digital parcel and tax assessors data from SRPEDD. Land use databases contain traditional information regarding land use classifications (MADOR, 2002) plus additional information developed by each town, including use of public drinking water supplies and connection to the municipal sewer systems in New Bedford and Dartmouth. The parcel data and assessors' databases were combined by MEP staff.

Figure IV-1 shows the land uses within the Slocums River estuary watershed. Land uses in the study area are grouped into nine land use categories: 1) residential, 2) commercial, 3) industrial, 4) mixed use, 5) undeveloped, 6) agricultural, 7) recreational, 8) public service/government, including road rights-of-way, and 9) freshwater features (*e.g.* ponds and streams). Figure IV-2 shows the corresponding grouping of land uses within the Little River estuary watershed. Land uses in the Little River watershed are grouped into five land use categories: 1) residential, 2) commercial, 3) undeveloped, 4) agricultural, and 5) public service/government, including road rights-of-way. In both watersheds, these land use categories, except the freshwater features, are aggregations derived from the major categories in the Massachusetts Assessors land uses classifications (MADOR, 2002). These land use categories are common to both town and the city in the watersheds. “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.

In the overall Slocums River System watershed, the predominant land use based on area is public service/government, which accounts for 30% of the overall watershed area (Figure IV-3). This percentage is largely a reflection of land use in the Paskamanset River sub-watershed, which is the largest sub-watershed in the overall system watershed, and has 41% of its area in the public service/government category. Specific watershed land uses in this category that have large areas are: New Bedford Airport, the Acushnet Cedar Swamp, and the University of Massachusetts at Dartmouth. In the smaller sub-watersheds, closer to the estuary, residential land uses are generally about half of the sub-watershed area. Residential land area is the second highest percentage in the Paskamanset River sub-watershed and for the whole system watershed, as well. Residential is also the majority parcel type in the watershed with 69% of all the parcels in the whole system watershed. Single-family residences (MADOR land use code 101) are 90% of the residential land area in the whole system watershed. Undeveloped is usually the third highest land use area percentage, except for the sub-watersheds discharging directly to the estuary, where agricultural land use is the third highest percentage (13%). In the overall system watershed, land classified as undeveloped is 19% of the watershed area, while agricultural is 5% and commercial is 3%.

In the Little River system watershed, residential land is the dominant land use area with undeveloped land occupying the second highest total area (27%). Residential parcels are also the majority parcel type (64%) with 60% of the residential land area being single-family residences. Undeveloped areas are 27% of the watershed area, public service/government uses are 20%, and agricultural uses are 16%.

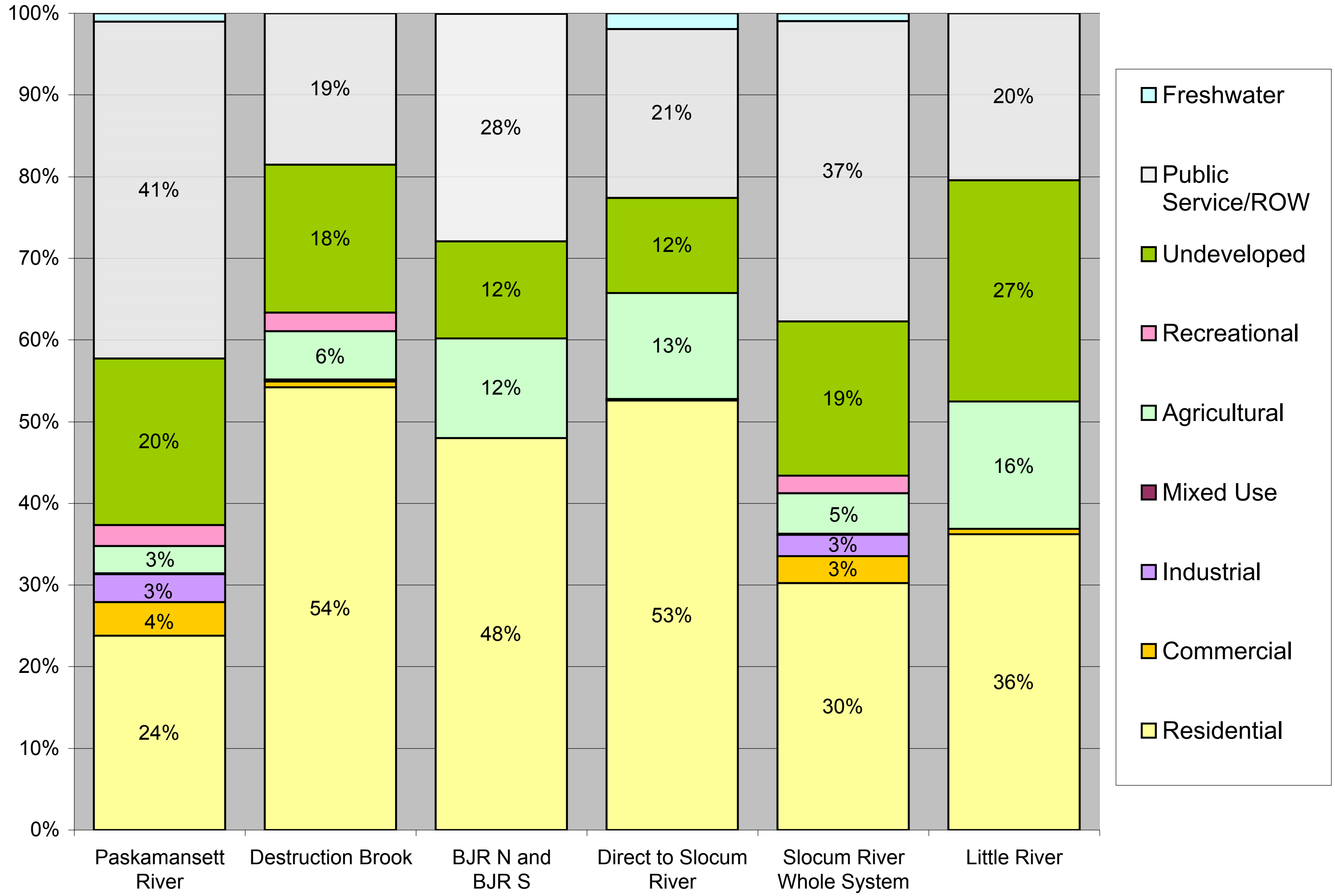


Figure IV-3. Distribution of land-uses within the major sub-watersheds and whole watershed to the Slocums River and Little River estuary systems. Only percentages greater than or equal to 3% are shown.

Generally, in MEP analyses, project staff obtain parcel-by-parcel water use information to be used as a proxy for wastewater generation. This type of information was not available within the Slocums and Little River watersheds, but MEP staff contacted town water suppliers in the watershed and obtained average water use. Project staff also obtained information listing all parcels connected to the Town of Dartmouth and City of New Bedford wastewater treatment facilities, as well as facility performance data from MassDEP. No other treatment facilities, public or private, have a state discharge permit within the Slocums or Little River watersheds. Wastewater-based nitrogen loading from the individual parcels using on-site septic systems is based upon the average water-use, nitrogen concentration, and consumptive loss of water before the remainder is treated in a septic system (see Section IV.1.2).

IV.1.2 Nitrogen Loading Input Factors

Wastewater/Water Use

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

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

All nitrogen losses within the septic system are incorporated 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 indicate that further nitrogen loss during aquifer transport is negligible (Robertson et al. 1991, DeSimone and Howes 1996).

In its application of the water-use approach to septic system nitrogen loads, the MEP has ascertained for the Estuaries Project region that while the per capita septic load is well constrained by direct studies, the consumptive use and nitrogen concentration data are less certain. As a result, the MEP has derived a combined term 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). 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 form town-wide occupancy rates. These analyses provide additional support for the use of the water use approach in the MEP study region.

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

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

In order to evaluate average residential water use within the Slocums River and Little River watersheds, MEP staff reviewed US Census population values for the City of New Bedford and Town of Dartmouth. 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 the watershed towns are 2.91 (Dartmouth) and 2.46 (New Bedford) (Table IV-1). Seasonal properties are a small component of the housing stock in each town, so potential variability associated with seasonal fluctuations should not be significant. Since water use was not available on a per-parcel basis within the Slocums River or Little River watersheds, MEP staff obtained average water use for all properties within Dartmouth and New Bedford. In Dartmouth, 8,184 active accounts use an average of 188 gpd of water (Steve Sullivan, Dartmouth Water Department, personal communication, 6/07). In New Bedford, 23,000 active accounts use an average of 514 gpd of water (Billing Clerk, New Bedford Water Division Billing Department, personal communication, 5/07). Since both of these averages include all properties, not just residential units, the comparison to population numbers is somewhat misaligned, but the data is representative of water use in the watershed. Multiplying the two averages by 0.9 to account for consumptive use, the town averages are 169 gpd and 462 gpd, respectively.

The characteristics of land use in the watershed suggest that the 169-gpd average is most appropriate for use in the nitrogen loading analysis. Of the 2,804 developed New Bedford properties in the watershed, approximately 90% are connected to the municipal sewer system. In addition, the relatively high percentage of industrial uses in New Bedford, also suggests that the average water use in New Bedford may be inflated by commercial and industrial processes that utilize large quantities of water (*e.g*., fish processing plants). The 169 gpd average also approximates the average water use (163 gpd) in Acushnet (Billing Clerk, Acushnet Water/Sewer Department, personal communication, 5/07), which was the water use estimate for the New Bedford Harbor MEP Technical Report (Howes, et al., in review). The 169-gpd average divided by 55 gpd per person, results in an average occupancy of 3.08. Considering the land use distributions within the watershed and since this occupancy rate is within 6% of the 2000 Census occupancy for Dartmouth, MEP Technical Team felt confident that the Dartmouth average water use is an appropriate basis for determining septic system wastewater nitrogen loads within Slocums River and Little River estuary watersheds.

Table IV-1. Town Occupancy Data from the 2000 Census used to evaluate potential per capita water use in the Slocums River and Little River watersheds.				
Town/City	Occupied Housing Units	Average Occupancy	Seasonal Properties	Estimated Title 5 flow per housing unit
		People per occupied housing unit	% of total housing units	gpd based on 55 gpd/person
New Bedford	38,178	2.46	0%	135.1
Dartmouth	30,666	2.91	4%	159.8

Municipal Wastewater Treatment Facilities

NEW BEDFORD WASTEWATER POLLUTION CONTROL FACILITY AND COMBINED SEWER OVERFLOWS

The New Bedford Wastewater Pollution Control Facility (WPCF) is located at the end of Clarks Point in New Bedford and discharges treated effluent into Buzzards Bay through an outfall pipe located off the end of the point and outside of the Slocums River MEP study area. There are 2,513 developed properties within the Paskamanset River sub-watershed that are connected to the New Bedford WPCF.

DARTMOUTH WASTEWATER POLLUTION CONTROL FACILITY

The Dartmouth Wastewater Pollution Control Facility (DWPCF) is located off Russells Mills Road in Dartmouth (Figure IV-4). The DWPCF has a National Pollutant Discharge Elimination System (NPDES) permit from US Environmental Protection Agency (USEPA) and MassDEP that allows direct discharge into Buzzards Bay (outfall location shown in Figure IV-4) at a location that is outside of the Slocum River and Little River study area. The NPDES permit limits total flow to 4.2 million gallons per day and it does not specify an effluent nitrogen concentration limit (www.epa.gov/region1/npdes/permits/dartmouthpermit.pdf). The sewer collection system connected to the WWTF receives wastewater flow only from the Town of Dartmouth.

Since the DWPCF discharges outside of the Slocum River and Little River watersheds, the sewer collection system removes wastewater nitrogen loads from developed properties within the watersheds. Properties within the Slocums River watershed that were identified through town parcel information as having sewer connections were not assigned a wastewater nitrogen load. All other properties were assumed to utilize on-site septic systems and were assigned a wastewater load based on the assigned average water use. According to the land use databases, there are 1,522 properties in the Slocum River watershed that are connected to the DWPCF. Overall, there are 4,035 properties in the Slocum River watershed that have their wastewater nitrogen loads removed from the watershed by connection to a sewer system. No properties in the Little River watershed are sewered.

Figure IV-4 also shows planned sewer lines that the Town of Dartmouth is considering. The layout of these lines was used during the development of the buildout scenario for the watershed.

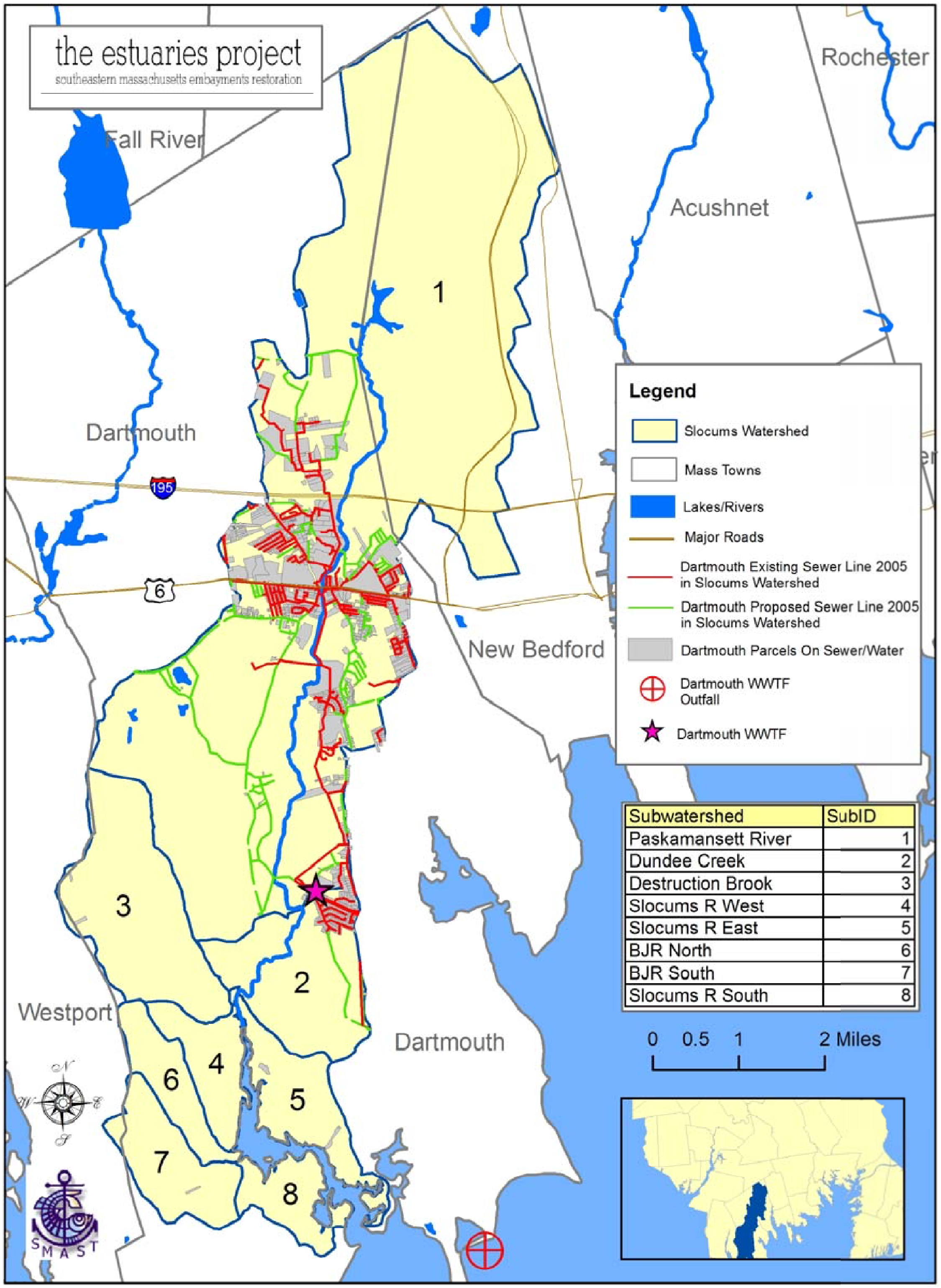


Figure IV-4. Dartmouth Existing and Proposed Sewer Collection System, Wastewater Pollution Control Facility and outfall location. Data supplied by SRPEDD and Town of Dartmouth.

NITROGEN LOADING INPUT FACTORS: FERTILIZED AREAS

The second largest source of estuary watershed nitrogen loading is usually fertilized lawns, golf courses, and cranberry bogs and other agricultural crops, with lawns usually being the predominant source within this category. In order to add this source to the nitrogen loading models for the Slocums River and Little River estuary systems, MEP staff reviewed available information about residential lawn fertilizing practices and incorporated site-specific information to determine nitrogen loading from other fertilization application practices in the watershed. Cranberry bog and crop nitrogen loading was determined based on previous studies conducted in southeastern Massachusetts and nitrogen loads from the three golf courses in the watershed were based on information gathered from other golf courses in previous MEP reviews.

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 among the standard factors used in the Watershed Nitrogen Loading Sub-Model.

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

In order to determine nitrogen loading from cranberry bogs, MEP staff reviewed aerial photographs of properties classified as cranberry bogs and digitized the areas of the bogs using GIS techniques. This step was taken to apply the nitrogen loading factors only to the bog surfaces and not to the upland on the bog properties. Fertilizer application rate and percent nitrogen attenuation in the watershed nitrogen loading model for these bog areas is based on the only annual study of nutrient cycling and loss from cranberry agriculture that has been conducted in southeastern Massachusetts (Howes and Teal, 1995). There are a total of 76 acres of bog surface in the Slocums River watershed and none in the Little River watershed.

The Slocum River and Little River watersheds also contain a number of properties classified by town assessors as agricultural [codes in the 300s, 600s and 700s of MADOR's (2002) classification system]. MEP staff reviewed prior analyses of agricultural nitrogen loading in Southeastern Massachusetts, including Costa (2000) and Howes (1987), and utilized factors for each assessors code that are listed in Table IV-2. These factors include application rates of 0.1 to 0.7 lbs of nitrogen applied per 1,000 square feet. MEP staff reviewed aerial photographs of the properties and determined that, on average, approximately 85% of each property appears to be in agricultural use; agricultural fertilizer rates were applied to the area of each property determined to be in use. Based on the land use analysis, MEP staff determined that 572 acres of fertilized agricultural land is in the Slocum River watershed and 175 acres are in the Little River watershed.

In the Paskamanset River sub-watershed to the Slocum River, there are also three golf courses: the municipally owned Whaling City Golf Course, the New Bedford Country Club, and the Allendale Country Club. MEP staff were unsuccessful in contacting a staff person at these courses who could provide course-specific fertilizer application rates, so the watershed nitrogen loading model utilized averages from 14 other courses contacted through a number of previous MEP watershed analyses. MEP staff reviewed aerial photographs of the golf courses and digitized the tees, greens, fairways, and rough areas using GIS techniques and determined a total nitrogen load for the courses based on a 20% leaching rate and the following nitrogen application averages to these areas: greens, 3.8 lbs per 1,000 square feet; tees, 3.5 lbs per 1,000 square feet; fairways, 3.3 lbs per 1,000 square feet and roughs, 2.5 lbs per 1,000 square feet.

There are also 34.5 acres of sports fields at the University of Massachusetts Dartmouth that were identified using the same GIS techniques. These areas were added to the Paskamanset River sub-watershed in the Slocum River watershed nitrogen loading model and they are assigned the same loading factors as residential lawns.

Nitrogen Loading Input Factors: Other

In addition to fertilizers and wastewater, other factors add nitrogen loads to a watershed and MEP staff developed loads for a number of watershed and site-specific sources. These loads included farm animals, large areas of impervious surfaces around the Dartmouth Mall, New Bedford Airport, and UMASS-Dartmouth, and non-standard loads from the extensive wetlands that surround most of the streams in the Slocum River watershed. Project staff also reviewed available monitoring data for the capped Dartmouth landfill and determined that it is not currently contributing nitrogen loads to the Paskamanset River; further discussion is included in Section 4.2.2.

MEP staff obtained a count of farm animals within the watershed from Town of Dartmouth staff (P. DeMello, personal communication, 6/07). Using GIS techniques, MEP staff generated approximate locations for these counts, summarized the counts by sub-watershed and generated nitrogen loads for the sub-watersheds based on nitrogen information from USDA (1979) and horse nitrogen loading information developed by the Cape Cod Commission (Table IV-3). Based on best professional judgment, 40% of nitrogen loads from farm animals were assumed to reach groundwater. These loads were added to the watershed nitrogen loading model for Slocums River; town information did not list any farm animals within the Little River watershed.

MEP staff reviewed aerial photographs for commercial properties in and around the Dartmouth Mall and on the University of Massachusetts Dartmouth campus and determined site specific impervious surface areas using GIS techniques. The same techniques were also used to determine the area of the runways at the New Bedford airport. All of these areas are included in the impervious surface nitrogen loading calculations for Paskamanset River sub-watershed portion of the Slocum River watershed nitrogen loading model.

In the Slocums River watershed exist extensive wetland and swamp lands surrounding most of the streams and rivers feeding into the estuary (Figure IV-5). Based on nitrogen species and loading information collected at the gauges to the Paskamanset River, Destruction Brook, BJR North and BJR South, it is clear that these wetlands are nearly saturated with nitrogen and are exporting nearly the same nitrogen loads as are being added to them by precipitation. This is equivalent to how surface waters act and how they are incorporated into the watershed nitrogen loading model. Because of this, MEP staff digitized these wetland areas using GIS techniques and treated these areas as surface waters for the purposes of developing their nitrogen loads in the Slocum River watershed nitrogen loading model. A total of 5,511 acres of this type of wetland exists in the Slocum River watershed; no wetlands of this type were assigned in the Little River watershed.

An additional load was also added to the Destruction Brook sub-watershed based on data collected at the gauge location. Field monitoring was completed along lower Destruction Brook where a tributary feeds into the brook. This tributary drains a sub-watershed area that consists largely of a farm that used to have a large number of dairy cows. Monitoring along the brook on three occasions produced an average 47% increase in total nitrogen concentration when comparing concentrations upstream and downstream of the tributary. Based on this average and the estimated nitrogen load in the rest of the watershed, MEP staff determined that the tributary was adding 2,295 kg per year of nitrogen load to Destruction Brook. Attenuation of the total load was estimated based on monitoring data at the Brook gauge (see **Section IV.2.2**).

Another factor in accounting for all nitrogen loads within a watershed is atmospheric deposition, both on impervious surfaces and natural areas. Nitrogen loading factors used in the Slocums River and Little River watershed nitrogen loading models are generally from the MEP Embayment Modeling Evaluation and Sensitivity Report (Howes and Ramsey 2001), the Cape Cod Commission's Nitrogen Loading Technical Bulletin (Eichner and Cambareri, 1992), and Massachusetts DEP's Nitrogen Loading Computer Model Guidance (1999). MEP staff reviewed precipitation data, in particular, to support the use of these factors in the study areas. Factors used in the MEP nitrogen loading analysis for the Slocums River and Little River watersheds are summarized in Table IV-2.

Table IV-2. Primary Nitrogen Loading Factors used in the Slocums River and Little River MEP analyses. General factors are from MEP modeling evaluation (Howes & Ramsey 2001). Site-specific factors are derived from Dartmouth and New Bedford data. *Data from MEP lawn study in Falmouth, Mashpee & Barnstable 2001.

Nitrogen Concentrations:	mg/l
Road Run-off	1.5
Roof Run-off	0.75
Direct Precipitation on Embayments and Ponds	1.09
Natural Area Recharge	0.072
Wastewater Coefficient	23.63
Fertilizers:	
Average Residential Lawn Size (sq ft)*	5,000
Residential Watershed Nitrogen Rate (lbs/lawn)*	1.08
Golf Courses	lb/1,000 sq ft
Greens	3.8
Tees	3.5
Fairways	3.3
Roughs	2.5
Leaching rate for all fertilized turf	20%

Recharge Rates:	in/yr
Impervious Surfaces	40
Natural and Lawn Areas	27.25
Water Use/Wastewater:	
All developed parcels and buildout residential parcels not connected to municipal sewer systems:	186 gpd
Commercial Buildout	
Wastewater flow (gpd/1,000 ft2 of building):	98
Building coverage of lot:	13%
Industrial Buildout	
Wastewater flow (gpd/1,000 ft2 of building):	16
Building coverage of lot:	10%

Agricultural Fertilizer Loads		
	Application (lbs/ac)	Leaching rate
Cranberry Bogs	31	66%
Various crops (state land use codes: 317, 393, 394, 395, 601, 712, 714, 717, 720)	30.33	30%
Pasture & Nurseries (state land use codes: 718, 719) (application includes leaching)	4.46	100%

NOTE: Review of water quality monitoring data indicates that the capped Dartmouth landfill is not contributing nitrogen loads to the Paskamanset River; review Section 4.2.2 for discussion.

Table IV-3. Farm animal nitrogen loads within the Slocum River watershed based on information supplied by the Town of Dartmouth. Loading rates based on USDA (1979) and horse nitrogen loading information from Cape Cod Commission files.

	Paskamansett River	Dundee Creek	Destruction Brook	Total # of animals	Loading Rate	Total Load	Leaching Rate	Load to GW
animal type	# of animals	# of animals	# of animals		kg N/ animal/y	kg/y		kg/y
Horse	11	0	7	18	32.4	584.1	40%	233.6
Mini Horse	1	0	0	1	13.0	13.0	40%	5.2
Pony	3	0	0	3	13.0	38.9	40%	15.6
Cow	72	0	0	72	55.8	4017.0	40%	1606.8
Steer	1	0	0	1	55.8	55.8	40%	22.3
Calves	3	0	0	3	27.9	83.7	40%	33.5
Goat	34	0	7	41	7.3	297.6	40%	119.0
Dwarf Goat	3	0	0	3	3.6	10.9	40%	4.4
Sheep	18	0	0	18	7.3	130.6	40%	52.3
Pig	0	0	2	2	14.5	29.0	40%	11.6
Rabbits	39	0	0	39	0.4	14.2	40%	5.7
Chickens/ Guinea Hens	181	12	18	211	0.4	90.0	40%	36.0
Rooster	1	0	1	2	0.4	0.9	40%	0.3
Pigeons	85	0	0	85	0.1	8.8	40%	3.5
Duck	39	0	0	39	0.4	16.6	40%	6.7
Peacock	0	2	0	2	1.4	2.8	40%	1.1
Turkey	0	3	0	3	1.4	4.1	40%	1.7
Pheasant	3	0	0	3	0.4	1.3	40%	0.5
Dove	8	0	0	8	0.1	0.8	40%	0.3
					TOTAL	5400.1		2160.0

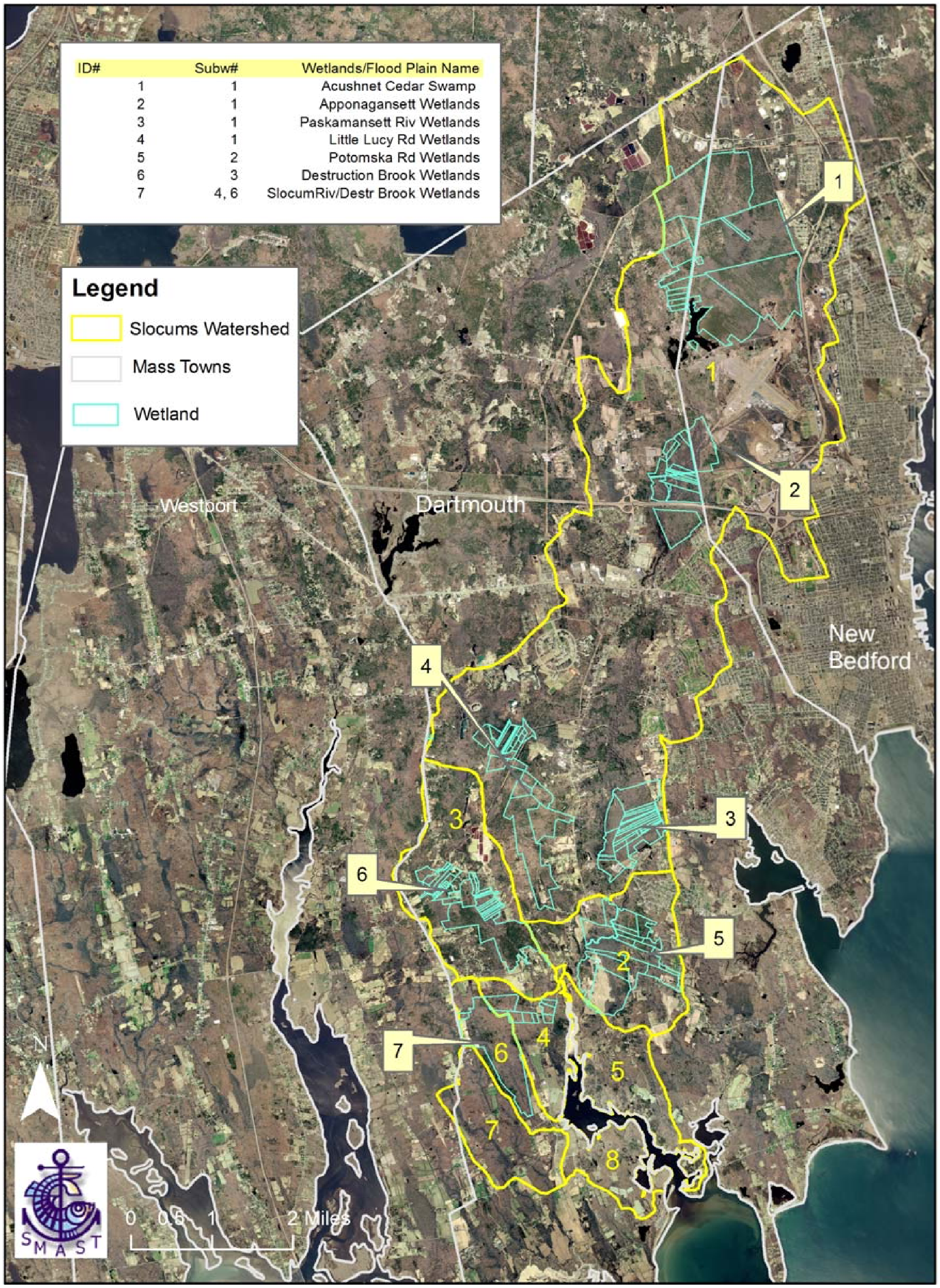


Figure IV-5. Wetland areas surrounding Paskamanset River, Destruction Brook, BJR N and BJR S. Based on monitoring at the stream gauges for these systems, these appear to be near nitrogen saturation and, as such, are treated like surface waters in the watershed nitrogen loading model for Slocums River.

IV.1.3 Calculating Nitrogen Loads

Once all the land and water use information was linked to the parcel coverages, parcels were assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel was located within a respective watershed. Following the assigning of boundary parcels, all large parcels were examined individually and were split (as appropriate) in order to obtain less than a 2% difference between the total land area of each sub-watershed and the sum of the area of the parcels within each sub-watershed. The resulting “parcelized” watersheds to Slocums River are shown in Figure IV-6 and the parcelized watershed for Little River is shown in Figure IV-7.

The review of individual parcels straddling watershed boundaries included corresponding reviews and individualized assignment of nitrogen loads associated with lawn areas, septic systems, and impervious surfaces. Individualized information for parcels with atypical nitrogen loading (condominiums, golf courses, municipal sewer connections, etc.) was also assigned at this stage. It should be noted that small shifts in nitrogen loading due to the above assignment procedure generally have a negligible effect on the total nitrogen loading to the Slocums River and Little River estuaries. The assignment effort was 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 eight Slocum River and one Little River sub-watersheds summarizing water use, parcel area, frequency, sewer connections, private wells, and road area. The individual sub-watershed modules were then integrated to create a Slocums River and Little River Watershed Nitrogen Loading module with summaries for each of the individual sub-embayments and sub-estuaries. The sub-embayments represent the functional embayment 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 Slocums River and Little River study area, the major types of nitrogen loads are: wastewater from septic systems, lawn and golf course fertilizers, agricultural fertilizers, animal loads, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (Table IV-4). The output of the watershed nitrogen-loading model is the annual mass (kilograms) of nitrogen added to the contributing area of component sub-embayments, by each source category (Figure IV-8 a-c). In general, the annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation during transport to the estuarine system before use in the embayment water quality sub-model.

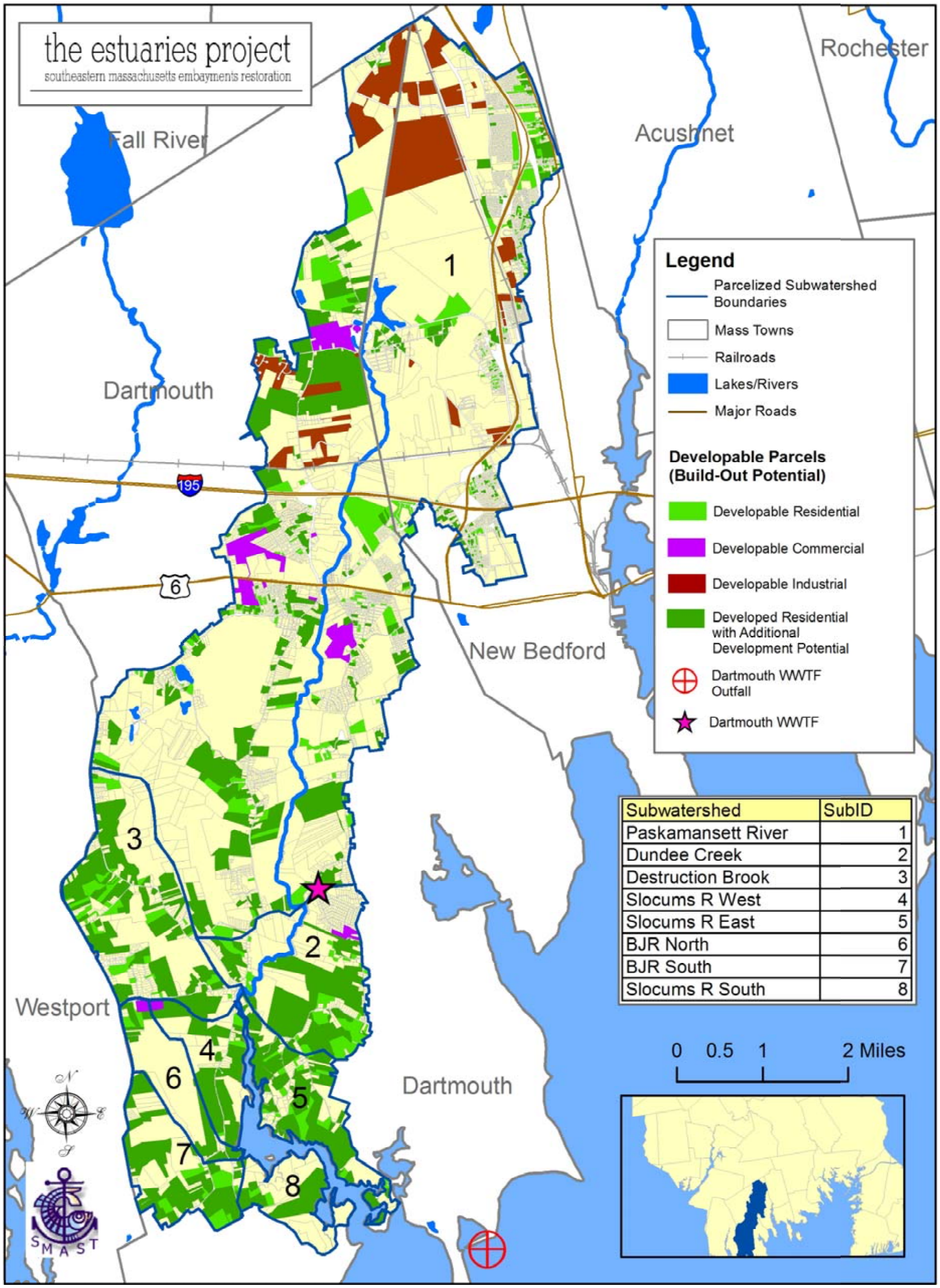


Figure IV-6. Parcels, Parcelized Watersheds, and Developable Parcels in the Slocums River watershed.

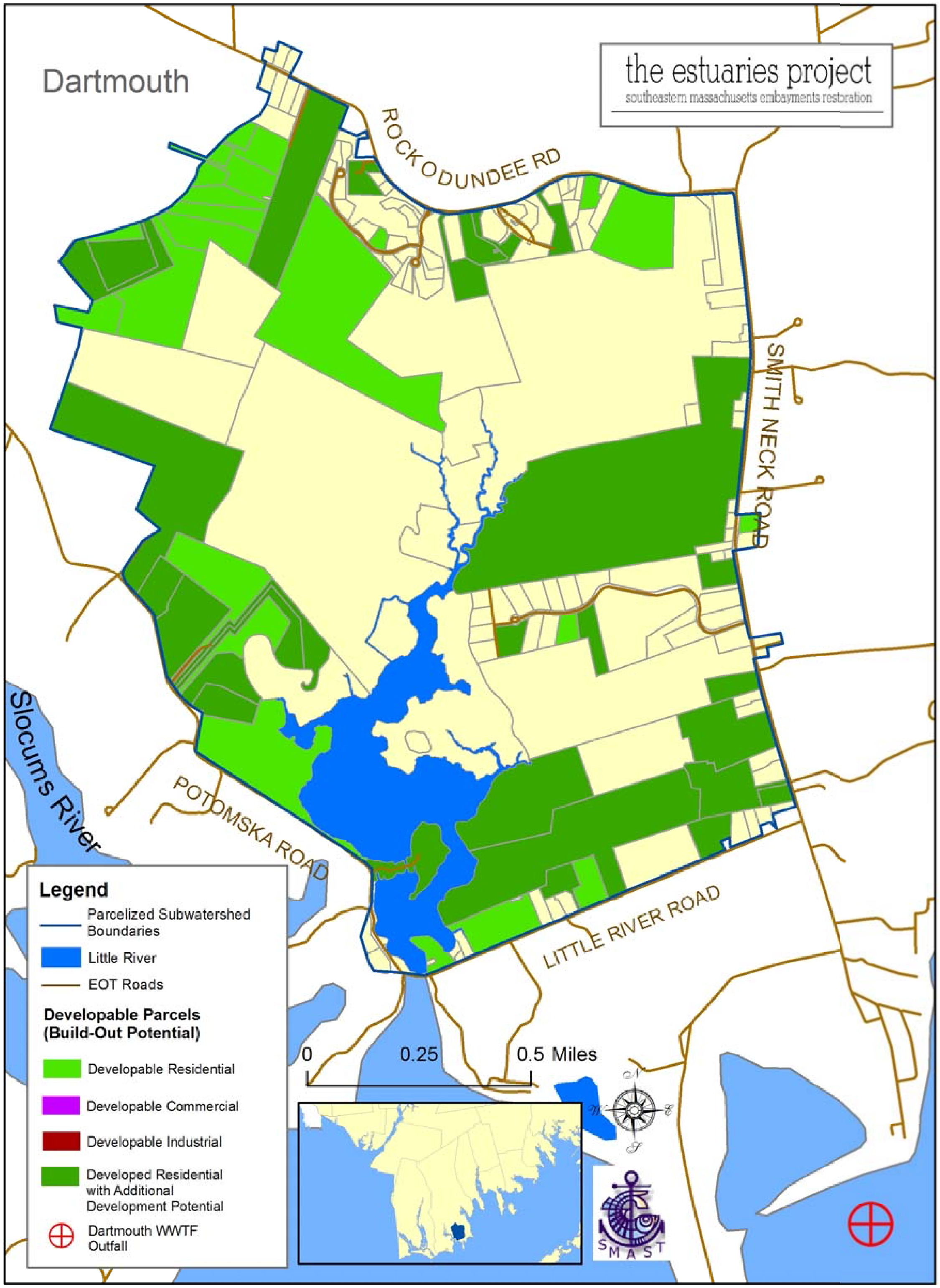
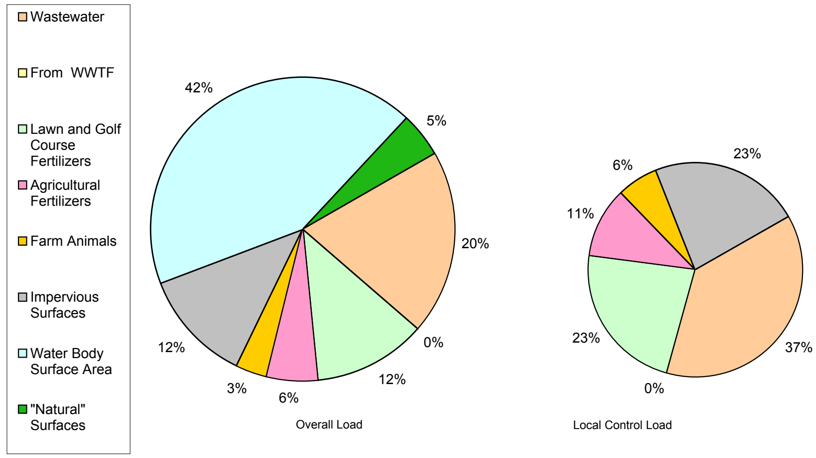


Figure IV-7. Parcels, Parcelized Watersheds, and Developable Parcels in the Little River watershed.

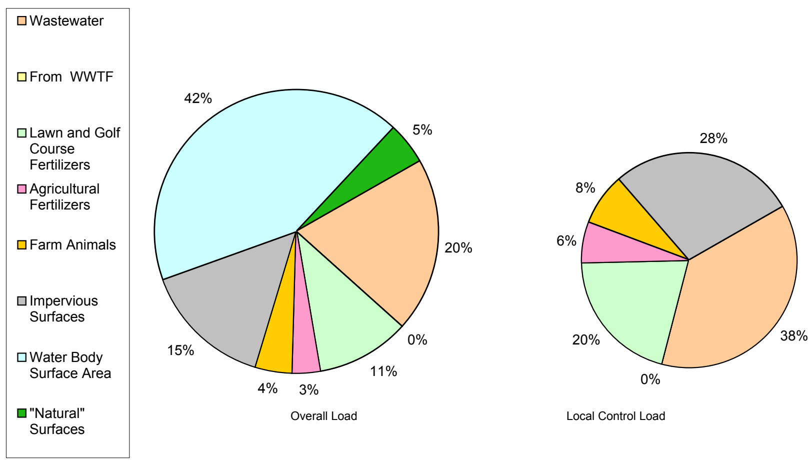
Table IV-4. Slocums River and Little River Watershed Nitrogen Loads. Attenuation of Slocums River system nitrogen loads occurs as nitrogen moves through up gradient streams during transport to the estuary. All values are kg N yr^{-1}.

		Slocum River/Little River N Loads by Input (kg/y):									***Present N Loads***			***Buildout N Loads***		
Name	**Watershed ID#**	**Wastewater**	**From WWTF**	**Lawn and Golf Course Fertilizers**	**Agricultural Fertilizers**	**Farm Animals**	**Impervious Surfaces**	**Water Body Surface Area**	**"Natural" Surfaces**	**Buildout**	**UnAtten N Load**	**Atten %**	**Atten N Load**	**UnAtten N Load**	**Atten %**	**Atten N Load**
Slocum River Estuary System		12818	0	7686	3584	2160	7682	27688	3097	34179	64715		51624	98894		77113
Slocums R West	5	270	0	20	78	0	54	444	103	1267	969		969	2236		2236
Slocums R East	6	693	0	57	120	0	113	105	165	1651	1254		1254	2905		2905
Slocums R South	10	49	0	4	671	0	15	61	75	573	875		875	1449		1449
BJR S Gaged	9	331	0	27	338	0	85	1375	93	1527	2249	11%	2002	3776	11%	3360
Paskamansett River Total	1 + 2	9609	0	5131	1624	2034	7137	20478	2329	25783	48342	23%	37223	74125	23%	57077
Paskamansett River	1	8553	0	4936	1548	2029	6802	17767	2152	23963	43788		43788	67750		67750
Dundee Creek	2	1055	0	195	76	5	334	2711	178	1821	4554		4554	6375		6375
Destruction Brook		1730	0	2436	699	126	236	1708	290	2708	7225	15%	6142	7638	15%	6492
Destruction Brook N	3	1700	0	138	634	126	233	1708	279	2576	4817		4817	7394		7394
Destruction Brook S	4	31	0	2	65	0	3	0	11	131	112		112	244		244
Old Dairy Stream				2295	0	0					2295		2295	0		0
BJR N Total		135	0	11	54	0	42	1549	41	670	1831	35%	1190	2501	35%	1626
BJR N Gaged	7	110	0	9	54	0	21	1547	34	601	1776		1776	2377		2377
BJR N Ungaged	8	25	0	2	0	0	20	1	7	69	55		55	124		124
Slocum River Estuary Surface								1969			1969		1969	1969		1969

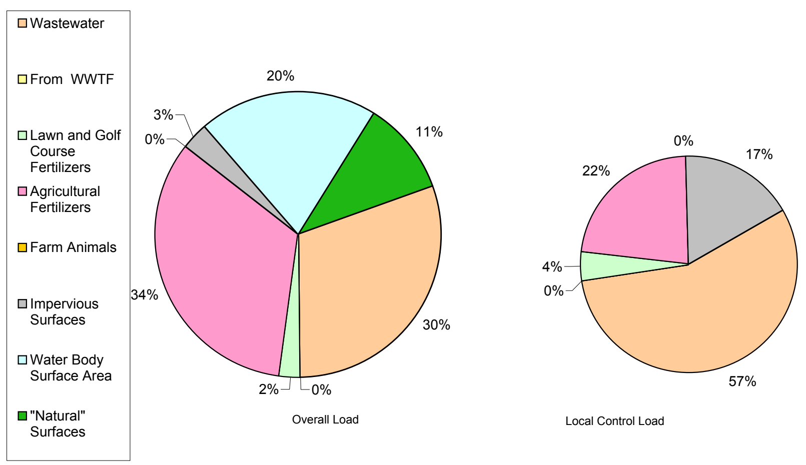
Little River Estuary System		650	0	52	716	0	66	433	227	1969	2145		2145	4114		4114
Little River (Dartmouth)	11	650	0	52	716	0	66		227	1969	1712		1712	3680		3680
Little River Estuary Surface								433			433		433	433		433



a. Slocum River Estuary System



b. Paskamansett River Total



c. Little River Estuary System

Figure IV-8 (a-c). Land use-specific unattenuated nitrogen load (by percent) to the (a) overall Slocums River Estuary System watershed, (b) Paskamanset River sub-watershed and c) overall Little River Estuary System watershed. "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.

Buildout

Part of the regular MEP watershed nitrogen loading modeling is to prepare a buildout assessment of potential development within the study area watershed. For the Slocums River and Little River modeling, MEP staff consulted with SRPEDD staff to determine the factors that would be used in the assessment (Bill Napolitano and Karen Porter, personal communications). The buildout analysis was somewhat complicated by accounting for future connections to the Dartmouth and New Bedford municipal wastewater treatment facilities. MEP staff first reviewed the development potential of each property based on existing zoning within New Bedford and Dartmouth. The buildout procedure used, and generally completed for MEP analyses, is to evaluate town zoning to determine minimum lot sizes in each of the zoning districts, including overlay districts (*e.g.*, water resource protection districts). Larger lots are subdivided by the minimum lot size to determine the total number of new lots and existing developed properties are reviewed for additional development potential; for example, residential lots that are twice the minimum lot size, but have only one residence. MEP staff also included additional development on residential parcels that are classified as developable residential (state class land use codes 130 and 131) but are less than the minimum lot size and are greater than 5,000 square feet. These parcels are assigned one residence in the buildout; 5,000 square feet is a common minimum buildable lot size in Massachusetts town regulations. Properties classified by the town assessors as “undevelopable” (*e.g.*, codes 132, 392, and 442) were not assigned any development at buildout. Commercially developable properties were not subdivided; the area of each parcel and the factors in Table IV-2 were used to determine a wastewater flow for these properties. All the parcels included in the buildout assessment of the Slocums River watershed are shown in Figure IV-6, while all parcels in the Little River buildout assessment are shown Figure IV-7. Table IV-5 provides a summary of the buildout results.

Table IV-5. MEP Buildout Summary for Slocums River and Little River

Watershed	Additional Residential Units		Commercial Area	Industrial Area
	Sewered	Septic	acres	acres
Paskamanset River Total	1,521	2,764	137.1	1,057.6
Destruction Brook Total	-	373	-	-
Slocums River West	-	147	-	-
Slocums River East	-	239	-	-
BJR North	-	62	12.2	-
BJR South	-	221	-	-
Slocums River South	-	83	-	-
SLOCUM RIVER TOTAL	1,521	3,908	162.0	1,057.6
LITTLE RIVER TOTAL	-	285	-	-

Although approximately 90% New Bedford properties within the watershed are connected to the municipal sewer system, it was unclear from a review of sewered properties whether all properties identified as having future development potential would be connected to the sewer system. MEP staff conservatively assumed for the buildout scenario that only residential properties with existing sewer connections and additional development potential would be connected to the New Bedford sewer system. Overall, 1,500 additional residential properties within New Bedford and the Slocum River watershed are assumed at buildout to use septic systems for wastewater treatment.

Additional buildout connections to the Dartmouth sewer system presented similar challenges. SRPEDD staff provided an existing and proposed sewer layout from the Town of Dartmouth and land use databases identified properties with existing connections to the municipal sewer collection system (see Figure IV-4). MEP staff used the following approach to determine residential properties that would be connected to the sewer for the buildout scenario: 1) properties within 500 feet of existing or proposed sewer lines were identified and 2) using best professional judgment, MEP staff identified areas with existing sewer connections. Only those additional buildout properties that met both criteria were counted as being connected to the sewer for the buildout nitrogen loading scenario. Based on this analysis, 1,084 residential parcels in the Slocum River watershed were added to the Dartmouth municipal sewer system under the buildout scenario. As indicated in Table IV-5, between the Dartmouth and New Bedford sewer systems, 1,521 sewered parcels are added to the Slocum River watershed at buildout.

The overall buildout assessment for Slocum River added 3,908 residential parcels utilizing septic systems for wastewater treatment to the buildout nitrogen loading scenario. Additional commercial and industrial development were assumed in the buildout scenario to also utilize septic systems (see Table IV-5). Overall, each additional residential, commercial, or industrial property added at buildout is assigned nitrogen loads for wastewater, fertilizer, and impervious surfaces. Cumulative unattenuated buildout loads are indicated in a separate column in Table IV-4. Buildout additions within the overall Slocums River System watershed will increase the unattenuated loading rate by 53%; 75% of this increase is projected to come from the Paskamanset River sub-watersheds.

The overall buildout assessment for Little River added 285 residential parcels utilizing septic systems for wastewater treatment to the buildout nitrogen loading scenario. No additional commercial or industrial development were assumed (see Table IV-5). Overall, each additional residential property added at buildout is assigned nitrogen loads for wastewater, fertilizer, and impervious surfaces. Cumulative unattenuated buildout loads are indicated in a separate column in Table IV-4. Buildout additions within the overall Little River System watershed will increase the unattenuated loading rate by 92%.

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 Slocums River and Little River 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 region of the watersheds to these Town of Orleans systems). The lack of nitrogen attenuation in these aquifer systems results from the lack of biogeochemical conditions needed for supporting nitrogen sorption and denitrification.

However, in most watersheds in southeastern Massachusetts, nitrogen passes through a surface water ecosystem (pond, wetland, stream) on its path to the adjacent embayment. Surface water systems, unlike sandy aquifers, do support the needed conditions for nitrogen retention and denitrification. The result is that the mass of nitrogen passing through lakes, ponds, streams and marshes (fresh and salt) is diminished by natural biological processes that represent removal (not just temporary storage). However, this natural attenuation of nitrogen load is not uniformly distributed within the watershed, but is associated with ponds, streams and marshes. In the case of the Dartmouth embayment system watersheds for Slocums River and Little River, a portion of the freshwater flow and transported nitrogen passes through several surface water systems (Destruction Brook, the Paskamanset River, Barneys Joy Creek and Giles Creek) prior to entering estuarine system, producing the opportunity for significant nitrogen attenuation.

Failure to determine the attenuation of watershed derived nitrogen overestimates the nitrogen load to receiving estuarine waters. If nitrogen attenuation is significant in one portion of a watershed and insignificant in another the result is that nitrogen management would likely be more effective in achieving water quality improvements if focused on the watershed region having unattenuated nitrogen transport (other factors being equal). In addition to attenuation by freshwater ponds (see Section IV.1.3, above), attenuation in surface water flows is also important. An example of the significance of surface water nitrogen attenuation relating to embayment nitrogen management was seen in the Agawam River, where >50% of nitrogen originating within the upper watershed was attenuated prior to discharge to the Wareham River Estuary (CDM 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.

Given the importance of determining accurate nitrogen loads to embayments for developing effective management alternatives and the potentially large errors associated with ignoring natural attenuation, direct integrated measurements of upper watershed attenuation were undertaken as part of the MEP Approach. MEP conducted long-term measurements of natural attenuation relating to surface water discharges to the head of Slocums River embayment system considered in this report in addition to the natural attenuation measures by fresh kettle ponds, addressed above (Section IV.1). The Little River embayment system does not support a surface water feature such as a river stream or creek and as such no attenuation studies could be conducted as was completed for the Slocums River. These additional site-specific studies were conducted in the 4 major surface water flow systems in the watersheds to the head of the Slocums River, 1) Paskamanset River, 2) Destruction Brook, 3) Barneys Joy Creek, 4) Giles Creek (Figure IV-9 and 10).

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 streams discharging to the estuaries provides a direct integrated measure of all of the processes presently attenuating nitrogen in the contributing area up-gradient from the various gauging sites. Flow and nitrogen load were measured at the gages in each freshwater stream site for between 16 and 24 months of record depending on the stream gaging location (Figures IV-11,17,20,21). During each study period, velocity profiles were completed on each creek every month to two months. The summation of the products of stream subsection areas of the stream cross-section and the respective measured velocities represent the computation of instantaneous stream flow (Q).

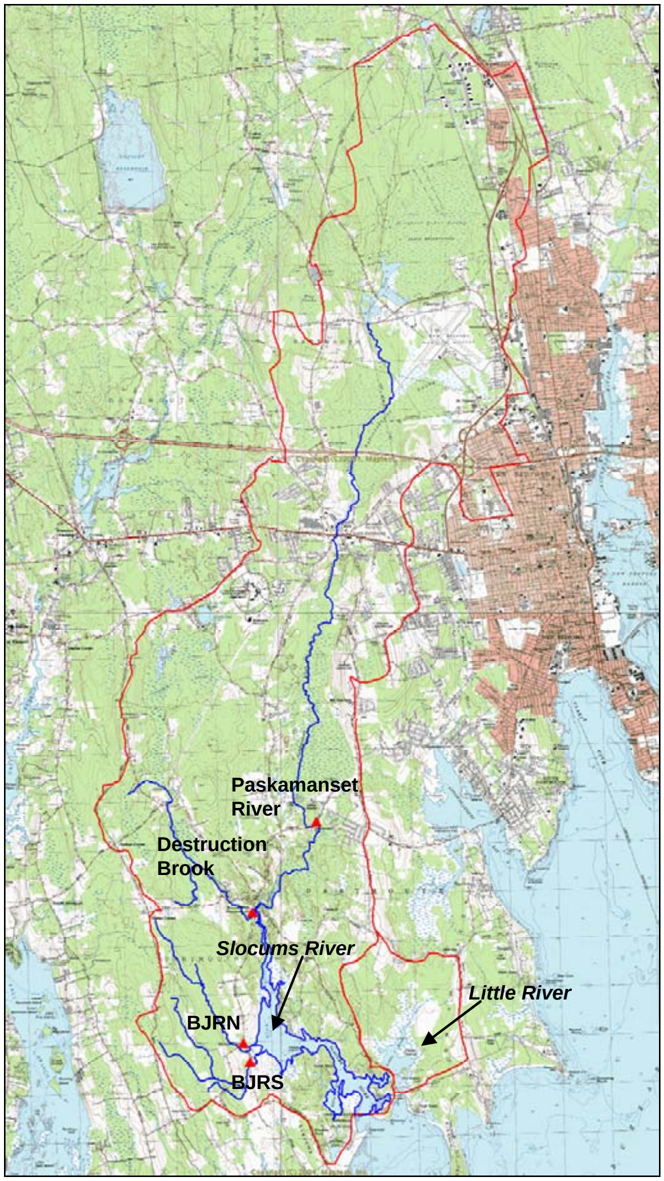


Figure IV-9. Locations of the four stream gauging sites in the Slocums River watershed. Red line is the watershed boundary. Paskamanset River gauge is maintained by the US Geological Survey. Little River watershed is shown at the lower right and has no significant freshwater streams.

Figure IV-10. Location of Stream gages (red symbols) in the Slocums River embayment systems.

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

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

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

where by:

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

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

Periodic measurement of flows over the entire stream gage 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 gages. Water level data obtained every 10-minutes was averaged to obtain hourly stages for a given river. These hourly stages values where then entered into the stage-discharge relation to compute hourly flow. Hourly flows were summed over a period of 24 hours to obtain daily flow and further, daily flows summed to obtain annual flow. In the case of tidal influence on stream stage, the diurnal low tide stage value was extracted on a day-by-day basis in order to resolve the stage value indicative of strictly freshwater flow. The two low tide stage values for any given day were averaged and the average stage value for a given day was then entered into the stage – discharge relation in order to compute daily flow. A complete annual record of stream flow (365 days) was generated for the surface water discharges flowing into the Slocums River system.

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

IV.2.2 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Paskamanset River to head of Slocums River

The streams flowing into the Slocums River are primarily fed by surface water runoff, though groundwater provides a significant proportion of flow in the Paskamanset River system and more so in Destruction Brook (Bent, 1995). The Paskamanset River has three impoundments (mill ponds) where nitrogen attenuation can occur. Moreover, the Paskamanset River has significant freshwater wetlands, consisting of both riparian or fringing, streamside wetlands along the main channel and other wetlands in source areas of the streams and their tributaries. As noted above, the wetlands can provide significant biological attenuation of nitrogen entering the watershed. Additional nitrogen attenuation can occur as local groundwater flows into the stream through the stream bottom sediments. The combined rate of nitrogen attenuation by these processes was determined by comparing the present predicted nitrogen loading to the Paskamanset River sub-watershed region contributing to the Slocums River above the USGS gauge site and the measured annual discharge of nitrogen from the Paskamanset River discharging to the head of the Slocums River embayment system.

At the Paskamanset River stream gage site (Russells Mills Road), the US Geological Survey has been operating and maintaining a long term stream gauging station (01105933) from which a detailed record of stage and flow was obtained for the purpose of this MEP analysis. As portions of many stream gage locations in the MEP are tidally influenced, salinity at the USGS gage location was checked to confirm that freshwater flow from the watershed was being observed. As the USGS gage is located up gradient of a dam there was little doubt that salinity would be indicative of freshwater. Spot checking the salinity yielded a concentration not greater than 0.1 ppt on the handful of dates when salinity was measured.

Water samples were collected weekly for nitrogen analysis at the USGS gauging location. Integrating the USGS flow record and nitrogen concentration datasets allowed for the determination of nitrogen mass discharge to the head of the Slocums River system flowing into Buzzards Bay **(Figure IV-11 and Table IV-6)**. In addition, a water balance was constructed based upon the US Geological Survey watershed delineations to determine long-term average freshwater discharge expected at the gage site.

The annual freshwater flow record for the Paskamanset River measured by the USGS was compared to the long-term average flows determined based on watershed area and recharge rate. The measured freshwater discharge from Paskamanset River Stream was 22% above the long-term average flows based on the area of the watershed multiplied by the recharge rate for the region. The average daily flow based on the USGS measured flow data for one hydrologic year beginning September and ending in August (low flow to low flow) was 109,884 m^3/day compared to the long term average flows based on recharge rate (140,772 m^3/day).

The difference between the long-term average flow based on recharge rates over the watershed area and the USGS measured flow in the Paskamanset River may in part be due to below average rainfall during the MEP data collection period based on rainfall records obtained from a rain gage in the City of New Bedford. Twelve years of rainfall data (1993-2005) indicate that the average rainfall in the vicinity of the Paskamanset River system was 49.2 inches. By comparison, rainfall in 2002 and 2003 was 50.80 and 38.54 inches respectively. Rainfall in 2003 was 38.54 inches (below long tern average). This was in contrast to rainfall amounts

Table IV-6. Comparison of water flow and nitrogen discharges from streams (freshwater) discharging to the head of each Orleans marsh. The "Stream" data is from the MEP stream gauging effort. Watershed data is based upon the MEP watershed modeling effort by USGS.

Stream Discharge Parameter	Paskamansett River Discharge[(a)]	Destruction Brook Discharge[(a)]	Barneys Joy Creek Discharge[(a)]	Giles Creek Discharge[(a)]	Data Source
Total Days of Record	365[(b)]	365[(b)]	365[(b)]	365[(b)]	(1)
Flow Characteristics					
Stream Average Discharge (m3/day) **	109884	11380	5381	5699	(1)
Contributing Area Average Discharge (m3/day)	140772	14869	4325	6545	(2)
Discharge Stream 2003-04 vs. Long-term Discharge	22%	23%	-24%	13%	
Nitrogen Characteristics					
Stream Average Nitrate + Nitrite Concentration (mg N/L)	0.259	0.904	0.2	0.383	(1)
Stream Average Total N Concentration (mg N/L)	0.927	1.502	0.629	0.964	(1)
Nitrate + Nitrite as Percent of Total N (%)	28%	60%	32%	40%	(1)
Total Nitrogen (TN) Average Measured Stream Discharge (kg/day)	101.81	17.09	3.55	5.49	(1)
TN Average Contributing UN-attenuated Load (kg/day)	132.5	20.0	5.02	6.16	(3)
Attenuation of Nitrogen in Pond/Stream (%)	23%	15%	29%	11%	(4)

(a) Flow and N load to streams discharging to Slocums River includes apportionments of Pond contributing areas.
(b) September 1, 2003 to August 31, 2004.
** Flow is an average of annual flow for 2003-2004

(1) MEP gage site data except for Paskamansett River (USGS flow record)
(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 streams to Slocums River;
and the annual recharge rate.
(3) As in footnote (2), with the addition of pond and stream conservative attentuation rates.
(4) Calculated based upon the measured TN discharge from the rivers vs. the unattenuated watershed load.

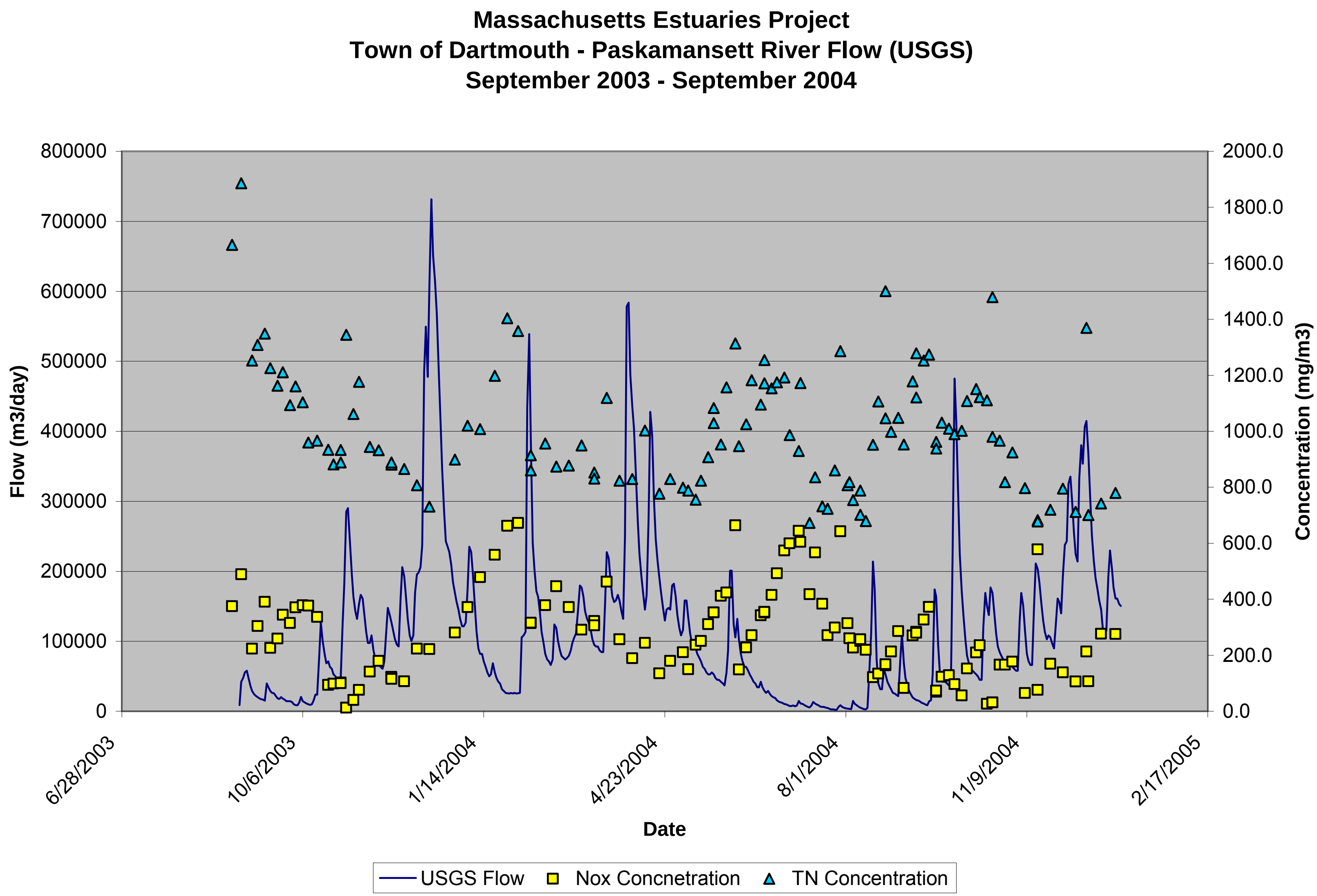


Figure IV-11. Paskamanset River discharge (solid blue line), nitrate+nitrite (yellow square) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Slocums River (Table IV-6).

totaling 31.85 inches in 2001. It should be recognized that 2001 and 2003 rainfall was below average with only one year (2002) above average, thus the water table is likely to have been lower than usual due to the 2 years of lower rainfall. This is significant relative to measured flow in the Paskamanset River surface water system as it is essentially a groundwater fed feature. Based upon the rainfall and groundwater levels associated with the stream measurement (suggesting a lower flow than the long-term average) and the some what lower measured stream discharge then predicted (-22%) it appears that the stream is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Paskamanset River stream outflow were moderate, 0.93 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 101.8 kg/day and a measured total annual TN load of 37162 kg/yr. In the Paskamanset River discharge to Slocums River, dissolved organic nitrogen (DON) was the predominant form of nitrogen (~60%), while DIN, (Nitrate + Ammonia) accounted for about 32% (~26% and ~6%) respectively, of TN. This balance of nitrogen forms indicates that about 1/3 of the nitrogen in the river discharge is available for immediate uptake by primary producers (algae) in the Slocums embayment and about two-thirds of the total nitrogen in the river discharge is not immediately available for uptake in the Slocums River, but would need to be processed (mineralized) by estuarine biota before being available to primary production. The predominance of DON in the Paskamanset River discharge may be a reflection of several factors. First, the headwaters portion of the watershed north of Route 195 includes two large forested freshwater wetlands, the Acushnet Cedar Swamp and the Apponagansett Swamp, whose presence contributes large amounts of dissolved organic matter, giving the Paskamanset River water its characteristic red-brown coloration. Second, there are substantial forested riparian or stream-side wetlands between Route 6 and the mouth of the river and in both types of forested wetlands biogeochemical processes within the wetlands typically reduce nitrate in the riparian flow systems and export more DON than NOx (Willett et al, 2004; Campbell et al, 2004). Third, the three mill dam impoundments on the Paskamanset River at Turner Pond, Route 6 and at Rock o'Dundee Road also are likely sites for nitrogen attenuation by plants and pond sediment geochemical processes.

From the measured nitrogen load discharged by the Paskamanset River to the head of the estuarine portion of the Slocums River and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower total nitrogen load (37,162 kg yr^{-1}) discharged from the freshwater Paskamanset River compared to that added by the various land-uses to the associated watershed (48,363 kg yr^{-1}), the integrated attenuation in passage through ponds, streams and freshwater wetlands prior to discharge to the estuary is 23% (i.e. 23% of nitrogen input to watershed does not reach the estuary). This slightly lower level of attenuation compared to other streams evaluated under the MEP is expected given the limited network of up-gradient ponds and the fact that the Paskamanset River flows mostly through a large network of wetland area which in certain ways can potential contribute nutrients in the form of dissolved organic nutrients. The directly measured nitrogen loads from the river was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

In addition to the stream attenuation study described above, the MEP sampled the Paskamanset River above and below the Town of Dartmouth landfill on Russells Mills Road to determine to what extent the landfill added to the nitrogen load to the Paskamanset River and then the Slocums River system. Little evidence was found indicating that the landfill was increasing the TN load in the Paskamanset River. The Dartmouth Town Landfill on Russells

Mills Road in the Paskamanset River/Slocums River watershed consists of about twenty–eight acres of un-lined fill area. The landfill is located close to the Paskamanset River, about 1 km upstream from the Russells Mills Dam and the River's discharge point into the Slocums River estuary (Figure IV-12). Prior to capping in 1996, the groundwater flowing to the river had been contaminated with leachate from the landfill. Monitoring wells installed before and during the closure process showed groundwater contamination typical of contaminants and other indicators that are found downgradient from landfills (arsenic, barium, copper, silver, zinc; chloride, nitrogen, and elevated alkalinity and total dissolved solids). Results of sampling for metals in the wells associated with the landfill are provided in Tables IV-7, IV-8 and IV-9. In only a few instances were metal levels found that exceeded the Drinking Water Standard, specifically cadmium, manganese and iron. Fortunately, the iron and manganese do not represent an ecological threat, and the cadmium level was very close to the Drinking Water Standard. Overall, these metals levels do not represent a significant negative impact to the receiving surface water systems. In 1995 a single sampling found very high levels of ammonia nitrogen in several groundwater monitoring wells (8-146 mg/l NH4) between the landfill and the Paskamanset River and in runoff from the landfill (US EPA, 1995 unpublished data from before capping). The capping of the landfill in 1996 included the installation of surface water drainage systems designed to divert rainwater water away from moving into and through the landfill. As a result, the levels most of the other contaminant concentrations in the monitoring wells that were elevated for a time following the capping, have decreased over time (Town of Dartmouth Russells Mills Landfill Monitoring Reports, Camp Dresser McKee; 1998-2006).

For the purposes of this study, determining the nitrogen load added to the Slocums River watershed by the landfill is important in that landfills can be a significant source of nitrogen through groundwater transport. We can make some estimates based upon measurements of the concentration of nitrogen in groundwater monitoring wells and from the concentrations of nitrogen in the Paskamanset River at locations upstream of the landfill and downstream of the landfill. TKN and nitrate (NOx) data from which total nitrogen can be summed has been collected for the Town's landfill monitoring program only since 2002 at sites just downstream from the landfill (SW-2; Figure IV-12) and upstream of the landfill at the stone bridge on Russells Mills Road near the Friends Meetinghouse (SW-1; Figure IV-12). Additional TN data was collected for this study in the Fall of 2004 and is shown in Figures IV-13 and IV-14. From this data set, the increase in total nitrogen concentration at the downstream Rock o Dundee site is not consistent through time: sometimes nitrogen increases above the upstream value at the downstream site and sometimes the reverse happens (Figures IV-13, IV-14).

If we look to the larger set of data from the paired sampling dates for this project, 29 dates between 2003 and 2005, the TN data upstream and downstream was also inconsistent: the upstream site was higher than the downstream site on 10 of 27 sampling dates, however as a mass load of TN there was a mean net increase between Russells Mills Road and Rock o' Dundee Road dam of 5.12 kg total nitrogen/day or about 1,869 kg per year added to the annual Paskamanset nitrogen load. The annual load measured for this project for the Paskamanset River at Rock o Dundee Road was approximately 37,162 kg total nitrogen per year so the net addition of 1,869 kg for the lower Paskamanset River is about 5% of the upstream contribution from the rest of the watershed. For comparison, the additional watershed land area of the Paskamanset River basin between Russells Mills Road and Rock o' Dundee dam is about 10 percent of the total watershed. Thus, the zone which includes the landfill is contributing less nitrogen per unit area than that contributed per unit area from the remainder of the watershed upstream of the Russells Mills Road bridge.

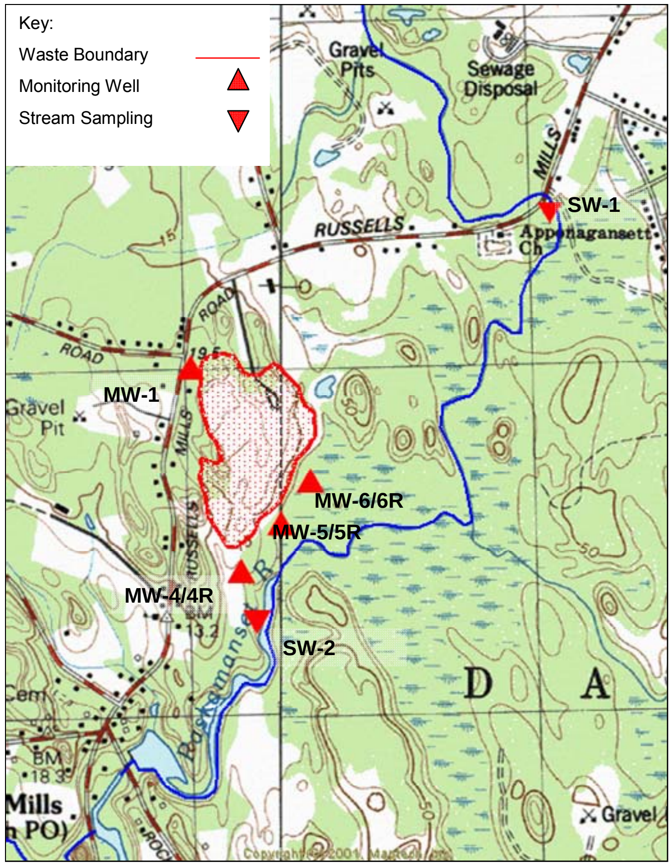


Figure IV-12. The Russells Mills Road municipal landfill site. The extent of the fill material is denoted by the red line. Groundwater monitoring wells are located both upgradient of the landfill (MW-1) and downgradient (MW -4, 5, 6 , R) between the landfill and the Paskamanset River. SW-1 and SW-2 are stream monitoring sites. The wells and stream sites have been monitored twice a year since about 1995.

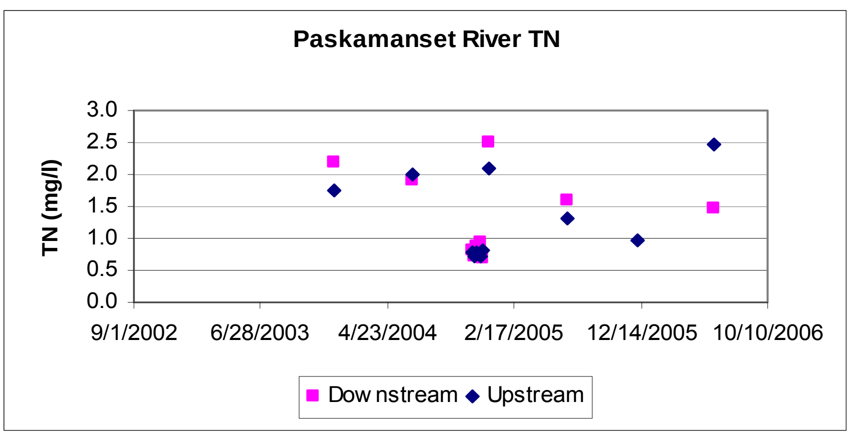


Figure IV-13. Total nitrogen concentrations (Nitrate + TKN) at the two Paskamanset River sampling sites. On five of the ten dates downstream nitrogen exceeds upstream nitrogen concentrations, while on three occasions, upstream TN was higher, and twice Tn was the same at both sites. The cluster of points in late 2004 is shown in a shorter time frame in Figure IV-14. (Source: Camp Dresser McKee Landfill Monitoring Reports and SMAST).

Table IV-7. Metal concentrations of samples collected from groundwater monitoring wells associated with the Town of Dartmouth Landfill.

CONSTITUENT	Groundwater Monitoring Wells							Streamwater		MassDEP
	MW-1	MW-4	MW-4R	MW-5	MW-5R	MW-6	MW-6R	SW-1 Upstream	SW-2 Downstream	Drinking Water Standard
	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)
Arsenic										
% Samples > 50 ug/L	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**50**
max	all	7.6	5.9	7.0	12.0	9.1	5.8	all	all	
min	< MDL	7.6	5.9	5.2	12.0	6.0	5.8	< MDL	< MDL	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	12	11	11	10	11	10	11	12	12	
Barium										
% Samples > 2000 ug/L	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**2000**
max	327	270	610	910	1100	580	350	390	340	
min	15	146	127	47	352	133	30	6	14	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	0	0	0	0	0	0	0	0	0	
Cadmium										
% Samples > 5 ug/L	**0%**	**0%**	**0%**	**25%**	**17%**	**17%**	**0%**	**17%**	**0%**	**5**
max	all	3	3	7	7	10	1	16	all	
min	< MDL	3	3	7	7	10	1	16	< MDL	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	12	10	10	9	10	10	10	10	12	
Chloride										
% Samples > 250ug/L	**0%**	**0%**	**0%**	**33%**	**42%**	**0%**	**0%**	**0%**	**0%**	**250**
max	100	160	75	340	390	110	99	71	69	
min	6	38	37	28	20	47	64	26	26	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	0	0	0	0	0	0	0	0	0	

Table IV-8. Metal concentrations of samples collected from groundwater monitoring wells associated with the Town of Dartmouth Landfill.

CONSTITUENT	Groundwater Monitoring Wells							Streamwater		MassDEP
	MW-1 (ug/L)	MW-4 (ug/L)	MW-4R (ug/L)	MW-5 (ug/L)	MW-5R (ug/L)	MW-6 (ug/L)	MW-6R (ug/L)	SW-1 Upstream (ug/L)	SW-2 Downstream (ug/L)	Drinking Water Standard (ug/L)
Chromium										
% Samples > 100 ug/L	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**100**
max	all	all	10	all	11	all	all	all	all	
min	< MDL	< MDL	10	< MDL	11	< MDL	< MDL	< MDL	< MDL	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	12	12	10	12	10	12	12	12	12	
Copper										
% Samples > 1300 ug/L	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**1300**
max	all	all	7	14	10	all	all	all	all	
min	< MDL	< MDL	7	14	10	< MDL	< MDL	< MDL	< MDL	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	12	12	11	11	11	12	12	12	12	
Iron										
% Samples > 300 ug/L	**92%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**92%**	**92%**	**300**
max	35000	44000	36000	58000	65000	92000	14000	1600	6900	
min	360	3200	6800	5600	30000	47000	5100	230	260	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	1	0	0	0	0	0	0	0	0	
Lead										
% Samples > 15 ug/L	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**15**
max	all	all	all	all	all	all	all	6	all	
min	< MDL	< MDL	< MDL	< MDL	< MDL	< MDL	< MDL	6	< MDL	
Total Samples	4	4	4	4	4	4	4	4	4	
Total Samples >MDL	4	4	4	4	4	4	4	3	4	

Table IV-9. Metal concentrations of samples collected from groundwater monitoring wells associated with the Town of Dartmouth Landfill.

CONSTITUENT	Groundwater Monitoring Wells							Streamwater		MassDEP
	MW-1 (ug/L)	MW-4 (ug/L)	MW-4R (ug/L)	MW-5 (ug/L)	MW-5R (ug/L)	MW-6 (ug/L)	MW-6R (ug/L)	SW-1 Upstream (ug/L)	SW-2 Downstream (ug/L)	Drinking Water Standard (ug/L)
Manganese										
% Samples > 50 ug/L	**67%**	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**	**83%**	**100%**	**50**
max	2500	5200	15000	4200	13000	4500	1900	170	1800	
min	10	3800	10000	940	7400	3000	1300	40	50	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	0	0	0	0	0	0	0	0	0	
Mercury										
% Samples > 2 ug/L	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**2**
max	all	all	all	all	all	all	all	all	all	
min	< MDL	< MDL	< MDL	< MDL	< MDL	< MDL	< MDL	< MDL	< MDL	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	12	12	12	12	12	12	12	12	12	
Selenium										
% Samples > 50 ug/L	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**50**
max	all	all	14	all	all	all	19	all	all	
min	< MDL	< MDL	14	< MDL	< MDL	< MDL	19	< MDL	< MDL	
Total Samples	12	12	12	12	12	12	12	12	12	
Total Samples >MDL	12	12	11	12	12	12	11	12	12	
Silver										
% Samples > 100 ug/L	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**100**
max	all	7	6	10	11	9	8	10	8	
min	< MDL	6	6	8	8	7	6	8	7	
Total Samples		2	1	2	2	2	2	2	2	
Total Samples >MDL	12	10	11	10	10	10	10	10	10	
Zinc										
% Samples > 5000 ug/L	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**0%**	**5000**
max	230	60	190	80	130	120	170	170	180	
min	20	21	40	25	26	20	30	51	20	
Total Samples	4	4	11	10	9	7	8	3	6	
Total Samples >MDL	8	8	1	2	3	5	4	9	6	

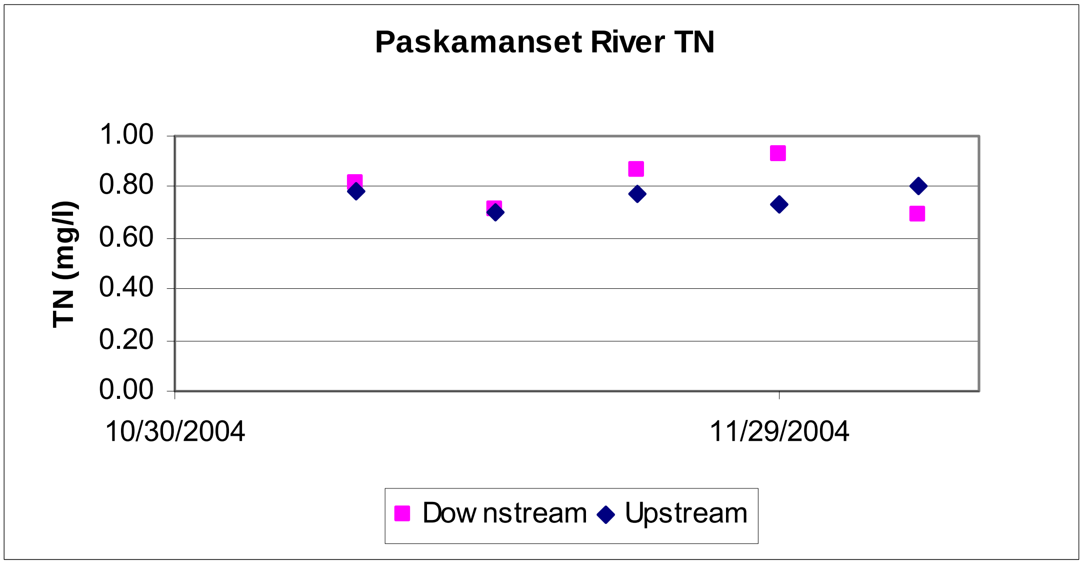


Figure IV-14. Total nitrogen concentrations at the two Paskamanset River sampling sites taken during fall 2004. Of the five sampling dates downstream nitrogen concentrations are higher on two occasions, lower once and the same on two dates (Source: SMAST sampling).

Factors that affect assessing the nitrogen export from the landfill to the River

The variability in comparative nitrogen levels measured in the Paskamanset River upriver and downriver from the landfill is likely due to multiple factors. First, capping of the landfill in 1996 should have reduced the amount of nitrogen exported by the landfill by reducing percolation of rainfall through the landfill mass, slowing the release of nitrogen to the aquifer beneath the land-fill and both slowing and reducing the total mass of nitrogen flowing via groundwater into the Paskamanset stream bed. However, over the short period of record, 2002-2006 when TKN (Total Kjeldahl Nitrogen = all N species but nitrate) was collected in landfill monitoring wells, the data shows no clear downward trend in most of the highest concentration wells between the landfill and river, with the exception of MW-5 (Figure IV-15). One day data collected by US EPA in 1995 found 145 mg/L of NH^4 nitrogen in the "mid" monitoring well which may correspond to the MW-5 and if correct, may indicate a modest decline in that well. Other data from the landfill monitoring wells, such as declining metals concentrations suggests that many landfill leachate concentrations in the landfill plume have fallen since capping. There is also other indirect evidence for a marked decrease in landfill plume strength entering the Paskamanset River in the chemical oxygen demand (COD) data collected at the upstream and downstream sample sites, SW-1 and SW-2 since 1997 (Figure IV-16). COD is an indicator of the amount of organic material in waters. Levels of COD in the Paskamanset River increased at the downstream site by a factor of 1.5 to about 16 times the upstream levels during 1997-2002 sampling period. By 2003 the high COD levels measured downstream had fallen to a range similar to that measured at the upstream SW-1, suggesting that there have been long-term plume strength or volumetric (or both) declines that are the result of the installation of impermeable cap and surface water diversion drainage.

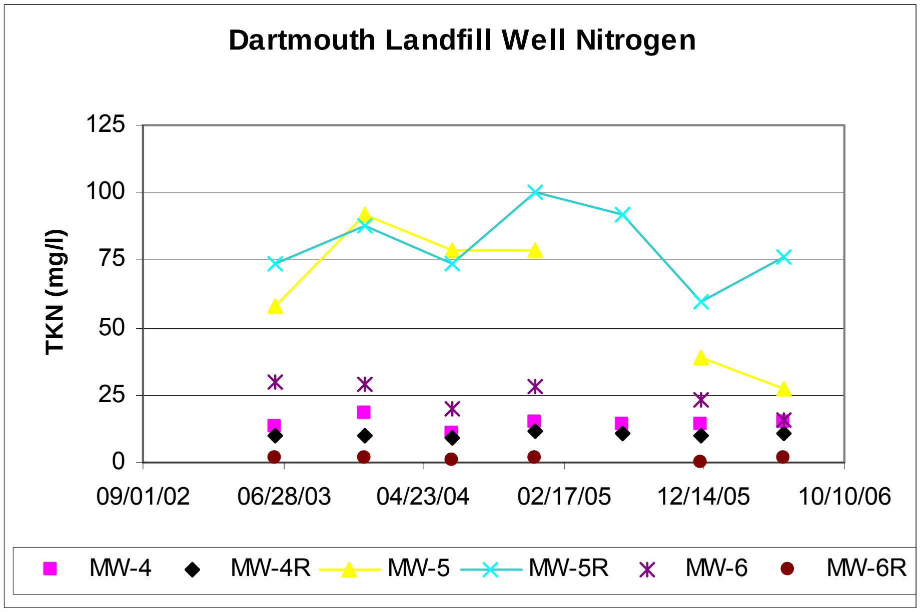


Figure IV-15. Total Kjeldahl Nitrogen (TKN) in monitoring wells between the landfill and the Paskamanset River, MW-4 are at the southern limit of the landfill, while MW-5 and MW-6 lie to the northeast between the landfill and river (see Figure IV-12 for well locations; data source: Camp Dresser McKee Landfill Monitoring Reports).

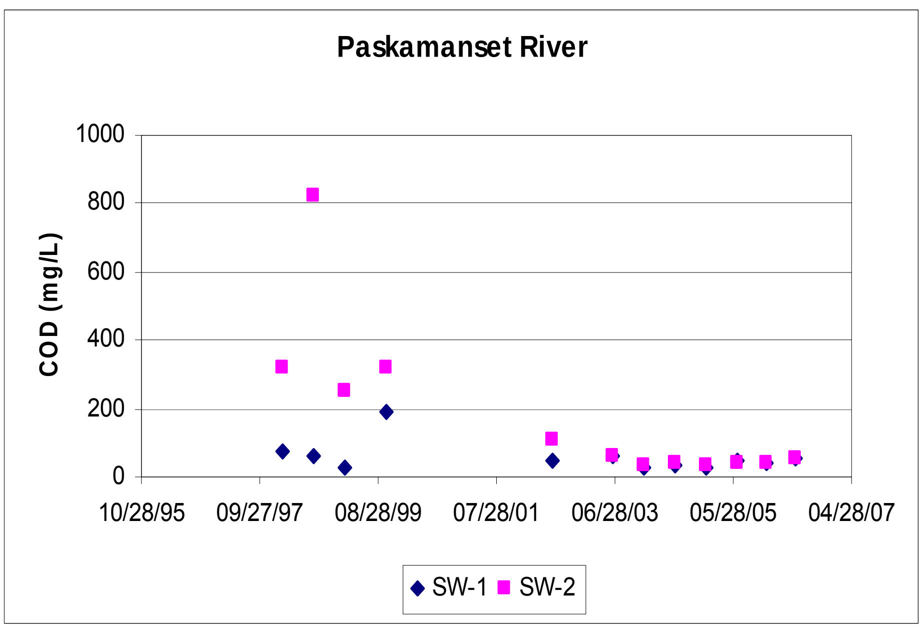


Figure IV-16. Reductions in chemical oxygen demand (COD) at the upstream (SW-1) and downstream (SW-2) monitoring sites on the Paskamanset River since 1997. Note the substantial increases before the year 2003 between the concentrations of COD in the downstream and upstream sites, indicating that a substantial landfill leachate COD signal was added to the downstream measurement (data source: Camp Dresser McKee Landfill Monitoring Reports).

Second, as landfill-exported nitrogen enters the Paskamanset River streambed, biological processes can act to convert dissolved nitrogen in the groundwater to nitrogen gas which is released into the atmosphere (de-nitrification). This process is common in stream beds when anoxic and low oxygen groundwater carrying dissolved nitrogen enters the alluvial sediments of the subsurface stream zone. Groundwater both beneath a landfill and within a landfill leachate plume is usually very low in dissolved oxygen due to the high oxygen demand (COD) of the organic matter in the landfill material. The rate of denitrification is dependent upon groundwater flow rates, nitrogen concentrations and the amount of food (organic matter) that is available in the alluvial sediments that the groundwater passes through on the way to the stream bottom. The loss of nitrogen through alluvial denitrification can be substantial and combined with lowered mass movement of nitrogen due to the effects of landfill-capping, is likely reducing the total nitrogen amount entering the river.

Third, the transformation of nitrogen within the river itself could mask the input of landfill nitrogen. The stretch of stream that flows by the landfill has a slope or gradient of about 0.53 m/km (2.59 ft/mi) and flows through a large area of freshwater wetlands. The moderate gradient leads to relatively slow flow in this part of the stream, allowing more time both for biological transformation of stream-transported nitrogen and for seasonal deposition of particulate nitrogen. Thus, within-stream factors also are favorable to reduction of the transiting nitrogen loads, in much the same way that other freshwater impoundments (natural ponds and mill ponds) act to remove stream nitrogen.

Fourth, the Rock o Dundee mill pond very likely also acts to attenuate nitrogen by promoting the deposition of nitrogen bearing particles and by providing a setting where other pathways of nitrogen attenuation such as denitrification can occur in a zone where water flows slowly.

Fifth, intensity of development in the most-downstream Paskamanset River sub-watershed is relatively low when compared to the middle, more intensively developed section of the watershed.

In relation to the total annual nitrogen load transported from the whole Paskamanset River basin to the Slocums River, the data gathered indicates that the Russells Mills landfill is likely to be contributing only a modest amount of nitrogen to the Slocums River system.

IV.2.3 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge from Destruction Brook to the head of Slocums River

At the Destruction Brook gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the discharge that carries nitrogen load from the wetland to the head of the Slocums River estuary. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average salinity was determined to be no greater than 0.1 ppt. Based on the salinity, the gage location was deemed acceptable for making freshwater flow measurements at low tide. Calibration of the gage was checked monthly. The gage on Destruction Brook to Slocums River was installed on May 29, 2003 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 March 21, 2005 for a total deployment of 22 months. The 12-month uninterrupted record used in this analysis encompasses the summer 2004 field season. Despite the relatively long deployment, only one complete hydrologic year was captured due to instrument failures. The period of record ultimately used in this analysis was September 2003 to August 2004.

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 Destruction Brook site based upon these flow measurements and measured water levels at the gage 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 Slocums River **(Figure IV-17 and Table IV-6)**. In addition, a water balance was constructed based upon the US Geological Survey watershed delineations to determine long-term average freshwater discharge expected at the gage site.

The annual freshwater flow record for Destruction Brook measured by the MEP was compared to the long-term average flows determined by the watershed area/recharge rate approach. The measured freshwater discharge from Destruction Brook to Slocums River was 23% below the long-term average modeled flows. Measured flow in Destruction Brook was obtained for one hydrologic year (September 2003 to August 2004). The average daily flow based on the MEP measured flow data was 11,380 m^3/day compared to the long term average flows based on recharge rate (14,869 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 Destruction Brook are in part be due to below average rainfall during the stream gage deployment period based on rainfall records obtained from a rain gage in the City of New Bedford. Twelve years of rainfall data (1993-2005) indicate that the average rainfall in the vicinity of Destruction Brook was 49.2 inches. By comparison, rainfall in 2002 and 2003 was 50.80 and 38.54 inches respectively. Rainfall in 2003 was 38.54 inches (below long tern average). This was in contrast to rainfall amounts totaling 31.85 inches in 2001. It should be recognized that 2001 and 2003 rainfall was below average with only one year (2002) above average, thus the water table is likely to have been lower than usual due to the 2 years of lower rainfall. This is significant relative to measured flow in the Destruction Brook surface water system as it is essentially a groundwater fed feature. Based upon the rainfall and groundwater levels associated with the stream measurement (suggesting a lower flow than the long-term average) and the some what lower measured stream discharge then predicted (-23%) it appears that the stream is capturing the up-gradient recharge (and loads) accurately.

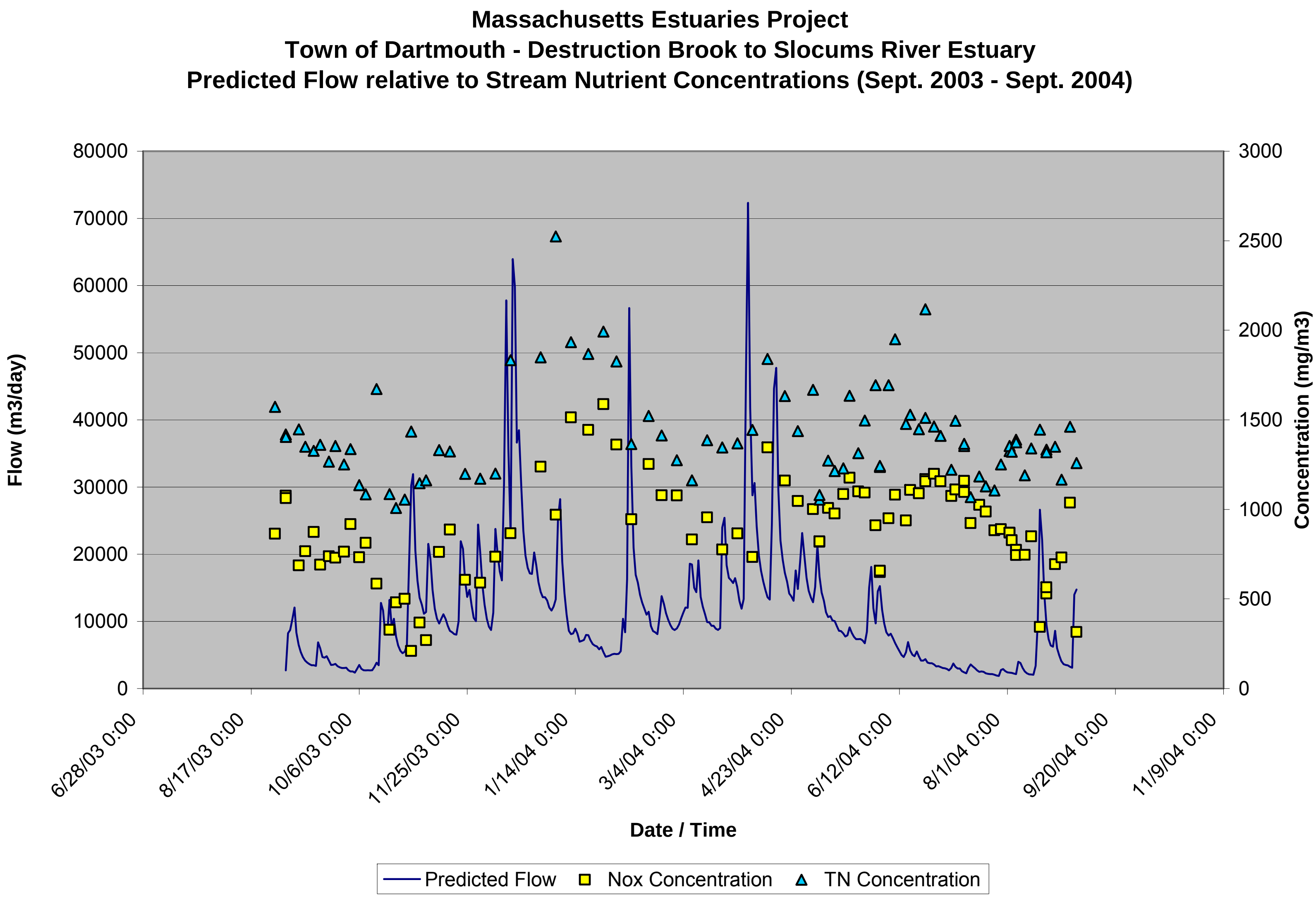


Figure IV-17. Stream discharge (solid blue line), nitrate+nitrite (yellow square) and total nitrogen (blue triangle) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Slocums River (Table IV-6).

Total nitrogen concentrations within the Destruction Brook outflow to Slocums River were high, 1.502 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 17.09 kg/day and a measured total annual TN load of 6,237 kg/yr. In the Destruction Brook surface water system, nitrate + nitrite (NOx) was the predominant form of nitrogen (60%), while DON dissolved organic matter accounted for about 32% of TN. This pattern may reflect the influx of DIN rich water or the predominance of DIN in Destruction Brook watershed may also reflect the higher permeability of the watershed sediments, which have a high relative amount of sand and gravel and thus groundwater transport plays a more dominant role in the watershed hydrologic regime. In this case, nitrate from septic systems, fertilizers and other watershed sources may have less opportunity for uptake and transformation in the soils before entering the groundwater flow system. The nutrient characteristics of the Destruction Brook flow indicates that groundwater nitrogen (typically dominated by nitrate) discharging to the small wetland up-gradient of the gage site and to Destruction Brook was not completely taken up by plants within the wetland or stream ecosystems. The high concentration of inorganic nitrogen in the out-flowing Destruction Brook waters also suggests that plant production within the limited up-gradient freshwater ecosystems is not nitrogen limited. In addition, the high nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system, potentially within the wetland up-gradient of the stream gage location.

Given that the Destruction Brook watershed has a relatively low density of land usage, it was suspected that there was a substantial, localized source of nitrogen in the Destruction Brook watershed. An investigation was conducted up stream of the gage in order to better elucidate stream nitrogen levels at various points along the destruction brook stream reach and a source for the “excess” nitrogen entering Destruction Brook was identified which accounted for approximately 24-56% of the total nitrogen in the Destruction Brook TN total discharge to Slocums River. Most of the “excess” TN added was in the form of nitrate (80-99%).

In the fall 2004, a preliminary MEP review of the nitrogen data generated from weekly sampling in Destruction Brook indicated that the mean concentration of total nitrogen flowing from Destruction Brook into Slocums River was relatively high in comparison to the levels measured in the Paskamanset River, Barneys Joy North and Barneys Joy South. Though Destruction Brook total nitrogen concentrations were lower than those found in the more urbanized Buttonwood Brook and Apponagansett Bay Brook over the same period, the levels found in Destruction Brook (TN =105.9 uM; n=173)) were higher than one might expect for a relatively low intensity of development within the watershed. Additional sampling in 2004 and 2005 was conducted at sites spaced upstream of the mouth of the brook at Horseneck Road (**Figure IV-18**). These sampling rounds indicated that there was an incremental increase of nitrogen from the upper reaches of the stream that was roughly proportional to the increase in watershed contribution area to the stream (**Figure IV-19**). Samples from the middle reach of the stream showed little increase or decrease until the most downstream portion of the brook, in the area between Horseneck Road and the Beach sampling site southeast of Slades Corner Rd. For example, mean total nitrogen concentration for the Horseneck Road outlet site was 81.7 uM (n=3) while samples drawn from the upstream Beach site were 59.5 uM (n=4), suggesting an increase in nitrogen in the lowest reach of about 33%. This increase was out of proportion to the additional watershed area (less than 5% more) and expected additional nitrogen load of about 5%, also. The watershed of the lowest stretch of the stream consisted of extensive fringing wetlands, forested upland, fewer than five residences and part of a dairy farm.

Follow-up sampling in the spring of 2006 concentrated upon the lowest reach of the stream to try to find a source area for the increased nitrogen concentrations. A small tributary brook was located flowing from the west into the main brook (**Figure IV-19**). Samples were collected upstream of the tributary mouth, downstream at Horseneck Road and in the tributary at two sites, near the mouth of the tributary and some distance upstream along the tributary (**Figure IV-19**). Additional samples were collected upstream on the main stream on the first of the three sampling rounds, while subsequent rounds sampled only the lowest reach of the brook and the tributary.

Data collected in 2006 is summarized in **Table IV-10**. The concentration of TN in the tributary water was found to be very high, ranging from 545.6 uM to 739.7 uM (7.6 mg/l to 10.4 mg/l). While flow measured in the tributary was relatively small, about 5% of main stem flow, the high TN concentration was sufficient to raise the main stream TN levels by between 24 and 57 percent, again far greater than the less than 5 percent increase in watershed area. The sampling upstream on the tributary on 5/23/06 suggested that the source area was the uplands to the west and northwest of the tributary, an area which consists of fields and farm buildings of a former dairy farm. The bulk of the TN found in the tributary's water was in the form of nitrate +nitrite (NOx) while ammonium (NH4) was low, a pattern that suggests that the nitrogen is not from surface runoff but is transported to the stream via groundwater flow.

The data on this survey was passed to Dartmouth Town officials at the Board of Health and Conservation Commission in June 2006 for further site investigation and action.

Table IV-10. 2006 Lower Destruction Brook Survey

Location	Date	NH4 (uM)	NOX (uM)	TDN (uM)	TN (uM)	TN (mg/l)	TN Increase (%)
Fisher North	5/23/2006	0.7	4.4	41.7	42.9	0.6	
Fisher	5/23/2006	1.0	1.9	45.6	47.0	0.7	
Parsons	5/23/2006	0.8	20.6	60.7	62.6	0.9	
SW Trib Mouth	5/23/2006	0.3	593.2	737.0	739.7	10.4	
SW Trib Upstream	5/23/2006	0.6	465.5	583.3	585.8	8.2	
Horseneck	5/23/2006	0.9	53.0	95.2	97.8	1.4	56.2
Parsons	5/31/2006	1.5	27.0	61.2	63.3	0.9	
SW Trib Mouth	5/31/2006	0.6	570.5	599.7	601.7	8.4	
Horseneck	5/31/2006	1.9	60.8	96.7	99.4	1.4	57.1
Parsons	6/5/2006	1.7	17.0	52.6	52.6	0.7	
SW Trib Mouth	6/5/2006	1.0	575.3	545.6	545.6	7.6	
Horseneck	6/5/2006	1.8	31.5	65.0	65.0	0.9	23.6

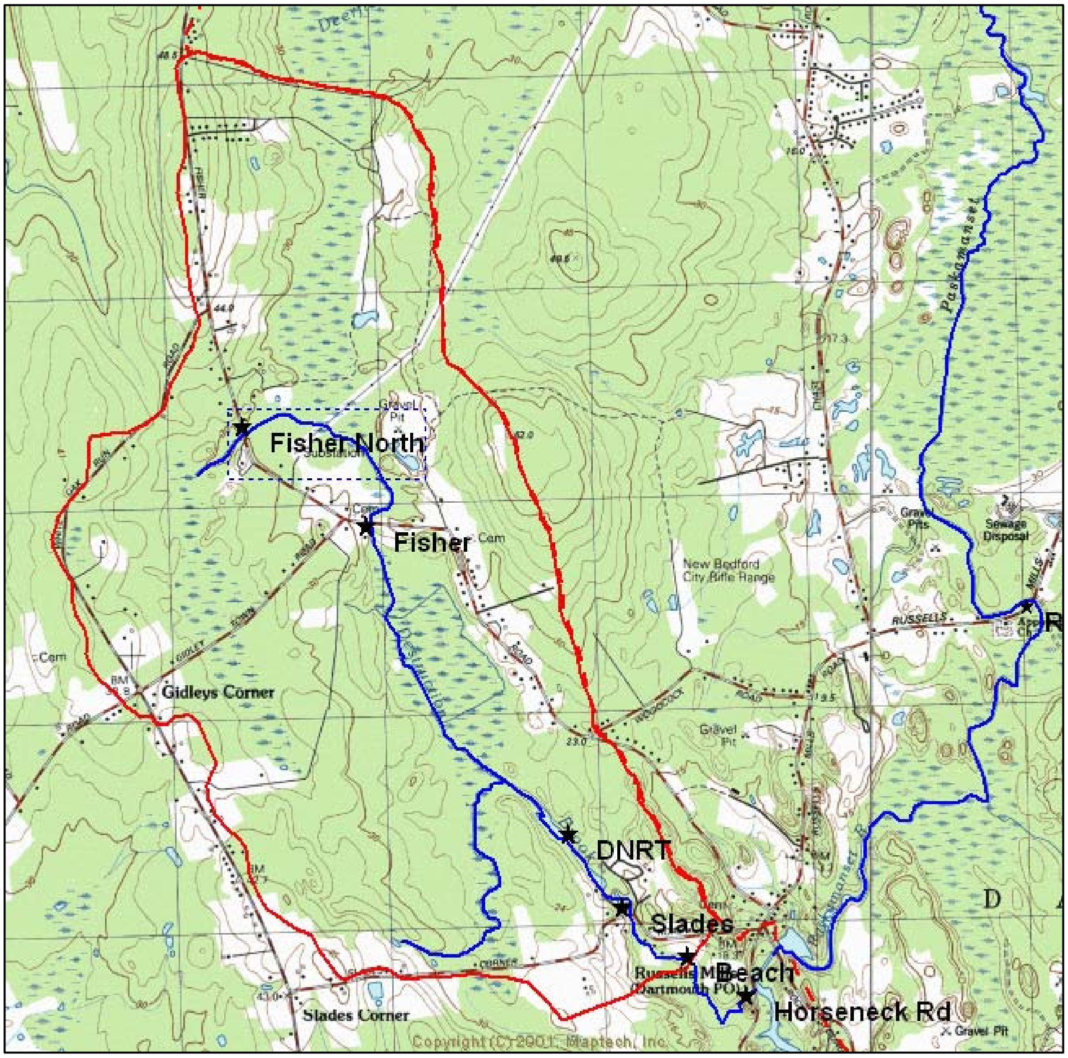


Figure IV-18. Sampling site location for 2004-2006 upstream survey for nitrogen source areas with the gaged watershed boundary (red line).

From the measured nitrogen load discharged by Destruction Brook to the Slocums River system and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon the lower nitrogen load (6,237 kg yr^{-1}) discharged from the freshwater brook compared to that added by the various land-uses to the associated watershed (7,300 kg yr^{-1}), the integrated attenuation in passage through the wetland and stream prior to discharge to the estuary is 15% (i.e. 15% of nitrogen input to watershed does not reach the estuary). This slightly lower level of attenuation compared to other streams evaluated under the MEP is expected given the limited number of up-gradient ponds available to naturally attenuate nitrogen in the stream flow. The directly measured nitrogen loads from the creek was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

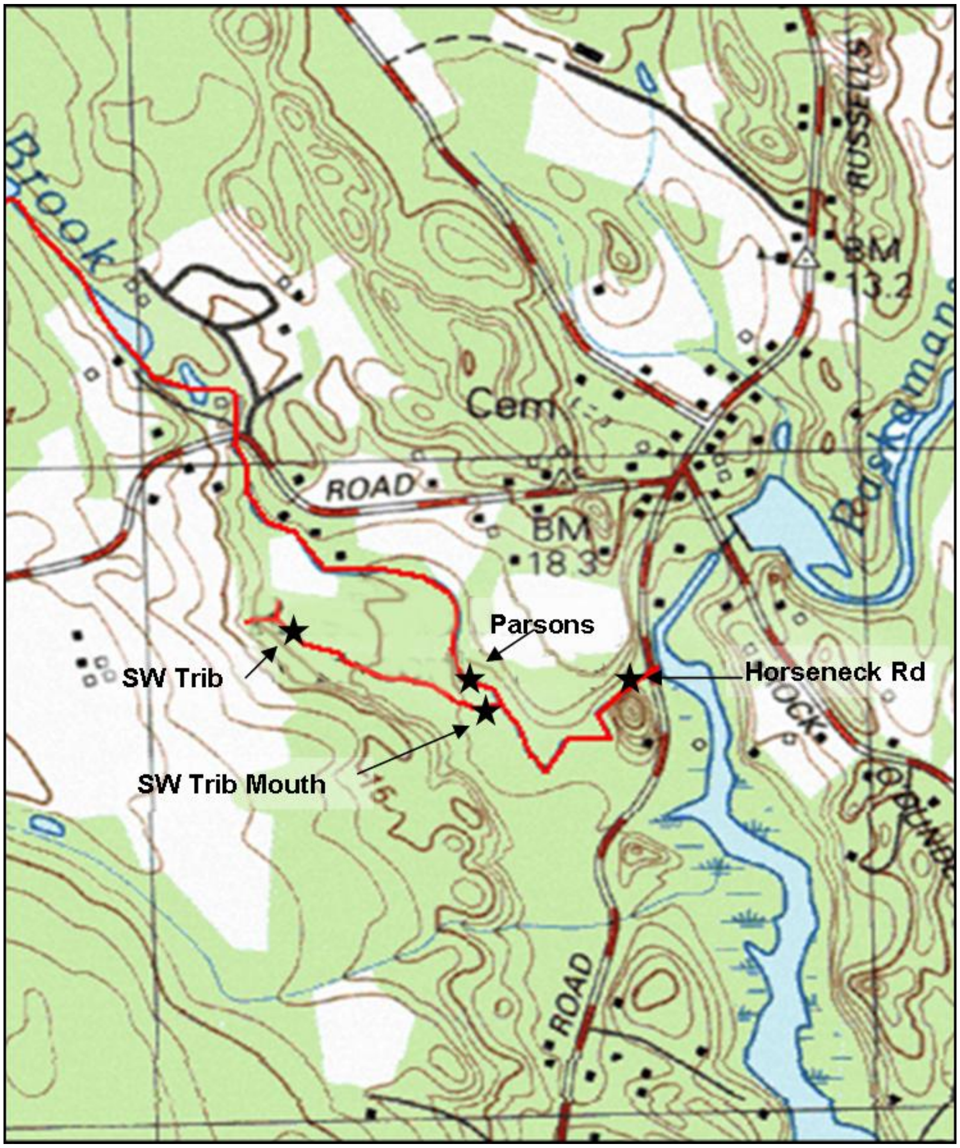


Figure IV-19. Relation of the southwest tributary sampling sites (stars) and the lower Destruction Brook area. Horseneck Rd. site is the downstream sampling site monitored for approximately 22 months.

IV.2.4 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge Barneys Joy (north) Creek to head of Slocums River

At the Barneys Joy Creek gage site, a continuously recording vented calibrated water level gage was installed to yield the level of water in the discharge that carries nitrogen load from the up-gradient sub-watershed (relatively devoid of aquatic resources such as ponds, bogs, wetlands) to the middle portion of the Slocums River system. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average salinity was determined to be no greater than 0.1 ppt. Based on the low salinity, the gage location was deemed acceptable for making freshwater flow measurements. Calibration of the gage was checked monthly. The gage on the Barneys Joy (north) stream outflow to Slocums River was installed on November 26, 2003 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 July 28, 2005 for a total deployment of 20 months. The 12-month uninterrupted record used in this analysis covered the period of November 26, 2003 to November 25, 2004.

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 Barneys Joy (n) stream gage site based upon these flow measurements and measured water levels at the gage 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 middle section of the Slocums River system **(Figure IV-20 and Table IV-6)**. In addition, a water balance was constructed based upon the US Geological Survey watershed delineations to determine long-term average freshwater discharge expected at the gage site based on recharge rates appropriate to the region.

The annual freshwater flow record for the Barneys Joy (n) stream as measured by the MEP was compared to the long-term average flows based on watershed recharge. The measured freshwater discharge from the Barneys Joy (n) stream was 24% above the long-term average modeled flows. The average daily flow based on the MEP measured flow data was 5,381 m^3/day compared to the long term average flows (4325 m^3/day) determined by the watershed area-recharge rate approach.

The difference between the long-term average flow based on recharge rates over the watershed area and the MEP measured flow in Barneys Joy (n) stream 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 Barneys Joy (n) discharging to the middle section of the Slocums River would indicate that the Stream is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Barneys Joy (n) stream outflow were low, 0.629 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 3.55 kg/day and a measured total annual TN load of 1,202 kg/yr. In the Barneys Joy (n) surface water system, nitrate+nitrite (NOx) was less than half of the total nitrogen load (32%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the wetland or stream ecosystems. In the Barneys Joy (n) stream discharge to Slocums River, dissolved organic nitrogen (DON) was the predominant form of nitrogen (~55%). Similar to the Paskamanset River, this balance of nitrogen species indicates that about 1/3 of the nitrogen is available for immediate uptake by primary producers (algae) in the Slocums embayment and about two-thirds of the total nitrogen in the river discharge is not immediately available for uptake in the Slocums River, but would need to be further processed by estuarine biota before being available to primary production.

Forested areas form a significant portion of the total Barneys Joy (n) stream watershed area and thus would tend to retain and transform NOx. The watershed also has relatively low amounts of sand and gravel in its soils and thus groundwater movement would tend to be relatively slow, allowing more time for NOx to be retained in plants and transformed in soils. Thus, the relative amounts of NOx and DON may be a both a reflection of forest cover and hydrologic regime. The moderate concentration of inorganic nitrogen in the out-flowing stream waters also suggests that plant production within the up-gradient freshwater ecosystems is not nitrogen limited. In addition, the nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system up-gradient of the stream gage assuming an appropriate location can be identified.

From the measured nitrogen load discharged by the Barneys Joy (n) stream to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower nitrogen load (1,202 kg yr^{-1}) discharged from the stream compared to that added by the various land-uses to the associated watershed (1,831 kg yr^{-1}), the integrated attenuation in passage through the wetland prior to discharge to the estuary is 29% (i.e. 29% of nitrogen input to watershed does not reach the estuary). This slightly lower level of attenuation compared to other streams evaluated under the MEP is expected given the limited number of up-gradient ponds or wetlands available to naturally attenuate nitrogen in the stream flow. The directly measured nitrogen loads from the stream was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

IV.2.4 Surface water Discharge and Attenuation of Watershed Nitrogen: Stream Discharge Giles Creek to the head of the Slocums River

At the Barneys Joy (south) stream gage site, also known as Giles Creek, a continuously recording vented calibrated water level gage was installed to yield the level of water in the discharge that carries nitrogen load from the wetland to the middle section of Slocums River. As the Barneys Joy (s) discharge could potentially be tidally influenced, the gage was located as far above the saltwater reach of the Slocums River such that freshwater flow could be measured without tidal influence. To confirm that freshwater was being measured, salinity measurements were conducted on the weekly water quality samples collected from the gage site. Average low tide salinity was determined to be no greater than 0.1 ppt. Based on the low salinity, the gage location was deemed acceptable for making freshwater flow measurements at low tide. Calibration of the gage was checked monthly. The gage on the stream outflow from Barneys Joy (s) was installed on June 24, 2003 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 July 28, 2005 for a total deployment of 25 months. The 12-month uninterrupted record (hydrologic year low flow to low flow) used in this analysis covers the period 2003-2004 and captures the summer 2004 field season when the majority of MEP data collection was undertaken on the Slocums and Little River estuarine systems.

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 Barneys Joy (s) stream gage site based upon these flow measurements and measured water levels at the gage 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 middle portion of the Slocums River **(Figure IV-21 and Table IV-6)**. In addition, a water balance was constructed based upon the US Geological Survey watershed delineations to determine long-term average freshwater discharge expected at the gage site based on recharge rates appropriate to the region.

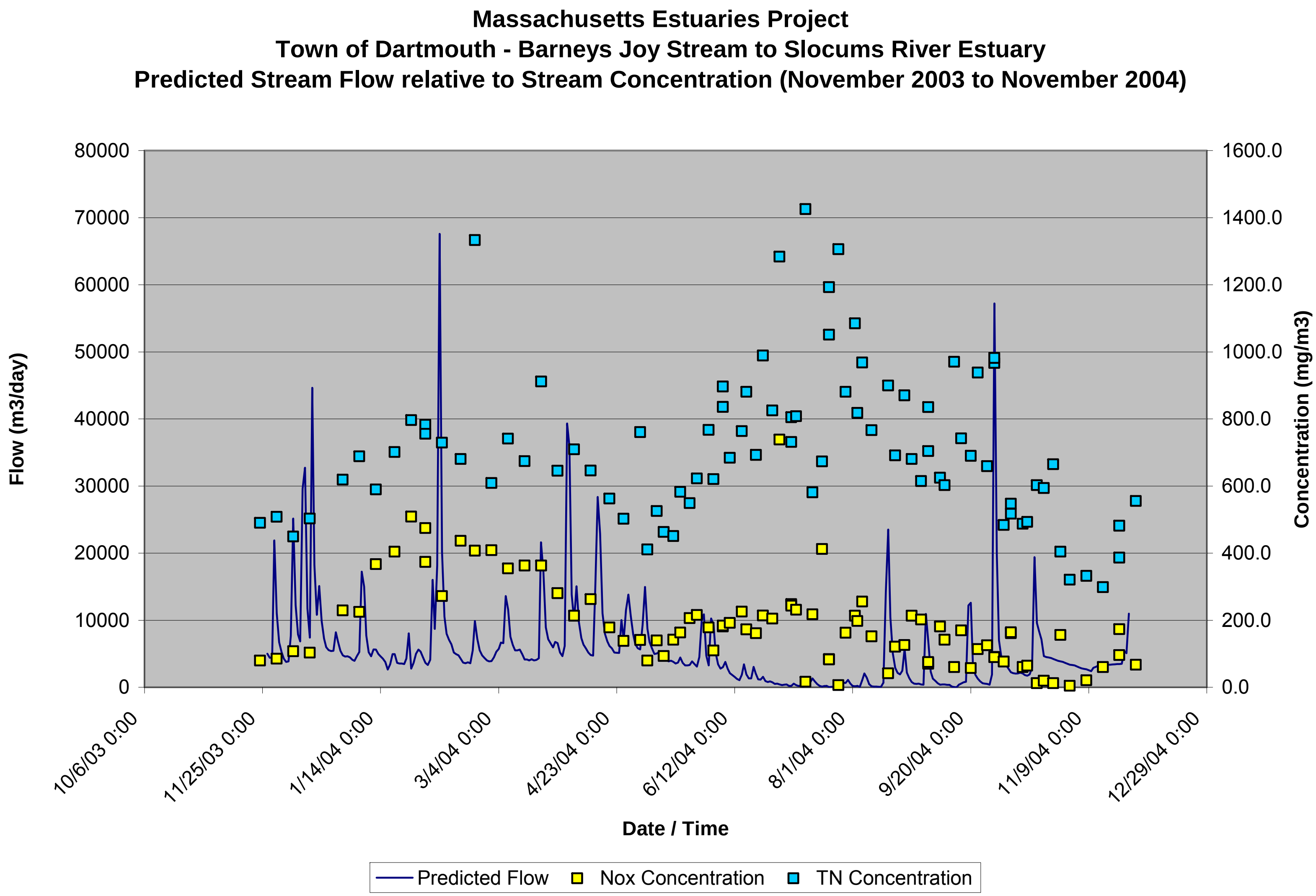


Figure IV-20. Discharge from Barneys Joy Creek (solid blue line), nitrate+nitrite (yellow squares) and total nitrogen (blue triangles) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Slocums River (Table IV-6).

The annual freshwater flow record for the Barneys Joy (s) stream as measured by the MEP was compared to the long-term average flows determined by the watershed area-recharge rate approach (Table IV-11). The measured freshwater discharge from Barneys Joy (s) was 13% below the long-term average modeled flows. Measured flow in the Barneys Joy (s) stream was obtained for the hydrologic year (September 1, 2003 to August 31, 2004). The average daily flow based on the MEP measured flow data was 5,699 m^3/day compared to the long term average flows based on the recharge rate (6,545 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 the Barneys Joy (s) stream are in part be due to below average rainfall during the stream gage deployment period based on rainfall records obtained from a rain gage in the City of New Bedford. Twelve years of rainfall data (1993-2005) indicate that the average rainfall in the vicinity of the Slocums River system was 49.2 inches. By comparison, rainfall in 2002 and 2003 was 50.80 and 38.54 inches respectively. Rainfall in 2003 was 38.54 inches (below long tern average). This was in contrast to rainfall amounts totaling 31.85 inches in 2001. It should be recognized that 2001 and 2003 rainfall was below average with only one year (2002) above average, thus the water table is likely to have been lower than usual due to the 2 years of lower rainfall. This is significant relative to measured flow in the Barneys Joy (s) stream surface water system as it is essentially a groundwater fed feature. Based upon the rainfall and groundwater levels associated with the stream measurement (suggesting a lower flow than the long-term average) and the some what lower measured stream discharge then predicted (-13%) it appears that the stream is capturing the up-gradient recharge (and loads) accurately.

Total nitrogen concentrations within the Barneys Joy (s) stream outflow were moderate, 0.964 mg N L^{-1}, yielding an average daily total nitrogen discharge to the estuary of 5.49 kg/day and a measured total annual TN load of 2,005 kg/yr. In the Barneys Joy (s) surface water system, nitrate was slightly less than half of the total nitrogen load (40%), indicating that groundwater nitrogen (typically dominated by nitrate) discharging to the freshwater ponds and to the river was not completely taken up by plants within the wetland or stream ecosystems. The moderate concentration of inorganic nitrogen in the out-flowing stream waters also suggests that plant production within the up-gradient freshwater ecosystems is not nitrogen limited. In addition, the nitrate level suggests the possibility for additional uptake by freshwater systems might be accomplished in this system within the wetland up-gradient of the Hurley Bog stream gage.

From the measured nitrogen load discharged by the Barneys Joy (s) stream to the estuary and the nitrogen load determined from the watershed based land use analysis, it appears that there is nitrogen attenuation of upper watershed derived nitrogen during transport to the estuary. Based upon lower nitrogen load (2,005 kg yr^{-1}) discharged from the freshwater Barneys Joy (s) stream compared to that added by the various land-uses to the associated watershed (2,249kg yr^{-1}), the integrated attenuation in passage through the wetland prior to discharge to the estuary is 11% (i.e. 11% of nitrogen input to watershed does not reach the estuary). This slightly lower level of attenuation compared to other streams evaluated under the MEP is expected given the hydraulic nature of the small up-gradient pond which is essentially shallow flow through system. The directly measured nitrogen loads from the stream was used in the Linked Watershed-Embayment Modeling of water quality (see Chapter VI, below).

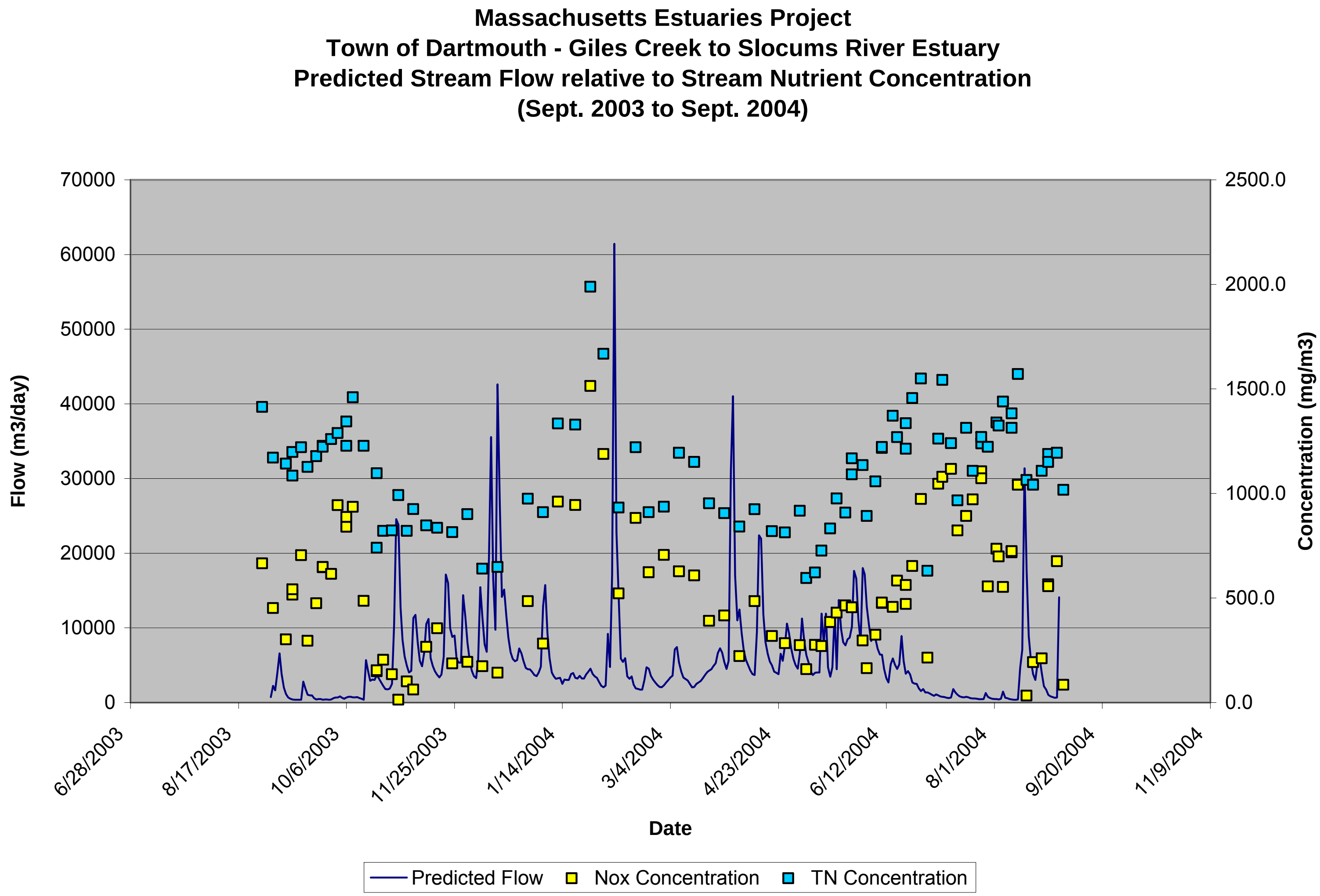


Figure IV-21. Discharge from Giles Creek (solid blue line), nitrate+nitrite (yellow squares) and total nitrogen (blue triangles) concentrations for determination of annual volumetric discharge and nitrogen load from the upper watershed to Slocums River (Table IV-6)

Table IV-11. Summary of annual volumetric discharge and nitrogen load from the Rivers and Streams (freshwater) discharging to the Slocums River based upon the data presented in Figures IV-11,17,20,21 and Table IV-6.

Stream	Annual Flow (m3/yr)	Annual Load Nox (kg/yr)	Annual Load TN (kg/yr)	Watershed Area (Km2)
Slocums River				**95.78**
Paskamansett River	**40107718**	**10370**	**37162**	**73.56**
Destruction Brook	**4153769**	**3754**	**6237**	**7.77**
Barneys Joy (N)	**1964035**	**369**	**1202**	**2.26**
Barneys Joy (S) Giles Creek	**2079997**	**796**	**2005**	**3.42**
(other subwatershed areas)				8.77

Stream	Watershed Area (Km2)	Annual Unit Flow (m3/yr/Km2)	Annual Unit Load Nox (Kg/yr/Km2)	Annual Unit Load TN (Kg/yr/Km2)
Slocums River	**95.78**			
Paskamansett River	**73.56**	**545238**	**141**	**505**
Destruction Brook	**7.77**	**534591**	**483**	**803**
Barneys Joy (N)	**2.26**	**869042**	**163**	**532**
Barneys Joy (S) Giles Creek	**3.42**	**608186**	**233**	**586**
(other subwatershed areas)	8.77			

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 Slocum's River and Little River Estuarine System. 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.

IV.3.1 Sediment-Watercolumn Exchange of Nitrogen

As stated in above sections, nitrogen loading and resulting levels within coastal embayments are the critical factors controlling the nutrient related ecological health and habitat quality within a system. Nitrogen enters the complex Slocum's River and Little River Estuarine System predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of the nitrogen remained within the 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 bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, i.e. it is converted from dissolved forms into phytoplankton “particles”. Most of these “particles” remain in the 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 bays.

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

Once organic particles become incorporated into surface sediments they are decomposed by the natural animal and microbial community. This process can take place both under oxic (oxygenated) or anoxic (no oxygen present) conditions. It is through the decay of the organic matter with its nitrogen content that bioavailable nitrogen is returned to the embayment 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 salt marsh tidal creeks and basins, like Little River and Giles Creek, 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; Namskaket and Little Namskaket Salt Marshes). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, such as found within the lower reach of the Slocum's River. In contrast, regions of enhanced deposition typically support moderate levels of nitrogen release during summer months.

Failure to account for the site-specific nitrogen balance of the sediments and its spatial variation from the tidal creeks and basins will result in significant errors in determination of the threshold nitrogen loading to the Slocum's River and Little River Estuaries. In addition, since the sites of recycling can be different from the sites of nitrogen entry from the watershed, both recycling and watershed data are needed to determine the best approaches for nitrogen mitigation.

IV.3.2 Method for determining sediment-watercolumn nitrogen exchange

For the Slocum's River and Little River Estuaries in order to determine the contribution of sediment regeneration to nutrient levels during the most sensitive summer interval (July-August), sediment samples were collected and incubated under *in situ* conditions. Sediment samples were collected from 24 sites, 16 within the Slocum's River and 8 within Little River, **(Figure IV-22)** in July-August in 2 years, 2004 and 2005. Measurements of total dissolved nitrogen, nitrate + nitrite, ammonium were made in time-series on each incubated core sample.

Rates of nitrogen release were determined using undisturbed sediment cores incubated for 24 hours in temperature-controlled baths. Sediment cores (15 cm inside diameter) were collected by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The number of core samples from each site **(Figure IV-22)** per incubation are as follows:

Slocum's River Estuaries Benthic Nutrient Regeneration Cores

- Slocum's River Upper Reach-1 1 core (Basin)
- Slocum's River Upper Reach-2 2 cores (Basin)
- Slocum's River Upper Reach-3 2 cores (Basin)
- Slocum's River Upper Reach-4 2 cores (Basin)
- Slocum's River Upper Reach-5 2 cores (Basin)
- Slocum's River Middle Reach-6 2 cores (Basin)
- Slocum's River Middle Reach-7 2 cores (Basin)
- Slocum's River Middle Reach-8 2 cores (Basin)
- Slocum's River Middle Reach-9 2 cores (Basin)
- Giles Creek Salt Marsh Basin-12 2 cores (Basin)
- Giles Creek Salt Marsh Basin-13 1 core (Basin)
- Slocum's River Lower Reach-10 1 core (Basin)
- Slocum's River Lower Reach-11 1 core (Basin)
- Slocum's River Lower Reach-14 2 cores (Basin)
- Slocum's River Lower Reach-15 2 cores (Basin)
- Slocum's River Lower Reach-16 2 cores (Basin)

Little River Estuaries Benthic Nutrient Regeneration Cores

• Little River Salt Marsh Basin-1	1 core	(Basin)
• Little River Salt Marsh Basin-2	1 core	(Basin)
• Little River Salt Marsh Basin-3	2 cores	(Basin)
• Little River Salt Marsh Basin-4	2 cores	(Basin)
• Little River Salt Marsh Basin-5	2 cores	(Basin)
• Little River Salt Marsh Basin-6	2 cores	(Basin)
• Little River Salt Marsh Basin-7	1 core	(Basin)
• Little River Salt Marsh Basin-8	2 cores	(Basin)

Sampling was distributed throughout the primary embayment sub-basins of this system: the Slocum's River upper, middle and lower reaches and Giles Creek and throughout the Little River salt marsh basin. The results for each site were then combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

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

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

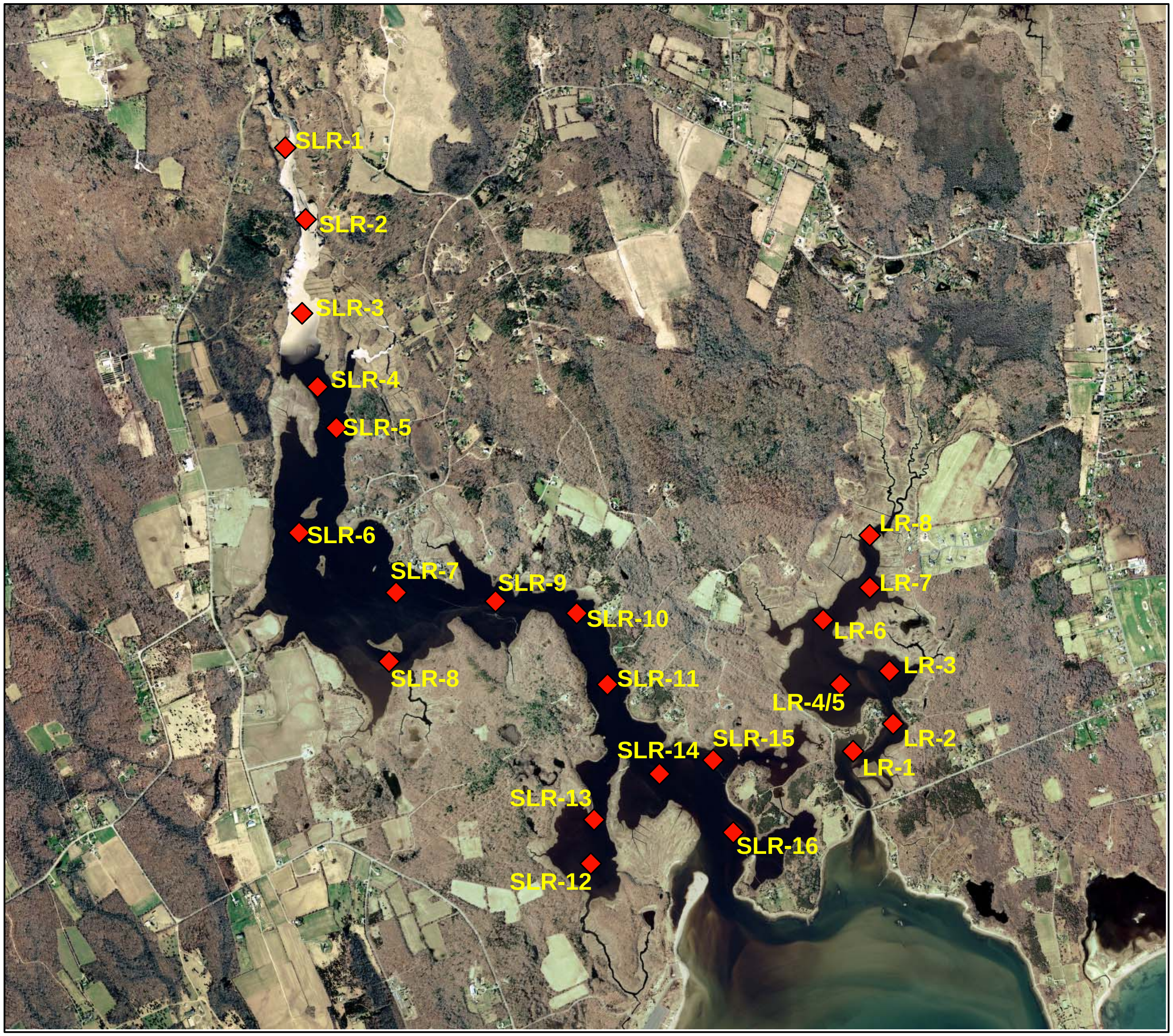


Figure IV-22. Slocums River and Little River embayment systems sediment sampling sites (red symbols) for determination of nitrogen regeneration rates. Numbers are for reference to station identifications listed above.

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 organic levels within the sediment (oxic/anoxic) and the concentration of nitrate in the overlying water. Organic rich sediment systems with high overlying nitrate frequently show large net nitrogen uptake throughout the summer months, even though organic nitrogen is being mineralized and released to the overlying water as well. The rate of nitrate uptake, simply dominates the overall sediment nitrogen cycle.

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

Overall, coastal sediments are not overlain by nitrate rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is taken into account, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature **(Figure IV-23)**.

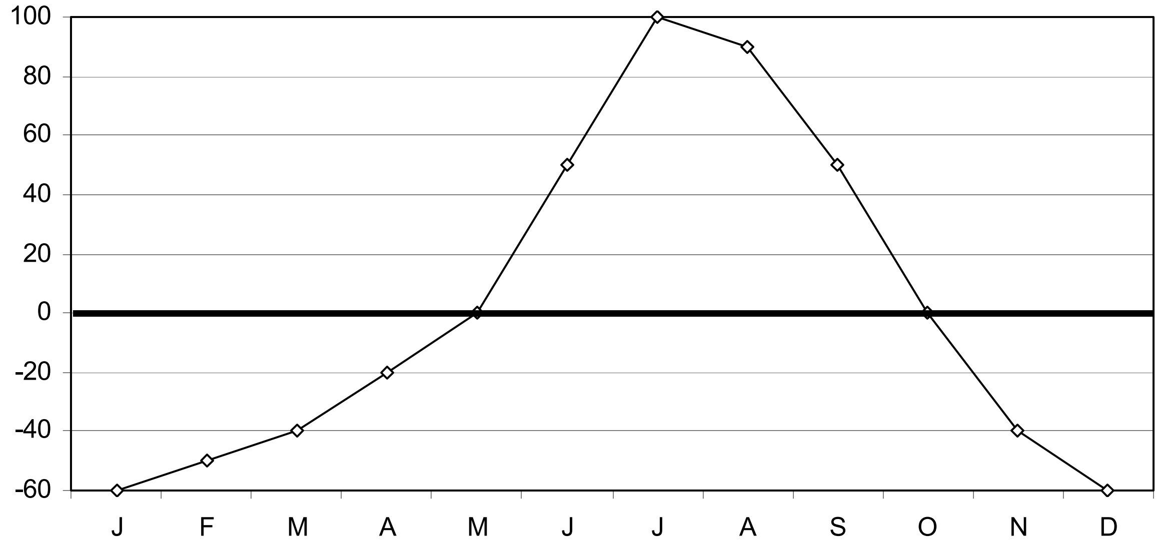


Figure IV-23. Conceptual diagram showing the seasonal variation in sediment N flux, with maximum positive flux (sediment output) occurring in the summer months, and maximum negative flux (sediment up-take) during the winter months.

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.

Sediment sampling was conducted throughout the primary embayment sub-basins of this system: the Slocum's River upper, middle and lower reaches and Giles Creek and throughout the Little River salt marsh basin. in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content and sediment type and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

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

Net nitrogen release or uptake from the sediments within the Slocum's and Little River Estuaries were comparable to other similar salt marsh dominated systems with similar configuration and flushing rates. The spatial distribution of nitrogen release/uptake by the sediments of both Rivers were was similar, with the narrow range, 0.6 to -13.2 mg N m^{-2} d^{-1}, for the entire Slocum's River, encompassing that measured for Little River, -3.1 mg N m^{-2} d^{-1}. The observed rates agree well with those from other salt marsh dominated systems in southeastern Massachusetts, for example Namskaket and Little Namskaket Marshes (Orleans) were found to have uptake in the lower larger creek areas of -21.2 vs -7.8 mg N m^{-2} d^{-1}, respectively, very close to that for the lower reach of the Slocum's River, -13.2 mg N m^{-2} d^{-1}. The observed rates of uptake were also similar to other salt marsh dominated systems on Cape Cod. For example, net nitrogen uptake in the salt marsh areas in the Centerville River System (-4.5 to -13.2 mg N m^{-1} d^{-1}) and Cockle Cove Salt Marsh, Chatham (MEP Centerville River Final Nutrient Technical Report 2006, MEP Cockle Cove Technical Memorandum-Howes et al. 2006).

The pattern of sediment N release was also similar to other systems, with the upper estuarine reaches where upper watershed nitrogen loads are focused and where tidal flushing is lowest showing slight summertime nitrogen release, consistent with MEP Technical Team field observations of unconsolidated sediments composed of fine material, organic rich in nature. The overall pattern of a gradient in nitrogen release/uptake from the upper reach to the lower reach within the Slocum's River is similar to that observed for the adjacent Acushnet River Estuary, which also receives significant riverine discharge to its headwaters.

Net nitrogen release rates for use in the water quality modeling effort for the component reaches of the Slocum's and Little River Estuarine System (Chapter VI) are presented in Table IV-12. There was a clear spatial pattern of sediment nitrogen flux, with lower rates of nitrogen release by the sediments of the upper Slocum's River and uptake in the mid and lower basins of both estuaries. The sediments within the Slocum's and Little River Estuarine showed nitrogen fluxes typical of similarly structured systems within the region and appear to be in balance with the overlying waters and the nitrogen flux rates consistent with the level of nitrogen loading to this system and its relatively high flushing rate.

Table IV-12. Rates of net nitrogen return from sediments to the overlying waters of the Slocum's River and Little River Estuaries. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July -August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			i.d. *
	Mean	S.E.	# sites	
Slocum's River Estuary				
Slocum's R. Upper Reach	0.6	4.1	9	SLR 1-5
Slocum's R. Mid Reach	-6.0	10.9	8	SLR 6-9
Giles Creek Salt Marsh Basin	-0.9	2.7	3	SLR 12,13
Slocum's R. Lower Reach	-13.2	9.1	8	SLR 10-16
Little River Estuary				
Little River Salt Marsh Basin	-3.1	5.7	13	LR 1-8

* Station numbers refer to Figures IV-7.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

A hydrodynamic study was performed for the Slocums River system. The system is located along the southern coast of Dartmouth, Massachusetts, at the entrance to Buzzards Bay. A site map showing the general study area is shown in Figure V-1. The system has two estuarine systems, Slocums River and Little River. The estuarine systems empty onto a small embayment connected to Buzzards Bay. A large sand shoal has developed at the head of the embayment, as shown in Figure V-2. A channel along the landward edge of the shoal hydraulically connects the estuaries. In general, flow between Buzzards Bay and the two estuarine systems is restricted to this channel running toward the eastern edge of the embayment. Although the large shoal inhibits tidal flow, this feature is submerged for a large portion of the tide cycle; therefore, some of the water entering Slocums and Little Rivers comes across the shoal.

Slocums River and Little River are moderately sized estuaries which discharge to a common bay formed between Mishaum and Barneys Joy Points. Both Slocums River and Little River are shallow tidal estuaries, with mean water depths of only 2.5 and 2.0 feet, respectively. The Little River embayment is completely surrounded by salt marsh, where only about 37 percent of the embayment holds water at low tide. Although Slocums River contains a larger overall area of salt marsh (approximately 230 acres), this marsh area only accounts for 37 percent of the estuary surface area.

Circulation in the Slocums River system is dominated by tidal exchange with Buzzards Bay. From measurements made in the course of this study, the average tide range at the entrance to Slocums River is approximately 3.1 feet. By flow restrictions caused by narrowing of channels and frictions losses, the tide range in upper Slocums River is slightly smaller, or approximately 3.0 feet. Similar tidal dampening occurs to in Little River due to bridge abutments and restrictions, where the tidal range is approximately 2.7 feet. In addition to tidal waters entering through the inlets, a relatively large freshwater inflow exists at the northern limit of Slocums River (the Paskamanset River).

The hydrodynamic study consisted of two major components. In the first portion of the study, bathymetry, Acoustic Doppler Current Profile (ADCP) measurements, salinity measurements, and tide data were collected in order to accurately characterize the physical system, and to provide data necessary for the hydrodynamic modeling portion of the study. The bathymetry survey of Slocums River and Little River was performed to determine the variation of embayment and channel depths throughout the system. This survey addressed the previous lack of adequate bathymetry data for this area. In addition to the survey, tides were recorded for 39.5 days at three locations within Slocums River, two locations in Little River, and at an offshore gage. This tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of the Slocums River system was developed in the second portion of this study. Using the bathymetry survey data, a finite element model grid was generated for use with the RMA-2 hydrodynamic code. The tide data from the offshore gage was used to define the open boundary condition that drives the circulation of the model, and data from the five locations within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the real, physical system. Existing daily flow records in the Paskamanset River also were used to parameterize the model.

In addition to the calibration process, the ADCP current measurements supplied the data needed as an independent verification of the hydrodynamic model results.

The calibrated computer model of the Slocums River system was used to compute the flushing rates of each of the sub-embayments of the system. Though water quality in an embayment cannot be directly inferred by use of the computed flushing rate alone, it can serve as a useful indicator of an embayments flushing performance relative to other similar systems. The ultimate utility of this hydrodynamic model is as input into a constituent transport model, where water quality constituents like nitrogen are modeled to determine the water quality dynamics of a system. This next level of modeling is planned as part of the Massachusetts Estuaries Project, a Massachusetts DEP program focused on the restoration of coastal embayments in southeastern Massachusetts (http://www.state.ma.us/dep/smerp/smerp.htm).

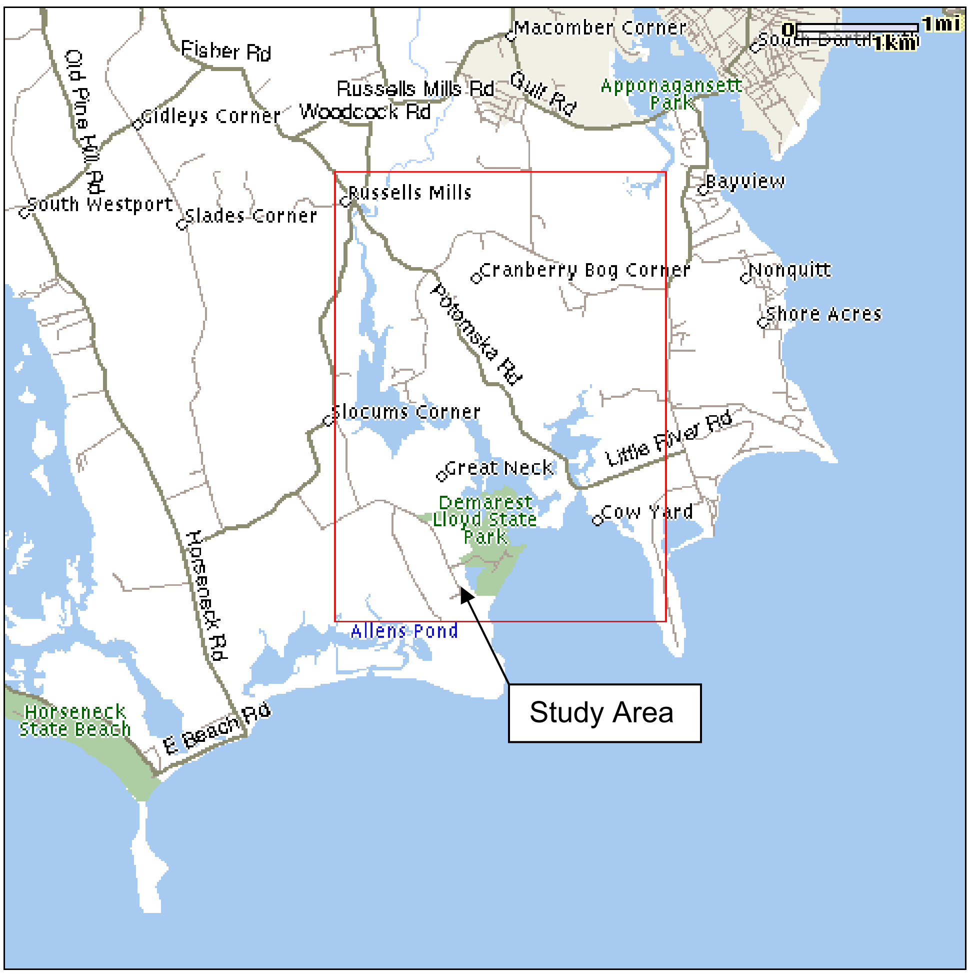


Figure V-1. Site map of the region around Slocums River. The box indicates the area studied.

V.2 GEOMORPHIC AND ANTHROPOGENIC EFFECTS TO THE ESTUARINE SYSTEM

V.3 FIELD DATA COLLECTION AND ANALYSIS

A precise description of embayment geometries and hydrodynamic forcing processes is required for the development of numerical hydrodynamic models. To support hydrodynamic and future water quality modeling efforts in Slocums River and Little River, tidal currents, water elevation variations, and bathymetry of the embayments were measured. Cross-channel current measurements were surveyed through a complete tidal cycle at three locations in Slocums River. Currents also were measured at a stationary position in the Little River inlet. Tidal elevation measurements within selected embayments were used for both forcing conditions and to evaluate tidal attenuation through each estuarine system. Bathymetry data were collected in detail necessary for evaluation of tidal hydrodynamics. The bathymetric data collection effort was focused on areas of flow constrictions: near inlets and narrow sections of the estuaries. This bathymetric information was utilized to develop the computational grid of the system for the hydrodynamic modeling effort.

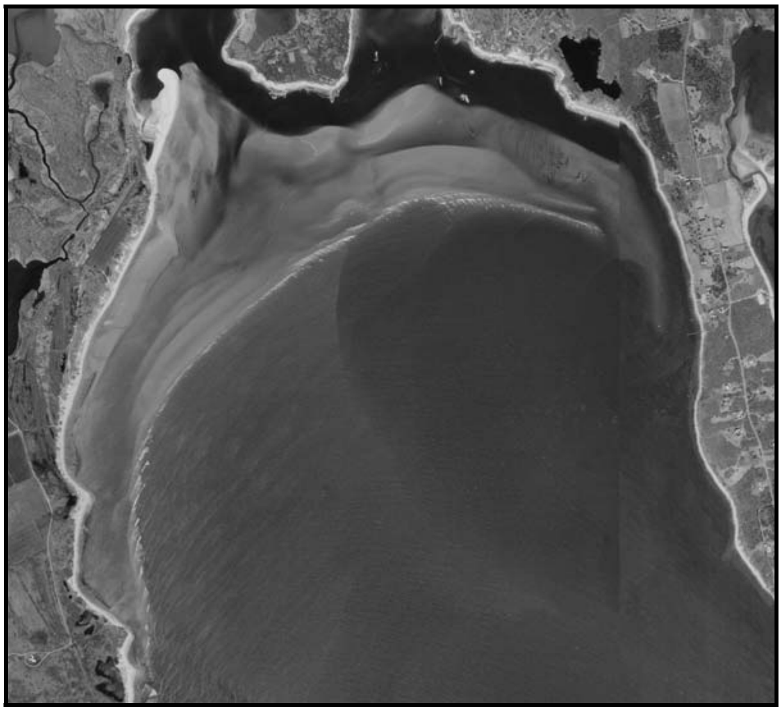


Figure V-2. Aerial photograph of the shoal at the mouths of Slocums River and Little River.

V.3.1 Data Acquisition

V.3.1.1 Water Elevation

Changes in water surface elevation were measured using internal recording tide gages. These tide gages were installed on fixed platforms (such as pier pilings or screw anchors secured to the seabed) to record changes in water pressure over time. Variations in the water surface can be due to tides, wind set-up, or other low frequency oscillations of the sea surface. The tide gages were installed in 6 locations in Slocums River estuary (Figure V-3) in late March 2002 and recovered mid-May 2002. Data records span at least 29 days to yield an adequate time period for resolving the primary tidal constituents.

The tide gages used for the study consisted of Brancker TG-205 and Brancker XR-420 instruments. Data were set for 10-minute intervals, with each 10-minute observation resulting from an average of 60 1-second pressure measurements. Each of these instruments use strain gage transducers to sense variations in pressure, with resolution on the order of 1 cm (0.39 inches) head of water. Each gage was calibrated prior to installation to assure accuracy.

Once the data were downloaded from each instrument, the water pressure readings were corrected for variations in atmospheric pressure. Hourly atmospheric readings were obtained from the NOAA buoy in Buzzards Bay (site BUZM3), interpolated to 10-minute intervals, and subtracted from the pressure readings, resulting in water pressure above the instrument. Further, a (constant) water density value of 1025 kg/m^3 was applied to the readings to convert from pressure units (psi) to head units (for example, feet of water above the tide gage). Several of the sensors were surveyed into local benchmarks to provide vertical rectification of the water level; these survey values were used to adjust the water surface to a known vertical datum. The result from each gage is a time series representing the variations in water surface elevation relative to NGVD29. Figures V-4 and V-5 present the water levels at each gage location.

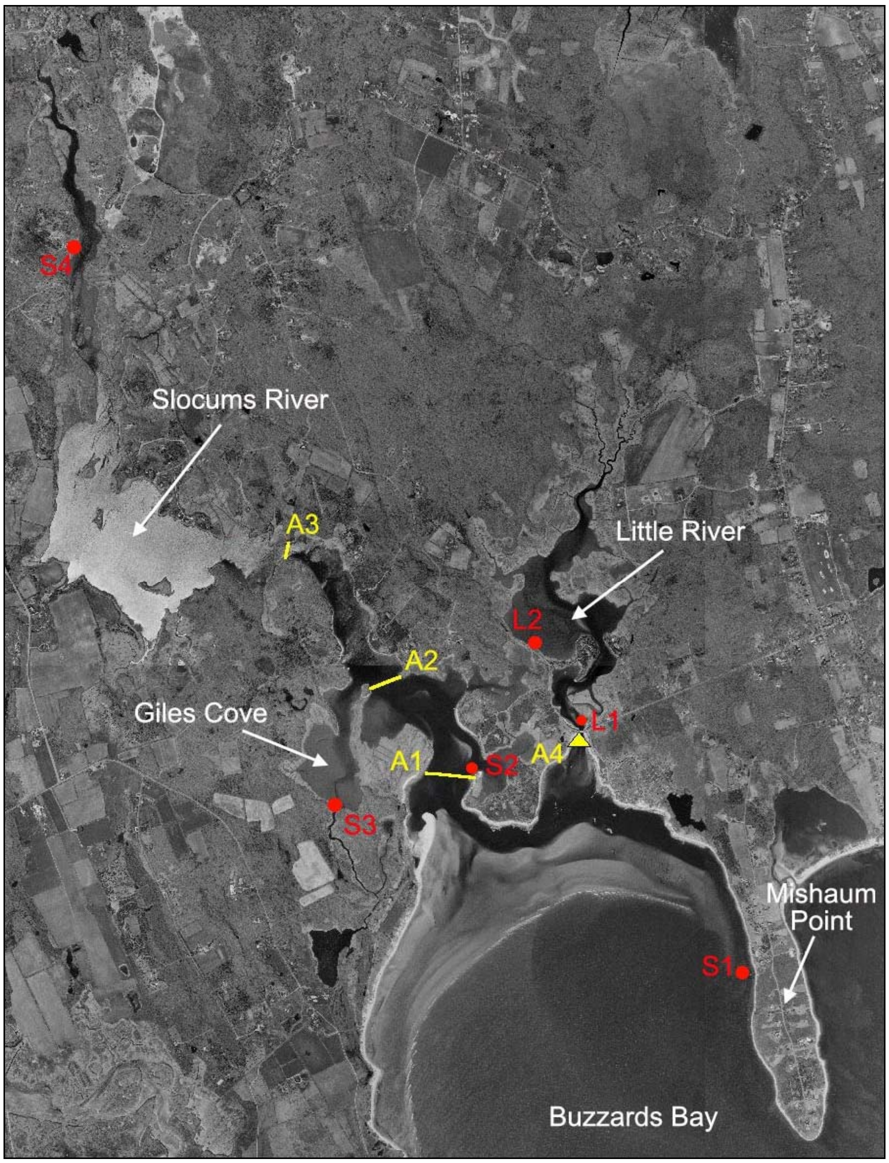


Figure V-3. Tide gage and ADCP transect locations in Slocums River and Little River S1 to S4, L1, and L2 are tide gage locations. Yellow lines A1 to A3 are ADCP transect locations and triangle A4 is the fixed ADCP location.

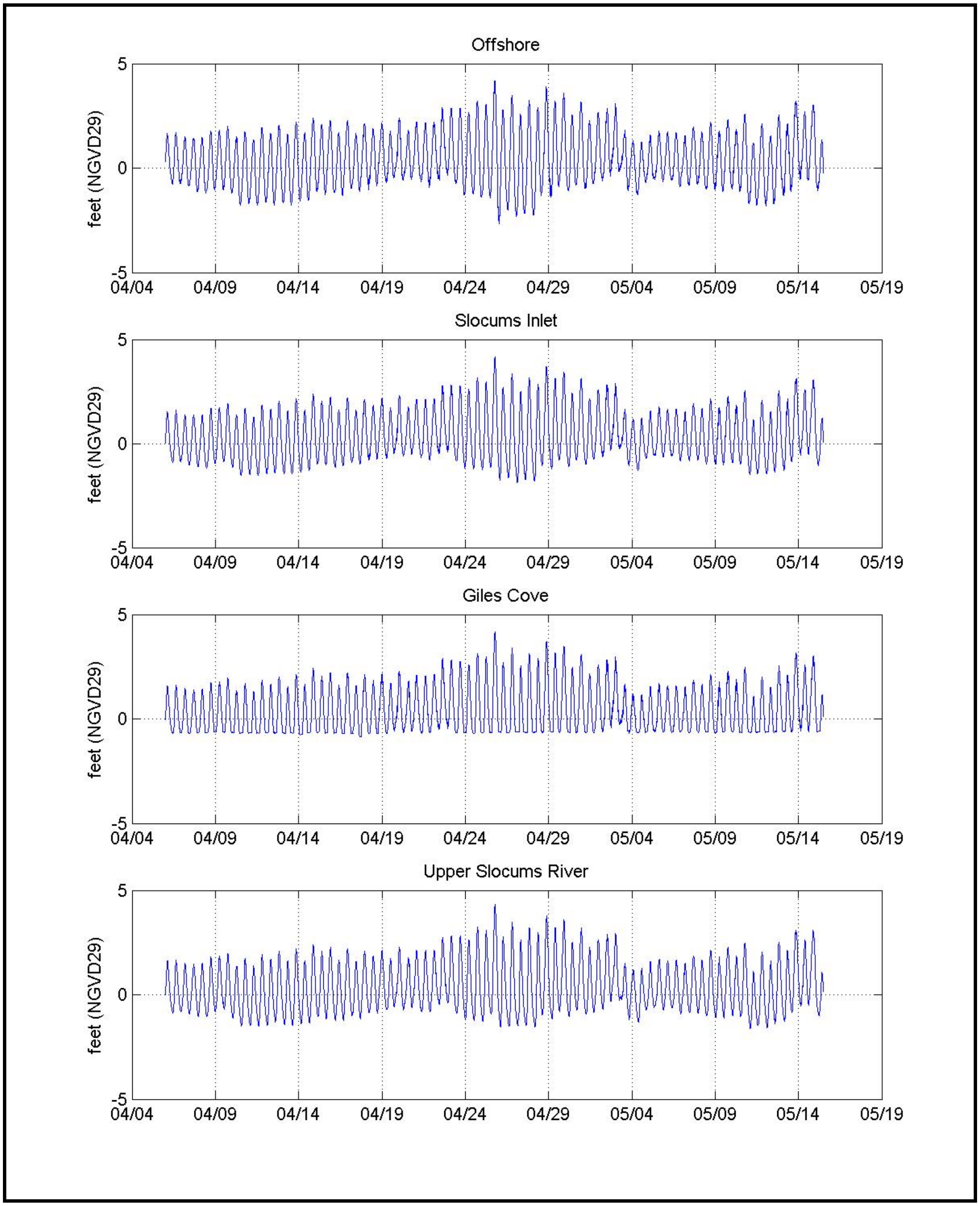


Figure V-4. Tidal elevation observations for Buzzards Bay (offshore, location S1 of Figure III-1), Slocums River Inlet (location S2), Giles Cove (location S3), and Upper Slocums River (location S4).

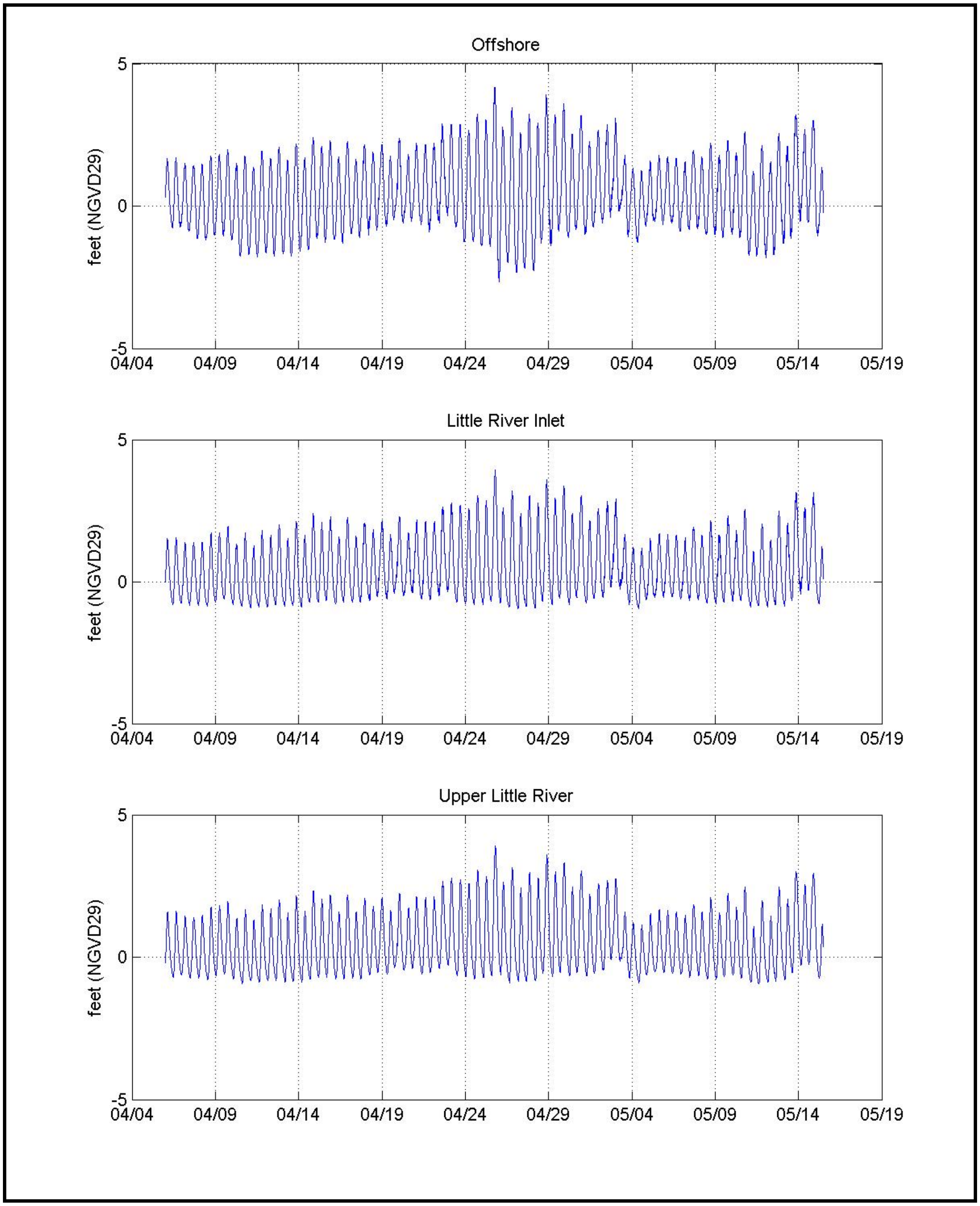


Figure V-5. Tidal observations for Buzzards Bay (offshore, location S1 of Figure III-1), Little River Inlet (location L1), and Upper Little River (location L2).

V.3.1.2 Bathymetry

Bathymetric, or depth, surveys of Slocums River and Little River were designed by Applied Coastal and conducted by CR Environmental in May 2002. The surveys were completed using a small vessel equipped with a precision fathometer interfaced to a differential GPS receiver. The fathometer has a depth resolution of approximately 0.1 foot and the differential GPS provides x-y position measurements accurate to approximately 1-3 feet. Digital data output from both the echosounder and GPS were logged to a laptop computer in Hypack.

GPS positions and echosounder measurements were merged to produce data sets consisting of water depth as a function of x-y horizontal position (in Massachusetts Mainland State Plane, 1983). The data were combined with water surface elevations to obtain the vertical elevation of the bottom (z) relative to the NGVD 1929 vertical datum (NGVD29). The resulting xyz files were input to mapping software to calculate depth contours for the system shown in Figure V-6.

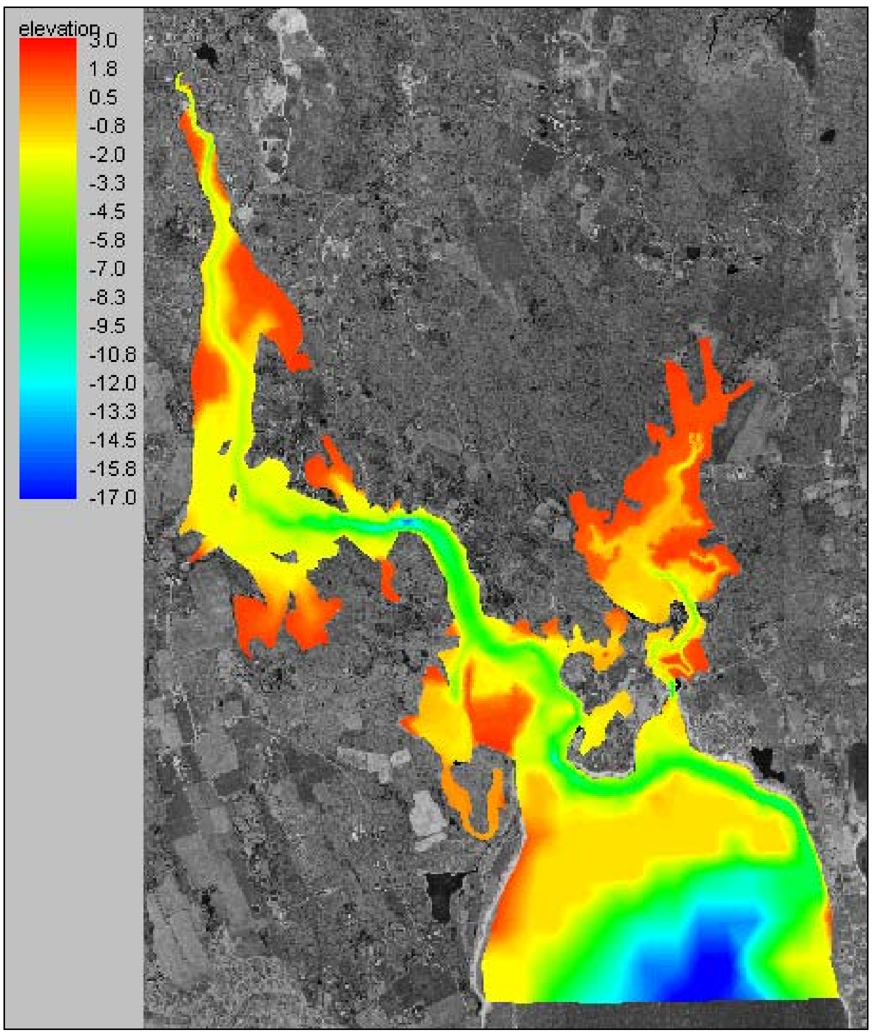


Figure V-6. Bathymetry map from model of Slocums River and Little River. Color contours indicate depth relative to the NGVD 29 vertical datum.

V.3.1.3 Current Measurements

V.3.1.3.1 Slocums River

The measurements were collected using an Acoustic Doppler Current Profiler (ADCP) mounted aboard a small survey vessel. The boat repeatedly navigated a pre-defined set of transect lines through the area, approximately every 60 minutes, with the ADCP continuously collecting current profiles. This pattern was repeated for an approximate 12.6-hour duration to ensure measurements over the entire tidal cycle. The results of the data collection effort are high-resolution observations of the spatial and temporal variations in tidal current patterns throughout the survey area.

Measurements were obtained with a BroadBand 1200 kHz Acoustic Doppler Current Profiler (ADCP) manufactured by RD Instruments (RDI) of San Diego, CA. The ADCP was mounted to a specially constructed mast, which was rigidly attached to the rail of the survey vessel. The ADCP was oriented to look downward into the water column, with the sensors located approximately 1 foot below the water surface. The mounting technique assured no flow disturbance due to vessel wake.

The ADCP emits individual acoustic pulses from four angled transducers (at 20° from the vertical) in the instrument. The instrument then listens to the backscattered echoes from discrete depth layers in the water column. The difference in time between the emitted pulses and the returned echoes, reflected from ambient sound scatters (plankton, debris, sediment, etc.), is the time delay. BroadBand ADCPs measure the change in travel times from successive pulses. As particles move further away from the transducers sound takes longer to travel back and forth. The change in travel time, or propagation delay, corresponds to a change in distance between the transducer and the sound scatter, due to a Doppler shift. The propagation delay, the time lag between emitted pulses, and the speed of sound in water are used to compute the velocity of the particle relative to the transducer. By combining the velocity components for at least three of the four directional beams, the current velocities are transformed using the unit's internal compass readings to an orthogonal earth coordinate system in terms of east, north, and vertical components of current velocity.

Vertical structure of the currents is obtained using a technique called 'range-gating'. Received echoes are divided into successive segments (gates) based on discrete time intervals of pulse emissions. The velocity measurements for each gate are averaged over a specified depth range to produce a single velocity at the specified depth interval ('bin'). A velocity profile is composed of measurements in successive vertical bins.

The collection of accurate current data with an ADCP requires the removal of the speed of the transducer (mounted to the vessel) from the estimates of current velocity. 'Bottom tracking' is the strongest echo return from the emission of an additional, longer pulse to simultaneously measure the velocity of the transducer relative to the bottom. Bottom tracking allows the ADCP to record absolute versus relative velocities beneath the transducer. In addition, the accuracy of the current measurements can be compromised by random errors (or noise) inherent to this technique. Improvements in the accuracy of the measurement for each bin are achieved by averaging several velocity measurements together in time. These averaged results are termed 'ensembles'; the more pings used in the average, the lower the standard deviation of the random error.

For this study, the standard deviation (or accuracy) of current estimates (resulting from an ensemble average of 8 individual pulses) was approximately 0.30 ft/sec. Each ensemble took approximately 5-6 seconds to collect. Averaging parameters resulted in a horizontal resolution of approximately 10 feet along the transect line. For example, ADCP transect A1 (Figure 3) near Slocums River Inlet was approximately 700 feet across, resulting in approximately 65 to 70 independent velocity profiles per transect. The vertical resolution was set to 0.82 ft, or one velocity observation per every 9.8 inches of water depth. The first measurement bin was centered 2.9 feet from the surface, allowing for the transducer draft as well as an appropriate blanking distance between the transducer and the first measurement.

Position information was collected by Hypack, an integrated navigation software package running on a PC computer, linked to a differential GPS. The position data were read from the device in the WGS-84 coordinate system, and transformed to NAD 1983 Massachusetts Mainland State Plane coordinates. Position updates were available every 1 second. Clock synchronization between the GPS and ADCP laptop computers allowed each ADCP ensemble to be assigned an accurate GPS position during post-processing.

Current measurements were collected by the ADCP as the vessel navigated repeatedly a series of three (3) pre-defined transect lines through Slocums River (Figure III-1). The line-cycles were repeated every hour throughout the survey. The first cycle was begun at 06:28 hours (Eastern Daylight Time, EDT) and the final cycle was completed at 18:56 hours (EDT), for a survey duration of approximately 12.5 hours on May 1, 2002. Each individual transect line was surveyed through a time span of approximately 12 hours, for example, transect Line A1 was crossed initially at 06:28 hours and crossed for the final cycle at 18:29 hours.

The transect lines were numbered sequentially A1 through A3, and run in ascending order. These lines were designed to measure as accurately as possible the volume flux through the constrictions during a complete tidal cycle. Line A1 ran across the throat of Slocums River Inlet in a west-to-east direction. Line A2 ran west-to-east across Slocums River just south of the entrance to Giles Cove. Line A3 ran across the mid-section of the river (south of Pelegs Island), beginning on the north bank, ending on the south bank adjacent to Great Neck.

V.3.1.3.2 Little River

The shallow water depths around the Little River Inlet created difficulty in navigation and limited accessibility required to survey current measurements with the boat-based ADCP technique. Therefore, current measurements were collected at a single location using an Acoustic Doppler Current Profiler (ADCP) mounted on a small tripod weighted to the bottom. Measurements were obtained with the same instrument (RDI BroadBand ADCP, 1200 kHz) that is used for boat-based current surveys. The ADCP was oriented to look upward into the water column, with the sensors located approximately 1.3 feet above the seabed. The tripod was deployed within the main entrance channel to Little River.

As discussed previously, the ADCP collects a velocity profile, composed of measurements in successive vertical bins measured over time. The fixed ADCP current measurements result in a time series of a slice of the water column at a single x-y location. The vertical resolution was set to 0.65 ft, or approximately one velocity observation per every 8 inches of water depth. The first measurement bin above the head of the ADCP was centered approximately 3 feet deep, allowing for the distance between the ADCP and the seabed as well as an appropriate blanking distance between the transducer and the first measurement.

Each bin is achieved by averaging several velocity measurements together in time to increase the accuracy of the measurements. For this study, each ensemble was a 5 minute average measured at a rate of 1 ping per second. The ADCP was deployed for approximately 5 hours (from 10:30 o 17:30) on May 14, 2002. At the time of deployment, the tide was flowing out (ebb), reaching low tide at approximately 14:00, then beginning the flood cycle.

V.3.1.4 Conductivity, Temperature, and Depth Measurements

Measurements of conductivity, temperature, and depth (CTD) were conducted to identify the influence of fresh water inflow to Slocum's River. CTD casts were taken at twelve stations along the river (Figure V-7). A Sea-bird CTD was placed in the water, and allowed to stabilize at the surface. The instrument was then cast through the water column (from surface to bottom) at a slow, continuous rate sampling at 1 foot intervals. This sampling scheme was used at each of the twelve stations on May 13, 2002 during the flood tide (0720 to 0930) and repeated at ebb tide (1320 to 1530).

Vertical profiles of salinity are shown in Figure V-8. Vertical stratification is seen in the upper portion of Slocum's River (Casts 1 and 2). On the day of sampling (May 13, 2002) the daily mean stream flow was approximately 100 ft^3/s. The monthly mean stream flow for May 2002 was approximately 65 ft^3/s and over a 5-year period (1996 to 2001) the mean stream flow for the month of May was 51.5 ft^3/s. The vertical stratification present on May 13, 2002 was due to the higher than average stream flow and is not expected to be present during average conditions.

V.3.1.5 USGS Stream Flow Measurements

The stream flow entering the system from the Paskamanset River into Slocums River was measured at the USGS Station #01105933. The station provided daily mean stream discharges throughout the deployment. A plot of the stream discharges is shown in Figure V-9. The average discharge for the month of April 2002 was 69 cfs. Which was slightly lower that the average April discharge over the previous six years (101 cfs). However, the slight decrease in discharge is not considered significant and should not alter the dynamics of the system in any significant way.

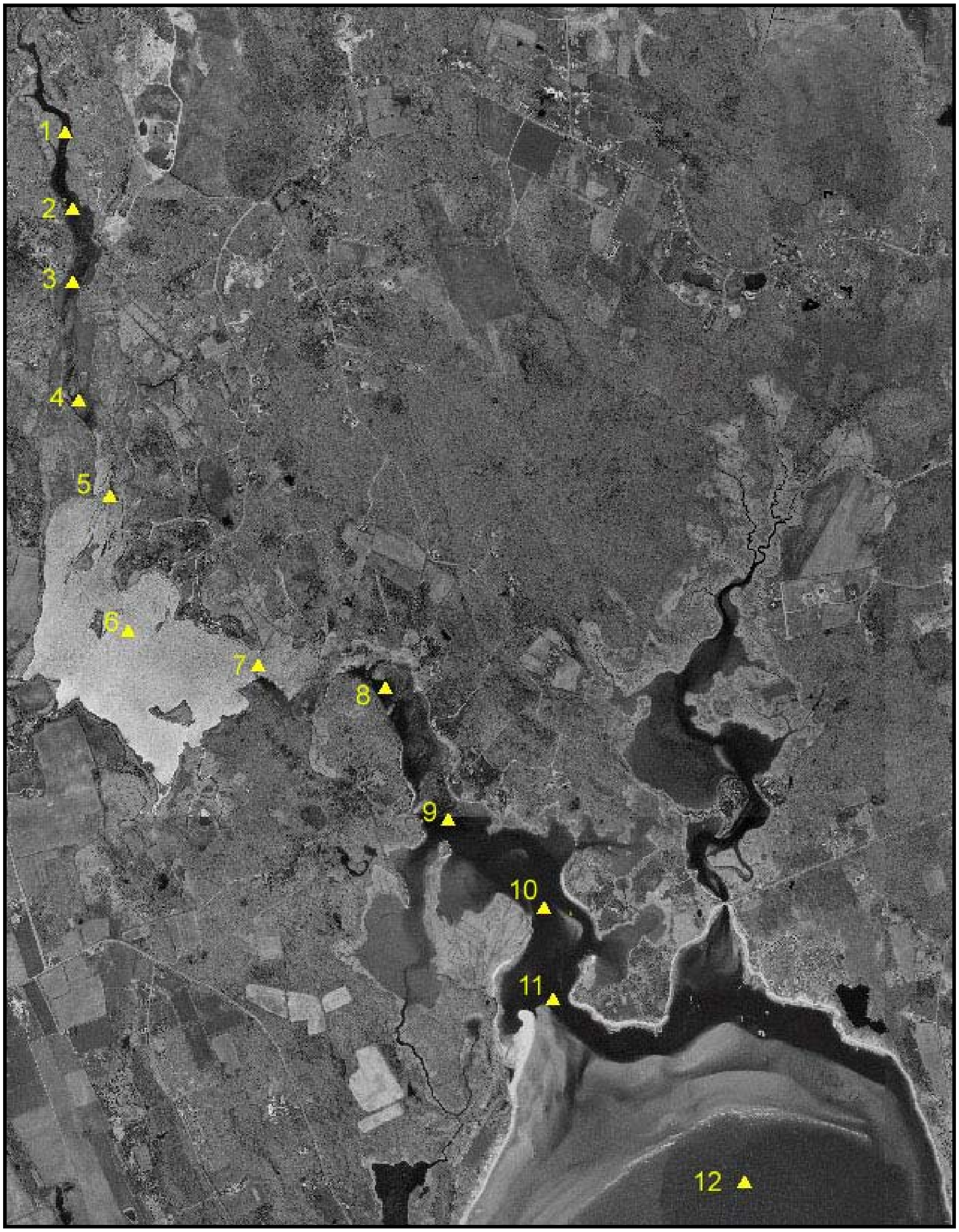


Figure V-7. Locations of CTD sampling stations 1 through 12 in Slocum's River.

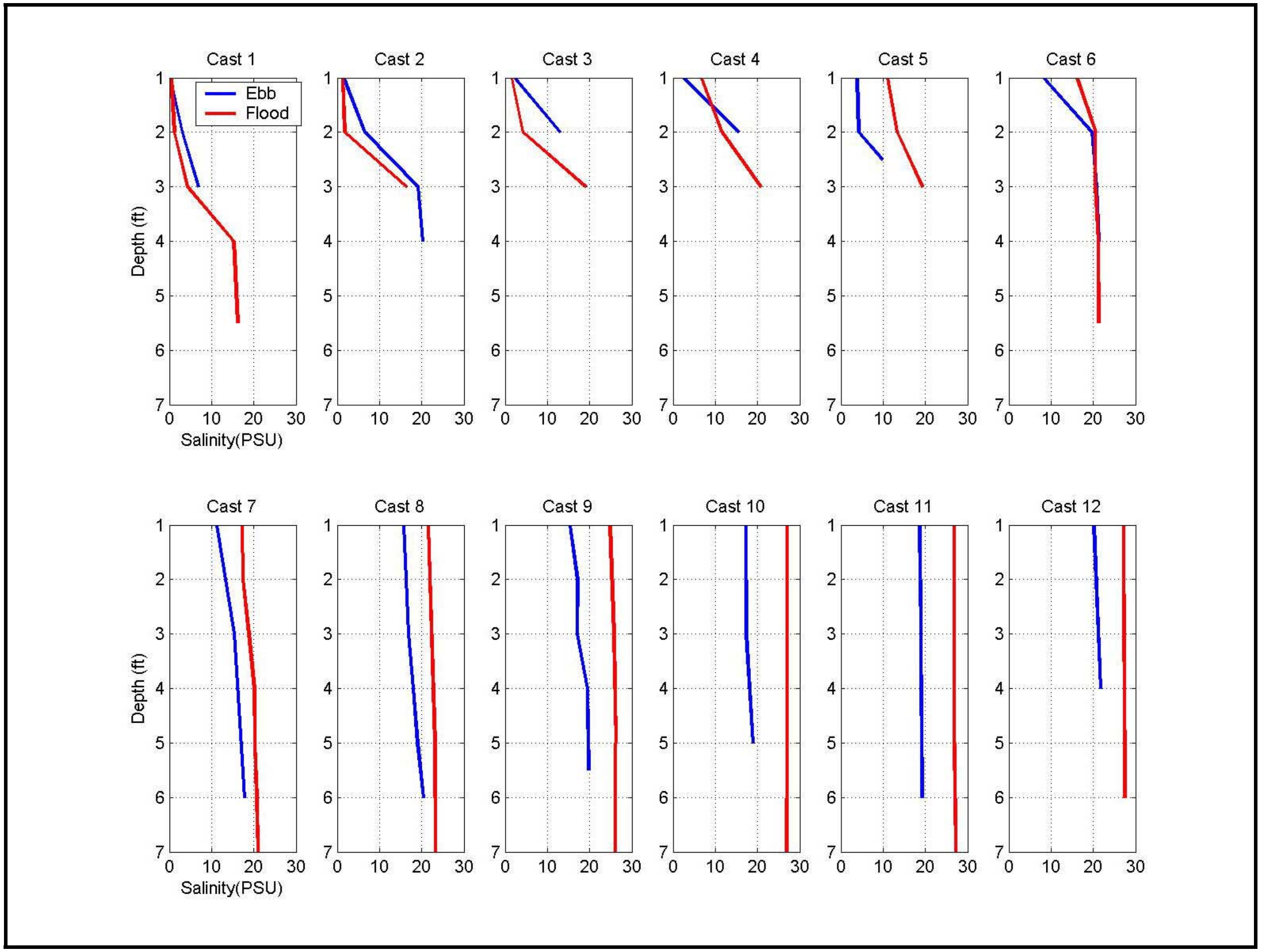


Figure V-8. Vertical profiles of depth versus salinity measured on May 13, 2002 at stations 1 through 12. Blue indicates measurements conducted during ebb tide and red indicates measurements conducted during flood tide.

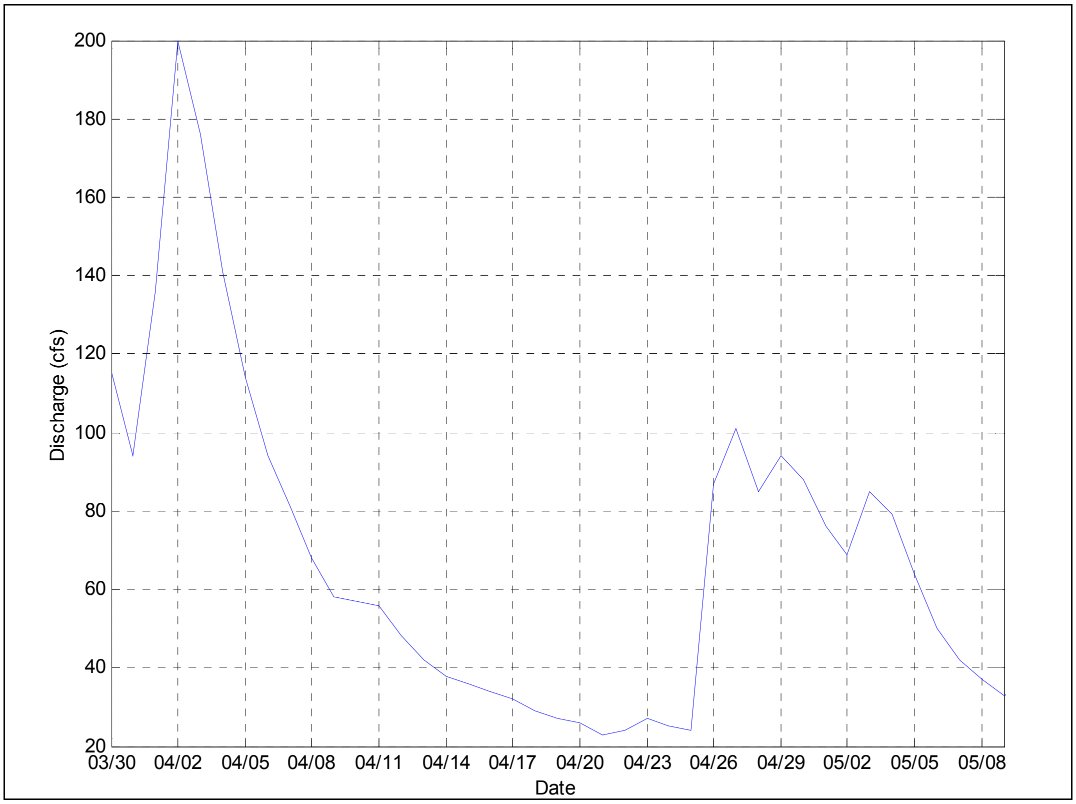


Figure V-9. Daily mean discharge from Paskamanset River into Slocums River. Recorded at USGS Station #01105933.

V.3.2 Data Processing Techniques

V.3.2.1 Boat-based ADCP survey measurements

Data processing consisted of the following:

- Convert raw ADCP (binary) files to engineering units
- Merge ADCP vertical profile data with GPS position data
- QA/QC procedures to verify the accuracy of both ADCP and position data
- Manipulate the ADCP data to calculate spatial averages and cross section discharge values

The data files were converted from raw binary format to engineering ASCII values using RDI's BBLIST conversion program. The command set for this conversion process is described in greater detail in the RDI ADCP manual, and consists of developing a user-defined output file format, through which all conversions are defined.

The output data file from this procedure consists of multiple ensemble data 'packets'. The ensemble 'packet' consists of a single line containing the time of the profile, the ensemble number, and the measured water temperature (measured by the ADCP's internal temperature sensor) followed by consecutive rows and columns of the profile data. Each row of profile data corresponds to one bin, or depth layer, with succeeding columns representing east and north components of velocity, error velocity, speed, direction, echo amplitudes (for 4 beams), and correlation magnitudes (for 4 beams). Each ensemble, collected approximately every 5-6 seconds, has 30 rows corresponding to each discrete depth layer, starting at 2.9 feet. A single data file consists of multiple ensembles, as few as 25-30 to as many as 100. A single data file was recorded for each transect.

The next step in the processing was the assignment of an accurate x-y position pair to each ensemble. This was accomplished using the time stamp of both the ADCP data file and the position data file. Prior to the survey, the clocks used for each system were synchronized to assure this operation was valid. The procedure finds the time of each ADCP ensemble, then searches the position data file for the nearest corresponding time. When the nearest time is found, subject to a 'neighborhood' limit of 1 second, the x-y pair for that time is assigned to the ADCP ensemble. This method produces some inaccuracies; however for this survey the error in position definition was less than approximately 3.5 feet (calculated as vessel speed of 2 knots times the neighborhood value of 1 second for this survey). If no time is found within 1 second of the ADCP time, then a position is calculated using the ADCP bottom track velocity for that ensemble, and the time interval between ensembles.

Once each ensemble was assigned a valid x-y position, the data were reduced to calculate vertical averages as well as total discharge. A mean value of each east and north component of velocity is calculated for each vertical profile. These component mean values are then used to determine the mean speed and mean direction.

The total discharge time series represents the total volumetric flow through a waterway cross-section over the duration of the tidal cycle. Discharge calculations were performed on velocity components normal and tangential to the transect azimuth, which in most cases was perpendicular to the channel axis. To determine accurately the discharge normal to the channel cross-section (i.e. along-stream), the east and north velocity components were rotated into normal (along-stream) and tangential (cross-stream) components. Only the along-stream component was used to calculate total discharge.

The discharge through a cross section, Q_t, is the product of the upstream velocity, $V_{upstream}$, multiplied by the cross sectional area, A_{cs}, or

$$\Sigma Q_t = \Sigma_{i=1...N} (V_{upstream} * A_{cs})$$

where the cross sectional area is the water depth times the lateral (cross-stream) distance from the previous ensemble profile. The summation occurs over i, where i represents each individual ensemble profile from 1 to N, with 1 representing the top (surface) bin and N representing the deepest (near-bottom) bin.

Data recorded for the bottom-most bins in the water column can be contaminated by side lobe reflections from the transducer. At times, the measurements can be invalid. Validity of the bottom bin measurements is determined by comparing the standard deviation of bottom values to the standard deviation of mid-column measurements. If the standard deviation at the bottom was more than twice the standard deviation of mid-column measurements, the bottom bin was discarded from the discharge calculation. If the bottom value was within the limits defined by adjacent measurements, the value was included in the calculation.

The total discharge calculations assume a linear extrapolation of velocity from the surface to the first measurement bin (centered at 2.9 feet). Since the ADCP cannot directly measure the surface velocity, it is assumed the surface layer discharge is equivalent to the discharge in the first depth layer. The same linear assumption was applied to bottom bins when the bin measurement was declared invalid; that is, the bottom bin value was assumed equivalent to the overlying bin velocity value.

V.3.2.2 Fixed Tripod ADCP measurements

The raw binary format ADCP data files collected on the fixed tripod in Little River were also converted to engineering ASCII values using RDI's BBLIST conversion program. Similar to the boat-based current measurements, the output data file from this procedure consists of multiple ensemble data. The ensemble consists of a single line containing the time of the profile, the ensemble number, and the measured water temperature (measured by the ADCP's internal temperature sensor) followed by consecutive rows and columns of the profile data. Each row of profile data corresponds to one bin, or depth layer, with succeeding columns representing east and north components of velocity, error velocity, speed, direction, echo amplitudes (for 4 beams), and correlation magnitudes (for 4 beams). Each ensemble, collected approximately every 5-6 seconds, has 30 rows corresponding to each discrete depth layer, starting at approximately 3 feet above the bottom. A single data file was recorded during the tripod deployment representing a time series of vertical current profiles at a single location. The data were then reduced to calculate vertical averages; a mean value of each east and north component of velocity for each vertical profile. These component mean values were then used to determine the mean speed and mean direction.

V.3.3 Discussion of Results

V.3.3.1 Tidal Harmonic Analysis

Analyses of the tide and bathymetric data provided insight into the hydrodynamic characteristics of each system. Harmonic analysis of the tidal time series produced tidal amplitude and phase of the major tidal constituents, and provided assessments of hydrodynamic 'efficiency' of each system in terms of tidal attenuation. This analysis also yielded an assessment of the relative influence of non-tidal, or residual, processes (such as wind forcing) on the hydrodynamic characteristics of each system.

Figure V-4 shows the tidal elevation for the period April 6 through May 15, 2002 at four locations in Slocums River: Offshore Mishaum Point in Buzzards Bay (Location S1), Slocums River Inlet (Location S2), Giles Cove (location S3), and Upper Slocums River (Location S4). The curves have a predominant 12.42-hour variation around the lunar semi-diurnal (twice-a-day), or M_2, tidal constituent. There was also a strong modulation of the lunar and solar tides, resulting in the familiar spring-neap fortnightly cycle. The spring (maximum) tide range was approximately 6 feet, and occurred on April 26. The neap (or minimum) tide range was 1.9 feet, occurring May 5.

Tidal elevations for two locations in Little River (L1at the inlet and L2 up river) are shown in comparison to the offshore gage (Buzzards Bay) in Figure V-5. Tidal elevations in Little River closely follow the measurements at the Buzzards Bay and Slocums River gages.

Harmonic analyses were performed on the time series from each gage location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured signal. The amplitudes and phase of 23 known tidal constituents result from this procedure. Table V-1 presents the amplitudes of the eight largest tidal constituents. The M_2, or the familiar twice-a-day lunar semi-diurnal, tide is the strongest contributor to the signal with an amplitude of 1.6 feet in Buzzards Bay (offshore Slocums River). The range of the M_2 tide is twice the amplitude, or 3.2 feet. The diurnal tides, K_1 and O_1, possess amplitudes of approximately 0.3 feet and 0.2 feet respectively, throughout the Slocums and Little River systems. Other semi-diurnal tides strongly contribute to the observed tide; the S_2 (12.00 hour period) and N_2 (12.66-hour period) tides both have amplitudes of 0.4 feet offshore Slocums River.

Table V-1 also shows how the constituents vary as the tide propagates into the upper reaches of the two tidal rivers. Note the reduction in the M_2 amplitude from Buzzards Bay to the inlets, and the further reduction at the upper portions of Slocums and Little Rivers. The amplitude reduction is greatest at the upper reaches of Little River, where the M_2 amplitude is 0.33 feet smaller than offshore. The decrease in the amplitude of M_2 constituent is evidence of frictional damping. Usually, a portion of the energy lost from the M_2 tide is transferred to higher harmonics (i.e., the M_4 and M_6), and is observed as an increase in amplitude of these constituents over the length of an estuary. This effect is observed in the analysis of the Slocums and Little River tides, where a maximum 0.1 ft increase occurs in the M_4.

Table V-2 presents the phase delay of the M_2 tide at all tide gage locations compared to the offshore gage in Buzzards Bay. Phase delay is another indication of tidal damping, and results with a later high tide at inland locations. The greater the frictional effects, the longer the delay between locations.

Table V-1. Tidal Constituents, Slocums River, Dartmouth, April-May 2002

	AMPLITUDE (feet)							
	M2	**M4**	**M6**	**S2**	**N2**	**K1**	**O1**	**Msf**
Period (hours)	12.42	6.21	4.14	12.00	12.66	23.93	25.82	354.61
Offshore	1.59	0.18	0.01	0.41	0.44	0.24	0.18	0.07
Slocums Inlet	1.48	0.20	0.02	0.35	0.41	0.25	0.17	0.04
Giles Cove	1.34	0.28	0.03	0.28	0.39	0.24	0.16	0.12
Upper Slocums	1.47	0.24	0.02	0.35	0.40	0.25	0.17	0.09
Little River Inlet	1.30	0.23	0.02	0.27	0.37	0.25	0.15	0.06
Upper Little River	1.26	0.26	0.03	0.27	0.36	0.25	0.15	0.14

Table V-2. M_2 Tidal Attenuation, Slocums River, Dartmouth, April-May 2002 (Delay in minutes relative to Offshore).

Location	Delay (minutes)
Offshore	--
Slocums Inlet	21.45
Giles Cove	30.80
Upper Slocums	38.73
Little River Inlet	29.12
Upper Little River	56.74

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

Table V-3. Percentages of Tidal versus Non-Tidal Energy, Slocums River, Dartmouth, April to May 2002

	Total Variance ($ft^2 \cdot sec$)	Tidal (%)	Non-tidal (%)
Offshore	1.55	92.4	7.6
Slocums Inlet	1.36	91.8	8.2
Giles Cove	1.14	90.9	9.1
Upper Slocums	1.37	91.0	9.0
Little River Inlet	1.06	90.7	9.3
Upper Little River	1.04	89.3	10.7

Table V-3 shows that the percentage of tidal energy was largest in the offshore signal in Buzzards Bay; as should be expected given the tidal attenuation through the system. In general, the energy of the signal decreases with distance from the offshore gage, with the lowest energy found in upper regions of the estuarine systems. The analysis also shows that tides are responsible for approximately 90% of the water level changes in Slocums River and Little River. Meteorological effects in this data set were significant (approximately 10%) contributors to the total observed water level changes. However, the change in the non-tidal variance from offshore to the systems' upper reaches (approximately 3%) indicates that the offshore tide is adequate for use as the forcing time series of the computer hydrodynamic model of these systems. This relative increase in non-tidal energy within this system is likely due to the decrease in tidal energy as a result of frictional forces rather than actual growth of residual forces.

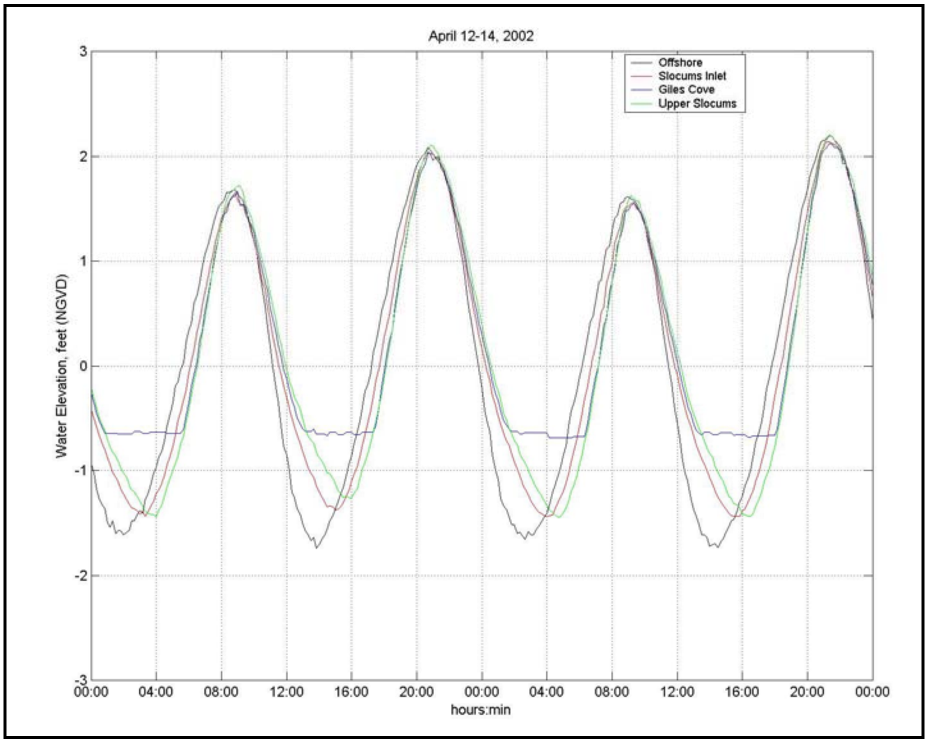


Figure V-10. Water elevation variations for a 2-day period in the Slocums River estuary. Notice the reduced amplitude as well as the delay in times of high- and low- tide relative to offshore (Buzzards Bay) due to frictional damping through the estuary.

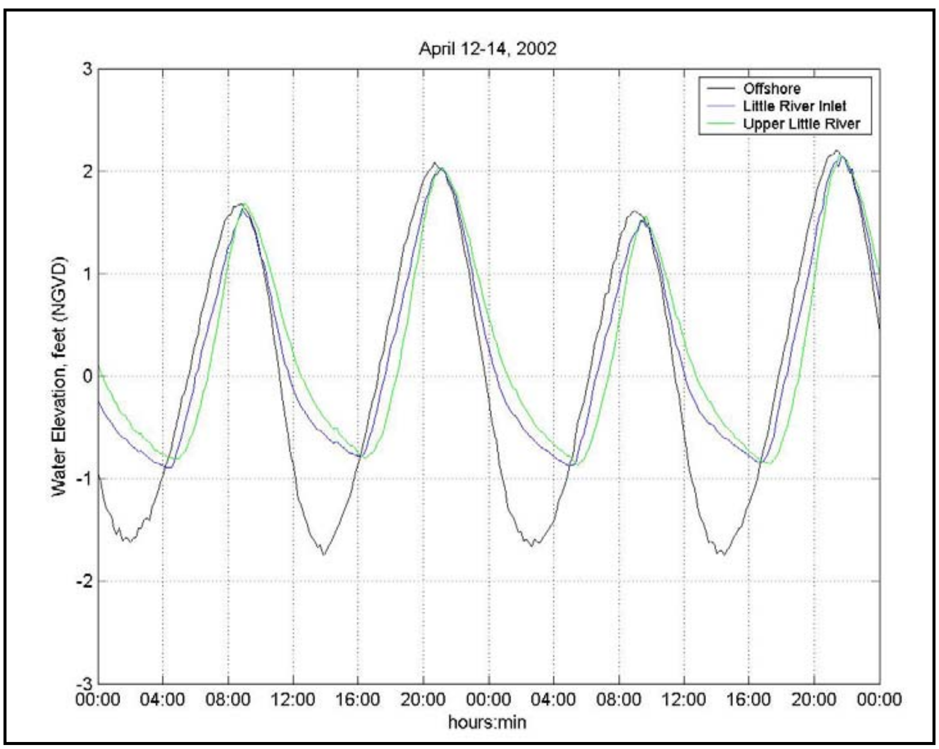


Figure V-11. Water elevation variations for a 2-day period in the Little River estuary. There is also a reduced amplitude as well as a delay in times of high- and low- tide relative to offshore (Buzzards Bay) due to frictional damping through the estuary.

V.3.3.2 Current Measurements

Current measurements in Slocums River, surveyed on May 1, 2002, provided observation of the temporal and spatial variability of the flow regime during a tidal cycle. The survey was designed to observe tidal flow through the Slocums River inlet, and attenuation by frictional damping through upstream constrictions at hourly intervals. The current measurements observed during the flood and ebb tides at each constriction can be seen in Figures V-12 through V-17. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel. For example, at the Slocums River inlet (line A1), positive along-channel is in the direction of north-northeast, and positive cross-channel is in the direction of southeast-south. In the lower left panel of the figures, the mean current or average currents across the channel are shown relative to the shoreline. The lower right panel indicates the stage of the tide during the transect illustrated (shown by a vertical line through the water elevation curve).

Large sand shoals and bars create a meandering channel that constricts flow through the inlet to Slocums River. Tidal currents through Slocums River inlet (line A1) reached maximum speeds of approximately 4.2 ft/sec directed out of the estuary. During periods of maximum currents (flood and ebb) the inlet tidal flows are strongest through the main channel (Figures V-12 and V-15). During slack-water periods, currents were vertically coherent, with negligible stratification in the water column. Maximum volume flux through the Slocums River inlet during flood tide was 4,295 ft^3/sec, while the maximum flux during ebb conditions was slightly less, -3,390 ft^3/sec.

ADCP Survey line A2, was measured upstream of Slocums inlet entrance. The channel at this location spans the distance between the eastern and western banks with an average depth of 8 ft. Measured currents across this transect reached maximum speeds of approximately 4.0 ft/s on the flood and ebb tides (Figures V-13 and V-16). Maximum volume flux across line A2 was nearly equivalent to the volume flux across line A1, since there were no losses in the system between the two transect lines. During flood tide, the volume flow rate was 4,634 ft^3/sec across line A2, and –2,930 ft^3/sec during ebb tide.

In Upper Slocums River, line A3, maximum current speeds were significantly lower; reaching 2.6 ft/s on the ebb tide (Figure V-17). The entrance to Giles Cove falls between lines A2 and line A3 resulting in a loss of water, and therefore lower volume flux. The maximum volume flux through the upper portion of Slocums River was 2,887 ft^3/sec on the flood tide, and –2,064 ft^3/sec on the ebb tide.

As discussed previously, the shallow entrance channel to Little River did not permit use of the survey vessel. Unfortunately, current measurements from the bottom-mounted fixed platform in Little River were contaminated by a severe tilt angle of the instrument relative to the water surface. To assess the validity of the data set retrieved from the fixed ADCP, the current data was compared to data obtained from a single transect using a vessel mounted ADCP near the time of high tide. The fixed ADCP measurements showed maximum current speeds of 1.5 ft/s on average, while vessel-mounted ADCP measurements indicated that current speeds were at least two times higher during peak volume flow. Therefore, the fixed ADCP current measurements were not deemed acceptable for verifying the hydrodynamic model of Little River.

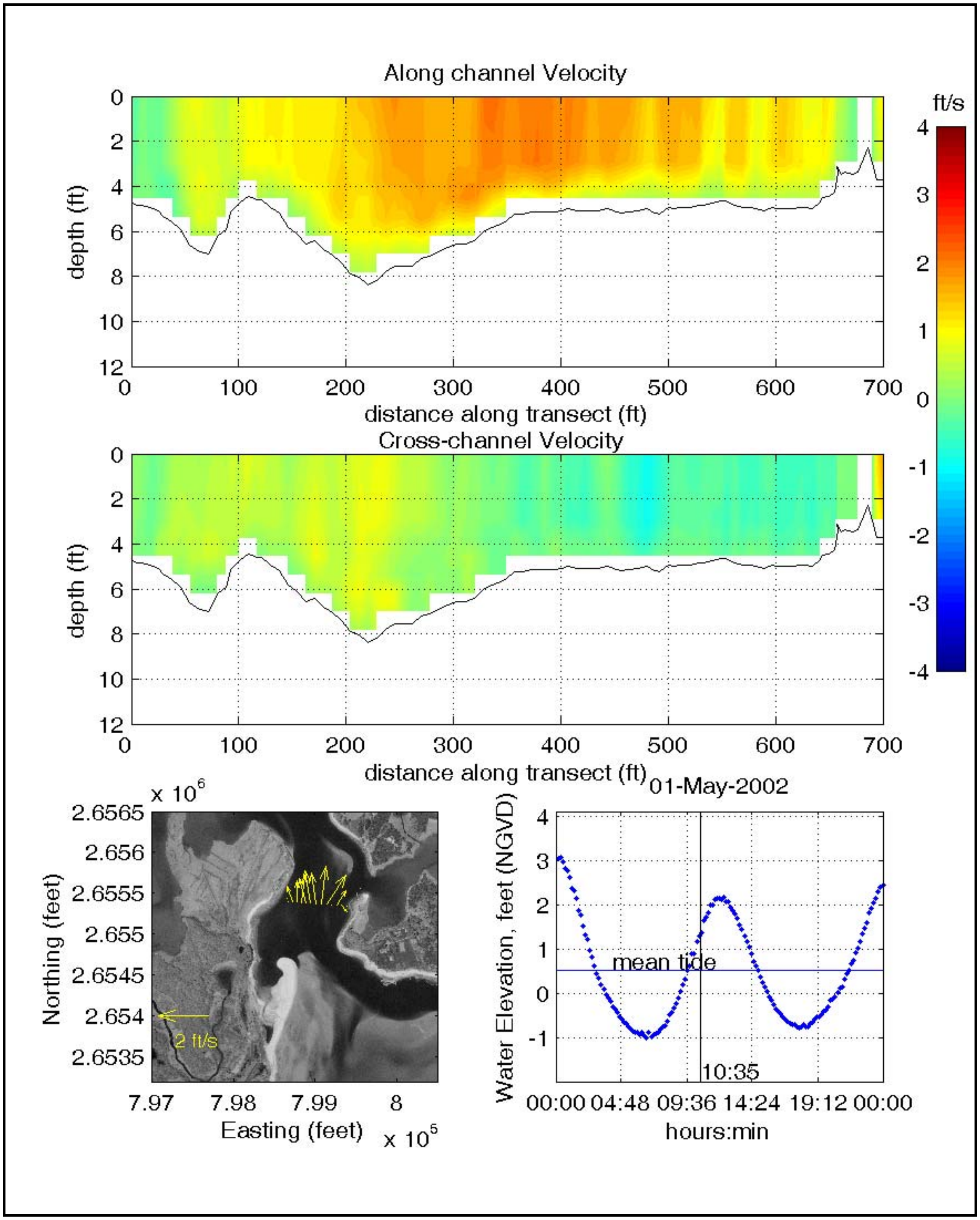


Figure V-12. Color contour plots of along-channel and cross-channel velocity components for transect line A1 across the Slocums River inlet measured at 10:35 on May 1, 2002 during the flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

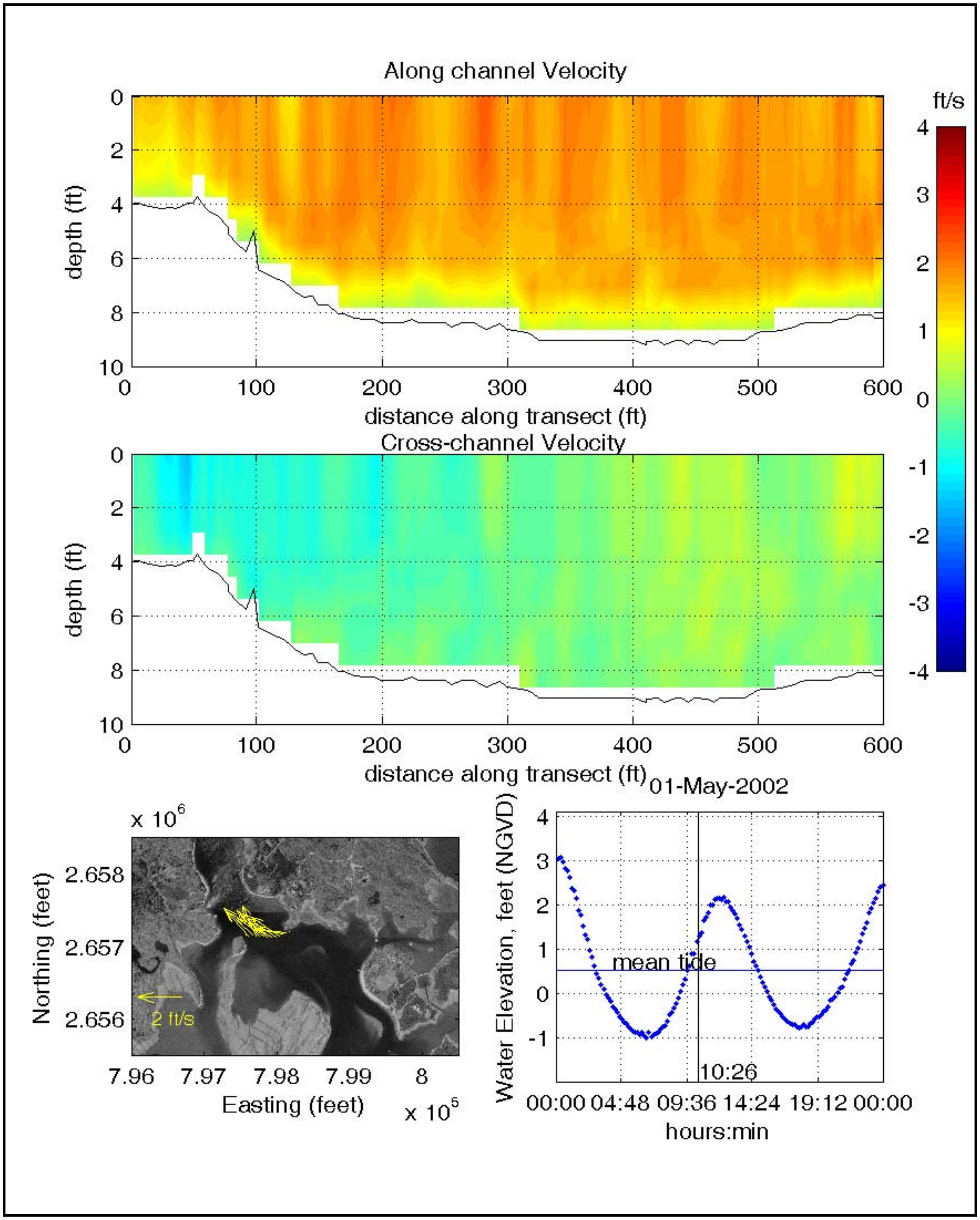


Figure V-13. Color contour plots of along-channel and cross-channel velocity components for transect line A2 across Slocums River measured at 10:26 on May 1, 2002 during the flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

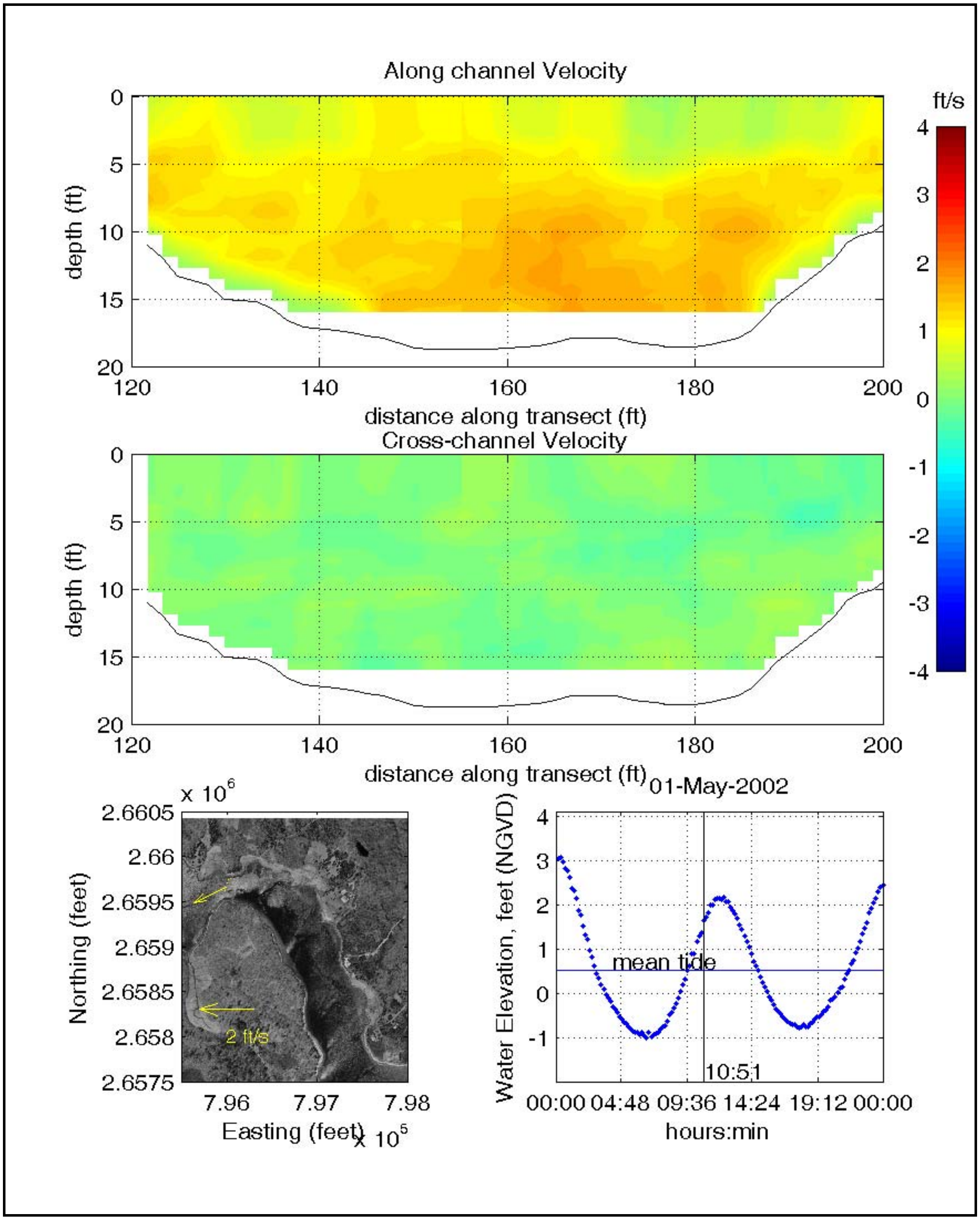


Figure V-14. Color contour plots of along-channel and cross-channel velocity components for transect line A3 across Slocums River measured at 10:51 on May 1, 2002 during the flood tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

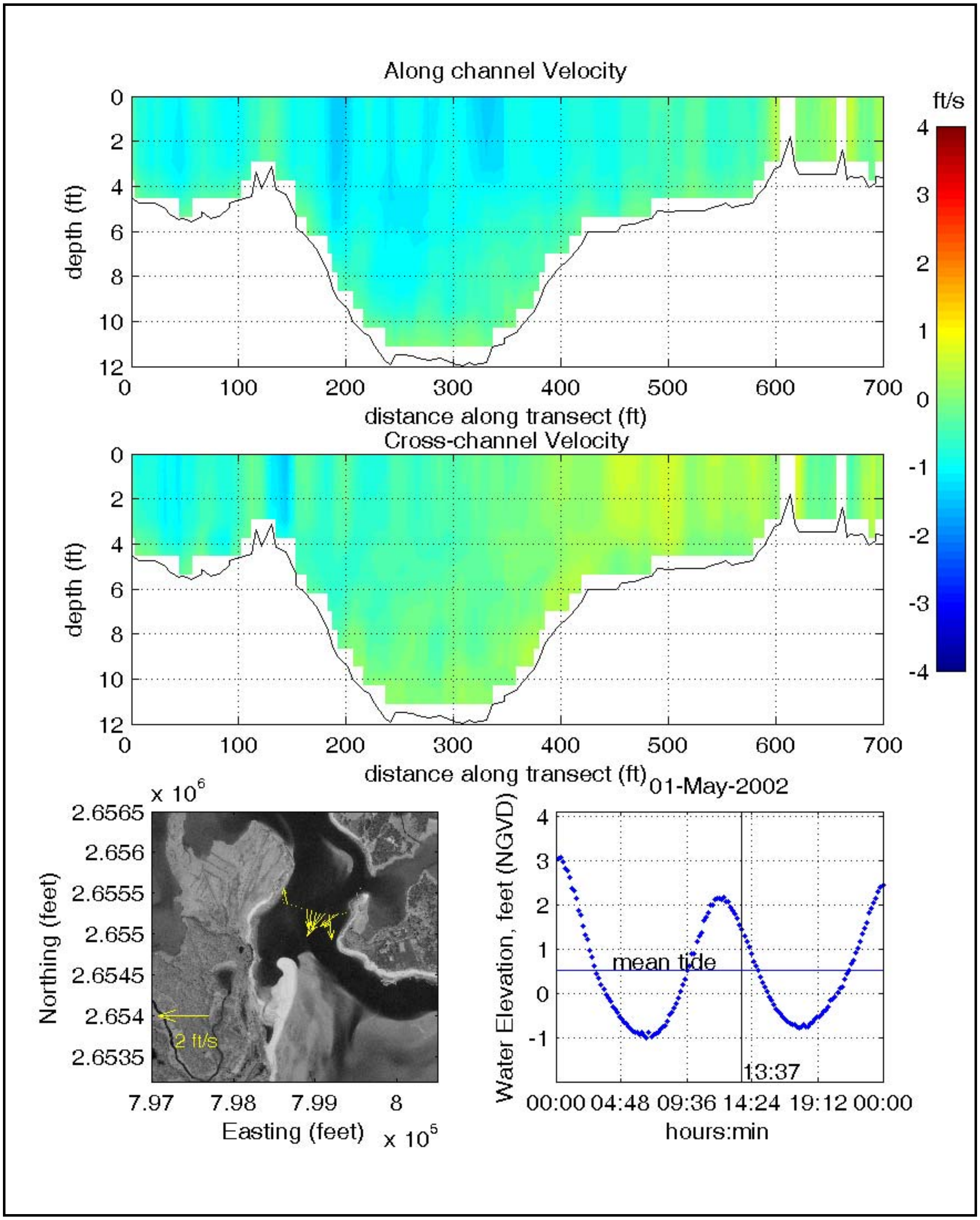


Figure V-15. Color contour plots of along-channel and cross-channel velocity components for transect line A1 across Slocums River inlet measured at 13:37 on May 1, 2002 during the ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

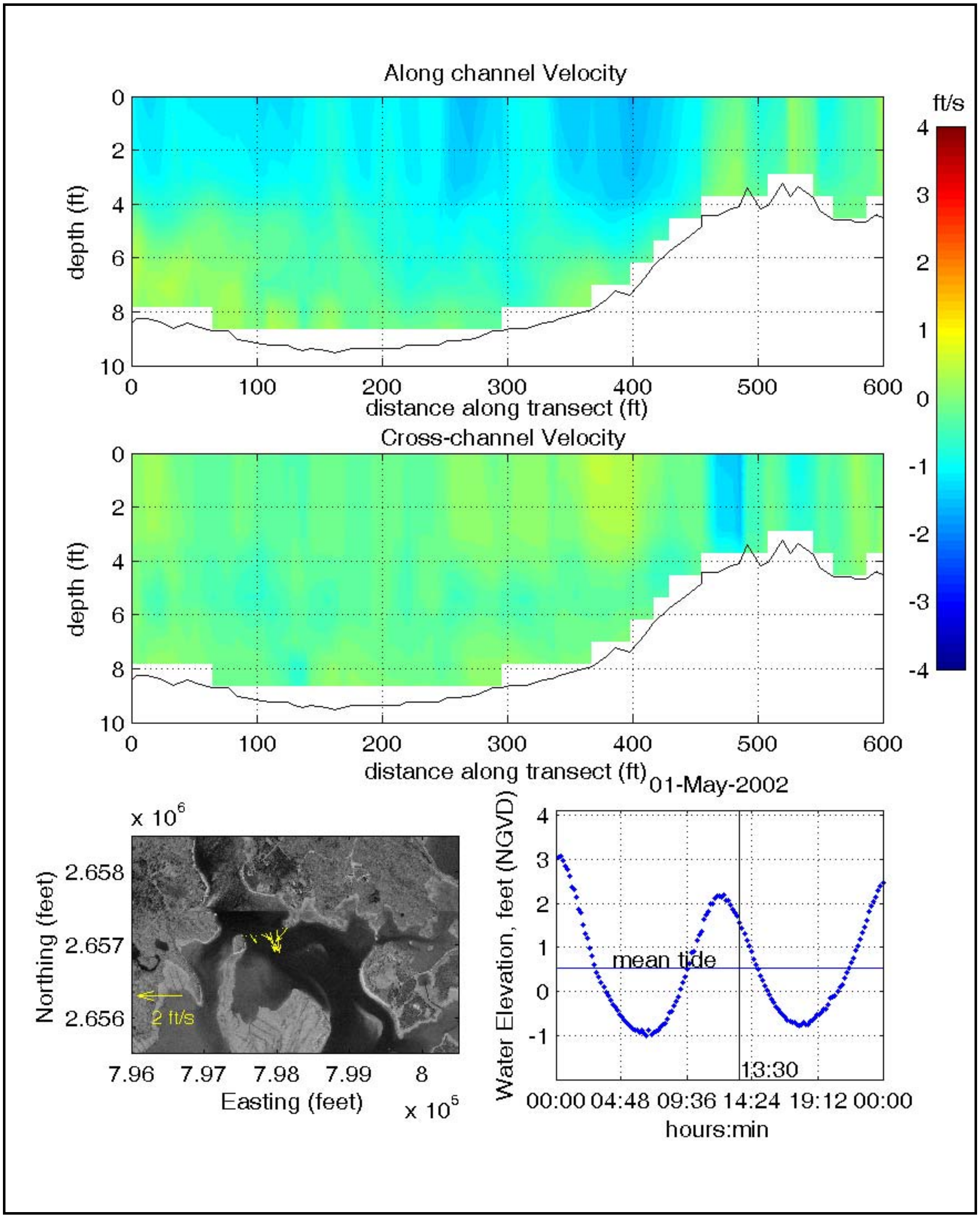


Figure V-16. Color contour plots of along-channel and cross-channel velocity components for transect line A2 across Slocums River measured at 13:30 on May 1, 2002 during the ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

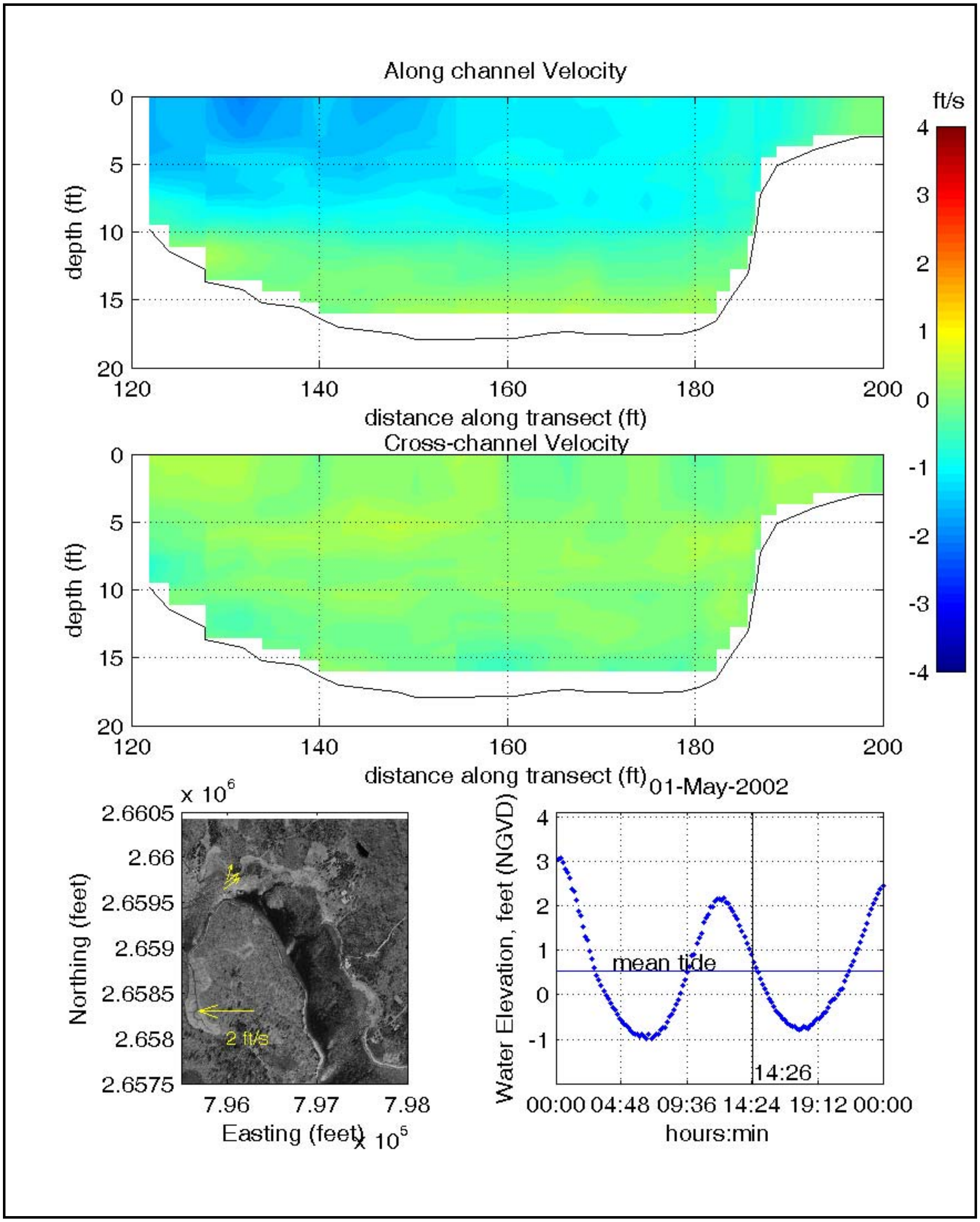


Figure V-17. Color contour plots of along-channel and cross-channel velocity components for transect line A3 across Slocums River measured at 14:26 on May 1, 2002 during the ebb tide. Positive along-channel currents (top panel) indicate the flow is moving into the estuary, while positive cross-channel velocities (middle panel) are oriented 90° clockwise of positive along-channel.

V.4 HYDRODYNAMIC MODELING

For the modeling of the Slocums River system, Applied Coastal utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in these systems. The particular model employed was the RMA-2 model developed by Resource Management Associates (King, 1990). It is a two-dimensional, depth-averaged finite element model, capable of simulating transient hydrodynamics. The model is widely accepted and tested for analyses of estuaries or rivers.

V.4.1 Model Theory

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

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

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

V.4.2 Model Setup

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

- Grid generation
- Boundary condition specification
- Calibration

The extent of each finite element grid was generated using 1994 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified within the larger embayment south of Potomska Point, at the confluence of Slocums and Little Rivers, based on the tide gage data collected along the eastern shore of this embayment. 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 (30+) model calibration simulations for the system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite hydrodynamic information for future detailed water quality modeling.

V.4.2.1 Grid Generation

The grid generation process was aided by the use of the SMS package. A 1994 digital aerial orthophoto and the bathymetry survey data were imported to SMS, and a finite element grid was generated to represent the embayments and waterways within the estuary. The aerial photograph was used to determine the land boundary of the system, as well as determine the surface coverage of salt marsh. The bathymetry data was interpolated to the developed finite element mesh of the system. The completed grid consists of 9,015 nodes, which describe 3,221 total 2-dimensional (depth averaged) quadratic elements. The maximum nodal depth was -17.75 ft (NGVD 29), along the open boundary to Buzzards Bay. The maximum modeled marsh plain elevation was +2.5 ft. In the model grid, an average marsh plain elevation of +1.8 ft was used, based on spot surveys across the marsh. The model marsh topography was varied to provide a monotonically sloping surface, in order to enhance the stability of the hydrodynamic model. The completed grid mesh of the Slocums River system is shown in Figure V-18.

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

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

V.4.2.2 Boundary Condition Specification

Three types of boundary conditions were employed for the RMA-2 model of the Slocums River system: 1) "slip" boundaries 2) tidal elevation boundaries, and 3) flow boundaries. All of the elements with land borders have "slip" boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. A tidal boundary condition was specified at the offshore boundary of the bay. TDR measurements provided the required data. The rise and fall of the tide in Buzzards Bay is the primary driving force for estuarine circulation in this system. Dynamic (time-varying) model simulations specified a new water surface elevation at the boundary to the bay every model time step (10 minutes). A flow boundary was utilized at the upper model boundary of Slocums River to account for this significant freshwater point source. Data from a United States Geological Survey (USGS) flow recording station, located along the river in South Dartmouth, was used to specify the flow values along the river boundary. Although freshwater also enters both Slocums and Little Rivers via groundwater, the rate of inflow can be considered negligible relative to the tidal flow that dominates the hydro dynamic processes.

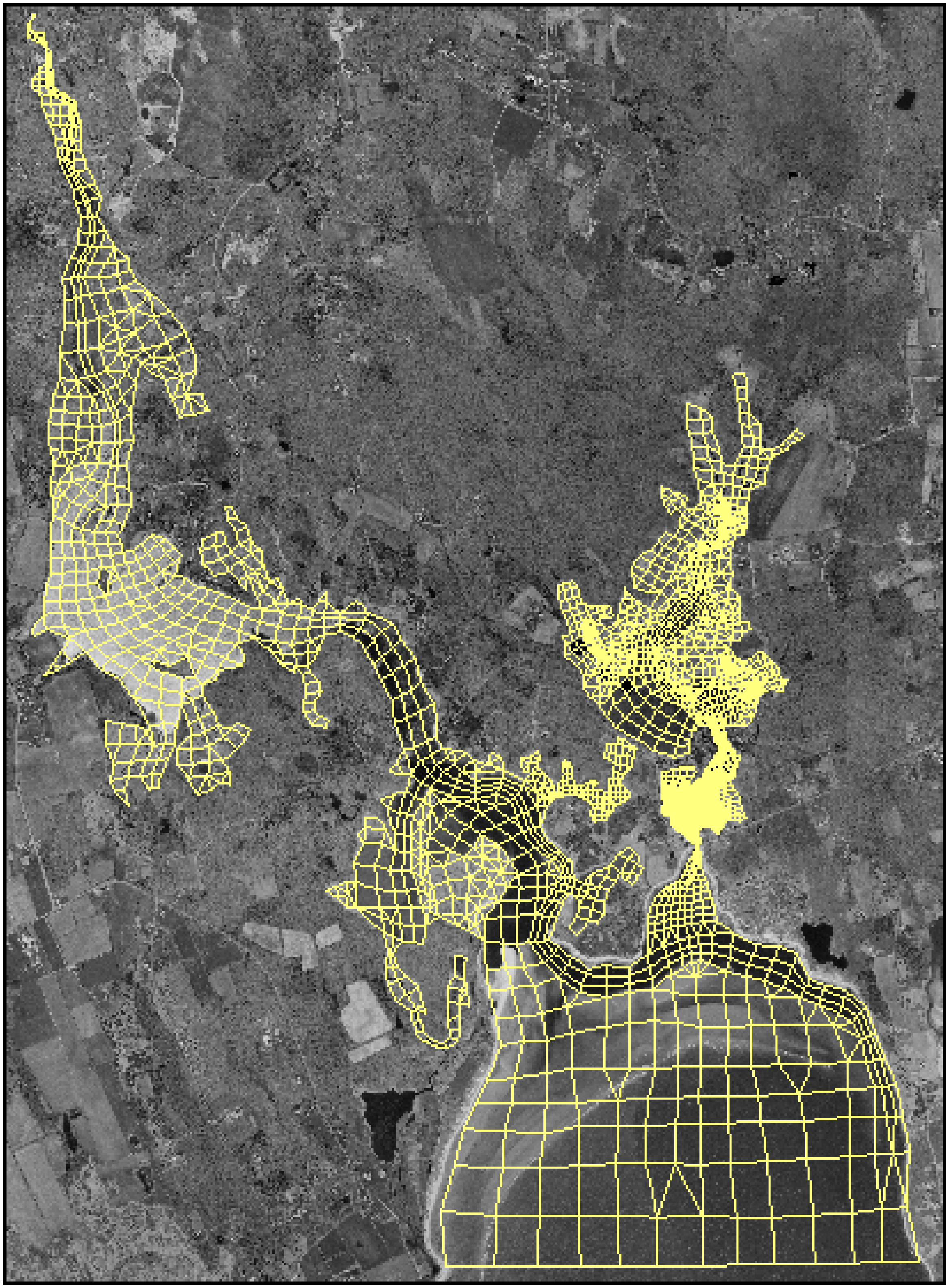


Figure V-18. Plot of hydrodynamic model finite element mesh for the Slocums River system.

V.4.2.3 Calibration

After developing the finite element grid, and specifying boundary conditions, the model for the Slocums River system was calibrated. The calibration procedure ensures that the model predicts accurately what was observed in nature during the field measurement program. Numerous model simulations are required (typically 30+) for an estuary model, specifying a range of friction and eddy viscosity coefficients, to calibrate the model.

Calibration of the hydrodynamic model required a close match between the modeled and measured tides in each of the sub-embayments where tides were measured (i.e., from the TDR deployments). Initially, the model was calibrated to obtain visual agreement between modeled and measured tides. Once visual agreement was achieved, an approximate seven-day period (14 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section V.3. The seven-day period was extracted from a longer simulation to avoid effects of model spin-up, and to focus on average tidal conditions. Modeled tides for the calibration time period were evaluated for time (phase) lag and height damping of dominant tidal constituents

The calibration was performed for a seven-day period beginning April 6, 2002 at 00:00 EDT. Representing the transition from spring to neap tide conditions, or a period of average tidal conditions for forcing conditions for use in model verification and flushing analysis.

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

V.4.2.3.1 Friction Coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of tidal signals. Friction is approximated in RMA-2 as a Manning coefficient, and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.02 and 0.06 were specified for all element material types. These values correspond to typical Manning's coefficients determined experimentally in smooth earth-lined channels with no weeds (low friction) to winding channels and marsh plains with higher friction (Henderson, 1966).

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

Table V-4. Manning's Roughness coefficients used in model simulations. These delineations correspond to the material type areas shown in Figure V-19.

System Embayment	Bottom Friction
Offshore	0.030
Lower Little River	0.031
Marsh Plain in Lower Little River	0.055
Upper Little River	0.024
Marsh Plain in Upper Little River	0.050
Lower Slocums River	0.031
Potomska Cove	0.035
East Cove	0.035
Marsh Plain in Lower Slocums River	0.058
Giles Cove	0.033
Marsh Plain in Giles Cove	0.055
Slocums River	0.027
Marsh Plain in Slocums River	0.060
Upper Slocums River	0.027
Marsh Plain in Upper Slocums River	0.060

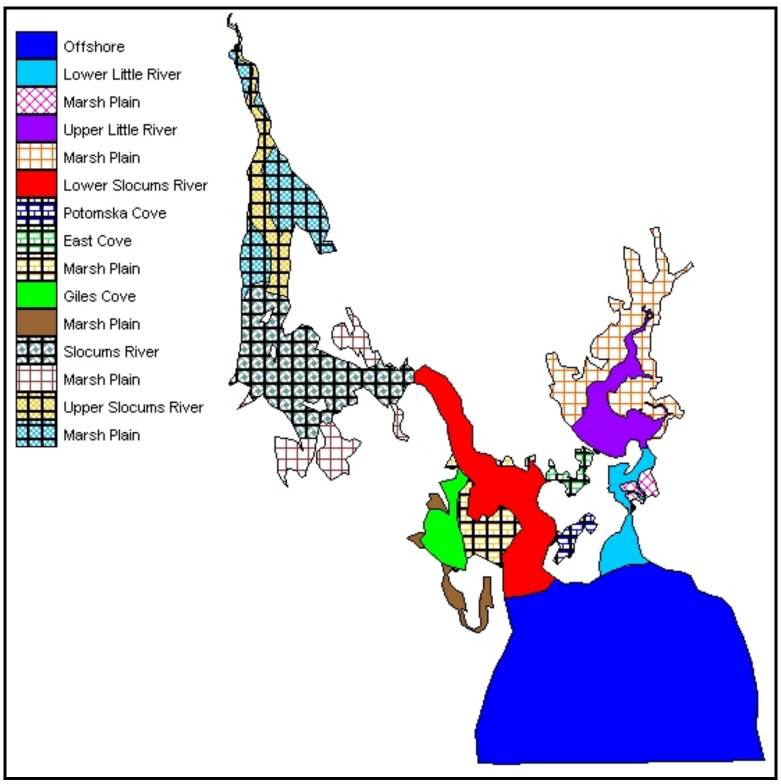


Figure V-19. Hydrodynamic model grid material properties. Color patterns designate the different model material types used to vary model calibration parameters and compute flushing rates.

V.4.2.3.2 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 swifter, such as inlets and bridge constrictions. According to King (1990), these values are proportional to element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 40 and 60 lb-sec/ft^2. Higher values (up to 120 lb-sec/ft^2) were used on the marsh plain, to ensure solution stability.

V.4.2.3.3 Marsh Porosity Processes

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

V.4.2.3.4 Comparison of Modeled Tides and Measured Tide Data

A best-fit of model predictions for the first TDR deployment was achieved using the aforementioned values for friction and turbulent exchange. Figures V-20 though V-24 illustrate the seven-day calibration simulation along with 72-hour sub-section, for upper and lower Little River, Potomska Point, Giles Cove, and Upper Slocums River. Modeled (dashed line) and measured (solid line) tides are illustrated at each model location with a corresponding TDR.

Although visual calibration achieved reasonable modeled tidal hydrodynamics, further tidal constituent calibration was required to quantify the accuracy of the models. Calibration of M_2 was the highest priority since M_2 accounted for a majority of the forcing tide energy in the modeled systems. Due to the duration of the model runs, four dominant tidal constituents were selected for constituent comparison: K_1, M_2, M_4, and M_6. Measured tidal constituent heights (H) and time lags (ϕ_{lag}) shown in Table 5 for the calibration period differ from those in Table V-2 because constituents were computed for only the seven-day section of the 39-days represented in Table V-2. Table V-5 compares tidal constituent height and time lag for modeled and measured tides at the TDR locations. Table V-5 compares tidal constituent height and phase for modeled and measured tides at the TDR locations.

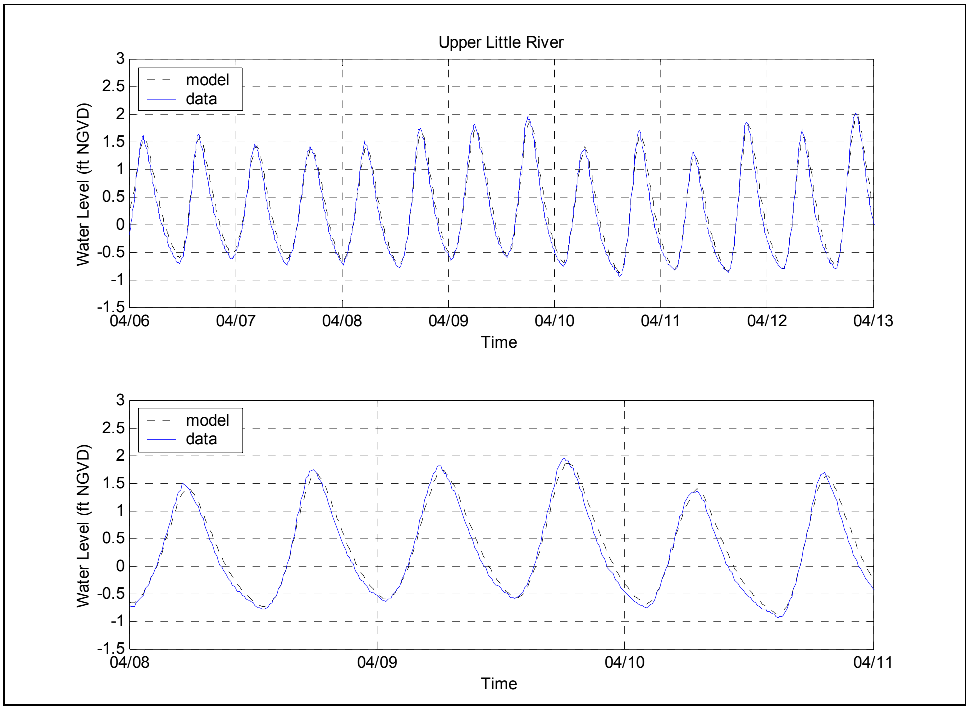


Figure V-20. Comparison of model output and measured tides for the TDR location in upper Little River. The bottom plot is a 72-hour sub-section of the total modeled time period, shown in the top plot.

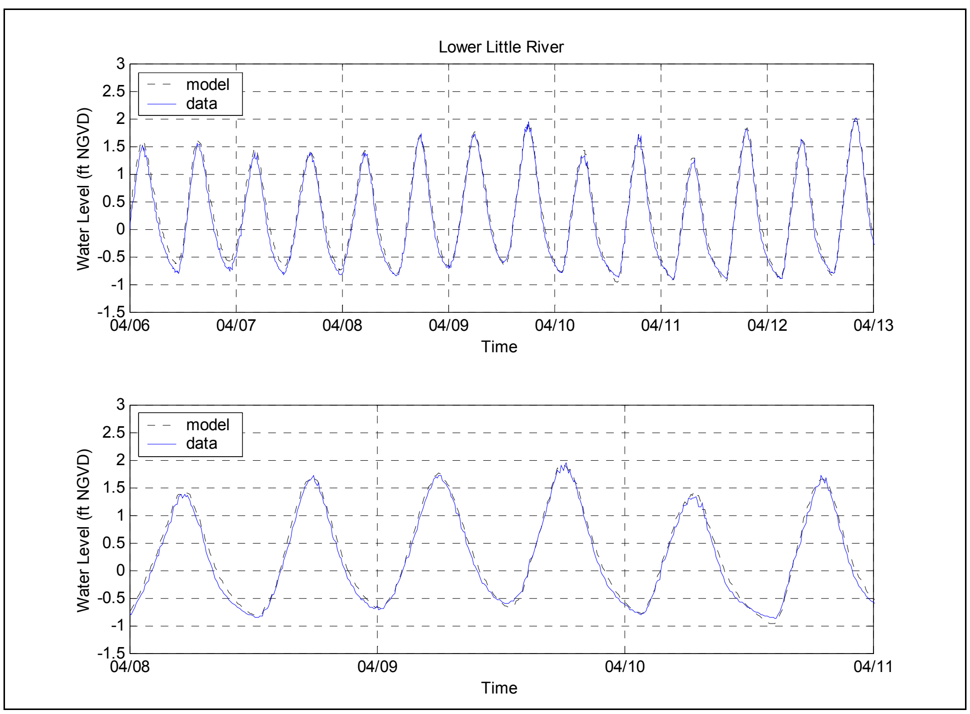


Figure V-21. Comparison of model output and measured tides for the TDR location in lower Little River. The bottom plot is a 72-hour sub-section of the total modeled time period, shown in the top plot.

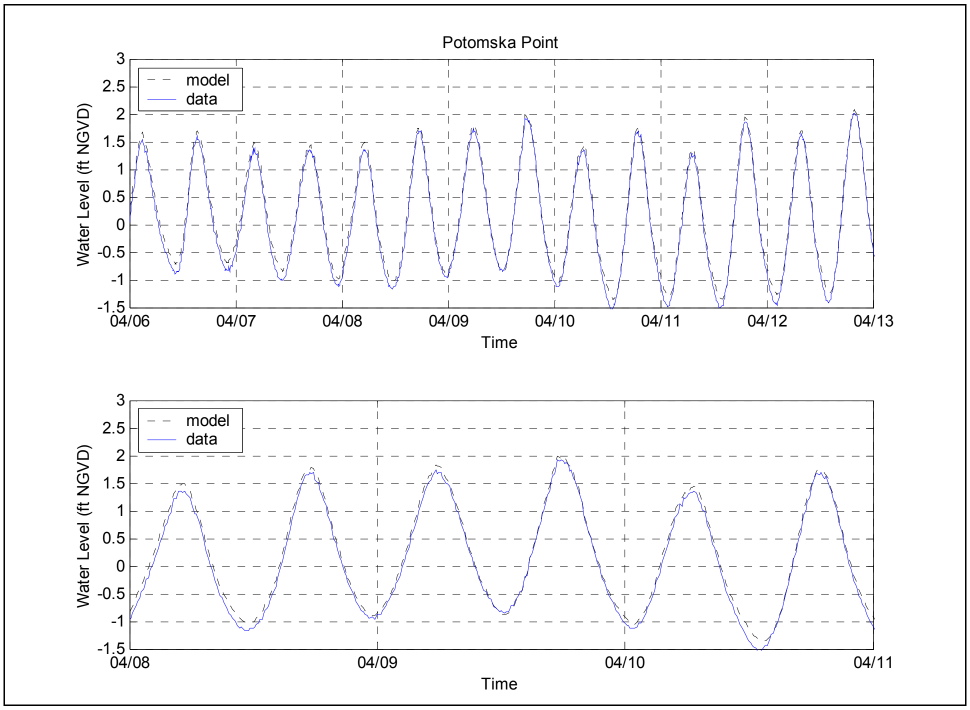


Figure V-22. Comparison of model output and measured tides for the TDR location at Potomska Point in Slocums River. The bottom plot is a 72-hour sub-section of the total modeled time period, shown in the top plot.

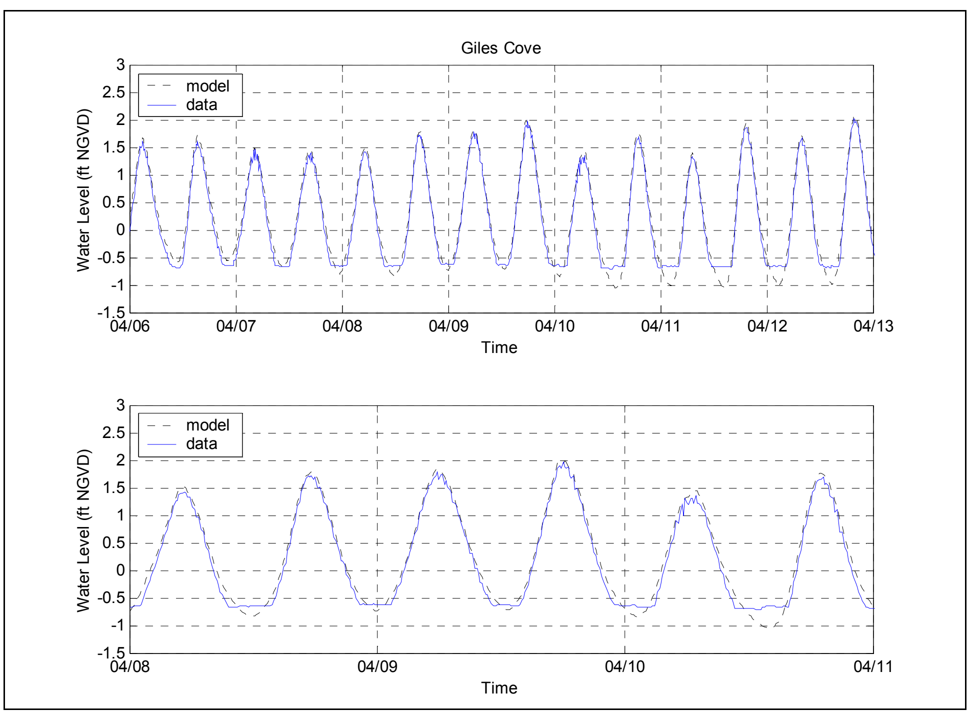


Figure V-23. Comparison of model output and measured tides for the TDR location in Giles Cove. The bottom plot is a 72-hour sub-section of the total modeled time period, shown in the top plot.

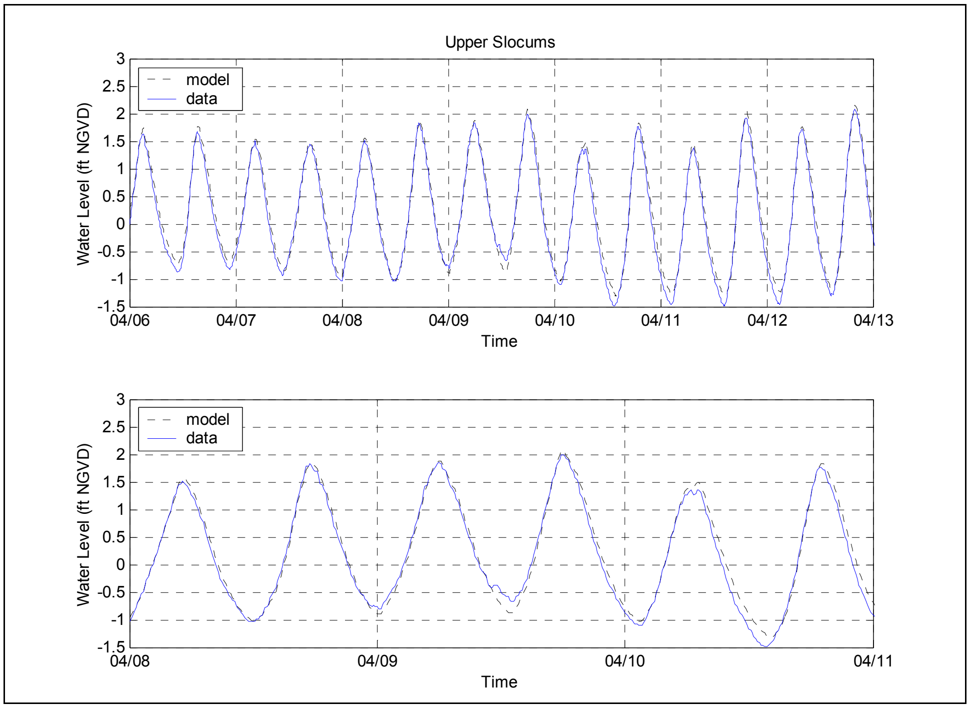


Figure V-24. Comparison of model output and measured tides for the TDR location in upper Slocums River. The bottom plot is a 72-hour sub-section of the total modeled time period, shown in the top plot.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The largest errors associated with tidal constituent amplitude were on the order of 0.01 ft, which is of the same order of the accuracy of the tide gages (0.032 ft). Time lag errors were typically less than the time increment resolved by the model (0.20 hours or 12 minutes), indicating good agreement between the model and data. The largest errors were in Giles Cove, where the TDR would become dry over low tide (see Figure V-12). The recording gage within the model was not allowed to dry over the simulation resulting in minor variations in the constituents between the gage and model.

V.4.2.4 Model Circulation Characteristics

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

Examining the results from the model run shows flood velocities in the channels are slightly larger than velocities during maximum ebb. The highest velocities occur at the entrance to Little River, where the channel width is constrained by the bridge abutments. Similar velocity magnitudes occur in the entrance channel to Slocums River; however, with the wider channels, the peak velocities are slightly lower. The maximum velocities in the entrance to Little River peaks at approximately 3.1 feet/sec during the flood tide, while maximum ebb velocities are about 2.6 feet/sec. In the inlet channel to Slocums River, maximum depth averaged flood velocities are approximately 2.0 feet/sec, while maximum ebb velocities are 1.5 feet/sec. A close-up of the model output is presented in Figure V-25, showing contours of velocity magnitude, along with velocity vectors that indicate the magnitude and direction of flow, for a single model time-step, at the portion of the tide cycle where maximum flood velocities occur at the entrance to Little River.

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

Location	Constituent Amplitude (ft)				Phase (deg)	
Model calibration run						
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Lower Little River	1.12	0.18	0.03	0.09	1.63	2.47
Upper Little River	1.05	0.20	0.02	0.10	1.97	2.98
Potomska Point	1.29	0.16	0.03	0.09	1.52	2.41
Giles Cove	1.19	0.20	0.02	0.09	1.64	2.61
Upper Slocums River	1.29	0.20	0.03	0.09	1.75	2.63
Measured tide during calibration period						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Lower Little River	1.10	0.20	0.04	0.11	1.67	2.82
Upper Little River	1.07	0.26	0.04	0.09	1.94	3.07
Potomska Point	1.31	0.14	0.04	0.11	1.60	2.64
Giles Cove	1.11	0.27	0.04	0.09	1.71	3.04
Upper Slocums River	1.29	0.20	0.03	0.09	1.75	2.72
Error						
Location	Error Amplitude (ft)				Phase error (min)	
	M_2	M_4	M_6	K_1	ϕM_2	ϕM_4
Lower Little River	-0.03	0.02	0.01	0.01	5.7	20.5
Upper Little River	0.02	0.06	0.02	-0.01	-3.9	5.3
Potomska Point	-0.01	-0.01	0.00	0.02	9.3	13.7
Giles Cove	-0.08	0.07	0.01	0.00	8.0	25.5
Upper Slocums River	0.00	0.00	0.00	0.01	0.6	5.6

In addition to depth averaged velocities, the total flow rate of water flowing through a channel can be computed with the hydrodynamic model. For the flushing analysis in the next section, flow rates where computed across a number of separate transects in the Slocums River system. The variation of flow as the tide floods and ebbs is seen in the plot of channel flow rates in Figure V-26. Maximum flow rates occur during flood tides in this system, an indication that this estuary system is flood dominant, and likely a sediment sink (a system that accumulates sediment). The maximum flood flow rates reach approximately 5,500 ft^3/sec at the Slocums River inlet. Maximum ebb flow rates are slightly less, or about 4,100 ft^3/sec. The flood flows at the inlet to Little River are significantly smaller than Slocums River (approximately 1,350 ft^3/sec) and ebb flows are approximately 1,000 ft^3/sec.

A verification of the model was conducted by comparing flow rates computed from ADCP measurements to flow rates extracted from the hydrodynamic model. The hydrodynamic model was run for the period of April 30, 2002 to May 4, 2002 to simulate the time period when the ADCP measurements were taken (May 1, 2002). This time period was not included in the initial calibration period described above. Flow measurements were extracted from the model at the locations of the three ADCP measurement transects (see Figure V-3 for transect locations). A comparison of the modeled and measured flow rates for each transect is shown in Figure V-27. The graphs show that the model follows the trends and characteristics of the ADCP data. However, the model slightly over-predicts the volume of water flow across each transect line. To quantify the error, a least square error analysis was performed on the results. The results, shown in Table 6, indicate that the error in the flows rates was approximately 15 percent.

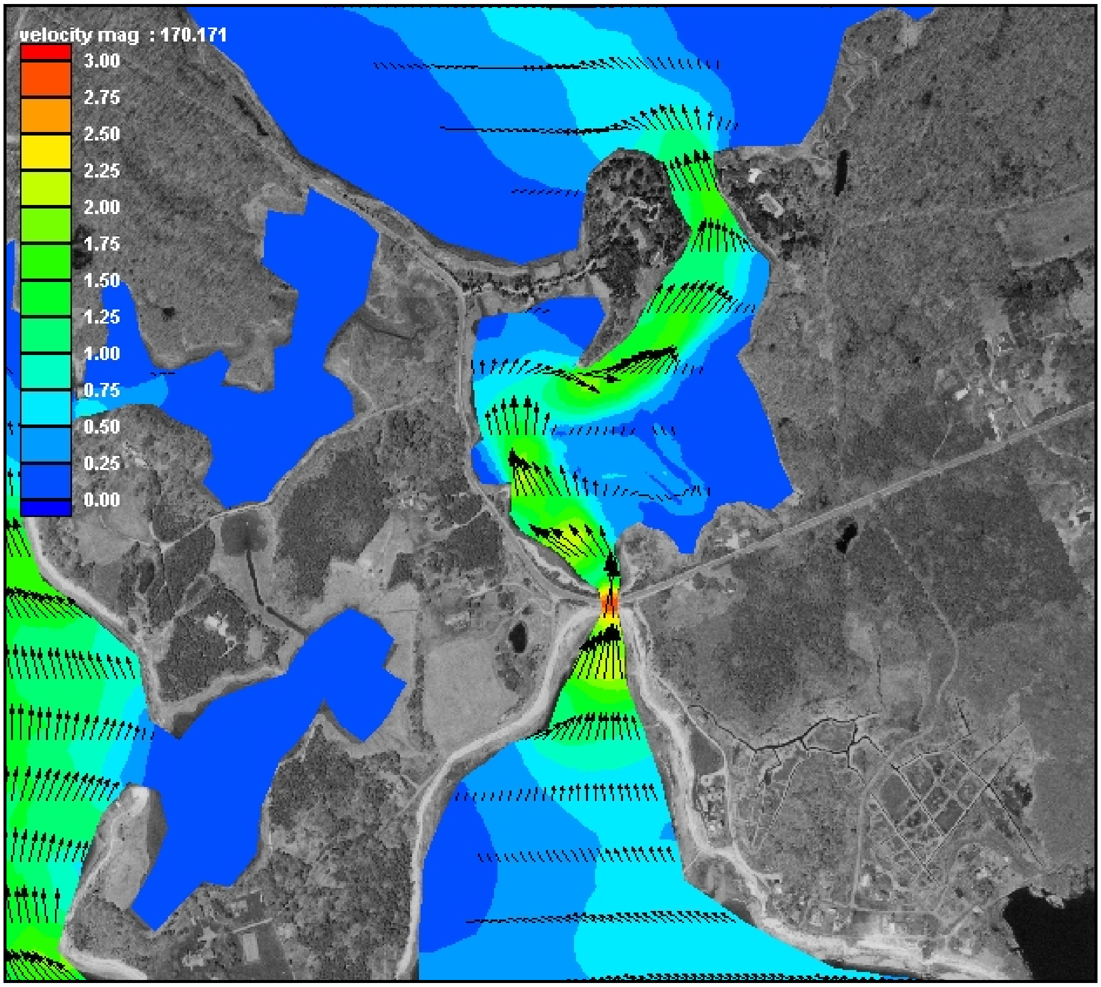


Figure V-25. Example of hydrodynamic model output for a single time step where maximum flood velocities occur for this tide cycle. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

There are several possible reasons for the model over-predicting the flow measurements. The primary limitation of the ADCP measurements was the inability to capture the outer edges of the channel as a result of depth limitations with the boat and the ADCP. The size of this gap was dependent of the side slopes of the channel. For Slocums River this ranged between 8 to 12 feet; therefore, the measurements do not account for the flow along the outer most edges of the channels. Thus, the measured flow rates are assumed to be 10 to 15 percent lower than actual flow rates. Secondly, the ADCP is unable to measure velocities in the first 1 to 2 feet of the water column, due to the ADCP transducer being suspended below the water surface and signal blanking across the first measurement cell. The ADCP cannot take measurements across the first measurement cell since a time gap is required between the transmission and receipt of the acoustic signal (this allows measurement of the Doppler shift). To account for the unmeasured portion of the water column, velocities from second measurement cell were used to represent the portion of water column above. This resulted in a slight under prediction in surface currents and thus adds to the under-prediction of flow rates. Although the measured flow rates were approximately 15 percent less than the modeled flows, the current measurement limitations (primarily the loss of data near the shallow channel edges) provide a reasonable explanation for this magnitude of error. Therefore, the ADCP measurements within Slocums River provided adequate measurements to verify the results of the hydrodynamic model.

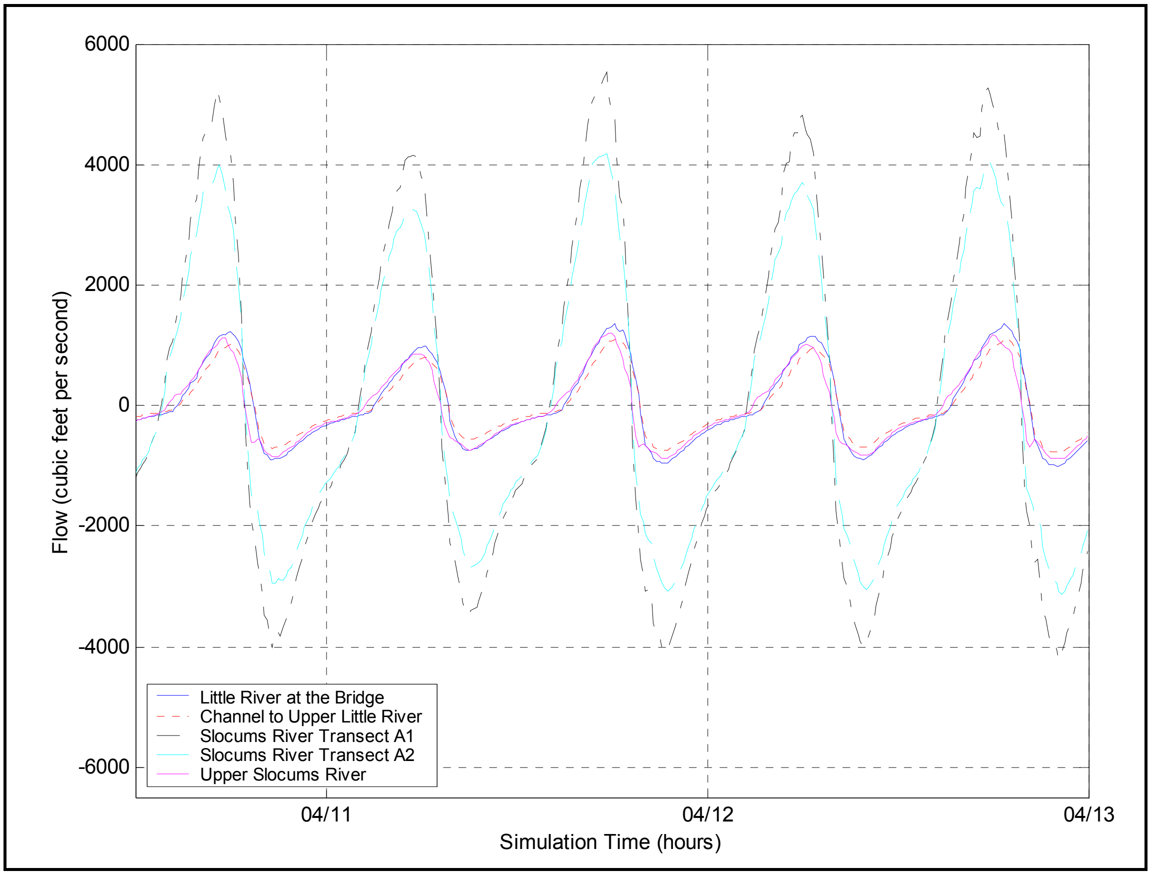


Figure V-26. Time variation of computed flow rates for five transects in the Slocums River system. Model period shown corresponds to period between spring and neap tide conditions, where the tide range is average. Plotted time period represents four tide cycles (12.42 h cycle). Positive flow indicated flooding tide, while negative flow indicates ebbing tide.

Table V-6. Least square error results on the flow analysis for Slocums River.

Transect	Least Square Error (ft^3/s)	Percent of Total
Transect A1	829	15
Transect A2	712	18
Transect A3	612	15

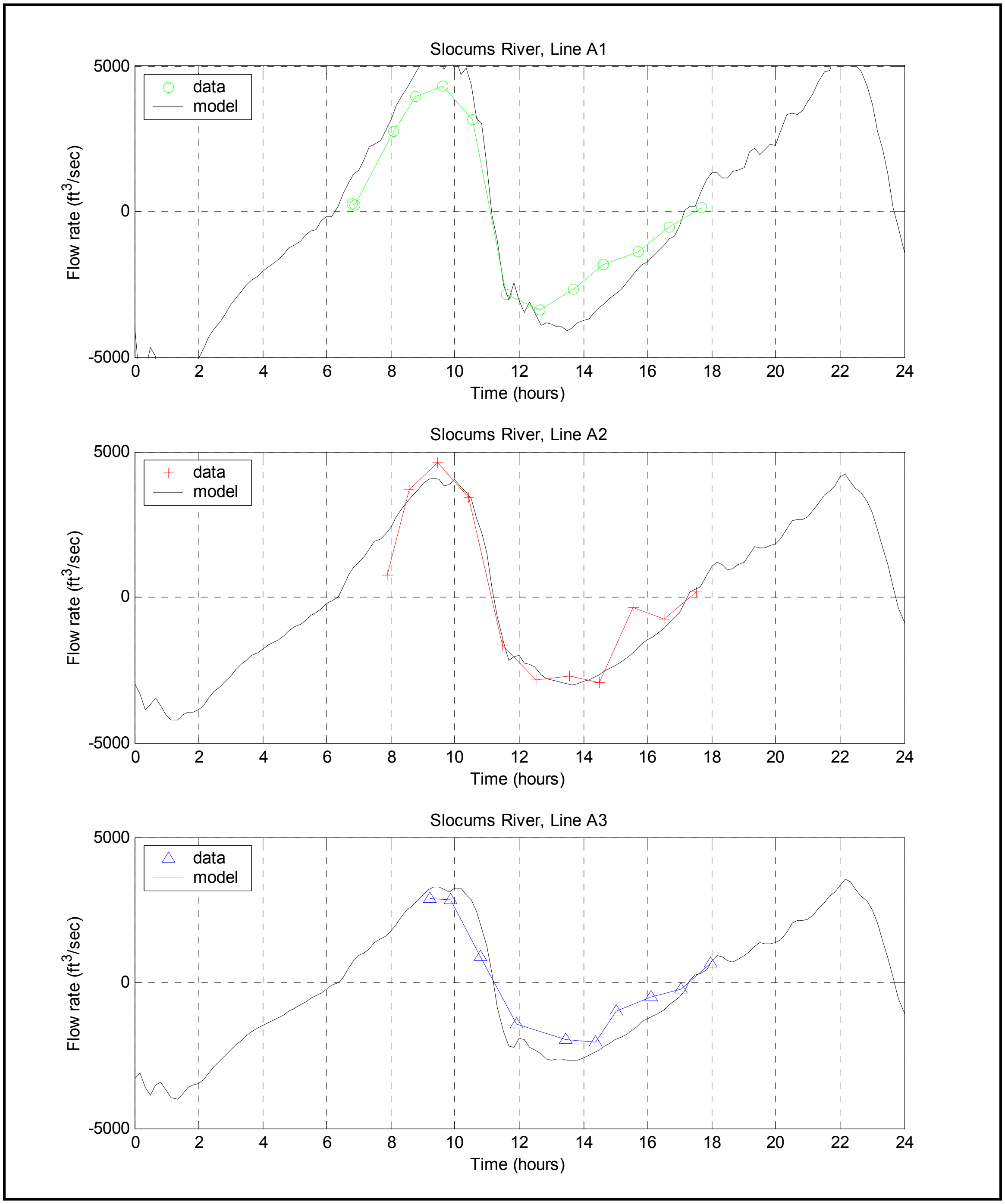


Figure V-27. Comparison of computed flow rates to the three ADCP transects in the Slocums River. Model period shown corresponds to transition from high to low tide. Positive flow indicated flooding tide, while negative flow indicates ebbing tide.

V.5 FLUSHING CHARACTERISTICS

Since the magnitude of freshwater inflow is much smaller than the tidal exchange through each inlet, the primary mechanism controlling estuarine water quality within the modeled Slocums River system is tidal exchange. A rising tide offshore in Buzzards Bay creates a slope in water surface from the ocean into the modeled systems. Consequently, water flows into (floods) the system. Similarly, each estuary drains into the open waters of Buzzards Bay on an ebbing tide. This exchange of water between each system and the Bay 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 Potomska Cove as an example, the **system residence time** is the average time required for water to migrate from Potomska Cove, through the entrance of Slocums River, and into Bay, where the **local residence time** is the average time required for water to migrate from Potomska Cove to just Slocums River (not all the way to the bay). 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 Slocums River system this approach is applicable, since it assumes the main system has relatively low quality water relative to Buzzards Bay.

The rate of pollutant/nutrient loading and the quality of water outside the estuary both must be evaluated in conjunction with residence times to obtain a clear picture of water quality. Efficient tidal flushing (low residence time) is not an indication of high water quality if pollutants and nutrients are loaded into the estuary faster than the tidal circulation can flush the system.

Neither are low residence times an indicator of high water quality if the water flushed into the estuary is of poor quality. Advanced understanding of water quality will be obtained from the calibrated hydrodynamic model by extending the model to include pollutant/nutrient dispersion. The water quality model will provide a valuable tool to evaluate the complex mechanisms governing estuarine water quality in the Slocums River and Little River systems.

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

Residence times were averaged for the tidal cycles comprising a representative 7.25 day period (14 tide cycles), and are listed in Table V-8. The modeled time period used to compute the flushing rates was different from the modeled calibration period, and included the transition from spring to neap tide conditions. Model divisions used to define the system sub-embayments include 1) the entire Little River system, 2) the upper portion of Little River 3) the entire Slocums River system, 4) the upper portion of Slocums River, 5) the upper and mid sections of Slocums River, 6) Potomska Cove, 7) East Cove, and 8) Giles Cove. The model calculated flow crossing specified grid lines for each sub-embayment to compute the tidal prism volume. Since the 7.25-day period used to compute the flushing rates of the system represent average tidal conditions, the measurements provide the most appropriate method for determining mean flushing rates for the system sub-embayments.

Table V-7. Embayment mean volumes and average tidal prism during simulation period.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)
Little River (entire embayment)	8,582,370	11,749,750
Upper Little River	6,415,100	9,192,495
Slocums River (entire embayment)	65,437,515	62,128,493
Upper Slocums River	7,737,980	10,419,114
Upper and Mid Slocums River	32,538,910	33,017,226
Potomska Cove	962,075	963,527
East Cove	626,835	825,541
Giles Cove	3,514,190	2,017,160

The computed flushing rates for the Slocums River and Little River show that as a whole, the system flushes well. A flushing time of 0.38 days for the Little River estuary and 0.55 days for Slocums River shows that on average, water is resident in the system for approximately a half of a day. The upper portions of Little River shows a similar result, while the upper portion of Slocums River lags with the resident time being approximately three days. East Cove has the greatest system residence time. A system residence time of approximately forty-one days for East Cove indicates that if the waters with which it exchanges exhibit marginal water quality, then water quality in East Cove will be relatively poor. However, since Slocums River flushes well, it should not be a concern.

Table V-8. Computed System and Local residence times for embayments in the Slocums River system.		
Embayment	System Residence Time (days)	Local Residence Time (days)
Little River (entire embayment)	0.38	0.38
Upper Little River	0.49	0.36
Slocums River (entire embayment)	0.55	0.55
Upper Slocums River	3.26	0.39
Upper and Mid Slocums River	1.03	0.51
Potomska Cove	35.32	0.52
East Cove	41.22	0.39
Giles Cove	16.87	0.90

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

V.6 PARTICLE TRACKING

The particle tracking model RMATRK was run for Slocums River and Little River to examine the movement of water throughout the system. The specific goal was to examine the potential movement of water between Slocums River and Little River. The use of a particle tracking model allowed for numerous particles to be individually tracked throughout the system to help understand pathways of water movement between the embayments. This contributed to the understanding of the flushing characteristics of the system.

RMATRK transports discrete objects (particles) through the finite element grid using the hydrodynamic solution from RMA-2. The model utilizes the water depth and velocity to compute the transverse and longitudinal mixing coefficients (see Fischer *et al.*, 1979, for a more complete description of this methodology). The velocities used for calculation of dispersion coefficients are the average velocities from the RMA-2 solution. The mixing coefficients are used to calculate the particle movements over time and space, allowing particles to be released and monitored at multiple time periods and geographical points throughout the simulation. The particle pathways can be analyzed to track water movement throughout the system.

Simulations were developed to track particle migration, with particles released both in the upper and lower portions of Slocums River, as well as in Little River. Particles released in the upper portion of the system would likely represent the high nutrient waters derived from this portion of the estuary. Water in the lower portion of Slocums River generally exhibits a lower total nitrogen concentration (Howes, *et al.*, 1999); therefore, water derived from this location presumably would have less impact on overall estuarine water quality.

Three particle tracking scenarios were modeled to assess general water movement characteristics within the estuarine systems: a release of 100 particles in upper Slocums River, a release of 100 particles in lower Slocums River, and a release of 100 particles in the middle portion of Little River. For every scenario, the particles were released at high tide to ensure that tidal advection would initially carry the particles toward Buzzards Bay. If the scenarios were begun at low tide, the migration rate of the particles into Buzzards Bay likely would increase by approximately one-half tidal cycle or 6.2 hours. For each scenario, particles that migrated beyond the seaward boundary of the model were removed from the simulation. Exclusion of these particles is appropriate for water quality analyses, since any water derived from Slocums River or Little River would be diluted with Buzzards Bay water seaward of the model boundary.

The results of the particle tracking model are shown in Figures V-28, V-29, and V-30. In Figure V-28, illustrates that water in the upper portion of Slocums River migrates relatively slowly toward Buzzards Bay, in general requiring at least two tidal cycles to move through the inlet. Since two tidal cycles are required, the following flood tide causes particles that migrated toward the inlet to migrate upstream for the approximate 6-hour flood cycle. The distance that water moves over a tidal cycle is referred to as the tidal excursion. In the case of upper Slocums River, the tidal excursion is less than the distance between the release point shown on Figure V-28 and the inlet. The second ebb cycle flushes nearly half of the particles into the common bay formed between Mishaum and Barneys Joy Points (Figure V-28 at 20 hours). However, most of these particles return to Slocums River on the following flood cycle, with a portion of the particles migrating into Little River. Approximately 10% of the particles released in upper Slocums River can be found in the Little River system after 24 hours. In addition, 96% of the particles released in upper Slocums River are found within the model grid after 24 hours. Based on these model results, it is likely that water derived from upper Slocums River is “recycled” for a number of tidal cycles and nutrients entering this portion of the estuary will have a significant impact on overall estuarine health. Additionally, a portion of water derived from upper Slocums River may impact estuarine health in Little River; however, this impact is relatively minor.

Figure V-29 illustrates tracking results for particles released in lower Slocums River. Due to the higher ambient water velocities in this region, the particles migrate through the inlet within 1.5 hours. Although the model was run for a 24-hour time period, all 100 particles had migrated through the seaward boundary of the model within the first 3 hours of the simulation. This rapid movement of particles into Buzzards Bay indicates that nutrient sources in the lower portion of Slocums River will have less impact on the overall estuarine health when compared to similar nutrient sources in upper Slocums River. This result is expected; however, the extent of the difference likely will be exacerbated by the limited tidal excursion in the upper portion of the estuary.

Similar to the conditions modeled for lower Slocums River, particles released within the central portion of Little River are flushed rapidly into Buzzards Bay. Figure V-30 indicates that particles released within the central portion of Little River migrate through the inlet within 1.5

hours and all 100 particles have migrated into Buzzards Bay within the first 3.5 hours of the simulation. Due to the large expanse of marsh and relatively shallow water depth, tidal flushing is relatively rapid through the Little River system. Therefore, nutrients entering Little River likely will be flushed from the system rapidly.

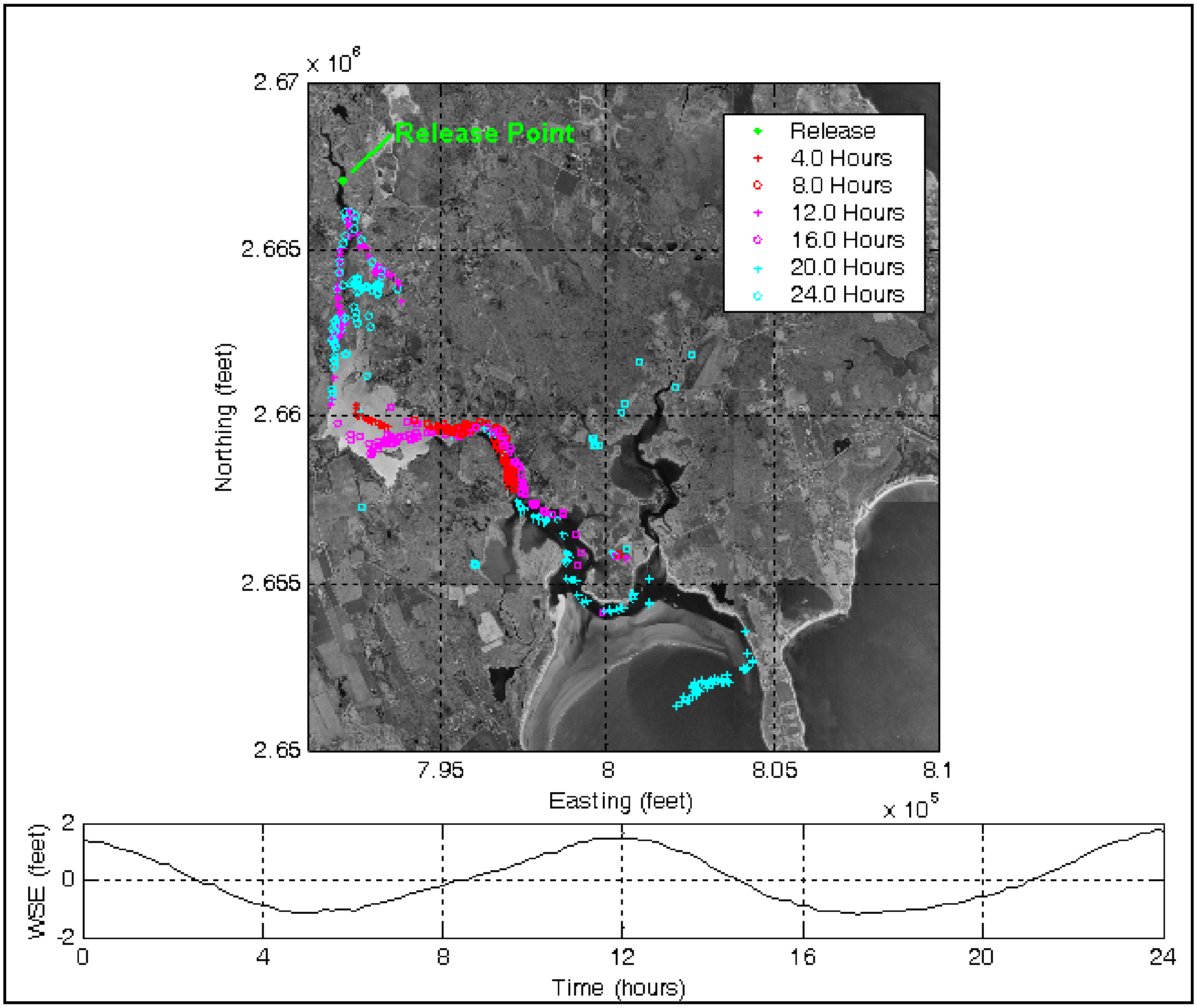


Figure V-28. Time representation of particles being released in upper portion of Slocums River on ebb tide. Green marker represents initial position and blue circles represent the final positions after 24 hours.

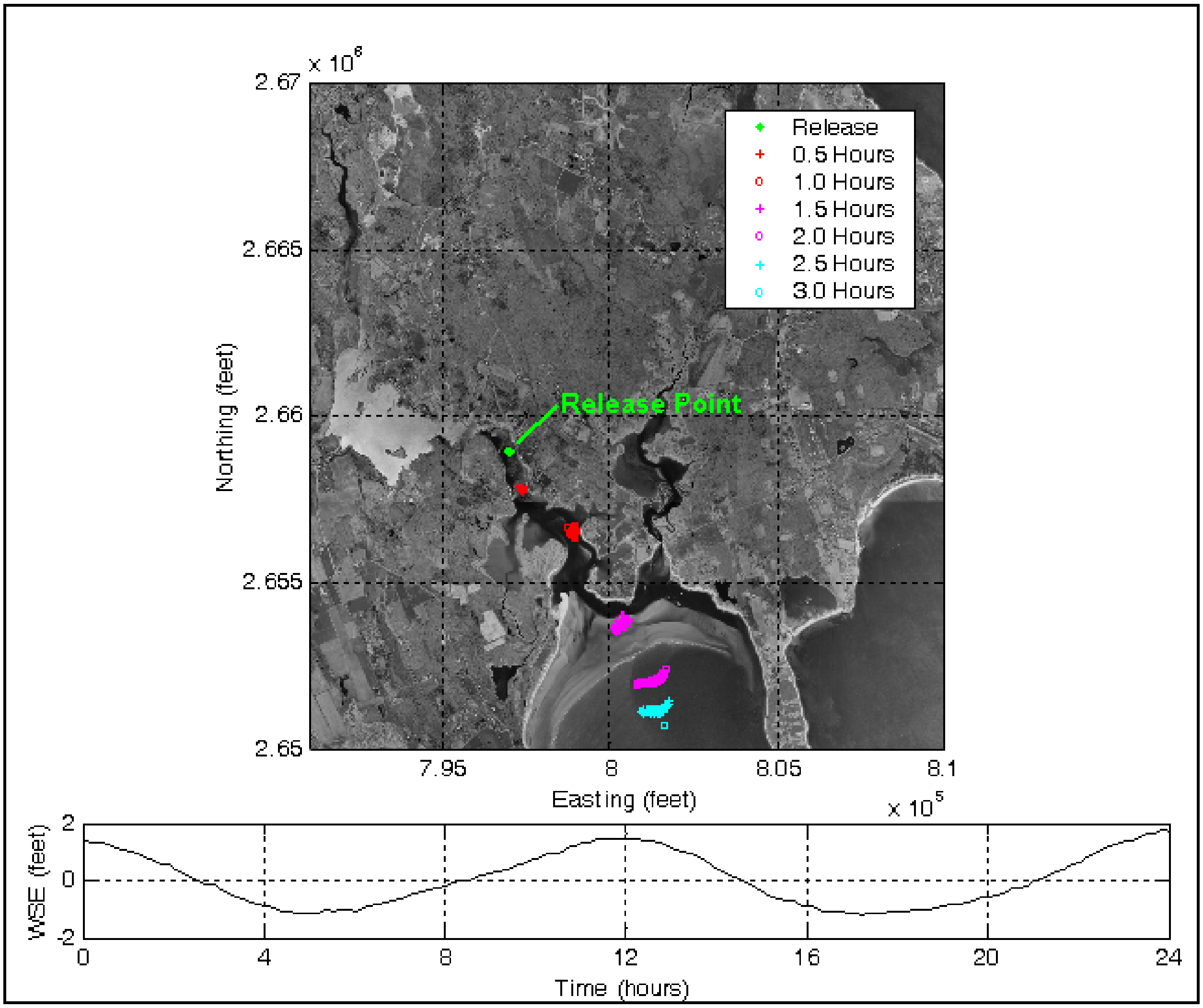


Figure V-29. Time representation of particles being released in lower Slocums River on ebb tide. Green marker represents initial position and blue circles represent the final positions after 3.0 hours.

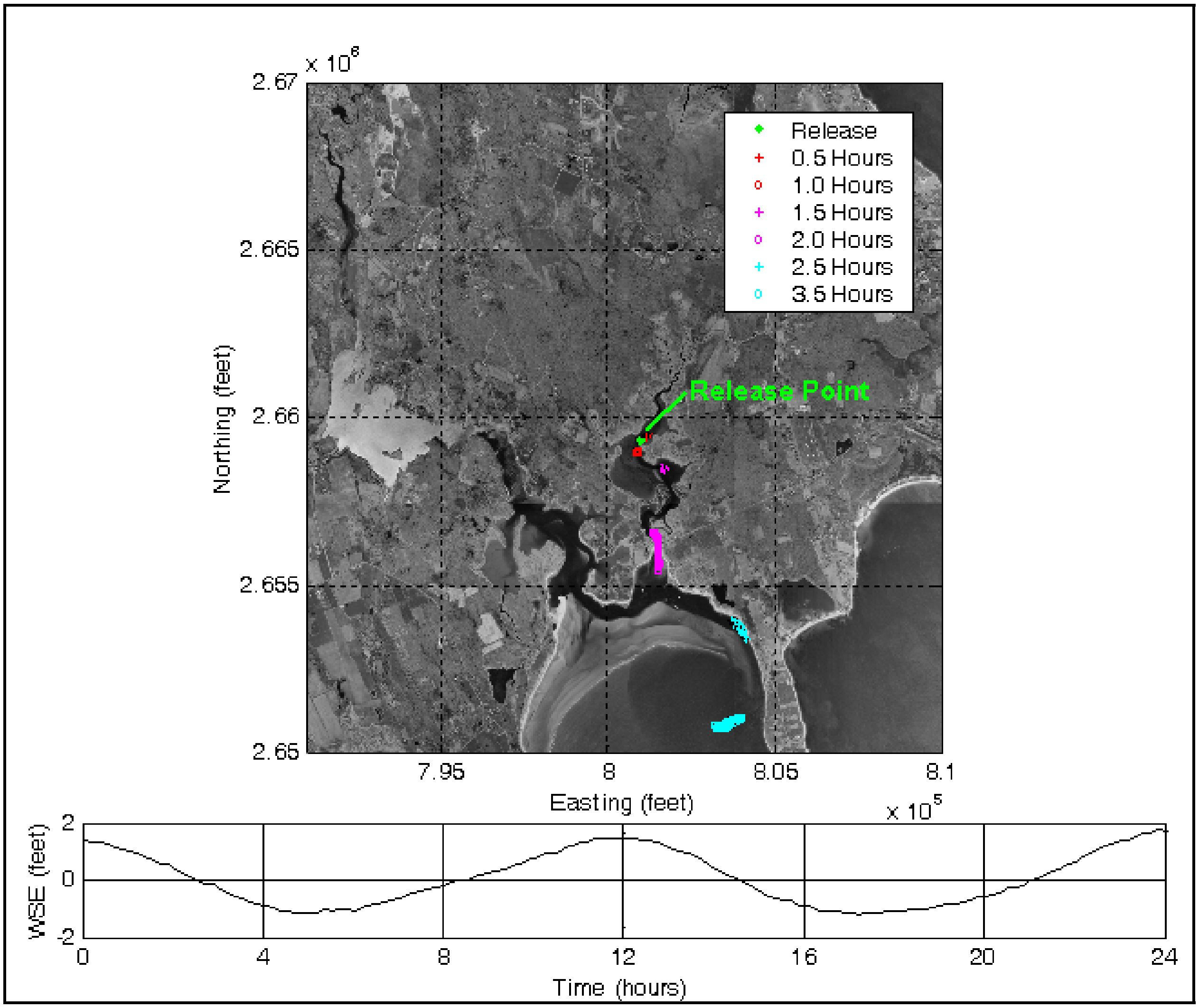


Figure V-30. Time representation of particles being released in Little River on ebb tide and transported into Buzzards Bay. Green marker represents initial position and blue circles represent the final particle positions after 3.5 hours.

V.7 CONCLUSIONS

A RMA-2 numerical hydrodynamic model was developed to represent the Slocums River system in South Dartmouth, Massachusetts. This model was created using bathymetry data collected in May 2002. Tide data collected during April and May 2002 was used to provide the model forcing open boundary condition, and to calibrate the model. Some important points from this study are:

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

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

- The computed flushing rates for the Slocums River system show that as a whole, the system flushes well. A flushing time of 0.38 days for the Little River estuary and 0.55 days for Slocums River shows that, on average, water is resident in the system for approximately a half of a day.

- A particle tracking model also was run, primarily to evaluate whether water flushing from Slocums River was potentially impacting the Little River estuarine system. This model utilized similar dispersion estimates as the planned Massachusetts Estuaries Project total nitrogen modeling; however, the particle tracking model only tracks water particles and is not dependent on water quality parameters. Regardless, the particle tracking model results provide useful information regarding water movement throughout the estuarine system.

- Results of the particle tracking model indicated that water derived from upper Slocums River is “recycled” for a number of tidal cycles and nutrients entering this portion of the estuary will likely have a significant impact on overall estuarine health. Particles initiated in lower Slocums River or in the central portion of Little River migrated through their respective inlets within 1.5 hours. Although the model was run for a 24-hour time period, all 100 particles had migrated through the seaward boundary of the model within the first ebb cycle. Additionally, a portion of water derived from upper Slocums River may impact estuarine health in Little River; however, this impact is relatively minor. Approximately 10% of the particles released in upper Slocums River can be found in the Little River system after 24 hours.

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 Slocums River and Little River Systems. These include the output from the hydrodynamics model, calculations of external nitrogen loads and freshwater inflows from the watersheds and atmosphere, measurements of internal nitrogen loads from the sediment (benthic flux), and measurements of nitrogen and salinity in the water column.

VI.1.1 Hydrodynamics and Tidal Flushing in the Embayment

Extensive field measurements and hydrodynamic modeling of the embayment were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated model output representing the transport of water within the system embayment. Files of node locations and node connectivity for the RMA-2V model grid were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model also was the computational grid for the water quality model. The period of hydrodynamic output for the water quality model calibration was an 11-tidal cycle period in April 2002. Each modeled scenario (e.g., present conditions, build-out) required the model be run for a 28-day spin-up period, to allow the model had reached a dynamic "steady state", and ensure that model spin-up would not affect the final model output.

VI.1.2 Nitrogen Loading to the Embayment

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

VI.1.3 Measured Nitrogen Concentrations in the Embayment

In order to create a model that realistically simulates the total nitrogen concentrations in a system in response to the existing flushing conditions and loadings, it is necessary to calibrate the model to actual measurements of water column nitrogen concentrations. The refined and approved data for each monitoring station used in the water quality modeling effort are presented in Table VI-1. Station locations are indicated in Figure VI-1. The multi-year averages present the "best" comparison to the water quality model output, since factors of tide, temperature and rainfall may exert short-term influences on the individual sampling dates and even cause inter-annual differences. Three years of baseline field data is the minimum required to provide a baseline for MEP analysis. The periods of data collect varied with a maximum of seven years of data (collected between 2000 and 2006) for stations monitored in the Slocums River and Little River System by the Coalition for Buzzards Bay (BayWatchers) and the Coastal Systems Program at SMAST.

Table VI-1. Measured data, and modeled Total Nitrogen concentrations for the Slocums River and Little River System used in the model calibration plots of Figure VI-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data are provided courtesy of the Coalition for Buzzards Bay (BayWatchers; 2000-06) and the Coastal Systems Program at SMAST (2004-05).

Sub-Embayment	Head Slocums	Upper Slocums	Upper Slocums	Mid Slocums	Mid Slocums	Mid Slocums	Lower Slocums / Giles	Lower Slocums	Lower Slocums	Inner Little River	Basin Little River	Inlet - Little River
Monitoring station	SRT-3	SRT-4	SRT-5	SRT-6	SRT-7	SRT-10	SRT-11	SRT-12	SRT-13	SRT-14	SRT-15	SRT-16
2000 mean	0.790	--	--	0.603	--	--	--	0.407	--	--	--	0.499
2001 mean	1.432	--	--	0.854	--	--	--	0.560	--	--	--	0.499
2002 mean	1.274	--	--	0.674	--	--	--	0.451	--	--	--	0.505
2003 mean	1.520	--	--	0.824	--	--	--	--	--	--	--	0.500
2004 mean	1.090	0.667	0.669	0.544	0.438	0.388	0.369	0.403	0.312	0.482	0.479	0.366
2005 mean	1.041	0.612	0.602	0.546	0.435	0.411	0.406	0.324	0.262	0.369	0.343	0.331
2006 mean	1.458	--	--	0.890	--	--	--	--	--	--	--	0.470
mean	1.175	0.641	0.636	0.620	0.437	0.399	0.385	0.390	0.285	0.409	0.403	0.394
s.d. all data	0.343	0.103	0.145	0.177	0.074	0.091	0.059	0.113	0.056	0.085	0.130	0.111
N	43	15	24	50	31	23	16	42	33	17	18	53
model min	1.442	0.845	0.656	0.532	0.419	0.301	0.348	0.293	0.287	0.327	0.313	0.289
model max	1.563	1.137	0.996	0.854	0.726	0.601	0.502	0.541	0.463	0.406	0.388	0.383
model average	1.499	0.994	0.826	0.690	0.586	0.450	0.398	0.392	0.337	0.365	0.349	0.325

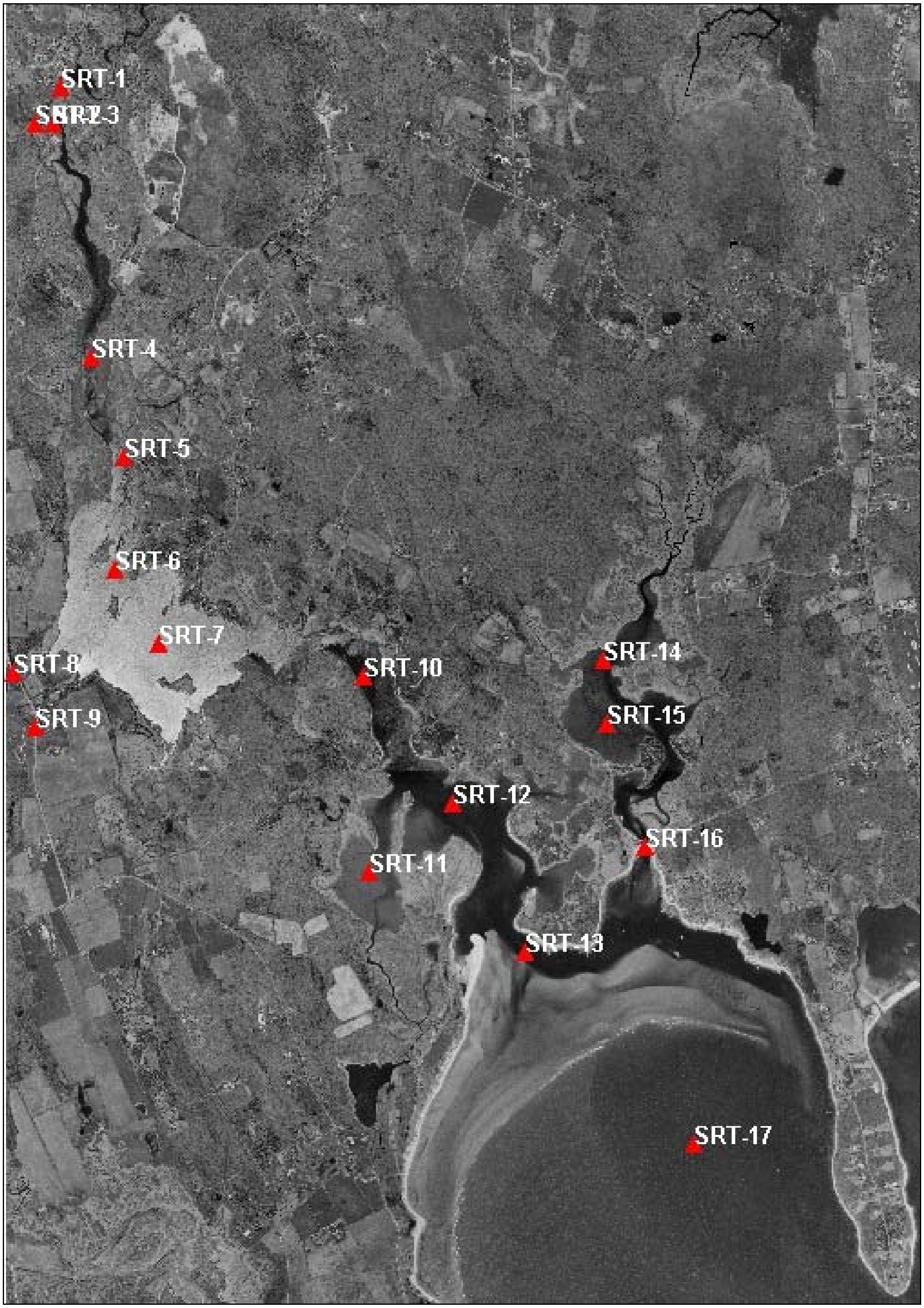


Figure VI-1. Estuarine water quality monitoring station locations in the Slocums River and Little River Systems. Station labels correspond to those provided in Table VI-1.

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 Slocums River and Little River 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 Slocums River and Little River 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).

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 MEP Technical Team and USGS watershed analysis), 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.

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

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

Based on measured stream flow rates from SMAST and groundwater recharge rates from the watershed analysis, the hydrodynamic model was set-up to include the latest estimate of surface water flows from Paskamanset River, Destruction Brook, Barneys Joy River North, and Barneys Joy River South along with ground water flowing into the system from watersheds. The Paskamanset River has a measure flow rate of 26.38 ft^3/sec (64,541 m^3/day), Destruction Brook has a measure flow rate of 2.73 ft^3/sec (6,679 m^3/day), Barneys Joy River North has a measure flow rate of 1.36 ft^3/sec (3,327 m^3/day), and Barneys Joy River South has a measure flow rate of 1.37 ft^3/sec (3,352 m^3/day). The overall groundwater flow rate into the system is 6.57 ft^3/sec (16,074 m^3/day) distributed amongst the watersheds.

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

VI.2.3 Boundary Condition Specification

Mass loading of nitrogen into each model included 1) sources developed from the watershed land-use analysis, 2) estimates of direct atmospheric deposition, 3) summer benthic regeneration, and 4) localized inputs developed from measured discharges of the Paskamanset River, Destruction Brook, Barneys Joy River North, and Barneys Joy River South. Nitrogen loads from each separate sub-embayment watershed were distributed across the sub-embayment. For example, the combined watershed direct atmospheric deposition load for Little River was evenly distributed at grid cells that formed the perimeter of the embayment. Benthic regeneration load was distributed among another sub-set of grid cells which are in the interior portion of each basin.

The loadings used to model present conditions in Slocums River and Little River Systems are given in Table VI-2. Watershed and depositional loads were taken from the results of the analysis of Sections IV.1 and IV.2. Summertime benthic flux loads were computed based on the analysis of sediment cores in Section IV.3. The area rate (g/sec/m^2) of nitrogen flux from that analysis was applied to the surface area coverage computed for each sub-embayment (excluding marsh coverages, when present), resulting in a total flux for each embayment (as listed in Table VI-2). Due to the highly variable nature of bottom sediments and other estuarine characteristics of coastal embayments in general, the measured benthic flux for existing conditions also is variable. For present conditions, some sub-embayments have almost twice the loading rate from benthic regeneration as from watershed loads. For other sub-embayments, the benthic flux is relatively low or negative indicating a net uptake of nitrogen in the bottom sediments.

In addition to mass loading boundary conditions set within the model domain, concentrations along the model open boundary were specified. The model uses concentrations at the open boundary during the flooding tide periods of the model simulations. TN concentrations of the incoming water are set at the value designated for the open boundary. The boundary concentration was set at 0.285 mg/L, based on monitoring data from measurement stations within Buzzards Bay. The open boundary total nitrogen concentration represents long-term average summer concentrations found within Buzzards Bay.

Table VI-2. Sub-embayment loads used for total nitrogen modeling of the Slocums River and Little River 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)
Slocums River[1]	8.488	5.395	-4.874
Little River[1]	4.690	1.186	8.898
Surface Water Sources			
Paskamanset R & Destruction Brk	118.863	-	-
Barneys Joy River North	3.260	-	-
Barneys Joy River South	5.485	-	-

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge and from surface water (stream) inflows.

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 estuary systems characterized by relatively wide channels (compared to channel depth) with moderate currents (from tides or atmospheric forcing). Generally, the relatively quiescent areas of Slocums River and Little River require values of E that are lower compared to the riverine estuary systems evaluated by Fischer, *et al.*, (1979). Observed values of E in these calmer areas typically range between order 10 and order 0.001 m^2/sec (USACE, 2001). The final values of E used in each sub-embayment of the modeled systems are presented in Table VI-3. These values were used to develop the “best-fit” total nitrogen model calibration. For the case of TN modeling, “best fit” can be defined as minimizing the error between the model and data at all sampling locations, utilizing reasonable ranges of dispersion coefficients within each sub-embayment.

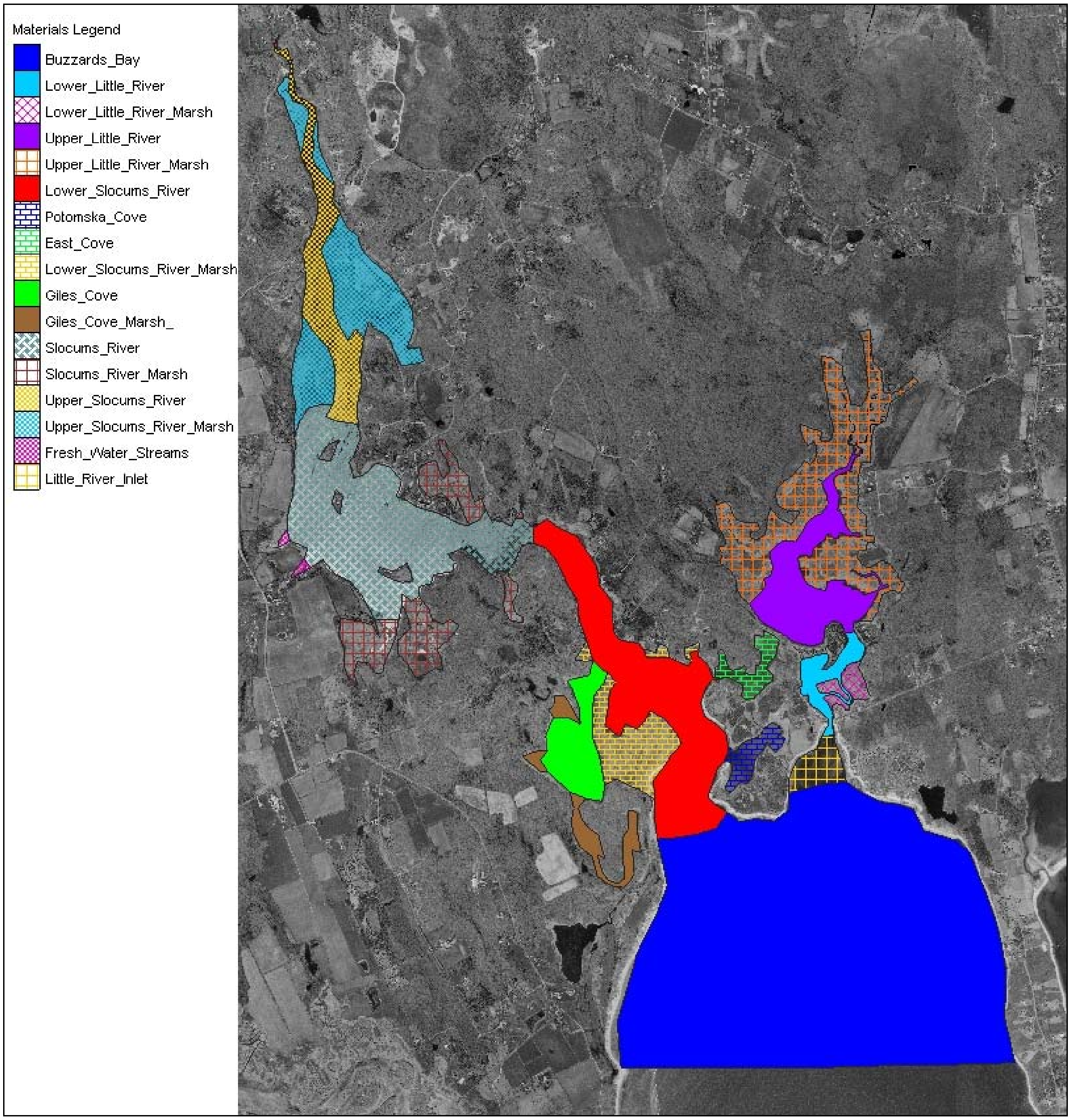


Figure VI-2. Map of Slocums River and Little River water quality model longitudinal dispersion coefficients. Color patterns designate the different areas used to vary model dispersion coefficient values.

Table VI-3. Values of longitudinal dispersion coefficient, E, used in calibrated RMA4 model runs of salinity and nitrogen concentration for Slocums River and Little River Systems.

Embayment Division	E m^2/sec
Buzzards Bay	50.0
Lower Little River	10.0
Marsh Plain in Lower Little River	2.0
Upper Little River	15.0
Marsh Plain in Upper Little River	2.0
Lower Slocums River	15.0
Potomska Cove	10.0
East Cove	10.0
Marsh Plain in Lower Slocums River	5.0
Giles Cove	15.0
Marsh Plain in Giles Cove	3.0
Slocums River	10.0
Marsh Plain in Slocums River	2.0
Upper Slocums River	10.0
Marsh Plain in Upper Slocums River	1.0

Comparisons between model output and measured nitrogen concentrations are shown in plots presented in Figure VI-3. In these plots, means of the water column data and a range of two standard deviations of the annual means at each individual station are plotted against the modeled maximum, mean, and minimum concentrations output from the model at locations which corresponds to the water quality monitoring stations. The emphasis during calibration was to concentrate on representing the conditions measured at the long term data collection stations (SRT-3, SRT-6, SRT-12, and SRT-16). It was felt that those stations more accurately reflected the average conditions within the systems.

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. Water quality monitoring stations SRT-4, SRT-5, SRT-7 were not used during the calibration do limited data record and issues associated with the time within the tidal cycle measurements were taken diminished their value for this analysis.

Also presented in this figure are unity plot comparisons of measured data versus modeled target values for the system. The model fit is exceptional for the Slocums River and Little River Systems, with rms error of 0.14 mg/L and an R^2 correlation coefficient of 0.93.

A contour plot of calibrated model output is shown in Figure VI-4 for Slocums River and Little River Estuaries. In the figure, color contours indicate nitrogen concentrations throughout the model domain. The output in the figure show average total nitrogen concentrations, computed using the full 5-tidal-day model simulation output period.

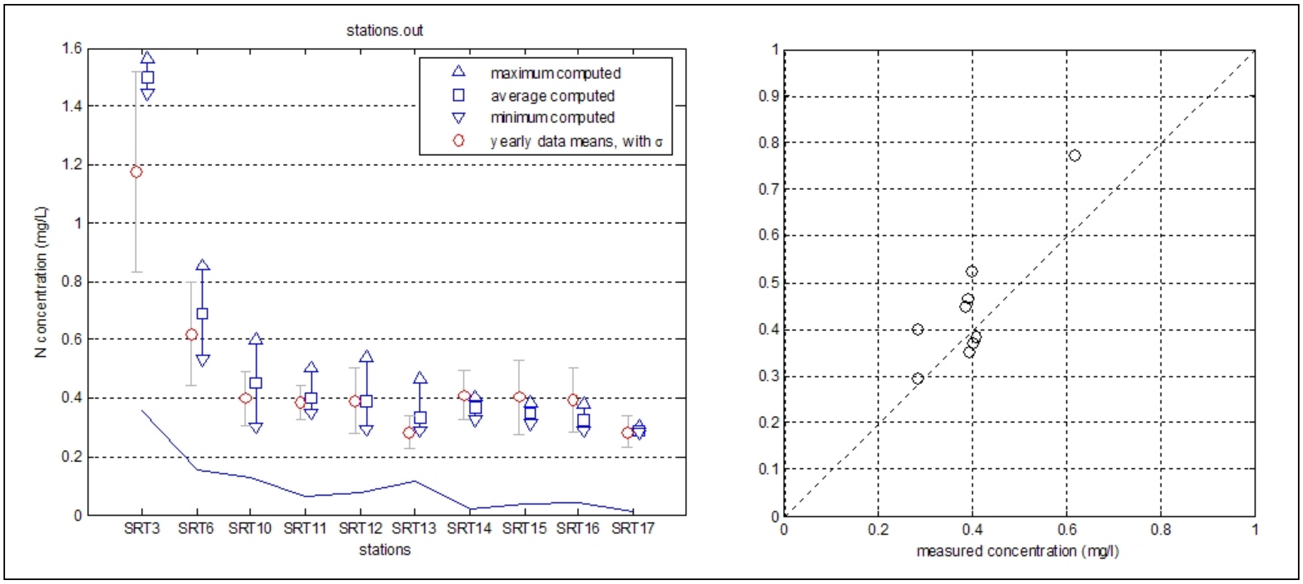


Figure VI-3. Comparison of measured total nitrogen concentrations and calibrated model output at stations in Slocums River and Little River Estuaries. For the left plot, station labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed concentration for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

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 Slocums River and Little River 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 31.1 ppt. For groundwater inputs salinities were set at 0 ppt. Groundwater input used for the model was 6.57 ft^3/sec (16,074 m^3/day) distributed amongst the watersheds. Groundwater flows were distributed evenly in each model through the use of several 1-D element input points positioned along each model's land boundary.

Comparisons of modeled and measured salinities are presented in Figure VI-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 Slocums River and Little River Systems. The rms error of the models was 1.21 ppt, and correlation coefficient was 0.97. 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.

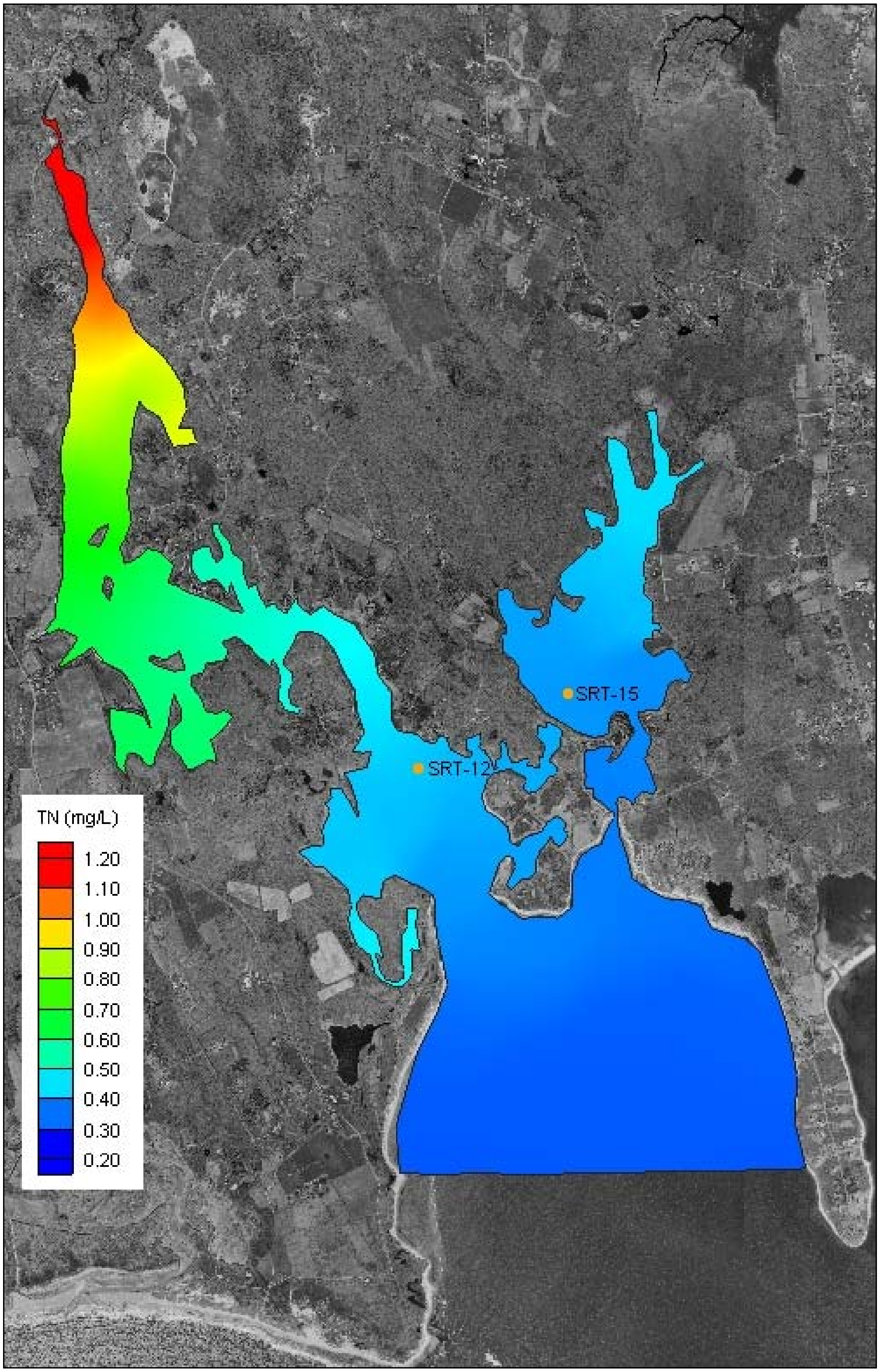


Figure VI-4. Contour plots of average total nitrogen concentrations from results of the present conditions loading scenario, for Slocums River and Little River Estuaries. The approximate location of the sentinel threshold stations for Slocums River (SRT-12) and Little River (SRT-15) Estuaries are shown.

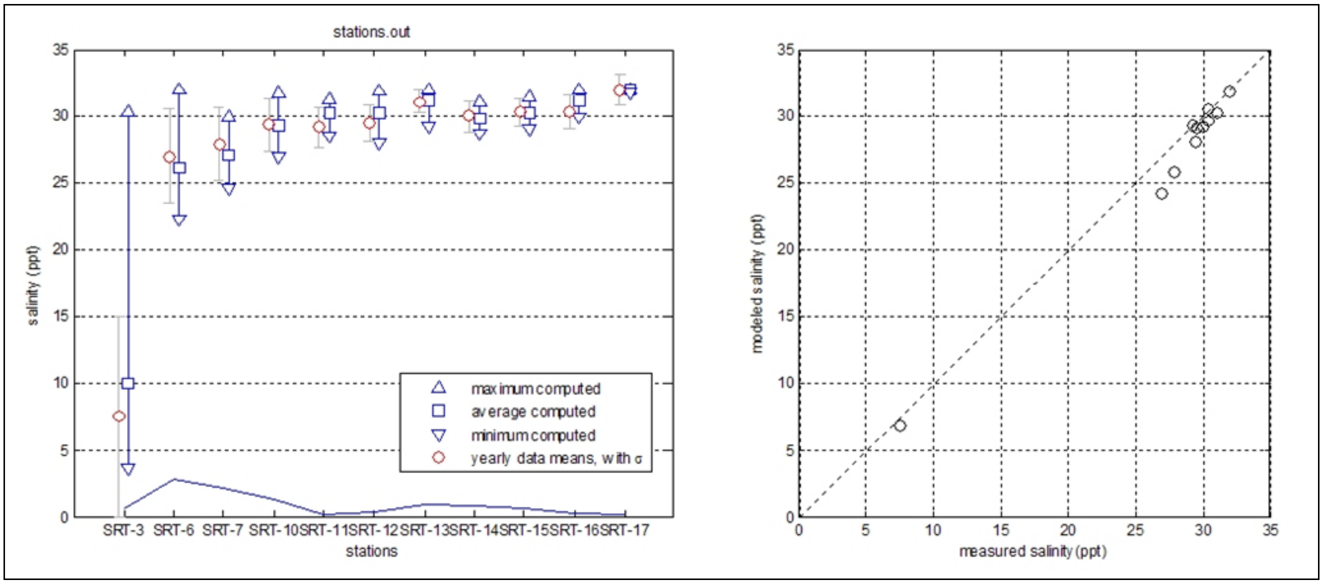


Figure VI-5. Comparison of measured and calibrated model output at stations in Slocums River and Little River Estuaries. For the left plots, stations labels correspond with those provided in Table VI-1. Model output is presented as a range of values from minimum to maximum values computed during the simulation period (triangle markers), along with the average computed salinity for the same period (square markers). Measured data are presented as the total yearly mean at each station (circle markers), together with ranges that indicate ± one standard deviation of the entire dataset. For the plots to the right, model calibration target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) and error (rms) for each model are also presented.

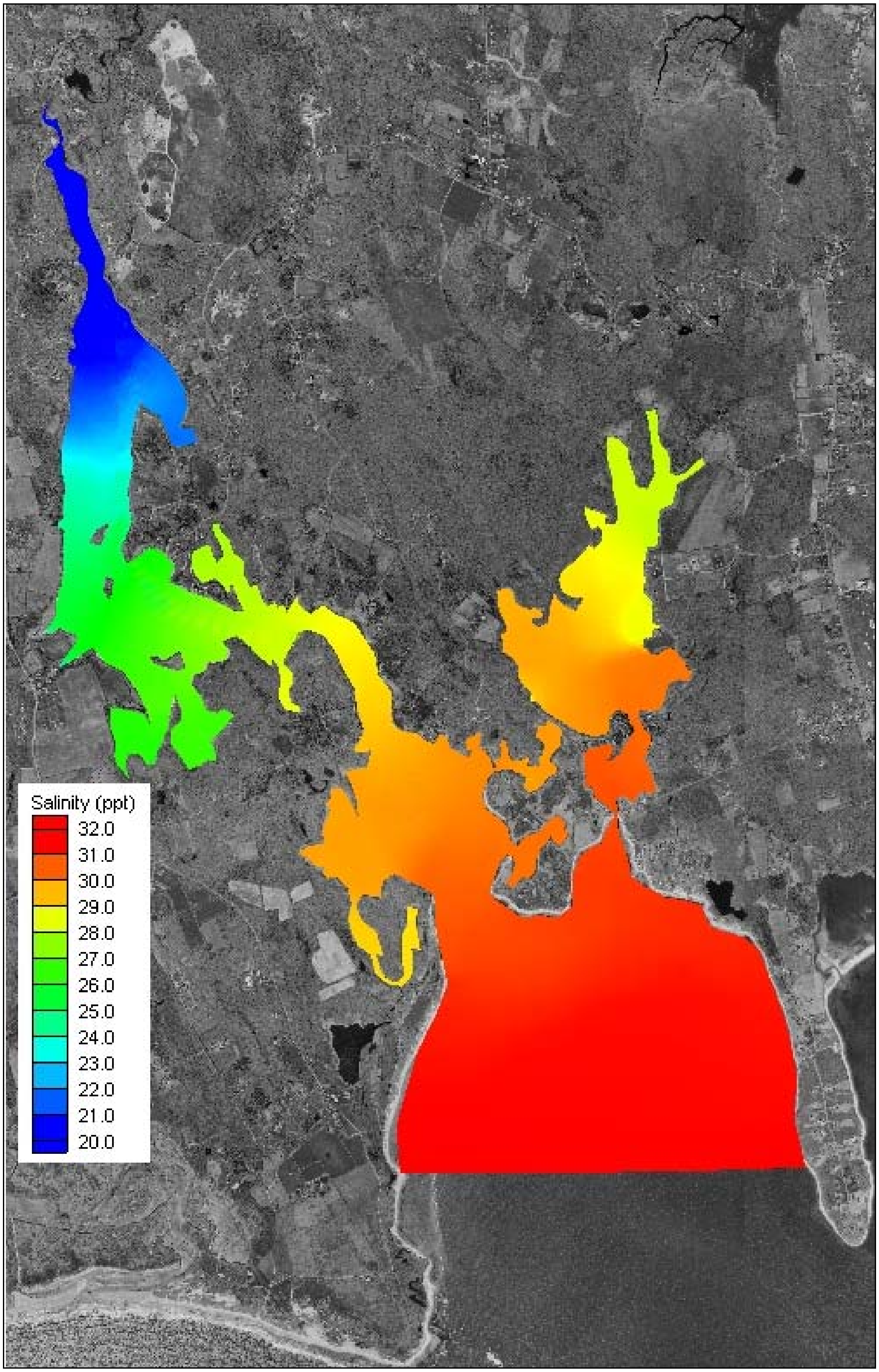


Figure VI-6. Contour plots of modeled salinity (ppt) in Slocums River and Little River Estuaries.

VI.2.6 Build-Out and No Anthropogenic Load Scenarios

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

Table VI-4. Comparison of sub-embayment watershed loads used for modeling of present, build-out, and no-anthropogenic ("no-load") loading scenarios of the Slocums River and Little River 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
Slocums River[1]	8.488	18.055	112.7%	1.630	-80.8%
Little River[1]	4.690	10.082	115.0%	0.732	-84.4%
Surface Water Sources					
Paskamanset River and Destruction Brook	118.863	174.162	46.5%	10.622	-91.1%
Barneys Joy River North	3.260	4.455	36.6%	0.208	-93.6%
Barneys Joy River South	5.485	9.205	67.8%	0.436	-92.1%

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge and from surface water (stream) inflows.

VI.2.6.1 Build-Out

In general, certain sub-embayments would be impacted more than others. The build-out scenario indicates that there would be more than a 100% increase in watershed nitrogen load to the Slocums River and Little Rivers a result of potential future development. For the no load scenarios, a majority of the load entering the watershed is removed; therefore, the load is generally lower than existing conditions by over 90% overall.

For the build-out scenario, a breakdown of the total nitrogen load entering the Slocums River and Little River 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,

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

and the present PON concentration above background,

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

Table VI-5. Build-out sub-embayment and surface water loads used for total nitrogen modeling of the Slocums River and Little River 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)
Slocums River	18.055	5.395	-6.988
Little River	10.082	1.186	12.655
Surface Water Sources			
Paskamanset R & Destruction Brk	174.162	-	-
Barneys Joy River North	4.455	-	-
Barneys Joy River South	9.205	-	-

Following development of the nitrogen loading estimates for the build-out scenario, the water quality model of Slocums River and Little River Systems was run to determine nitrogen concentrations within each sub-embayment (Table VI-6). Total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. Total N concentrations increased the most in the upper portion of Slocums River, with the largest change occurred at the head of Slocums River (46%) and the least change occurred in by the inlets of Slocums River and Little River (8% and 7%). 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.

Table VI-6. Comparison of model average total N concentrations from present loading and the build-out scenario, with percent change, for the Slocums River and Little River Systems. Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	build-out (mg/L)	% change
Head Slocums	SRT-3	1.499	2.193	+46.3%
Upper Slocums	SRT-4	0.994	1.413	+42.2%
Upper Slocums	SRT-5	0.826	1.148	+39.1%
Mid Slocums	SRT-6	0.690	0.934	+35.3%
Mid Slocums	SRT-7	0.586	0.768	+31.0%
Mid Slocums	SRT-10	0.450	0.549	+22.0%
Lower Slocums: Giles	SRT-11	0.398	0.463	+16.4%
Lower Slocums	**SRT-12**	**0.392**	**0.456**	**+16.1%**
Lower Slocums	SRT-13	0.337	0.366	+8.6%
Inner Little River	SRT-14	0.365	0.418	+14.4%
Basin Little River	**SRT-15**	**0.349**	**0.389**	**+11.4%**
Inlet - Little River	SRT-16	0.325	0.347	+7.1%
Outer Basin	SRT-17	0.290	0.292	+0.9%

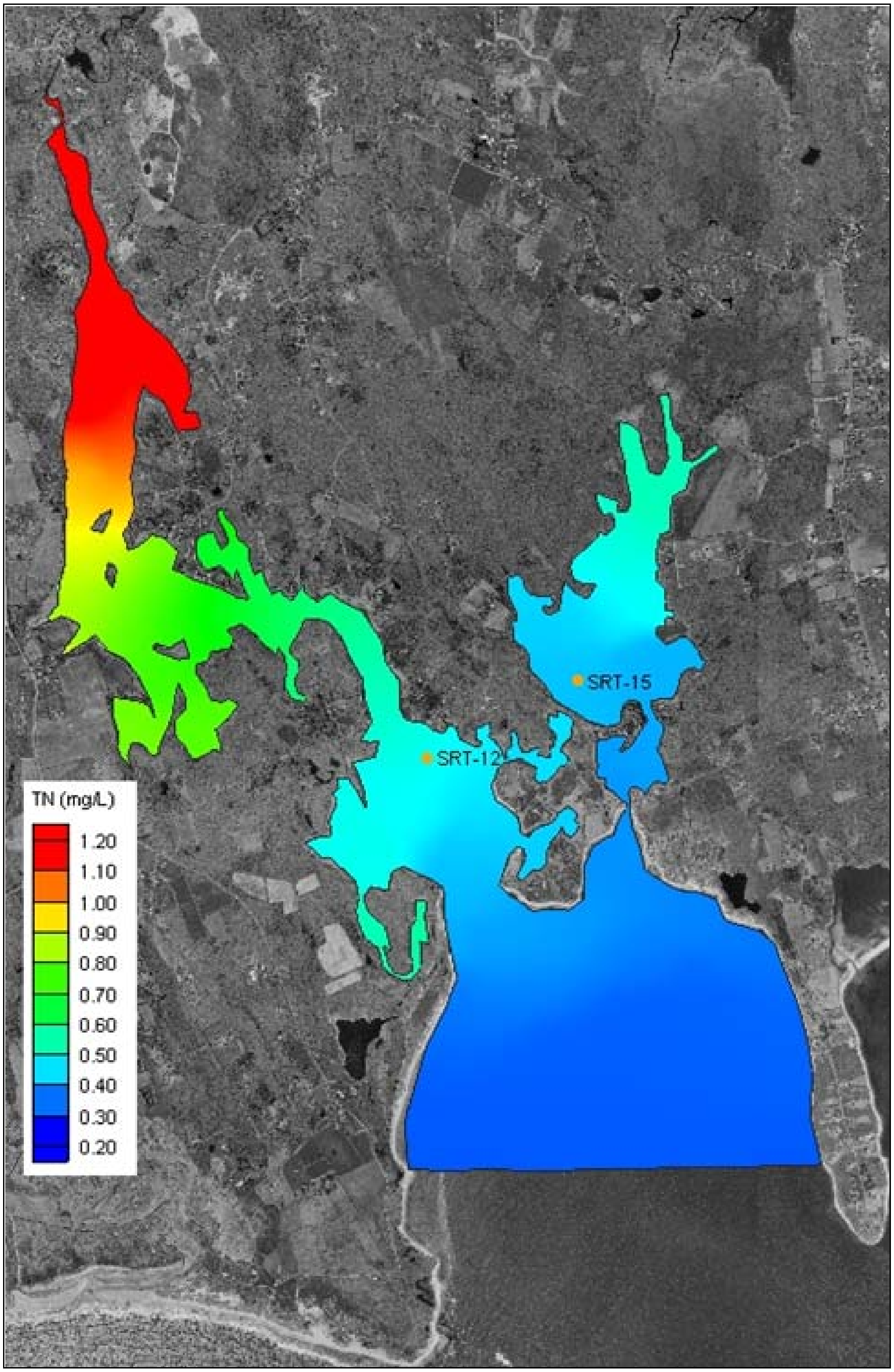


Figure VI-7. Contour plots of modeled total nitrogen concentrations (mg/L) in Slocums River and Little River Estuaries, for projected build-out loading conditions, and bathymetry. The approximate location of the sentinel threshold stations for Slocums River (SRT-12) and Little River (SRT-15) Systems are shown.

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.

Table VI-7. "No anthropogenic loading" ("no load") sub-embayment and surface water loads used for total nitrogen modeling of Slocums River and Little River 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)
Slocums River[1]	1.360	5.395	-1.123
Little River[1]	0.732	1.186	6.130
Surface Water Sources			
Paskamanset R & Destruction Brk	10.622	-	-
Barneys Joy River North	0.208	-	-
Barneys Joy River South	0.436	-	-

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge and from surface water (stream) inflows.

Following development of the nitrogen loading estimates for the no load scenario, the water quality model was run to determine nitrogen concentrations within each sub-embayment. Again, total nitrogen concentrations in the receiving waters (i.e., Buzzards Bay) remained identical to the existing conditions modeling scenarios. The relative change in total nitrogen concentrations resulting from "no load" was significant as shown in Table VI-8, with reductions ranging from 8% occurring at the mouth of Little River to approximately 90% at the head of Slocums River. Results for each system are shown pictorially in Figure VI-8.

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 Slocums River and Little River Systems. Loads are based on atmospheric deposition and a scaled N benthic flux (scaled from present conditions). Sentinel threshold stations are in bold print.

Sub-Embayment	monitoring station	present (mg/L)	no-load (mg/L)	% change
Head Slocums	SRT-3	1.499	0.156	-89.6%
Upper Slocums	SRT-4	0.994	0.217	-78.1%
Upper Slocums	SRT-5	0.826	0.238	-71.2%
Mid Slocums	SRT-6	0.690	0.252	-63.5%
Mid Slocums	SRT-7	0.586	0.263	-55.2%
Mid Slocums	SRT-10	0.450	0.277	-38.6%
Lower Slocums: Giles	SRT-11	0.398	0.285	-28.4%
Lower Slocums	**SRT-12**	**0.392**	**0.281**	**-28.3%**
Lower Slocums	SRT-13	0.337	0.285	-15.2%
Inner Little River	SRT-14	0.365	0.317	-13.3%
Basin Little River	**SRT-15**	**0.349**	**0.311**	**-11.1%**
Inlet - Little River	SRT-16	0.325	0.300	-7.6%
Outer Basin	SRT-17	0.290	0.286	-1.4%

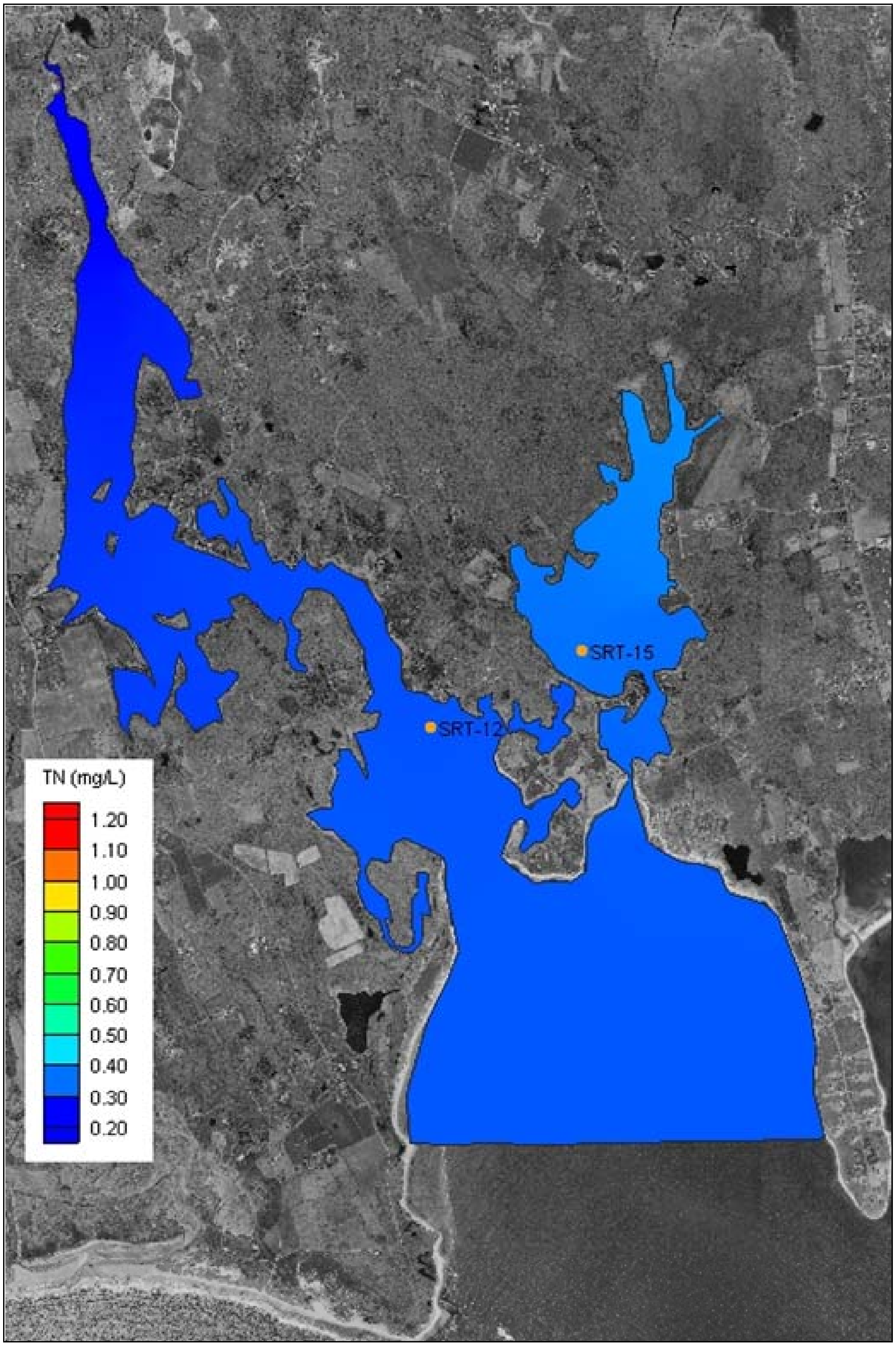


Figure VI-8. Contour plots of modeled total nitrogen concentrations (mg/L) in Slocums River and Little River Estuaries, for no anthropogenic loading conditions, and bathymetry. The approximate location of the sentinel threshold stations for Slocums River (SRT-12) and Little River (SRT-15) Systems are shown.

VII. ASSESSMENT OF EMBAYMENT NUTRIENT RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters as well as the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Slocums River and Little River embayment systems in the Town of Dartmouth, MA, the MEP assessment is based upon multiple sets of habitat related data. The water quality monitoring database was developed by the Coalition for Buzzards Bay and additional water quality, macroalgal and eelgrass survey data was developed by the Turn the Tide Project for the Restoration of Dartmouth's Estuaries (a partnership between the Town of Dartmouth, Coalition for Buzzards Bay, Lloyd Center and the Coastal Systems Program at SMAST-UMassD). The MEP generated surveys of eelgrass distribution, benthic animal communities and sediment characteristics, as well as dissolved oxygen records conducted during the summers of 2003 and 2004. Infaunal data collection was undertaken in the fall of 2004. 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), support complete nitrogen threshold development for these systems (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

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

As a basis for a nitrogen thresholds determination, the 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), (3) benthic animal communities (Section VII.4), and (4) surveys of macroalgal accumulations, as macroalgae had been previously identified as a site-specific issue within the Slocums River Estuary (Section VII.5). 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 while still having important effects on system health. To capture this variation, the MEP Technical Team deployed dissolved oxygen sensors within the upper, middle and lower reaches of the Slocums River Estuary, as well as in the main basin of the Little River embayment, to record the frequency and duration of low oxygen conditions during the critical summer period. The MEP habitat analysis uses eelgrass as a sentinel species for indicating nitrogen over-loading to coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Mapping of the eelgrass beds within the Slocums River and Little River systems was conducted for comparison to historic records (DEP Eelgrass Mapping Program, C. Costello and by the Turn The Tide Project). Temporal trends in the distribution of eelgrass beds are used by the MEP to assess the stability of the habitat and to determine trends potentially related to water quality. Eelgrass beds can decrease within embayments in response to a variety of causes, but throughout almost all of the embayments within southeastern Massachusetts, the primary cause appears to be related to increases in embayment nitrogen levels. Within the

Slocums River and Little River estuaries, temporal changes in eelgrass distribution provides a strong basis for evaluating recent increases (nitrogen loading) or decreases (increased flushing-new inlet) in nutrient enrichment.

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

VII.2 BOTTOM WATER DISSOLVED OXYGEN

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

Dissolved oxygen levels in temperate embayments vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. In addition, biological processes that consume oxygen from the water column (water column respiration) vary directly with temperature, with several fold higher rates in summer than winter (Figure VII-1). It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels (mg L^{-1}) are found during the summer in southeastern Massachusetts embayments when water column respiration rates are greatest. Since oxygen levels can change rapidly, several mg L^{-1} in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments (Taylor and Howes, 1994). To more accurately capture the degree of bottom water dissolved oxygen depletion during the critical summer period, autonomously recording oxygen sensors were moored 30 cm above the embayment bottom within key regions of the Slocums and Little River systems (Figure VII-2). The sensors (YSI 6600) were first calibrated in the laboratory and then checked with standard oxygen mixtures at the time of initial instrument mooring deployment. In addition periodic calibration samples were collected at the sensor depth and assayed by Winkler titration (potentiometric analysis, Radiometer) during each deployment. Each instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during a minimum deployment of 30 days within the interval from July through mid-September. All of the mooring data from the Slocums and Little River embayment systems was collected during the summer of 2003 and 2004.

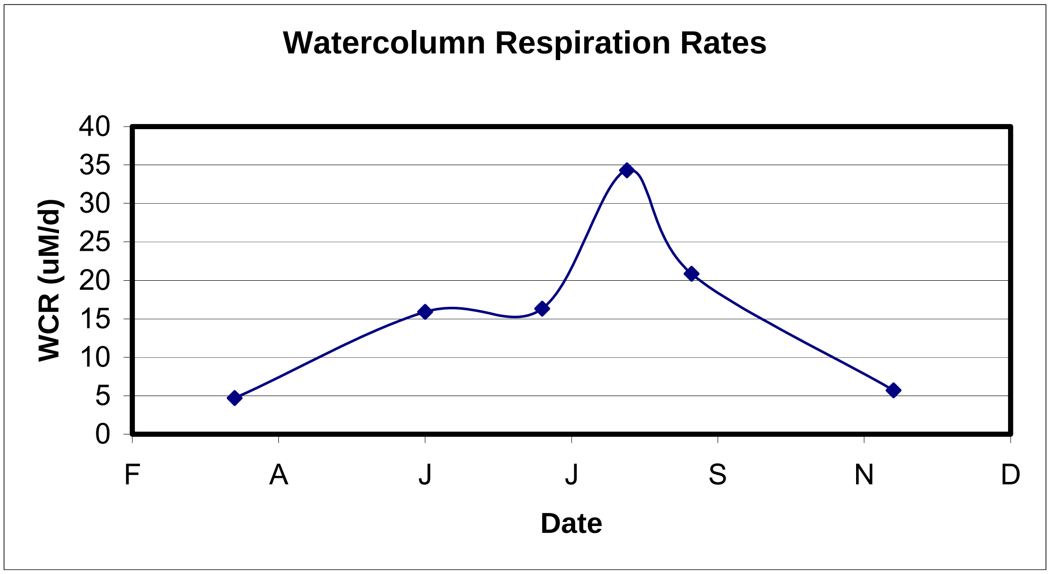


Figure VII-1. Average watercolumn respiration rates (micro-Molar/day) from water collected throughout the Popponesset Bay System (Schlezinger and Howes, unpublished data). Rates vary ~7 fold from winter to summer as a result of variations in temperature and organic matter availability.

Similar to other embayments in southeastern Massachusetts, the Slocums River and Little River 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 23-49 day deployment period that these parameters were below/above various benchmark concentrations (Tables VII-1, VII-2). These data indicate both the temporal pattern of minimum or maximum levels of these critical nutrient related constituents, as well as the intensity of the oxygen depletion events and phytoplankton blooms. However, it should be noted that the frequency of oxygen depletion needs to be integrated with the actual temporal pattern of oxygen levels, specifically as it relates to daily oxygen excursions.

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll a levels indicate nitrogen enrichment effects at all mooring sites within each estuary (Figures VII-3 through VII-10). Nitrogen levels within the upper and middle basins of the Slocums River were generally >0.6 and >0.5 mg TN L^{-1}, respectively. These levels are typically related to periodic oxygen depletion in many southeastern Massachusetts estuaries. However, total nitrogen (TN) levels in the lower Slocums River were generally only moderately enriched (<0.4 mg, N L^{-1}) and it appears that oxygen depletion in this region of the estuary is influenced by the water quality entering from the middle basin during ebbing tides. There was a strong gradient in chlorophyll-a levels from the headwaters to the tidal inlet of the Slocums River. Overall, chlorophyll levels also indicated a nitrogen enriched estuarine system with levels within the upper basin generally >10 ug/L and >20 ug/L for 20% of the 50 days of record. This was higher than the middle basin where levels >10 ug/L where observed for 36% of the record.

Chlorophyll-a levels were only moderate in the lower basin where levels >10 ug/L occurred only 25% of the time. It appears that phytoplankton generated in the upper and middle basins are being transported to the lower basin, causing organic matter enrichment effects in this basin. Oxygen conditions throughout the estuary showed generally similar levels of periodic oxygen depletion.

The oxygen records further indicate that the upper tidal reaches of the estuarine system has the largest daily oxygen excursion which further supports the assessment of nutrient enrichment as control on habitat health. The use of only the duration of oxygen below, for example 4 mg L^{-1}, can underestimate the level of nutrient enrichment effect 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 Slocums River is nitrogen enriched.

In contrast, Little River is primarily a salt marsh basin, naturally organic matter enriched, and is expected to exhibit periodic low oxygen at moderate to low nitrogen and chlorophyll-a levels. These patterns were documented for the Little River Estuary in the MEP analysis discussed below.

The dissolved oxygen and chlorophyll-a records indicate that much of the tidal reach of the Slocums River is currently under seasonal oxygen stress, consistent with nitrogen enrichment (Table VII-1). That the cause is eutrophication is supported by the moderate to high levels of chlorophyll-a, >15 µg/L 77%, 36% and 25% of the time for the upper, middle and lower basins, respectively (Table VII-2). Oxygen conditions and chlorophyll-a levels improved with decreasing distance to the tidal inlet, although all basins showed oxygen depletions below 5 mg L^{-1},and periodically below 4 mg L^{-1}. The observations of moderate to high nitrogen levels, moderate to high chlorophyll-a levels and periodic oxygen depletions to <4 mg L^{-1} all support the assessment that watershed nitrogen inputs are currently impairing habitat quality within the Slocums River, primarily through the process of nitrogen enrichment of estuarine waters. In contrast, Little River is presently supporting a low level of nitrogen enrichment, TN levels ~0.4 mg N L^{-1}, with associated low to moderate levels of chlorophyll-a. The difference in the nitrogen and chlorophyll-a levels and oxygen depletion status of this system compared to the Slocums River results from Little River being a salt marsh basin. A similar pattern was found in another Buzzards Bay sub-embayment, the Phinneys Harbor System. The Phinneys Harbor system contains a salt marsh dominated basin, the Back River, that is structurally similar to the present Little River basin. The Back River also exhibited oxygen depletions (to 3-4 mg/L), and similar low chlorophyll-a levels (general range 4-8 ug/L). This is consistent with it functioning primarily as a tidal salt marsh sub-basin. The low chlorophyll-a levels in both the Back River and Little River result from the near complete exchange of tidal waters on each tide (compared to the embayment basins), which prevents a significant "build-up" of phytoplankton biomass. The low oxygen levels in both systems are consistent with a salt marsh tidal creek where the organic matter enriched sediments support high levels of oxygen uptake at night thus depleting the overlying waters. While oxygen depletion to 3 mg/L would indicate impairment in an embayment like the Slocums River and Apponagansett Bay systems (and the Phinneys Harbor basin), it is consistent with the organically enriched nature of salt marsh creeks. A similar pattern in nitrogen, chlorophyll-a levels and oxygen depletion was observed in the Namskaket and Little Namskaket Salt Marshes (Town of Orleans), further supporting the assessment that these conditions within in the Little River basin are part of its natural function and therefore does not indicate habitat impairment for this type of estuarine basin. It is important to note that the uppermost reach of the Slocums River functions as a wetland dominated tidal river, much like the salt marsh creeks and basins just discussed. As a result, this portion of the Slocums River was assessed as a tidal wetland system, and the observed water quality indicators suggest high to moderately impaired habitat quality for this tidal reach, compared to the moderately to significantly impaired habitat within the middle and lower basins.

The assessments of habitat quality based upon the site-specific water quality analysis for both the Slocums River and Little River systems are consistent with the conclusions of the eelgrass, macroalgal and infaunal animal surveys discussed in sections below.

The embayment specific water quality results are as follows:

Slocums River Upper **(Figures VII-3 and VII-7):**
The "Upper" mooring was placed within the top third of the Slocums River estuary in water averaging 1.3 m in depth. This reach of the Slocums River functions primarily as a wetland dominated tidal river where oxygen depletions are typical of the systems organic matter enrichment. Dissolved oxygen concentrations dropped below the benchmarks of 6, 5, 4 and 3 mg L^{-1} for durations of 19.04, 6.57, 0.98 and 0.02 days respectively (Table VII-1). Diurnal variation was large, occasionally approaching 7 mg L^{-1}. Changes in both average daily dissolved oxygen and the extent of diurnal variation appeared to vary with tidal amplitude. The greatest diurnal variation and lowest average daily dissolved oxygen concentrations were often coincident with spring tides; the smallest diurnal variation and highest average daily dissolved oxygen concentrations were mostly coincident with neap tides. A similar, though more variable pattern, was also seen in the chlorophyll-a records where the benchmarks of >20 ug L^{-1} and >25 ug L^{-1} were exceeded for 21% and 7% of the deployment (Table VII-2). Nearly all instances of chlorophyll-a concentrations exceeding 20 ug L^{-1} occurred during neap tide. Thus, average daily dissolved oxygen and chlorophyll-a co-varied through time and both measures varied inversely with tidal amplitude. This suggests that during neap tides, when tidal flushing is at a minimum, phytoplankton is subjected to less dilution by the exchange of tidal water and may also increase in abundance in response to less diluted water column nutrient concentrations. Little variation in sediment oxygen uptake was observed with the tidal reach associated with the mooring, but chlorophyll-a concentrations generally decreased from the estuarine headwaters to the tidal inlet.

Slocums River Middle **(Figures VII-4 and VII-8):**
The mooring deployed within the middle basin of the system (Slocums River Mid) was located near the middle of the estuary near Pelegs Island at an average depth of 1.7 m. This basin functions primarily as a tidal embayment. Dissolved oxygen statistics were similar to those seen at the Upper station, though the deployments were not synoptic. Duration below the benchmarks of 5, 4 and 3 mg L^{-1} was 6.27, 1.92 and 0.13 days (Table VII-1), respectively. The chlorophyll-a levels were lower than in the upper tidal reach, with levels >15 ug L^{-1} equal to 15% vs. 45%, >20 ug L^{-1} equal to 3% vs. 21%, >25 ug L^{-1} equal to 0% vs. 7% (Table VII-2), for the middle and upper stations respectively. The overall pattern of variation over diurnal and lunar cycles was similar to that seen at the Upper station, though much less pronounced.

Slocums River Lower **(Figures VII-5 and VII-9):**
The Slocums River Lower mooring was located south of the entrance to the tributary basin of Giles Creek (primarily a salt marsh basin) and within the main channel of the estuary under an average of 1.3 m of water. Deployed synoptically with the Slocums River Middle mooring, the Lower station mooring displayed oxygen trends and statistics similar to those seen at the Middle station. The duration of dissolved oxygen concentrations less than the <5, <4 and <3 mg L^{-1}

benchmarks were 6.88, 1.41 and 0.09 days, respectively. The chlorophyll-a record was truncated as a result of continued fouling by drift macroalgae algae, primarily *Ulva* and *Cladophora* transported on the ebb tide from the dense accumulations just up-gradient within the middle basin. Nonetheless, the statistics from the recovered data suggests conditions similar to those seen at the middle station. Durations above benchmarks were nearly the same for >5, >20 and >25 ug L^{-1}, while a 30% and 50% decrease in duration was observed at the >10 ug L^{-1} (25% of deployment) and >15 ug L^{-1} (8% of deployment) benchmarks. Using the available calibration points at the end of the record for comparison, the lower basin appears to support slightly lower chlorophyll levels, but follows the same general pattern as the middle basin. It appears that the large middle basin of the Slocums River is sufficient to allow development of phytoplankton (and macroalgal) blooms which can be transported to the down gradient estuary that is much better flushed.

Little River **(Figures VII-6 and VII-10):**

The Little River mooring was located south of Cedar Island and west of the channel draining the main basin. Levels of oxygen depletion were greater than within the Slocums River Estuary, dropping below 4 mg L^{-1} more than 10% (6.52 days, Table VII-1) of the time. Even lower oxygen depletions to 2-3 mg L^{-1} were periodically observed (1.18 days). In contrast, chlorophyll concentrations were low. Chlorophyll-a concentrations >10 ug L^{-1} occurred only 7% of the time and >15 ug L^{-1} less than 1% of the time. The main basin was very shallow, ~ 0.3 m at low tide. In addition the main basin is wide and flat and exchanges tidal water through a relatively narrow inlet. These two factors create a situation where organic matter deposition (phytoplankton and salt marsh detritus) rates are enhanced and sediment oxygen uptake is the dominant process controlling depletion of water column oxygen levels. Atmospheric re-aeration of the water column is minimized by low current velocities. Hence, oxygen levels are generally depressed below air equilibration and oxygen minima are influenced by variations in tide range. These conditions are typical of salt marsh dominated tidal ponds.

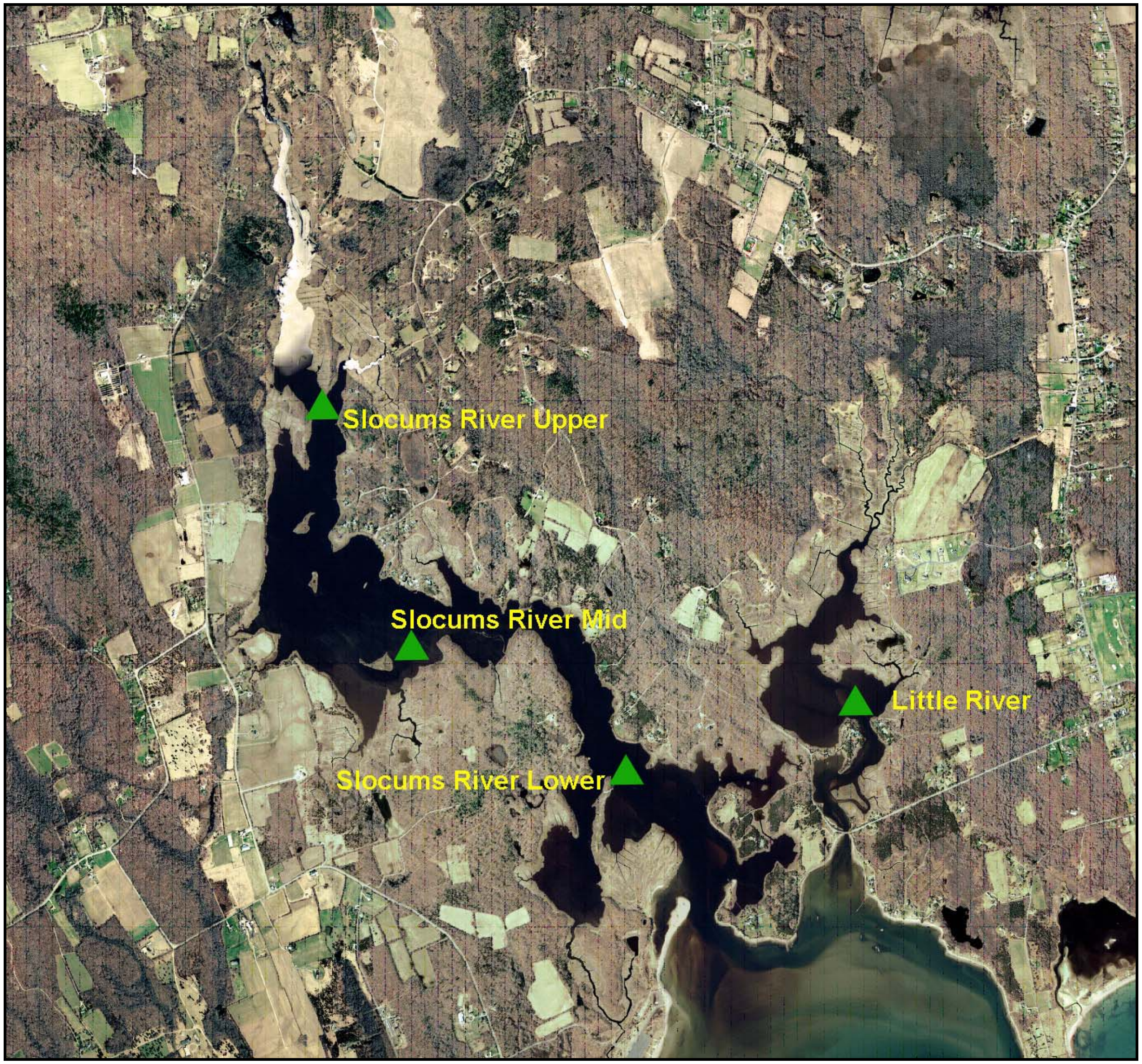


Figure VII-2. Aerial Photograph of the Slocums River and Little River systems in the Town of Dartmouth, MA. showing locations of Dissolved Oxygen mooring deployments conducted in the Summer of 2003 and 2004.

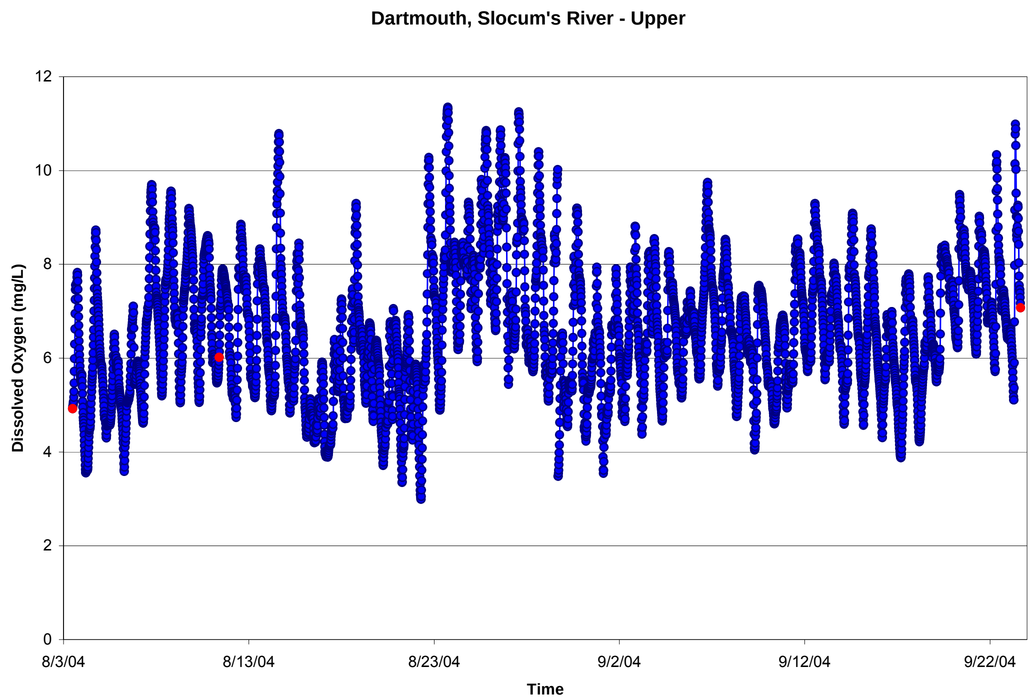


Figure VII-3. Bottom water record of dissolved oxygen at the Slocums River Upper station, Summer 2004. Calibration samples represented as red dots.

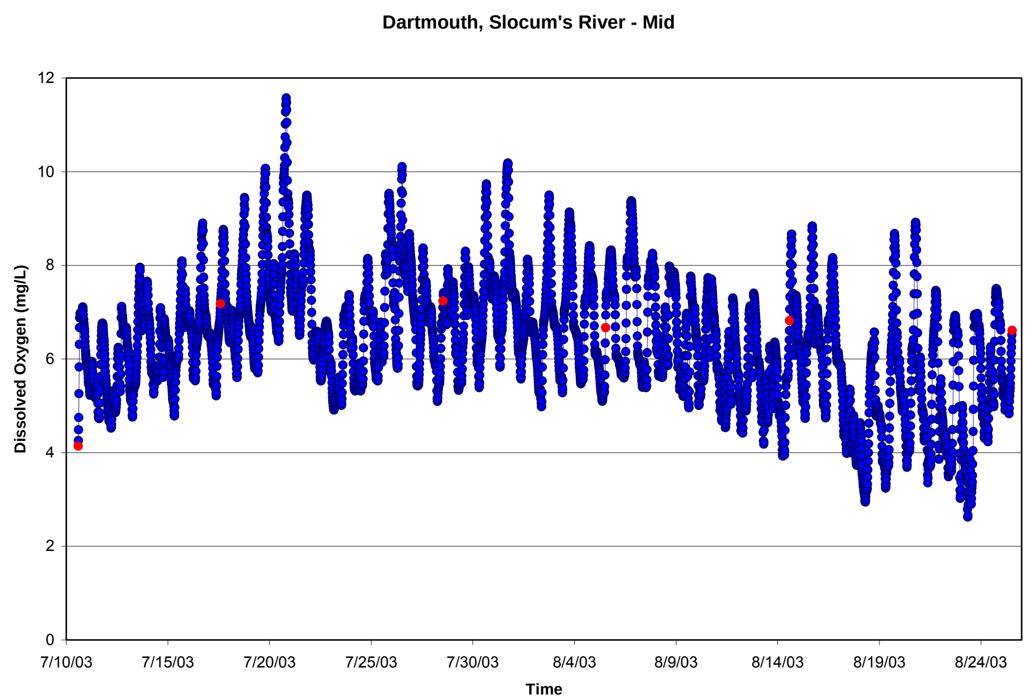


Figure VII-4. Bottom water record of dissolved oxygen at the Slocums River station, Summer 2003. Calibration samples represented as red dots.

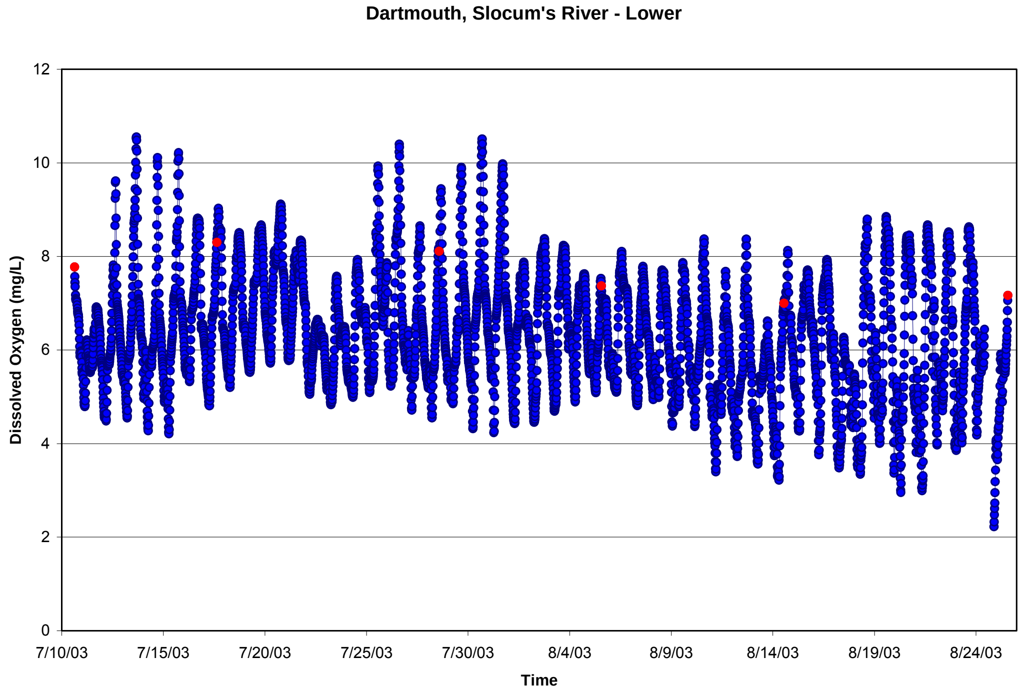


Figure VII-5. Bottom water record of dissolved oxygen at the Slocums River Lower station, Summer 2003. Calibration samples represented as red dots.

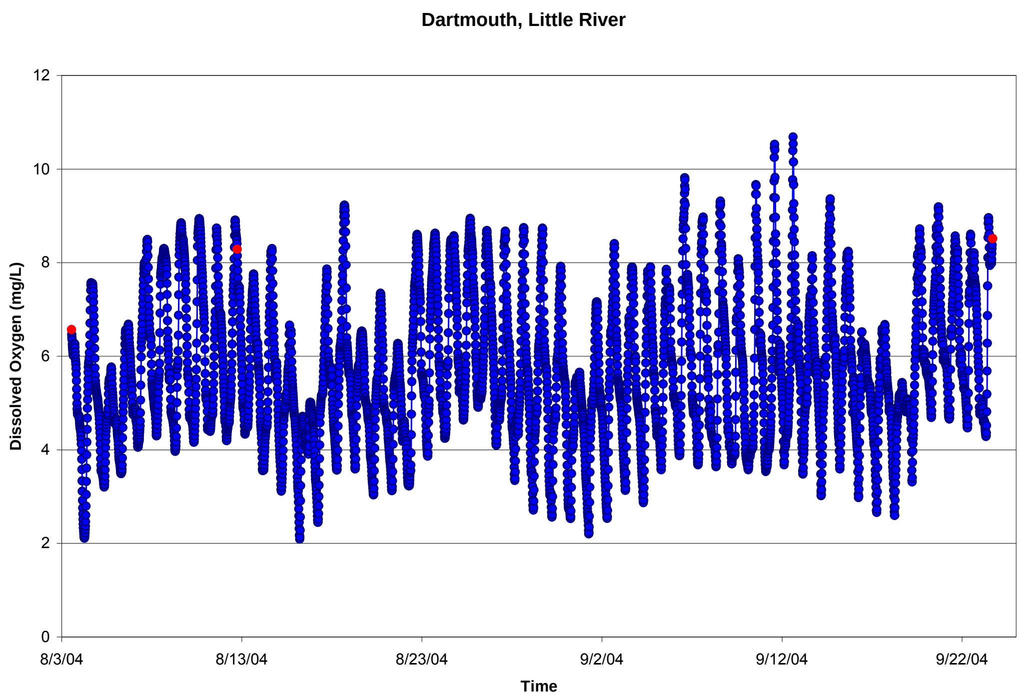


Figure VII-6. Bottom water record of dissolved oxygen at the Little River station, Summer 2004. Calibration samples represented as red dots.

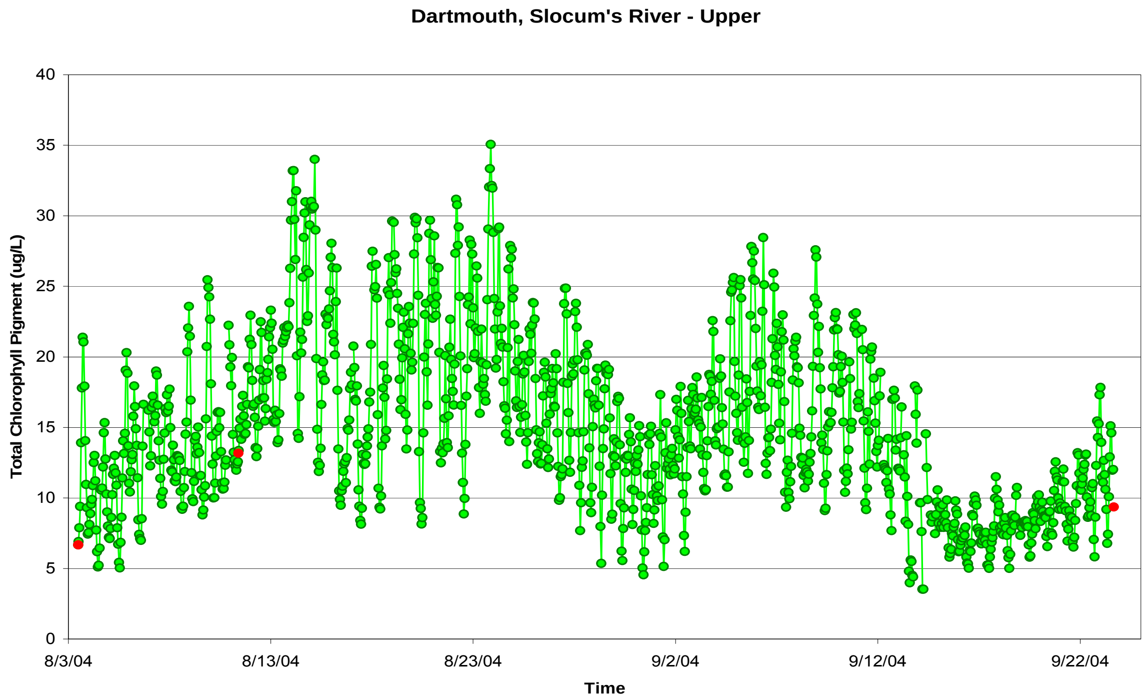


Figure VII-7. Bottom water record of Chlorophyll-*a* in the Slocums River Upper, Summer 2004. Calibration samples represented as red dots.

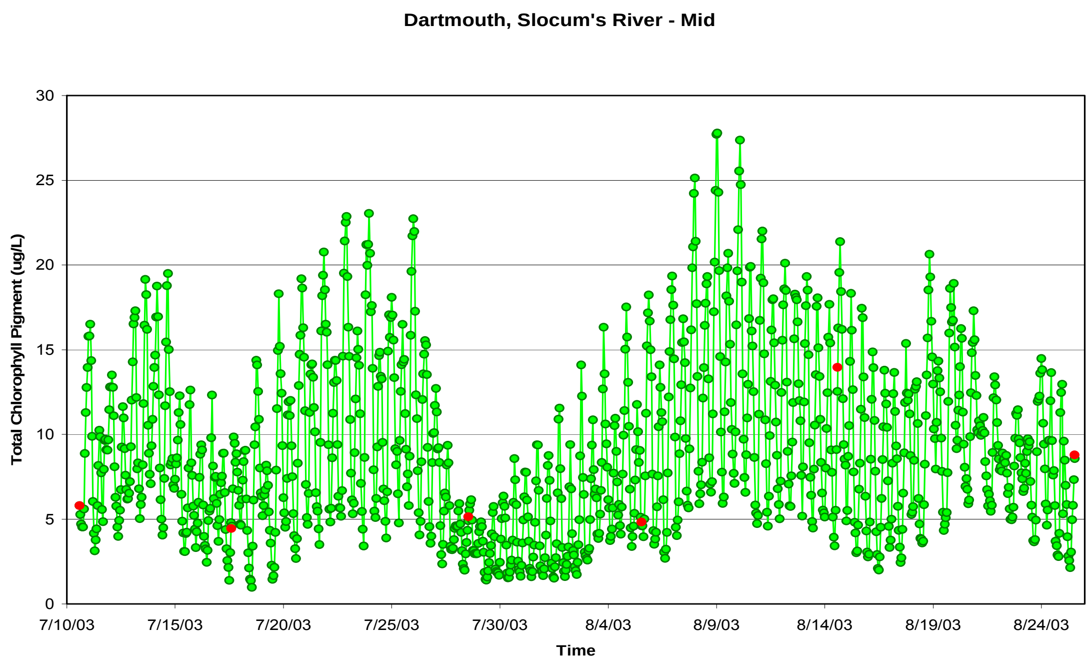


Figure VII-8. Bottom water record of Chlorophyll-*a* in the Slocums River Middle station, Summer 2003. Calibration samples represented as red dots.

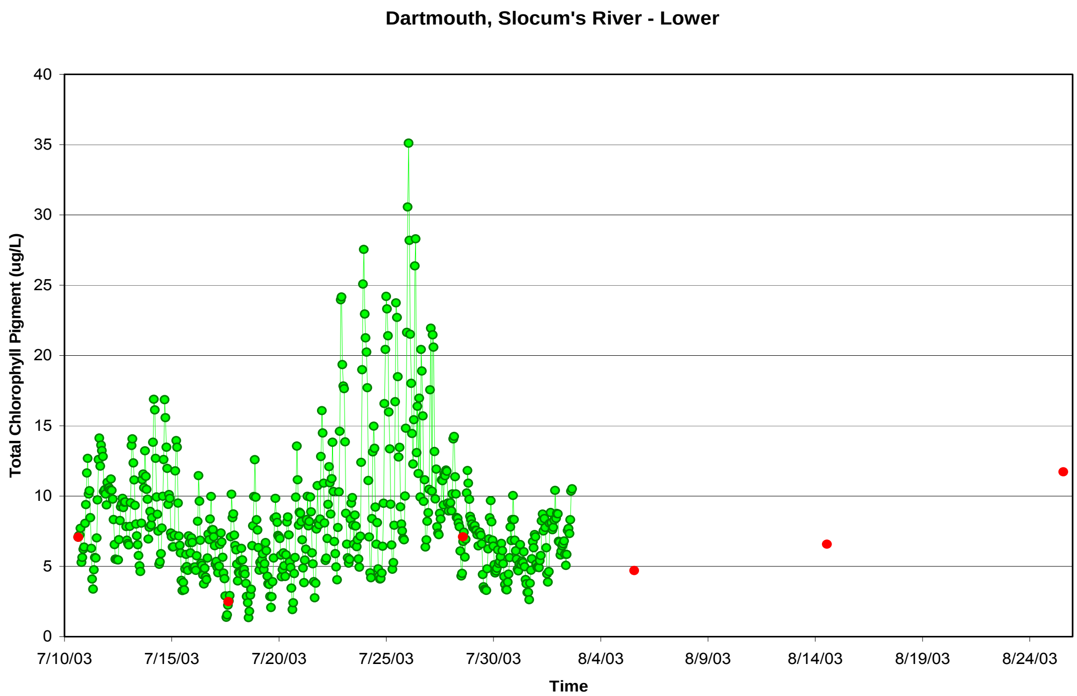


Figure VII-9. Bottom water record of Chlorophyll-*a* in the Slocums River Lower station, Summer 2003. Calibration samples represented as red dots.

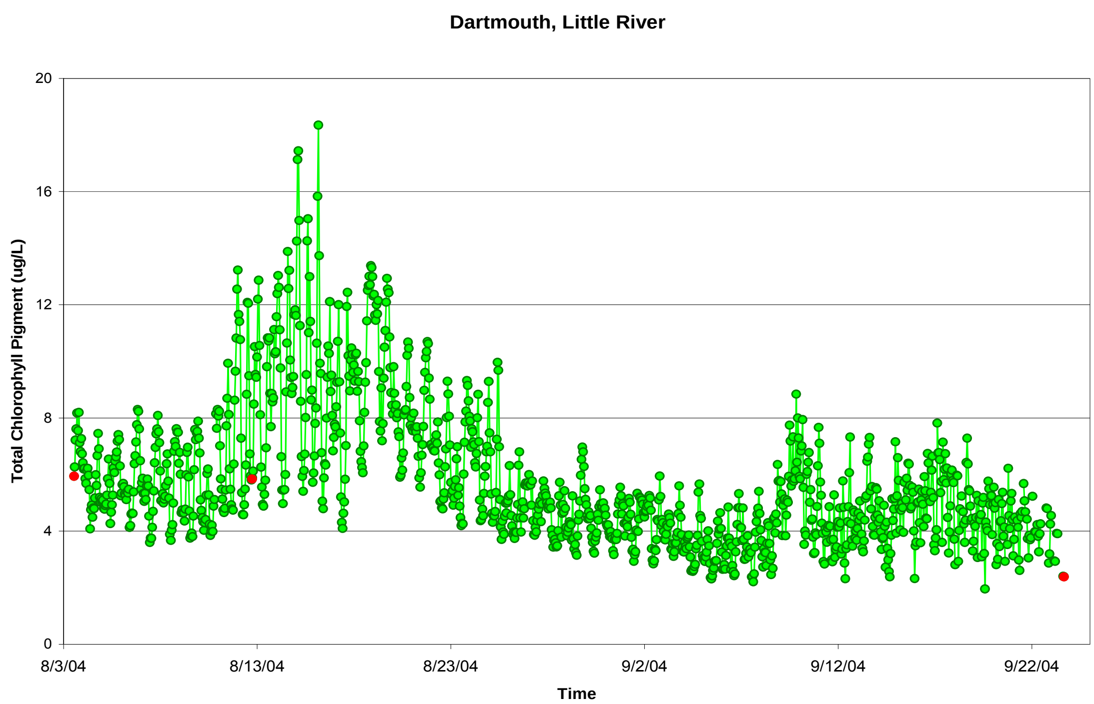


Figure VII-10. Bottom water record of Chlorophyll-*a* in the Little River station, Summer 2004. Calibration samples represented as red dots.

Table VII-1. Amount of time during deployment of in situ sensors that bottom water oxygen levels were below various benchmark oxygen levels. Data collected by the Coastal Systems Program, SMAST in association with the Turn the Tide Project.

Mooring ID.	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)
Slocum's River - Upper	8/3/2004	9/23/2004	51.1	19.04	6.57	0.98	0.02
			Mean	0.32	0.17	0.11	0.02
			Min	0.01	0.01	0.05	0.02
			Max	1.63	0.51	0.20	0.02
			S.D.	0.28	0.14	0.05	NA
Slocum's River - Mid	7/10/2003	8/25/2003	46.0	18.54	6.27	1.92	0.13
			Mean	0.30	0.17	0.11	0.03
			Min	0.01	0.01	0.01	0.01
			Max	1.59	0.93	0.44	0.05
			S.D.	0.28	0.21	0.13	0.02
Slocum's River - Lower	7/10/2003	8/25/2003	45.5	20.46	6.88	1.41	0.09
			Mean	0.37	0.13	0.07	0.02
			Min	0.01	0.01	0.01	0.01
			Max	0.90	0.42	0.17	0.06
			S.D.	0.19	0.10	0.05	0.03
Little River	8/3/2004	9/23/2004	51.1	32.03	20.00	6.52	1.18
			Mean	0.57	0.34	0.16	0.09
			Min	0.01	0.01	0.01	0.01
			Max	1.80	0.92	0.30	0.20
			S.D.	0.39	0.18	0.09	0.06

Table VII-2. Duration (% of deployment time) that chlorophyll a levels exceed various benchmark levels within the embayment system. "Mean" represents the average duration of each event over the benchmark level and "S.D." its standard deviation. Data collected by the Coastal Systems Program, SMAST in association with the Turn the Tide Project.

Embayment	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)
Slocums River								
Slocum's River - Upper	**8/3/2004**	**9/23/2004**	**49.8**	**99%**	**77%**	**45%**	**21%**	**7%**
Mean Chl Value = 15.14 ug/L			Mean	8.26	0.82	0.30	0.21	0.13
			Min	0.04	0.04	0.04	0.04	0.04
			Max	27.46	6.63	1.96	0.79	0.38
			S.D.	10.83	1.32	0.32	0.18	0.09
Slocum's River - Mid	**7/10/2003**	**8/25/2003**	**46.0**	**75%**	**36%**	**15%**	**3%**	**0%**
Mean Chl Value = 9.09 ug/L			Mean	0.55	0.24	0.17	0.10	0.07
			Min	0.04	0.04	0.04	0.04	0.04
			Max	3.63	0.46	0.33	0.21	0.08
			S.D.	0.64	0.10	0.08	0.06	0.02
Slocum's River - Lower	**7/10/2003**	**8/25/2003**	**23.1**	**80%**	**25%**	**8%**	**4%**	**1%**
Mean Chl Value = 8.05 ug/L			Mean	0.56	0.17	0.13	0.11	0.10
			Min	0.04	0.04	0.04	0.04	0.08
			Max	3.17	0.71	0.29	0.21	0.13
			S.D.	0.67	0.14	0.09	0.07	0.02
Little River								
Little River Mooring	**8/3/2004**	**9/23/2004**	**49.8**	**52%**	**7%**	**0%**	**0%**	**0%**
Mean Chl Value = 5.70 ug/L			Mean	0.29	0.19	0.07	N/A	N/A
			Min	0.04	0.04	0.04	0.00	0.00
			Max	5.04	0.63	0.08	0.00	0.00
			S.D.	0.60	0.13	0.02	N/A	N/A

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical data was conducted for the Slocums River and Little River Embayment Systems in order to assess the quality and stability of this critical habitat. The primary data was provided by the DEP Eelgrass Mapping Program based upon field surveys conducted in 1995 and 2001 and analysis of 1951 aerial photographs by MassDEP, as part of the MEP technical effort (Figure VII-11). The 1951 analysis used available aerial photos to reconstruct the eelgrass distribution prior to the recent residential development of the watershed (Figure VII-12). The 1951 data were only anecdotally validated, while the 1995 and 2001 maps were field validated. In addition, three other sets of survey data exist for these systems: (1) field observations during summer and fall 2004 and 2005 by the MEP Technical Team, (2) detailed field surveys in 2003 and 2005 by the Turn the Tide Project for the Restoration of Dartmouth's Estuaries and (3) a survey (Costa 1988) based upon aerial photography (1971, 1974, 1975, 1981) with field observations in 1985-1986. Analysis of available aerial photos from 1951 was conducted by MassDEP to reconstruct the eelgrass distribution prior to any substantial development of the watershed.

The primary use of the eelgrass data is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets provides a view of temporal trends in eelgrass distribution from 1951 to 1985 to 1995 to 2001-2005 (Figure VII-11, 12, 13). These data provide a significant record from which to assess temporal changes in eelgrass throughout the Slocums and Little River Embayment Systems. This temporal information can be used to determine the stability of the eelgrass community, as well as the potential area of eelgrass habitat that would be recovered as management actions are undertaken.

At present, the Little River and Slocums River Estuaries do not support eelgrass habitat. Little River is predominantly a salt marsh basin and the absence of eelgrass is typical of the basin configuration, water quality and hydrodynamics of this type of coastal system. There is no historical evidence of eelgrass coverage within this basin based on the 1951 analysis or any of the field surveys from 1985-2005. This conclusion is also supported by the absence of eelgrass in this system in 1985 (at very low watershed N loading), when eelgrass patches were still extant in the lower Slocums River (at much higher N loading). It should be noted that the absence of eelgrass in similar salt marsh dominated basins is typical throughout southeastern Massachusetts, for example Mill Creek in Lewis Bay, Upper Broad Marsh River in Wareham River Estuary, Namskaket Creek, and Back River in the Phinneys Harbor System. As a result of these findings, management of the Little River Estuary should focus on infaunal habitat quality.

It contrast, the Slocums River Estuary has historically supported eelgrass. The 1951 analysis indicates 2 small beds in the lower basin. The locations of these beds (Figure VII-13) are in shallow water flanking the deeper channel running from the inlet to the middle reach, along the eastern side of the basin (Chapter VI). Remnants of the southern bed were observed in the 1985 field survey, lending support to the 1951 analysis. However, most of the eelgrass coverage of 1951 was lost by 1985 survey and by the 1995 survey no eelgrass was observed in this system. The absence of eelgrass has been confirmed by surveys in 2001, 2003, 2005. As a result of these findings, management of the Slocums River Estuary should focus on restoration of eelgrass habitat in the lower basin and infaunal habitat quality within the upper reaches of the system.

The loss of historical eelgrass beds is expected given the moderate chlorophyll-a levels, low dissolved oxygen levels and enrichment of water column nitrogen concentrations within this system. The historical beds appear to have been restricted to the margins of the lower basin and were not observed in the deeper channel which runs from the tidal inlet along the eastern shore. Eelgrass was also not observed in the region of the tidal inlet due to the unstable substrate (shifting sands) and continuing alteration of the western barrier spit by coastal processes.

The temporal surveys also indicate that eelgrass habitat loss within the Slocums River Embayment System is a moderately recent phenomenon. The decline of eelgrass beds appears to have occurred primarily between 1951 and 1985 and continued to 1995. The current absence of eelgrass throughout the Slocums River is consistent with the depth of the basin and the chlorophyll levels measured by the MEP moorings (Section VIII.2) and the BayWatcher Program ~10 ug/L, as well as the total nitrogen levels 0.37-0.38 mg N L^{-1} in the lower basin (higher than the 0.35 threshold for eelgrass in nearby West Falmouth Harbor) and generally >0.5 mg N L^{-1} in the middle and upper reaches. The timing of the eelgrass habitat loss is also consistent with recent changes in land-use within the watershed. In addition, the spatial pattern of bed loss is consistent with the typical pattern of habitat decline related to increasing nitrogen loading from a watershed. The pattern is for highest nitrogen levels to be found within the innermost basins, with concentrations declining moving toward the tidal inlet. This pattern is also observed in nutrient related habitat quality parameters like phytoplankton, turbidity, oxygen depletion, etc. The consequence is that eelgrass bed decline typically follows a pattern of loss in the innermost basins (and sometimes also from the deeper waters of other basins) first. The temporal pattern is a “retreat” of beds toward the region of the tidal inlet.

This appears to be the pattern of retreat observed within the Slocums River Estuary. It appears that the inland most beds (those in the lower basin of the Slocums River) were lost before the decline of the large bed in the outer basin just outside of the inlets to the Slocums and Little Rivers. Only the outermost beds presently remain. This loss of beds from inshore to the offshore, suggests that the nutrient enriched waters of the Slocums River influences the outer beds extant within the ebb tide "plume". Although some regions of the Slocums River presently support healthy infaunal habitat (tolerant of higher levels of enrichment), this system appears to have become sufficiently nutrient enriched to significantly impair its eelgrass habitat. However, it is likely that if nitrogen loading were to decrease that eelgrass could be restored in the lower basin to the 1951 pattern, at a minimum.

Further evidence of nitrogen related eelgrass decline can be seen in the stability of the eelgrass beds just outside of the tidal inlet within the outer basin bounded by Mishaum Point and Barneys Joy Point. In each of the offshore assessments (1951, 1985, 1995, 2001) the major beds along the outer margin of both points appeared stable with the same areal coverage.

Other factors which influence eelgrass bed loss in embayments do not appear to be major factors in the Slocums River Embayment System. Eelgrass loss in this system seems completely in-line with nitrogen enrichment. However, a brief listing of these non-nitrogen related factors is useful. Eelgrass bed loss does not seem to be directly related to mooring density, as the region of documented eelgrass loss, supports a very low density of boat moorings, and there are very few moorings within the system overall. Similarly, pier construction and boating pressure may sometimes add additional stress but seem to be relatively minor factors in the overall system. It is not possible at this time to determine the potential effect of shell fishing on eelgrass bed distribution, although it is mediated by periodic closures in some of the shallower areas.

Based on the available data, it is possible to make a conservative estimate of the extent of eelgrass habitat that can be recovered through watershed nitrogen management. Eelgrass coverage in 1951 is typically used by the MEP, as the benchmark for recovery from nitrogen enrichment, since watershed nitrogen loading to most of the regions estuaries was relatively low until recent decades. Based upon the 1951 coverage data, it appears that a conservative estimate of the amount of eelgrass habitat that would be restored if nitrogen management alternatives were implemented would be approximately 8 acres (Table VII-3), although a greater acreage of recovery is likely as the outer basin (bounded by Mishaum Point and Barneys Joy Point) should also see an expansion of surviving eelgrass beds. Recovery of eelgrass within this down-gradient outer basin, should result as the major nitrogen source to this basin is the Slocums River ebb tide discharge.

Based upon the documented loss of eelgrass coverage in the lower basin of the Slocums River Estuary, this basin is classified as significantly impaired (SI) for eelgrass habitat. The outer basin would be classified as moderately impaired, as it still supports some eelgrass habitat, although this has declined in recent decades. The difference between the lower basin of the Slocums River and the offshore basin (outer basin) stems from the greater dilution of nitrogen enriched Slocums River waters by low nitrogen Buzzards Bay waters within the outer basin. The spatial and temporal pattern of the declining eelgrass habitat associated with the Slocums River Estuary is consistent with the results of the water quality and benthic infauna analysis and the observed eelgrass loss is typical of nutrient enriched shallow embayments (see below).

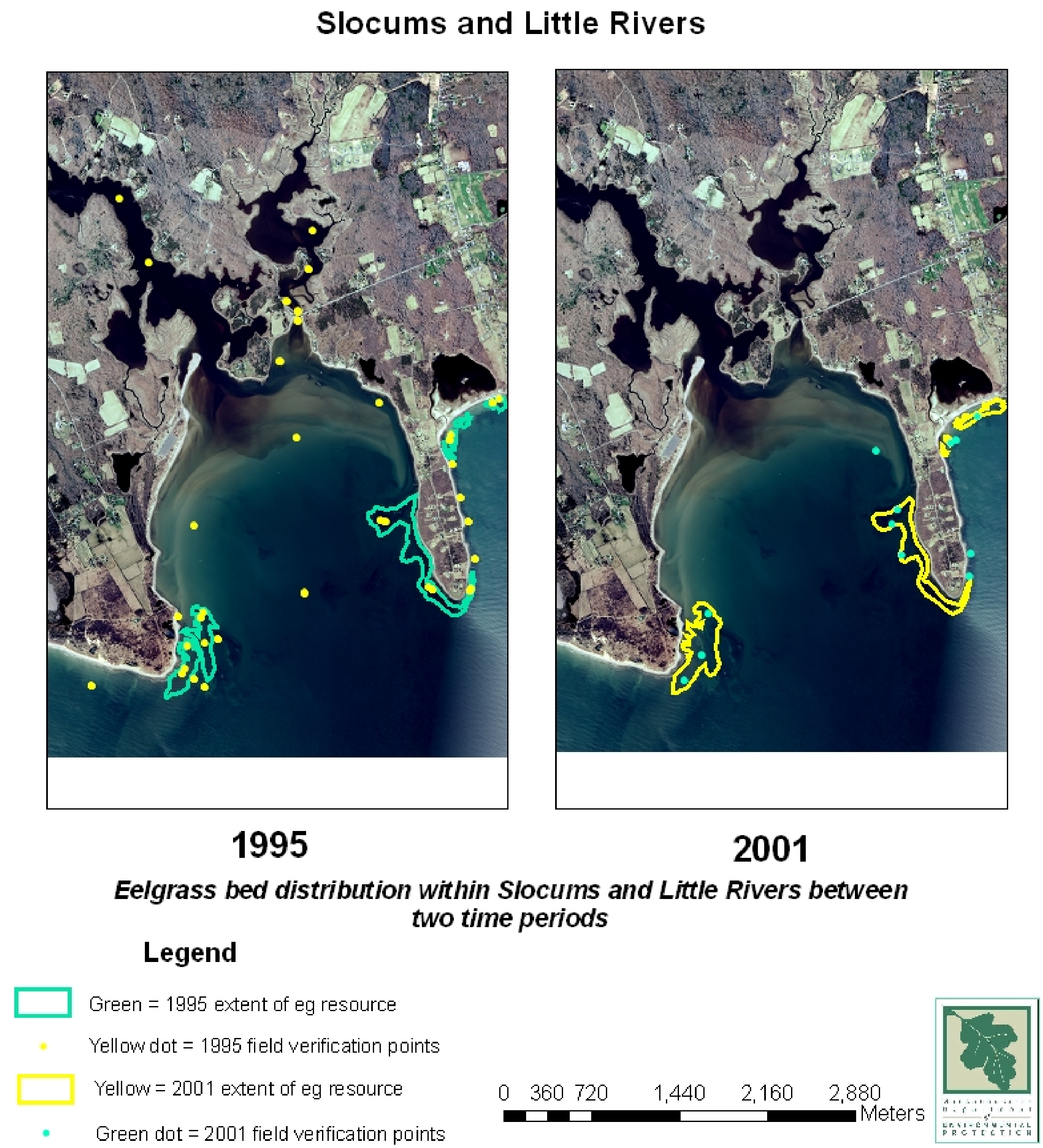


Figure VII-11. Eelgrass bed distribution within the Slocums and Little Rivers System. The 1995 coverage is depicted by the green outline inside of which circumscribes the eelgrass beds. The yellow (2001) areas were mapped by DEP. All data was provided by the DEP Eelgrass Mapping Program.

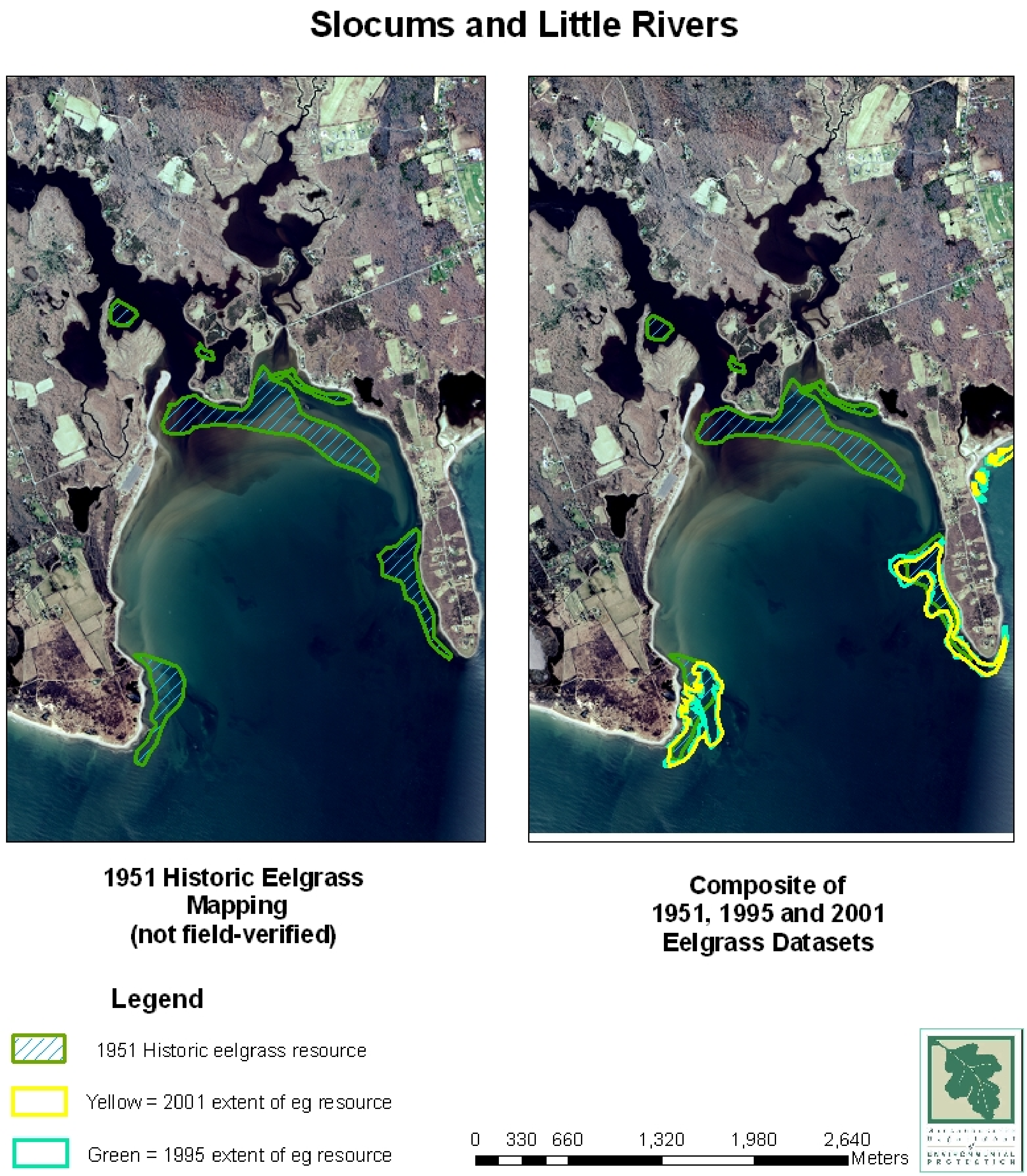


Figure VII-12. Eelgrass bed distribution within the Slocums and Little Rivers System. The 1951 coverage is depicted by the dark green outline (hatched area) inside of which circumscribes the eelgrass beds. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were mapped by DEP. All data was provided by the DEP Eelgrass Mapping Program.

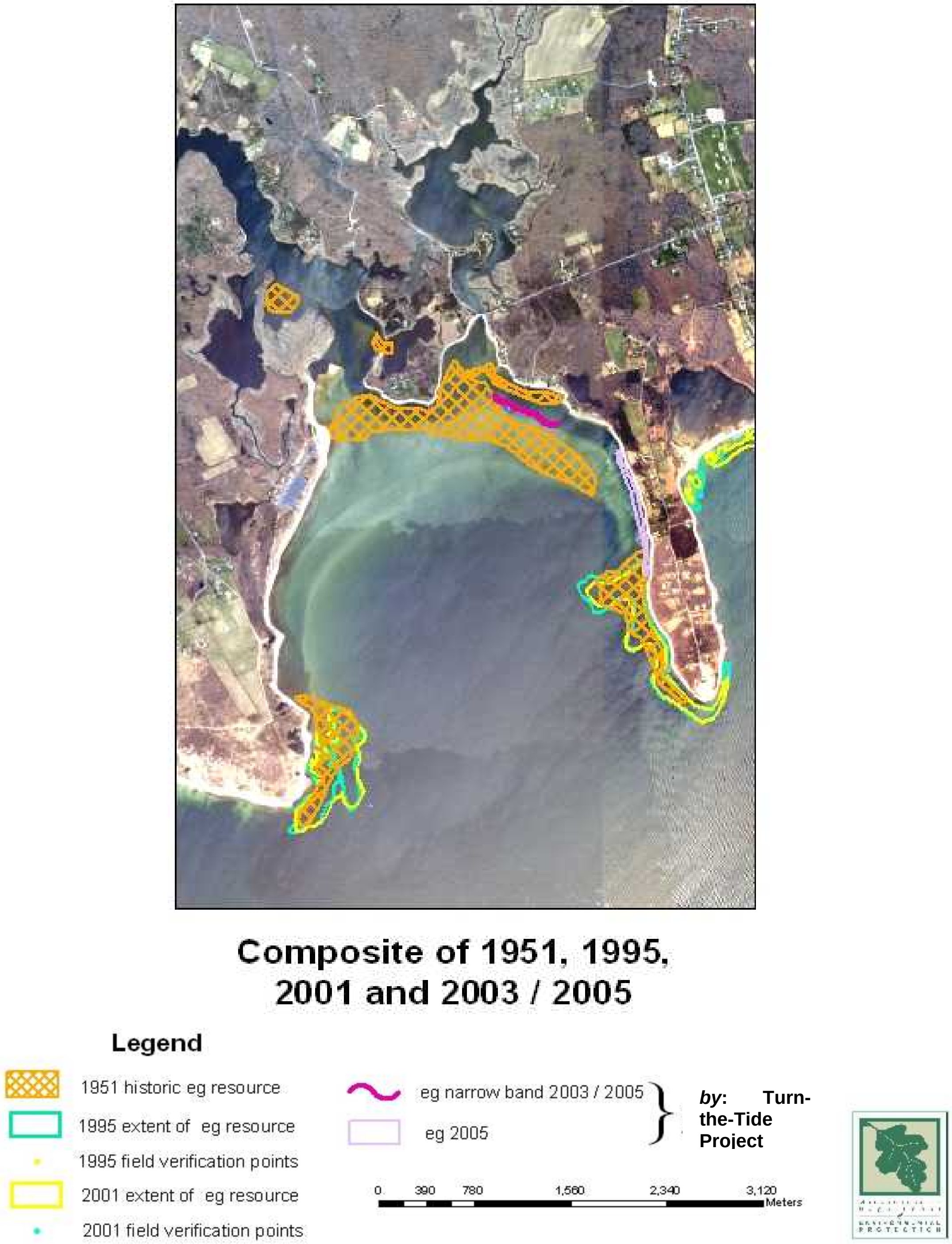


Figure VII-13. Eelgrass bed distribution within the Slocums and Little Rivers System. The 1951 coverage is depicted by the orange outline (hatched area), which circumscribes the eelgrass beds. In the composite photograph, the light green outline depicts the 1995 eelgrass coverage and the yellow outlined areas circumscribe the eelgrass coverage in 2001. The 1995 and 2001 areas were mapped by MassDEP, 2003 and 2005 mapping by the Turn the Tide Project a partnership of the Town of Dartmouth, Lloyd Center for the Environment, Coalition for Buzzards Bay and Coastal Systems Program-SMAST.

Table VII-3. Changes in eelgrass coverage in the Slocums River and Little River systems within the Town of Dartmouth over the past half century. 1951 analysis by MassDEP Mapping Program (C. Costello). There were only a few isolated patches of eelgrass near the inlet in 1985 and presently the Slocums River Estuary does not support eelgrass habitat.

Temporal Change in Eelgrass Coverage						
Estuary	1951[1] (Acres)	1995[1] (Acres)	2001[1] (Acres)	2003[2] (Acres)	2005[2] (Acres)	% Loss 1951-1995
Slocums River	8.4	0	0	0	0	100%
Little River	0	0	0	0	0	NA[3]
Outer Basin	142.1	67.5	68.3	--	--	52%

1- Data and analysis by MassDEP Mapping Program. 2- Data from Turn the Tide (partnership of Town of Dartmouth, Lloyd Ctr, Coalition for Buzzards Bay, Coastal Systems Program at SMAST).
3- No evidence that Little River has historically supported eelgrass habitat.

VII.4 BENTHIC INFAUNA ANALYSIS

Quantitative sediment sampling was conducted at 14 locations throughout the Slocums River and 5 locations in the Little River estuarine systems (Figure VII-14). In some cases multiple assays were conducted. In all areas and particularly those that do not support eelgrass beds, benthic animal indicators can be used to assess the level of habitat health from healthy (low organic matter loading, high D.O.) to highly stressed (high organic matter loading-low D.O.). The basic concept is that certain species or species assemblages reflect the quality of the habitat in which they live. Benthic animal species from sediment samples are identified and ranked as to their association with nutrient related stresses, such as organic matter loading, anoxia, and dissolved sulfide. The analysis is based upon life-history information and animal-sediment relationships (Rhoads and Germano 1986). Assemblages are classified as representative of healthy conditions, transitional, or stressed conditions. Both the distribution of species and the overall population density are taken into account, as well as the general diversity and evenness of the community. It should be noted that, given the loss of eelgrass beds, the Slocums River System is clearly impaired by nutrient overloading. However, to the extent that it can still support healthy infaunal communities, the benthic infauna analysis is important for determining the level of impairment (moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

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

The Infauna Study indicated that the Slocums River is presently supporting a range of healthy to significantly impaired habitat for infaunal animal communities (Table VII-4), while the Little River Estuary is generally supportive of healthy habitat. It should be kept in mind that assessment of infaunal habitat quality is based upon both the infaunal community characteristics (as noted above), the type of ecosystem (basin, salt marsh, eelgrass bed) and stresses represented by salinity variation, macroalgal accumulations and organic matter enrichment (e.g. nitrogen loading).

The habitat quality of the uppermost reach of the Slocums River Estuary is generally reflective of its function as a tidal river with bordering wetlands. This upper reach of the estuary is strongly influenced by the large freshwater inflows from the Paskamanset River and Destruction Brook and its related function as a wetland dominated tidal river. The upper reach of the river is nitrogen enriched, but at levels generally found in healthy salt marsh systems within the region, consistent with the low accumulation of macroalgae (generally in patches) within this estuarine reach. The infaunal community was consistent with its wetland dominated tidal river status, with moderate numbers of individuals and species, with high diversity and Eveness. The dominance by oligochaetes (small worms) and presence of some amphipods indicates organic enrichment, which is also reflected in the soft mud which forms most of the bottom sediments in this reach of the River. It is also clear that the large freshwater inflow represents a "stress" in this environment as it also contains fresh/brackish water invertebrates and appears to be transitional between fresh and estuarine habitat. The presence of the stress indicator species *Cyathura polita,* which is tolerant of the salinity stress, helps to define this as a wetland influenced sub-basin (this species was found in a similar environment in the Mashpee River in Popponesset Bay and the upper Agawam River in Wareham River). The interacting influences of nutrient enrichment, salinity and wetland effects in this shallow tidal environment, underscores the need for the use of multiple indicators in determining habitat health.

The middle basin, approximately between stations 5 and 9 in Figure VII-14, is presently supporting significantly impaired infaunal habitat. This assessment is based upon the low to moderate diversity and eveness of the community and the low to moderate numbers of species. While the number of individuals was generally high, "blooms" of opportunistic species elevated the numbers thereby indicating organic enrichment and disturbance. During the summer, an amphipod mat was observed within the lower region of this basin, indicative of nitrogen enrichment. Organic enrichment indicators typically dominated the community and there was variability in the numbers of individuals, suggesting localized disturbance, likely from periodic accumulation of drift algae.

The lower basin is comprised of 3 components, the salt marsh basin of Giles Creek, small tributary coves and the main deep channel. The basin of Giles Creek supports an infaunal community typical of a salt marsh basin, but does contain patches of drift algae (Ulva). The drift algae appear to be causing localized negative effects on the community that is covered. It is not clear the extent to which these drift algae grow within this basin or are transported from the middle basin and accumulate in the upper region of Giles Creek. The tributary coves to the east and west of the main channel (Chapter VI) are presently also supporting moderately impaired habitat. However, it appears that the habitat impairment is again associated with depositional areas where drift macroalgae periodically accumulate and low oxygen waters discharging from the middle basin possibly reach. The main channel, which does not accumulate macroalgae but has the same water quality as the tributary coves supports high quality nutrient related infaunal habitat, with high species diversity and eveness, high numbers of species and moderate numbers of individuals. The species were evenly distributed among polychaetes, crustaceans and mollusks, with deep deposit feeders evident. However, habitat within the lowermost reach near the tidal inlet is affected by the shifting substrate related to coastal processes that modify the tidal inlet and barrier beach. Overall, the lower reach of the Slocums River is supporting high infaunal habitat quality with small patches of moderate impairment associated with macroalgal accumulation, likely from transport from the large areas of accumulation within the middle basin.

The Little River Estuary is predominantly a salt marsh dominated tidal basin. As a consequence, this system has infaunal communities consistent with a wetland dominated organic matter enriched estuarine sediment, with moderate to high numbers of individuals and species and generally moderate to high diversity and eveness. The lowermost reach of this system is a tidal channel supporting the highest number of species within the Slocums and Little River complex. The assessment of high quality infauna habitat is consistent with the generally low total nitrogen and chlorophyll-a levels and oxygen depletion evident, but typical of salt marsh basins. Significantly, accumulations of drift macroalgae were not typical of this basin, with macroalgae present primarily as attached forms, e.g. *Codium, Enteromorpha, Fucus* (see below).

Overall, the infaunal habitat quality throughout the Slocums River and Little River Estuaries was consistent with the distribution of drift and attached macroalgae, as well as the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in these systems. Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to wetland dominated or tidal embayment dominated. Based upon this analysis it is clear that infaunal habitat within the middle reach of the Slocums River is significantly impaired as a consequence of organic matter nitrogen enrichment, particularly within the middle basin, and infaunal restoration should focus on this region. In contrast, the Little River Estuary is generally showing high quality infaunal habitat for a salt marsh dominated tidal basin.

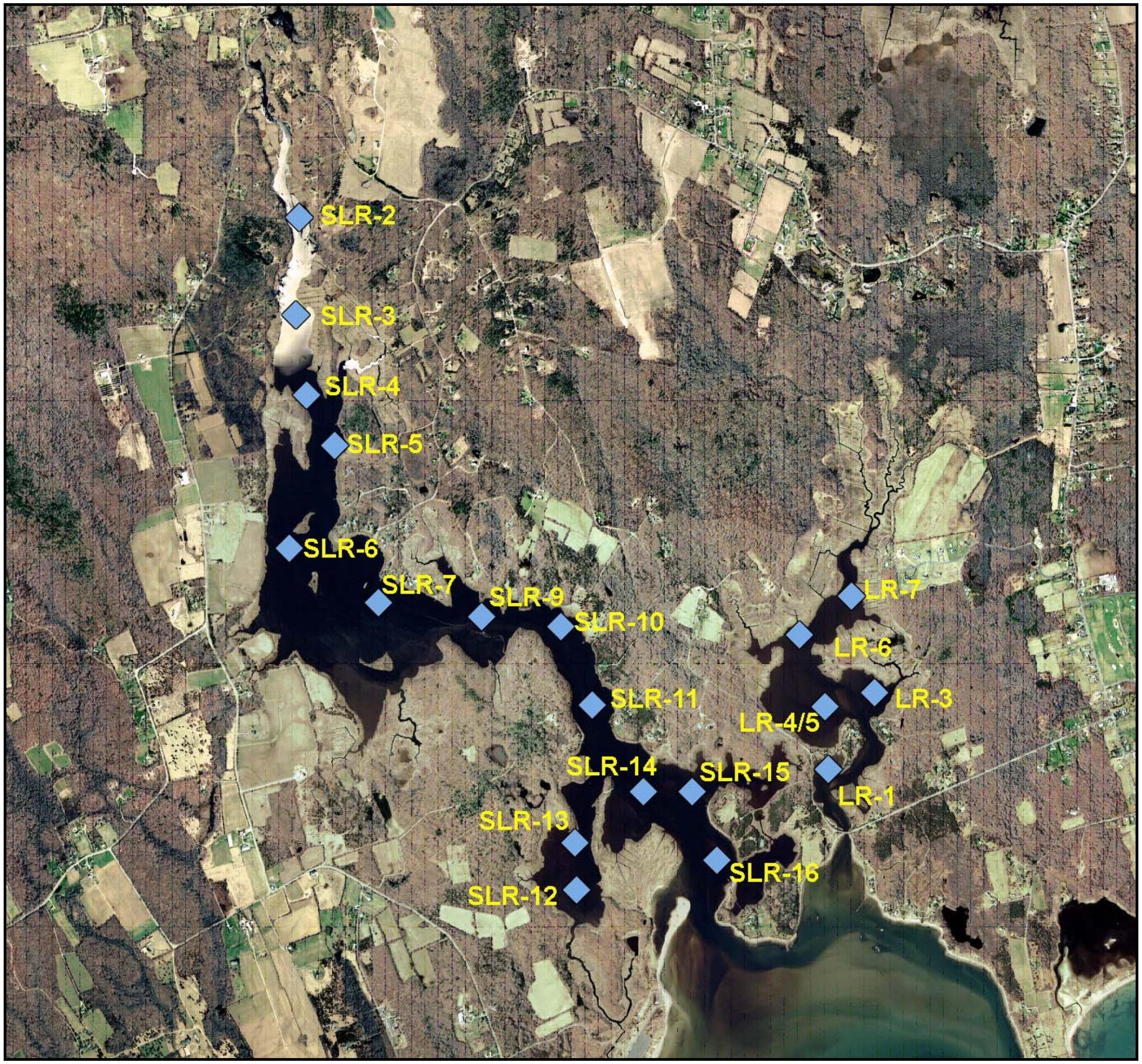


Figure VII-14. Aerial photograph of the Slocums River and Little River systems showing locations of benthic infaunal sampling stations (blue symbol).

Table VII-4. Benthic infaunal community data for the Slocums River and Little River 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). Station numbers refer to Figure VII-3.

Location	Sites	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
Slocums River Estuary						
Upper Reach	Sta. 2,3,4	15	210	12	3.00	0.78
Middle Reach	Sta. 5,6,7,9,	12	357	8	2.10	0.61
Giles Creek - Marsh	Sta. 12,13	12	326	6	2.33	0.65
Lower Basin	Sta. 14,15	8	158	6	1.91	0.65
Lower "Channel"	Sta. 10,11,16	18	129	14	3.13	0.75
Little River Estuary						
Upper	Sta. 6,7	12	273	10	2.64	0.75
Main Basin	Sta. 3,4,5	17	275	13	3.07	0.75
Channel	Sta. 1	24	1128	10	2.40	0.52

VII.5 MACROALGAL ANALYSIS

Macroalgae surveys were conducted in the Slocums River and Little River embayments in 2003 by staff from the Lloyd Center in collaboration with the MEP. At that time, the Slocums River macroalgae coverage in the southern third of estuary was generally low (0-25% coverage) with moderate levels of drift algae accumulating in patches within the tributary coves (25%-50%, Figure VII-15). In contrast, the middle reach of the Slocums River was found to contain large regions of high accumulations of drift algae, generally *Ulva lactuca* (sea lettuce). These accumulations ranged from 20-100% coverage of the bottom sediments and occurred throughout most of the large middle basin. It appears that in addition to affecting habitat quality within the middle basin, some of the drift algae may be transported to the lower basin as well. Macroalgae was generally absent from the upper estuarine reach, with only a few patches of drift algae present, although some thin algal mats were observed to colonize the sediment surface in some regions. These thin mats alter benthic habitat, and can affect infaunal colonization.

In the lower basin of Slocums River, the substrate in the central channel area is predominantly sand and gravel, while areas of more protected water as in Giles Creek and in other smaller coves have both muddy and mixed sand/mud substrates. Tidal velocities in the lower area are relatively high, while depths are generally shallow and in the high energy areas attached species predominated. The highest macroalgae coverage rates were found in the inlets and small bays like Giles Creek on the western shore and in the small inlet to the east inside Potomska Point where attached algae had favorable substrate and where drift algae could collect from current and wind action (Figure VII-15).

In the middle region of the system, *Ulva* dominated in shallow, muddy bottom areas, which predominate in this reach of the estuary. However, in limited areas of the shore line, where coarse substrate occurred, other species were observed such as *Fucus*, brown and red filamentous algae, *Enteromorpha* and some *Codium*. However, the infaunal habitat throughout this basin was significantly impaired by the large accumulations of *Ulva* at more than 50% while most of the total viewed area was covered by at least 20% macroalgae. Given that these are drift accumulations at high levels, the mobility of the macroalgae virtually ensures impact to the sediment animal communities throughout the middle basin. High concentrations of *Ulva* are typical of high terrestrial nitrogen inputs in shallow water basins, where light reaches the bottom and where low current velocities allow accumulations to occur. The soft muddy bottom in this estuarine reach also contributes to the accumulation of *Ulva*, as attached forms are unable to grow on this substrate. Ulva continues to grow as it "drifts" and is generally less sensitive to extended periods of low light and dissolved oxygen unlike other species and as such is more tolerant of chronically eutrophic conditions.

The TTT project compared the 2003 macroalgae coverage with data collected in the same area of the Slocums estuary in 1985 – 1986 (Adam 1989; and aerial photos provided by Dr. J. Sears, UMass-Dartmouth). The survey by Adam also showed macroalgae in the middle basin in attached and drift forms. However, it is clear that the amount of moderate to high density coverage, primarily by the species *Ulva,* has increased substantially in the 18 years from 1985-2003.

Another potential negative impact of the large drift algal accumulation within the middle basin has been noted by scientists within the Turn The Tide Project. A significant fish kill of tomcod was documented (near water quality station SRT6, Chapter VI) during a fish census in April, 2005 survey. Over 600 dead tomcod were collected in the haul seine. This location typically accumulates drift macroalgae (Figure VII-15) and during the fish kill, there was a very high density of macroalgae (*Ulva*) throughout the shallow basin. It appeared that the macroalgal accumulation may have impeded the escape of the juvenile fish (<2 inches) in the warm shallow water, during an abnormal spring low oxygen event.

The upper reach of the Slocums River supports generally low macroalgae coverage, with some patches occurring in "pockets" along the shoreline. *Ulva*, filamentous algae and *Enteromorpha* were present in this reach. The lower extent of macroalgae coverage is likely due to a variable combination of gradients in salinity, low light penetration of entering Paskamanset River water, and lack of "depositional zones" within this narrow tidal river..

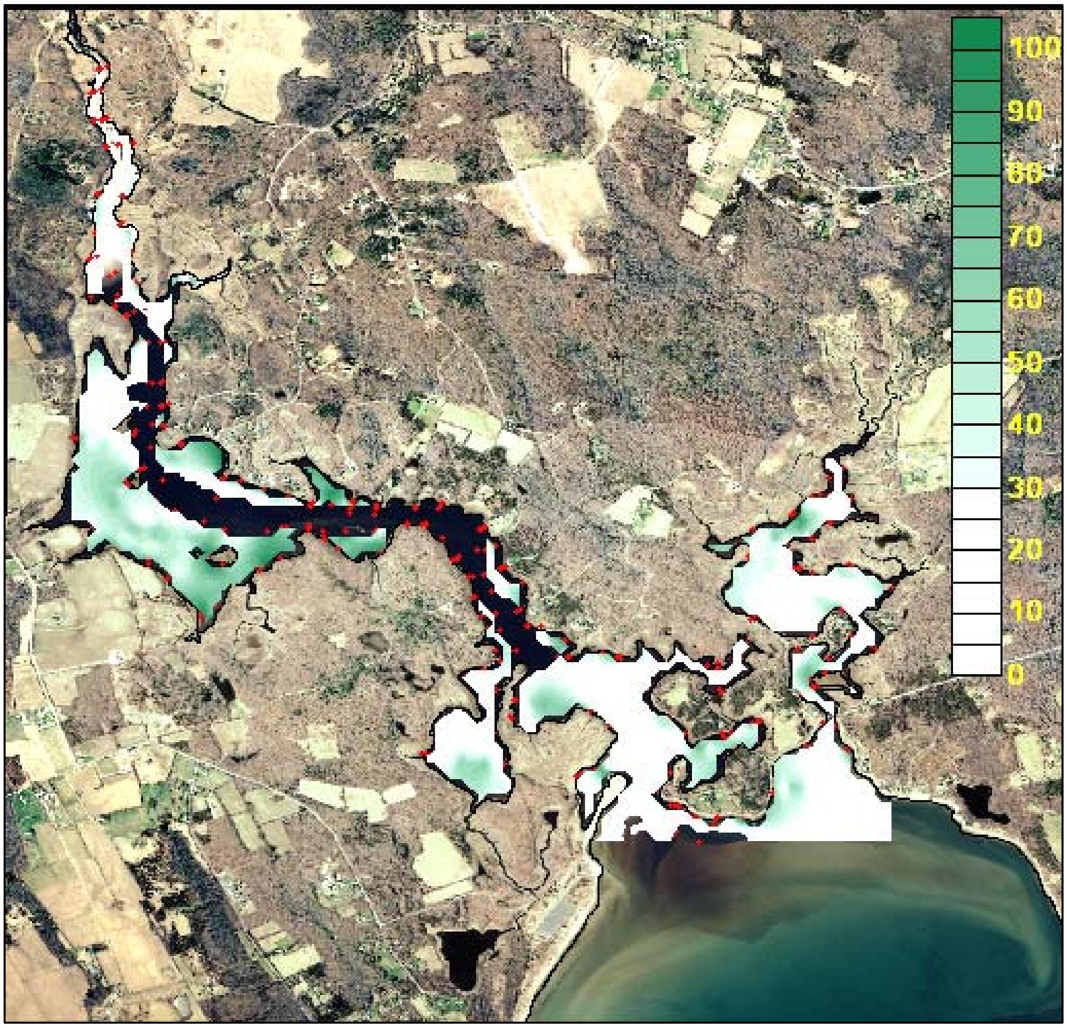


Figure VII-15. Percent coverage of bottom by macroalgae as determined by field survey of the Slocums River and Little River, 2003. Dominant macroalgal species observed was Ulva lactuca (sea lettuce), which is found in nitrogen enriched estuarine basins. Data provided by the Turn-The-Tide Project.

In contrast to the adjacent Slocums River, the Little River Estuary shows high habitat quality based upon its macroalgal community. Macroalgae coverage was generally low with only a few, small areas of high coverage (Figure VII-15). Most importantly, the system is dominated by attached forms, with little accumulation of drift algae, particularly *Ulva*. The community is diverse: *Ulva*, rockweed, red (*Gracillaria*) and brown filamentous algae, *Sargassum, Enteromorpha* and *Codium*. In addition, submerged aquatic vegetation (*Ruppia*) was also present over a significant area, in places covering substantial parts of the upper embayment at low plant densities. This species is also indicative of this system being predominantly a salt marsh basin. There was a shift in species moving from the inner reach to the tidal inlet with brown and red filamentous types, *Ulva* and *Ruppia* predominating in the north and *Sargassum*, rockweed, *Codium* dominating the channel and inlet area. In comparison with the Slocums River, the Little River Estuary had lower coverage percentages over smaller aggregate areas and had a higher diversity of species, dominated by attached forms. These conditions are likely due to the low watershed nitrogen loading, high tidal flushing and salt marsh nature of this system.

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, chlorophyll-*a* and macroalgae). Additional information on temporal changes within each sub-embayment and its associated watershed nitrogen load further strengthen the analysis. These data were collected by the MEP Technical Team to support threshold development for the Slocums River and Little River Estuaries and were discussed in Chapter VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels derived from the baseline BayWatcher Water Quality Monitoring Program (2000-2006), conducted by the Coalition for Buzzards Bay with technical support from the Coastal Systems Program at SMAST and, for 2004-05 sampling season, by the Turn the Tide Project for the Restoration of Dartmouth's Estuaries (a partnership between the Town of Dartmouth, Coalition for Buzzards Bay, Lloyd Center and the Coastal Systems Program at SMAST-UMassD),.

The Slocums River System is a riverine estuary composed of an upper tidal river dominated by fringing wetlands, a large depositional basin in the middle of the system and a lower reach comprised of a main tidal channel and tributary coves, one of which is predominantly a salt marsh pond (Giles Creek). Each of these functional components has different natural sensitivities to nitrogen enrichment and organic matter loading. Evaluation of eelgrass and infaunal habitat quality must consider the natural structure of each system and the systems ability to support eelgrass beds and a various types of infaunal communities. At present, the Slocums River System is showing variations in nitrogen enrichment and habitat quality among its various component basins (Table VIII-1). In general the system is showing healthy to moderately impaired benthic habitat within the upper tidal reach. As a wetland dominated basin, impairment in the upper tidal reach is only moderate resulting mainly from the patches of drift macroalgal accumulation and surface microphyte mats. However, the middle basin currently supports significantly impaired habitat for infaunal animals (with periodic fish kills), as a result of spatially distributed and significant accumulations of drift macroalgae, moderate to high chlorophyll levels and periodic oxygen depletions. The lower basin is generally supporting high quality infaunal habitat except in regions of macroalgal accumulation (likely transported from the middle basin). However, the lower basin is significantly impaired relative to eelgrass habitat. The lower basin historically supported eelgrass as indicated by the 1951 analysis by MassDEP and field data from 1985 (Costa 1988), but eelgrass beds are no longer present within the system. Based upon all lines of data, the Slocums River is presently impaired by nitrogen loading from its watershed and restoration of this estuary should focus on the impaired infauna habitat within the middle basin and eelgrass habitat within the lower basin.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Slocums River and Little River Estuaries on Buzzards Bay within the Town of Dartmouth, MA, based upon assessment data presented in Chapter VII. The Slocums River Estuary is a typical riverine estuary, while the Little River Estuary is primarily a salt marsh basin.

Health Indicator	Embayment System			
	Slocums River			Little River[A]
	Upper[A]	Mid	Lower	
Dissolved Oxygen	H[1]	MI-SI[2]	MI-SI[2]	H[1]
Chlorophyll	H-MI[6]	SI[4]	MI-SI[5]	H[3]
Macroalgae	H-MI[7]	SI[8]	H-MI[9]	H[10]
Eelgrass	--[11]	--[11]	SI[12]	--[11]
Infaunal Animals	H[13]	SI[14]	H-MI[15]	H[16]
Overall:	**H-MI[17]**	**SI[18]**	**SI[19]**	**H**

A -- basin or estuarine reach supports fringing salt marsh areas.
1 – primarily a salt marsh pond or wetland dominated tidal river, periodic oxygen depletions to <4 mg/L, very rarely to 3-2 mg/L.
2 -- oxygen depletions periodically to <4 mg/L, with infrequent declines to <3.5 mg/L.
3 – low to moderate chlorophyll a levels generally 2-8 ug/L, generally <6 ug/L
4 – high chlorophyll a levels generally 4-15 ug/L, frequently >15 ug/L (15% of time)
5 – moderate to high chlorophyll a levels generally 5-10 ug/L, >15 ug/L (8% of time)
6 – high chlorophyll a levels generally >10-15 ug/L, frequently >20 ug/L (21% of time)
7 -- drift algae in sparse patches, patches of surface algal mat
8 -- moderate to high accumulations of drift algae, primarily Ulva.
9 -- low accumulations of drift algae in tributary basins, little surface microphyte mat.
10 – diverse attached macroalgal community with some *Codium* & *Ruppia* (SAV), little drift algae
11 – no evidence this basin is supportive of eelgrass.
12 -- MassDEP mapping indicates that eelgrass lost from this system between 1951-1995.
13 -- Infauna: moderate numbers of individuals, moderate species, high diversity and Eveness; organic enrichment indicators typical of wetland dominated tidal rivers, indication of salinity "stress" (*Cyathura polita*), little accumulation of macroalgae (*Ulva*).
14 -- low to moderate numbers of species and individuals, low to moderate diversity and evenness. Organic enrichment indicators and opportunistic and disturbance indicators.
15 -- tributary coves: moderately impaired habitat in depositional areas where drift macroalgae periodically accumulate; main channel: high quality infaunal habitat, with high species diversity & Eveness, high # of species & moderate # of individuals, distributed evenly among polychaetes, crustaceans & mollusks & with deep deposit feeders evident.
16 -- moderate to high # of individuals and species, with moderate to high diversity & Eveness; lowermost reach supports the highest # of species within the Slocums/Little River complex.
17 -- Moderate Impairment based upon patches of drift macroalgae and moderate-high chlorophyll levels, assessment based upon this reach being a wetland dominated tidal river
18 -- Significant impairment of infaunal communities within this broad basin, large accumulations of macroalgae and periodic oxygen depletion.
19 -- Significant Impairment based upon loss of eelgrass from system, 1951-->1985-->1995.

H = healthy habitat conditions; MI = Moderate Impairment; SI = Significant Impairment; SD = Severe Degradation; -- = not applicable to this estuarine reach

The Little River Estuary is predominantly a salt marsh dominated tidal basin. This estuary is presently supporting high quality infaunal animal habitat and water quality conditions associated with a salt marsh basin receiving watershed nitrogen inputs below its tolerance level. This system has infaunal communities consistent with a wetland dominated organic matter enriched estuarine sediment, with moderate to high numbers of individuals, distributed among a diversity of species. The lower-most reach of this system is a tidal channel supporting the highest number of species within the entire Slocums and Little River complex. The assessment of high quality infauna habitat is consistent with the generally low total nitrogen and chlorophyll-a levels, with oxygen depletion evident, but typical of salt marsh basins. Significantly, accumulations of drift macroalgae are not typical of this basin, with macroalgae present primarily as attached forms, e.g. *Codium, Enteromorpha, Fucus* (see below).

Eelgrass:

At present, the Little River and Slocums River Estuaries do not support eelgrass habitat. Little River is predominantly a salt marsh basin and the absence of eelgrass is typical of the basin configuration, water quality and hydrodynamics of this class of coastal system. There is no historical evidence of eelgrass coverage within this basin, from the 1951 analysis or any of the field surveys from 1985-2005. That the Little River basin is not configured to sustain eelgrass is also supported by the absence of eelgrass in this system in 1985 (at very low watershed N loading), when eelgrass patches were still extant within the adjacent lower Slocums River (at much higher N loadings). It should be noted that the absence of eelgrass in similar salt marsh dominated basins is typical throughout southeastern Massachusetts, for example Mill Creek in Lewis Bay, Upper Broad Marsh River in Wareham River Estuary, Namskaket Creek, and Back River in the Phinneys Harbor System. As a result of these findings, management of the Little River Estuary should focus on maintaining the present high level of infaunal habitat quality.

It contrast, the Slocums River Estuary has historically supported eelgrass. The 1951 analysis indicates 2 small beds in the lower basin. Remnants of the southern bed were observed in the 1985 field survey, but these were lost by the 1995 survey and no eelgrass was recorded in the 2001-2005 surveys. As a result of these findings, management of the Slocums River Estuary should focus on restoration of eelgrass habitat in the lower basin and infaunal habitat quality within the upper reaches.

The current absence of eelgrass throughout the Slocums River is consistent with the depth of the basin and the chlorophyll levels measured by the MEP moorings (Section VIII.2) and the BayWatcher Program (~10 ug/L) in addition to the observed total nitrogen levels (0.38-0.40 mg N L^{-1}) in the lower basin (higher than the 0.35 threshold for eelgrass in nearby West Falmouth Harbor) and generally >0.5 mg N L^{-1} in the middle and upper reaches. The historical beds appear to have been restricted to the margins of the lower basin and were not observed in the deeper channel that runs from the tidal inlet along the eastern shore. Eelgrass was also not observed in the region of the tidal inlet due to the unstable substrate (shifting sands) and continuing alteration of the western barrier spit by coastal processes.

Although some regions of the Slocums River presently support healthy infaunal habitat (tolerant of higher levels of enrichment), this system appears to have become sufficiently nutrient enriched to significantly impair its eelgrass habitat. However, it is likely that if nitrogen loading were to decrease, eelgrass could be restored at a minimum in the lower basin to the 1951 pattern. A greater acreage of eelgrass recovery is certain as the outer basin (bounded by Mishaum Point and Barneys Joy Point) would also undergo an expansion of surviving eelgrass beds. Recovery of eelgrass within the down-gradient outer basin should result as the major nitrogen source to this basin is the Slocums River ebb tide discharge.

Based upon the documented loss of eelgrass coverage in the lower basin of the Slocums River Estuary, this basin is classified as significantly impaired (SI) for eelgrass habitat. The outer basin would be classified as moderately impaired as it still supports some eelgrass habitat, though it has declined in recent decades. The difference between the lower basin of the Slocums River and the offshore basin (outer basin) stems from the greater dilution of nitrogen enriched Slocums River waters by low nitrogen Buzzards Bay waters within the outer basin. The spatial and temporal pattern of the declining eelgrass habitat associated with the Slocums River Estuary is consistent with the results of the water quality and benthic infauna analysis and the observed eelgrass loss is typical of nutrient enriched shallow embayments.

Based upon the above analysis, eelgrass habitat should be the primary nitrogen management goal for the lower basin of the Slocums River Estuary while infaunal habitat quality should be the management target for the middle basin. These goals are the focus of the MEP management alternatives analysis presented below.

Macroalgae:

Macroalgae grows within the Slocums and Little River Estuarine basins in both attached and drift forms. The predominant drift algae is *Ulva lactuca,* also referred to as sea lettuce. This macroalgae is generally associated with nitrogen enrichment in both embayment basins and salt marsh creeks. It forms dense accumulations which "smother" the bottom communities, significantly impairing both infaunal animal communities and even eelgrass beds. Accumulations of drift macroalgae are indicative of significant to severe impairment of estuarine habitat. In contrast, macroalgal species which grow as attached forms, are not indicative of nitrogen enrichment and can be associated with high water quality and may even provide additional animal habitat (e.g. as SAV) in some cases.

The middle basin of the Slocums River presently has large regions of high accumulations of drift algae, generally *Ulva lactuca* (sea lettuce). The infaunal habitat throughout this basin was significantly impaired by the large accumulations of *Ulva* (at more than 50% coverage) while most of the area had coverages of at least 20%. Given that these are drift accumulations extant at high levels, the mobility of this drift macroalgae virtually ensures impact to the sediment animal communities throughout the middle basin. In contrast, macroalgae was generally absent from the upper estuarine reach, with only a few patches of drift algae consistently present, although some thin algal mats were observed to colonize the sediment surface in some regions. These thin mats also alter benthic habitat, and can affect infaunal colonization. The lower basin of Slocums River does not accumulate drift macroalgae in the channel regions due to high water velocities. However, in more protected waters as in Giles Creek and smaller coves, minor accumulations can develop (Figure VII-15). It appears that some drift algae within the lower basin is "imported" from the middle basin on ebbing tides.

The finding of higher macroalgal accumulations in the 2003 macroalgae survey discussed in Chapter VII compared to the 1985 – 1986 analysis (Adam 1989; and aerial photos provided by Dr. J. Sears, UMass-Dartmouth) is consistent with continuing nitrogen enrichment of the Slocums River and the loss of eelgrass from the lower basin over this same period.

Water Quality:

Overall, the level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-a concentrations was sufficient to impair infaunal habitat within the middle basin and eelgrass habitat within the lower basin of the Slocums River. In contrast, the Little River is primarily a salt marsh basin that is naturally organic matter enriched and is expected to exhibit periodic low oxygen at moderate to low nitrogen and chlorophyll-a levels. These patterns were documented for the Little River Estuary in the MEP analysis, as was the high quality of habitat for a salt marsh basin (refer to discussion in Chapter VII).

Nitrogen levels within the upper and middle basins of the Slocums River are generally moderate to high, >0.6 and >0.5 mg TN L^{-1}, respectively, and as such are levels that are typically related to periodic oxygen depletion in many southeastern Massachusetts estuaries. However, total nitrogen (TN) levels in the lower Slocums River are generally only moderately enriched <0.4 mg TN L^{-1},and it appears that oxygen depletion in this region of the estuary is influenced by the water quality entering from the middle basin during ebbing tides. Overall, chlorophyll levels also indicated a nitrogen enriched estuarine system with levels within the upper basin generally ~15 ug/L and the middle basin ~8 ug/L. It appears that phytoplankton generated in the upper and middle basins are being transported to the lower basin, causing organic matter enrichment effects.

The observed periodic depletion of dissolved oxygen indicates that much of the tidal reach of the Slocums River is currently under seasonal oxygen stress, consistent with nitrogen enrichment (Table VII-1). That the cause is eutrophication is supported by the documented moderate to high levels of chlorophyll-a (Table VII-2). Oxygen conditions and chlorophyll-a levels improved with decreasing distance to the tidal inlet, although all basins showed oxygen depletions below 5 mg L^{-1} and periodically below 4 mg L^{-1}. The observations of moderate to high nitrogen levels, moderate to high chlorophyll-a levels and periodic oxygen depletions to <4 mg L^{-1} all support the assessment that watershed nitrogen inputs are currently impairing habitat quality within the Slocums River through the process of nitrogen enrichment of estuarine waters.

In contrast, Little River is presently supporting a low level of nitrogen enrichment (TN levels ~0.4 mg N L^{-1}) with associated low to moderate levels of chlorophyll-a. The difference in the nitrogen and chlorophyll-a levels and oxygen depletion status of this system compared to the Slocums River results from it being a salt marsh basin which is naturally organic matter enriched. A similar pattern was found in another Buzzards Bay sub-embayment, the Phinneys Harbor System. This system contains a salt marsh dominated basin, the Back River, similar to the present Little River basin. The Back River also exhibited oxygen depletions (to 3-4 mg/L), and similar low chlorophyll-a levels (general range 4-8 ug/L). This is consistent with its functioning as primarily a tidal salt marsh sub-basin. While oxygen depletion to 3 mg/L would indicate impairment in an embayment like the Slocums River and Apponagansett Bay (and the Phinneys Harbor basin), it is consistent with the organically enriched nature of salt marsh creeks. It is important to note that the uppermost reach of the Slocums River functions as a wetland dominated tidal river, much like the salt marsh creeks and basins just discussed. As a result, this portion of the Slocums River was assessed as a tidal wetland system, and the observed water quality indicators suggest high quality to moderately impaired habitat quality for this tidal reach. This is in contrast to the moderately to significantly impaired habitat observed within the middle and lower basins.

The assessments of significantly impaired habitat quality within the middle basin of the Slocums River due to high and increasing levels of macroalgal accumulation is consistent with the site-specific water quality analysis and with the conclusions of the eelgrass and infaunal animal surveys.

Infaunal Communities:

The infauna study conducted by the MEP indicated that the Slocums River is presently supporting a range of high quality to significantly impaired habitat for infaunal animal communities (Table VII-4) while the Little River Estuary is generally supportive of high quality habitat. These habitat assessments are based upon both the infaunal community characteristics (Section VII.4), the ecosystem type (basin, salt marsh, eelgrass bed) and stresses represented by salinity variation, macroalgal accumulations and organic matter enrichment (e.g. nitrogen loading).

The habitat quality of the uppermost reach of the Slocums River Estuary is generally reflective of its function as a tidal river with bordering wetlands. This upper reach of the estuary is strongly influenced by the large freshwater inflows from the Paskamansett River and Destruction Brook as well as its related function as a wetland dominated tidal river. The upper reach of the river is nitrogen enriched, but at an level generally found in healthy salt marsh systems, and does exhibit little accumulation of macroalgae (generally in patches). The infaunal community is consistent with its wetland dominated tidal river status. However, it appears that the large freshwater inflow represents a "stress" in this environment as seen in the fresh/brackish/marine invertebrates typical of transition between fresh and estuarine habitats. The presence of the stress indicator species *Cyathura polita,* which is tolerant of the salinity stress, helps to define this as a wetland influenced sub-basin (this species was found in similar environment in the Mashpee River in Popponesset Bay and the upper Agawam River in Wareham River).

In contrast, the significant impairment of infaunal animal habitat within the large middle basin of the Slocums River is clearly associated with nitrogen enrichment. This assessment is based upon the low to moderate diversity and evenness of the community. While the number of individuals was generally high, the high numbers were related to "blooms" of opportunistic species, indicative of organic enrichment and disturbance. During the summer, an amphipod mat was observed within the lower region of this basin, also indicative of nitrogen enrichment and disturbance. Organic enrichment indicators typically dominated the community and there was variability in the numbers of individuals suggesting localized disturbance, likely from shifting accumulations of drift algae.

The lower basin is comprised of 3 components, the salt marsh basin of Giles Creek, small tributary coves and the main deep channel. The basin of Giles Creek supports an infaunal community typical of a salt marsh basin but does contain some patches of drift algae (Ulva), with localized negative effects. The tributary coves to the east and west of the main channel (Chapter VI) presently support moderately impaired habitat. However, it appears that the habitat impairment is again associated with depositional areas where drift macroalgae periodically accumulate and possibly low oxygen waters discharging from the middle basin build-up. Generally high quality habitat is associated with the main channel. The channel does not accumulate macroalgae but has the same water quality as the tributary coves, supports high species diversity and evenness, high numbers of species and moderate numbers of individuals. Species appeared to be distributed among polychaetes, crustaceans and mollusks with deep deposit feeders evident as well. Habitat near the tidal inlet is affected by the shifting substrate related to coastal processes as these processes are modifying the tidal inlet and barrier beach. Overall, the lower reach of the Slocums River is supporting high infaunal habitat quality with small patches of moderate impairment associated with macroalgal accumulation, likely from transport from the large areas of accumulation within the middle basin.

The Little River Estuary is predominantly a salt marsh dominated tidal basin. As a consequence, this system has infaunal communities consistent with a wetland dominated organic matter enriched estuarine sediment, with moderate to high numbers of individuals and species and generally moderate to high diversity and evenness. The lower-most reach of this system is a tidal channel supporting the highest number of species within the Slocums and Little River complex. The assessment of high quality infauna habitat is consistent with the generally low total nitrogen and chlorophyll-a levels, with oxygen depletion evident but typical of salt marsh basins. Significantly, accumulations of drift macroalgae were not typical of this basin, with macroalgae present primarily as attached forms, e.g. *Codium, Enteromorpha, Fucus* (see below).

Overall, the infaunal habitat quality throughout the Slocums River and Little River Estuaries was consistent with the distribution of drift and attached macroalgae, the gradients in dissolved oxygen, chlorophyll, nutrients and organic matter enrichment in these systems. Classification of habitat quality necessarily included the structure of the specific estuarine basin, specifically as to wetland dominance or characterization as a purely tidal embayment with open water and shoreline free of wetlands. Based upon this analysis it is clear that infaunal habitat within the middle reach of the Slocums River is significantly impaired as a consequence of organic matter nitrogen enrichment and infaunal restoration should focus on this region. In contrast, the Little River Estuary is generally showing high quality infaunal habitat for a salt marsh dominated tidal basin and management should focus on maintaining existing habitat quality within this system.

VIII.2. THRESHOLD NITROGEN CONCENTRATIONS

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

For the Slocums River and Little River Estuaries, determination of the critical nitrogen threshold for maintaining high quality habitat is based primarily upon the nutrient and oxygen levels, temporal trends in eelgrass distribution, macroalgal accumulations and current benthic community indicators. Given the database developed for the MEP analysis, it is possible to develop a site-specific threshold which is a refinement upon general threshold analysis frequently employed. All of the habitat assessment data clearly indicate that the Slocums River System is presently beyond its ability to tolerate nitrogen inputs, with the result being that the middle basin is supporting significantly impaired infaunal habitat throughout its tidal reach and the lower basin is supporting significantly impaired eelgrass habitat. Restoration of these impaired habitats is the primary target of the thresholds analysis. In contrast, the Little River Estuary is generally showing high quality infaunal habitat and the primary target of the thresholds analysis is the maintenance of existing habitat quality within this system.

Slocums River:

The present lack of eelgrass throughout the Slocums River System is consistent with the observed oxygen depletions in each basin and the chlorophyll levels and functional basin types comprising this estuary. This loss of eelgrass classifies the lower tidal reach as "significantly impaired", although it presently supports healthy to moderately healthy infaunal communities. The impairments to both the infaunal habitat (middle basin) and the eelgrass habitat (lower basin) are supported by a variety of other indicators: oxygen depletion, chlorophyll, and TN levels. Considered in combination, all the indicators support the conclusion that these impairments are the result of nitrogen enrichment, primarily from watershed nitrogen loading.

Based on the available data, it is possible to make a conservative estimate of the extent of eelgrass habitat that can be recovered through watershed nitrogen management. Based upon the 1951 coverage data, it appears that a conservative estimate of the amount of eelgrass habitat that would be restored in the inner portion of the Slocums River system if nitrogen management alternatives were implemented would be 8 acres (Table VII-3). A greater acreage of recovery is likely (74 acres) as the outer basin (bounded by Mishaum Point and Barneys Joy Point) should also see an expansion of surviving eelgrass beds. Recovery of eelgrass within this down-gradient outer basin should result as the major nitrogen source to this basin is the Slocums River ebb tide discharge.

The target nitrogen concentration (tidally averaged TN) for restoration of eelgrass at the sentinel location, SRT-12 (Chapter VI) within the lower reach of the Slocums River, was determined to be 0.37 mg TN L^{-1}. As the present TN level at this site is 0.390 mg TN L^{-1}, watershed nitrogen management will be required for restoration of the estuarine habitats within this system.

As there is no eelgrass habitat within the Slocums River Estuary, this threshold was based upon comparison to other local embayments of similar depths and structure under MEP analysis. A well studied eelgrass bed within the lower Oyster River (Chatham) has been stable at a tidally averaged water column TN of 0.37 mg N L^{-1}, while eelgrass was lost within the Lower Centerville River at a tidally averaged TN of 0.395 mg N L^{-1}, and also within Waquoit Bay at 0.39 mg N L^{-1}. The Slocums River threshold is the same as for the Centerville River System (0.37 mg N L^{-1}) and similar to the threshold for the lower main basin of Popponesset Bay and for the complex systems of Wareham River and Stage Harbor (0.38 mg N L^{-1}). These latter 3 systems have complex multi-component structures compared to the Slocums River Estuary. The selected threshold for the Slocums River System is higher than for the nearby deeper water systems of Phinneys Harbor and West Falmouth Harbor (0.35 mg TN L^{-1}), where detailed eelgrass/nitrogen analysis was available. The sentinel station under present loading conditions supports a tidally corrected average concentration of 0.390 mg TN L^{-1},

Although the nitrogen management target is restoration of eelgrass habitat (and associated water clarity, shellfish and fisheries resources), benthic infaunal habitat quality must also be supported as a secondary condition. Therefore, in addition to the primary nitrogen threshold at the sentinel station, the MEP establishes secondary criteria to ensure that all impaired regions are restored if the threshold at the sentinel station is achieved. These values merely provide a check on the acceptability of conditions within the up-gradient basins at the point that the threshold level is attained at the sentinel station. The secondary criteria for the Slocums River targeted infaunal habitat restoration within the presently significantly impaired middle basin. The infaunal "check" station is the long-term monitoring station, SRT-6, which has an average TN level of 0.594 mg N L^{-1}. The tidally averaged total nitrogen level required at this station (SRT-6) to restore the infaunal animal habitat throughout the Slocums River System is <0.5 mg N L^{-1}. Watershed nitrogen management to achieve this "check" nitrogen level will ensure restoration of infaunal habitats within the down-gradient reach as well.

The secondary criteria developed for the infaunal "check" stations were developed by the MEP Technical Team based upon comparison to other nearby estuaries. The observed significant impairment within the middle basin of the Slocums River is consistent with observations by the MEP Technical Team in enclosed basins along Nantucket Sound (e.g. Perch Pond, Bournes Pond, Popponesset Bay) where levels <0.5 mg N L^{-1} were found to be supportive of healthy infaunal habitat and in deeper enclosed basins of Buzzards Bay (e.g. Eel Pond in Bourne) where healthy infaunal habitat had a slightly lower threshold level (0.45 mg N L^{-1}) due to it being a "deep" depositional basin. The higher TN levels observed in the upper Slocums River wetland reach are within the nitrogen threshold to support the observed healthy infaunal habitat in this ecosystem type. Conversely, the Centerville River System supports moderately impaired infaunal habitat at tidally averaged TN levels of 0.526 mg N L^{-1} in its upper basin (Scudder Bay) and at 0.543 mg N L^{-1} within its middle reach. Similarly, within the nearby Wareham River System, the Wareham River and Broad Marsh River sub-basins were found to have moderately impaired infaunal habitat at total nitrogen (TN) levels in the range of 0.535 - 0.600 mg N L^{-1}.

Based upon the above analysis, eelgrass habitat should be the primary nitrogen management goal for the lower Slocums River System and infaunal habitat quality the management target for the upper reaches. These goals are the focus of the MEP management threshold loading analysis (Section VIII.3) and alternatives analysis. It must be stressed that the nitrogen threshold for the Slocums River Estuarine System is at the sentinel location. The secondary criteria (infaunal habitat) should be met when the threshold is met at the sentinel station. The secondary criteria were not used for setting the nitrogen threshold, but serve as a “check”. The nitrogen loads associated with the threshold concentration at the sentinel location and secondary infaunal check stations are discussed in Section VIII.3, below.

Little River:

Little River is presently supporting a low level of nitrogen enrichment (TN levels ~0.4 mg N L^{-1}) with associated low to moderate levels of chlorophyll-a. Infaunal communities within Little River are consistent with a wetland dominated organic matter enriched estuarine sediment, with moderate to high numbers of individuals and species, with generally moderate to high diversity and Eveness. The lower-most reach of this system is a tidal channel supporting the highest number of species within the Slocums and Little River complex. The assessment of high quality infauna habitat is consistent with the generally low total nitrogen and chlorophyll-a levels, with oxygen depletion evident, but typical of salt marsh basins. Accumulations of drift macroalgae were not typical of this basin, with macroalgae present primarily as attached forms, e.g. *Codium, Enteromorpha, Fucus* (see below).

The Little River Estuary does not support eelgrass habitat nor is there historical evidence of eelgrass coverage within this basin based on the analysis of the 1951 aerial photography (MassDEP Eelgrass Mapping Program) or any of the field surveys from 1985-2005. That this basin is not configured to support eelgrass, is also supported by the absence of eelgrass in this system in 1985 (at very low watershed N loading), when eelgrass patches were still extant within the adjacent lower Slocums River (at much higher N loadings). It should be noted that the absence of eelgrass in similar salt marsh dominated basins is typical throughout southeastern Massachusetts, for example Mill Creek in Lewis Bay, Upper Broad Marsh River in Wareham

River Estuary, Namskaket Creek, Back River in the Phinneys Harbor System. As a result of these findings, management of the Little River Estuary should focus on maintaining the present high level of infaunal habitat quality.

Since the Little River Estuary is presently supporting high quality habitat and low total nitrogen levels (ca. 0.4 mg TN L^{-1}) and is predominantly a salt marsh basin, its nitrogen threshold level is higher than the present conditions of watershed nitrogen loading (at present tidal flushing rates). A conservative estimate of the nitrogen threshold level of this system would follow the 0.5 mg TN L^{-1} developed above for the Slocums River System. However, as Little River is a wetland dominated system, it is capable of tolerating even higher levels of TN within its waters. The MEP has taken the approach to evaluate if the watershed build-out scenario (Chapter VI) exceeds the 0.5 mg TN L^{-1} infaunal habitat threshold (it does not) and then to determine the additional watershed loading that would be required to raise water column nitrogen levels at the sentinel station (SRT-15) to the threshold level, 0.5 mg TN L^{-1}. More specific evaluation of a still higher limit of loading to the Little River System that would result in habitat impairment will require some additional site-specific analysis and modeling but can be undertaken in the future as needed.

VIII.3. DEVELOPMENT OF TARGET NITROGEN LOADS

At present the Slocums River Estuary is supporting significantly impaired eelgrass habitat within its lower basin and significantly impaired infaunal habitat within its broad middle basin. These impairments result from watershed nitrogen inputs that exceed the nitrogen tolerance of these basins, resulting in the loss of historical eelgrass beds and stress to infaunal communities by organic enrichment through phytoplankton blooms, macroalgal accumulations and periodic oxygen depletion. In contrast, the Little River Estuary, which functions primarily as a salt marsh basin and therefore does not represent potential eelgrass habitat, is presently supporting high quality infaunal habitat typical of this type of estuary. This estuary is presently receiving watershed nitrogen inputs below its tolerance level with the result that some additional nitrogen loading can occur before habitat impairment occurs.

The nitrogen thresholds developed in the previous section were used to determine the amount of total nitrogen mass loading reduction required for restoration of eelgrass and infaunal habitats in the Slocums River Estuary and to maintain the high quality of infaunal habitat, within the Little River Estuary. 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 (Slocums River) or raised (Little River). Watershed nitrogen reduction was through lowering the total septic effluent discharges only (e.g. wastewater treatment), until the nitrogen levels reached the threshold level at the sentinel stations chosen for lower basin of the Slocums River and at the secondary station for the middle basin. 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 for the Slocums River 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. The Little River analysis focused on increases in watershed nitrogen at projected build-out of the watershed, which includes all nitrogen sources associated with changing land use (Section IV.1).

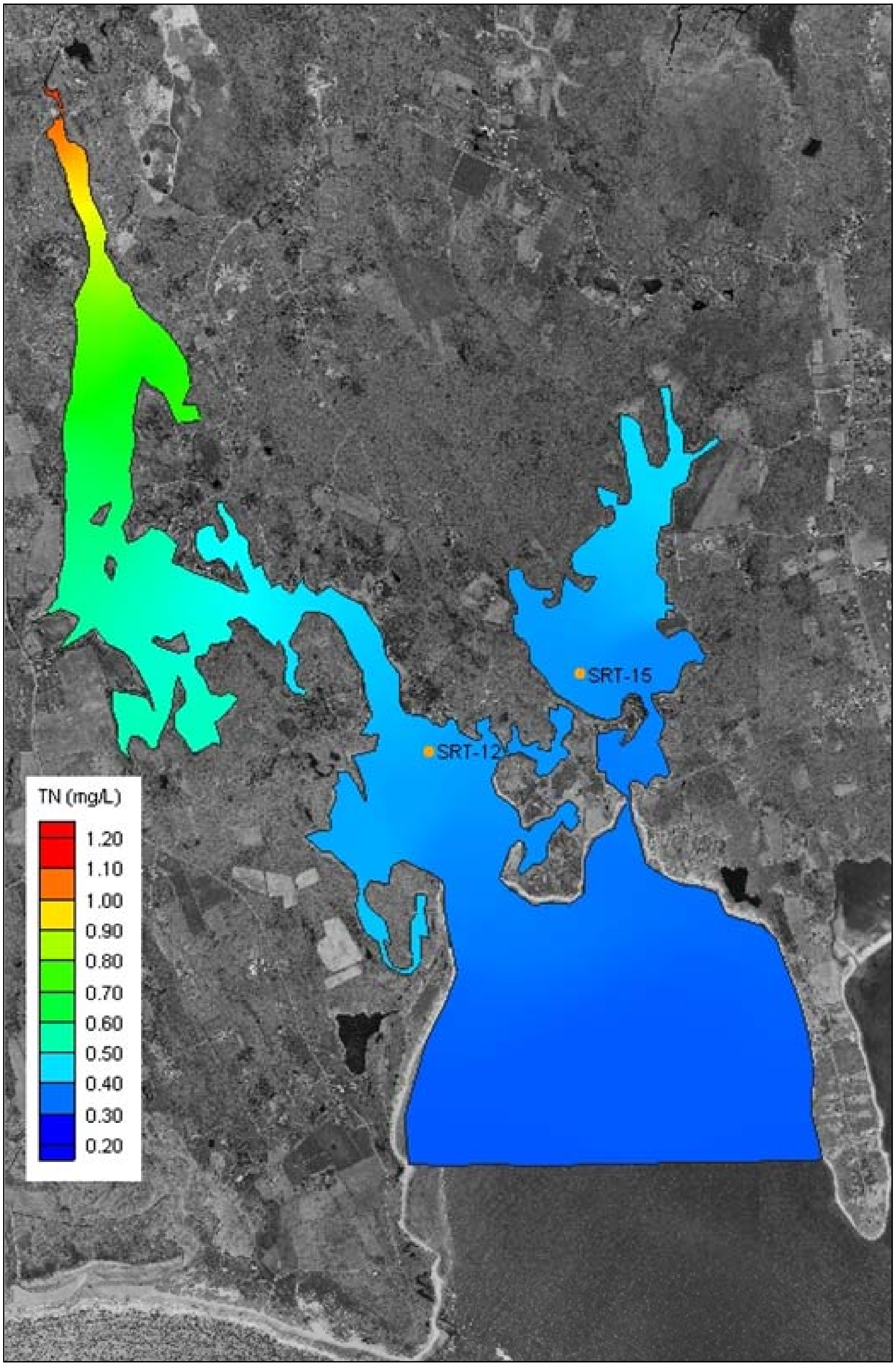


Figure VIII-1. Contour plot of modeled average total nitrogen concentrations (mg/L) in the Slocums River and Little River Estuary, for threshold conditions (<0.37 mg N L^{-1} at the sentinel station SRT-12 and <0.5 mg N L^{-1} at the secondary "check" station SRT-6, and 0.5 mg N L-1 at sentinel station SLR-15). Little River is presently below its threshold rate of nitrogen loading.

The nitrogen load reductions within the Slocums River Estuary necessary to achieve the threshold nitrogen concentrations required a 75% reduction in the total watershed N-load for the Slocums River West sub-watershed, Slocums River East sub-watershed, and Slocums River South sub-watershed, as well as removing 30% of total watershed N-load associated with the Paskamansett River (equivalent to 23.5% of the combined River and Destruction Brook load). The latter equal distribution was for demonstration since the removals could be distributed in a variety of combinations as long as the combined total mass load reduction for the River and Brook is met. The distribution of tidally-averaged nitrogen concentrations associated with the above thresholds analysis is shown in Figure VIII-1.

As a subset of the total nitrogen reduction required to achieve the threshold nitrogen concentrations for Slocums River and Little River, there was reduction of nitrogen septic loading to Slocums River Estuary West, East, and South sub-watersheds and Paskamanset River. The reduction in septic loading is shown in Table VIII-2. The nitrogen septic load reductions within the Slocums River Estuary West, East, and South sub-watersheds were reduced by approximately 75% for the threshold model run along with an approximate 75% reduction is nitrogen septic load for Paskamanset River. The reduction in nitrogen septic loads does not represent the entire reduction in nitrogen load required to meet the threshold. Removal of 100% of the septic load would not represent a large enough reduction in nitrogen to meet the threshold nitrogen concentrations for Slocums River and Little River Systems.

Table VIII-2. Comparison of sub-embayment watershed ***septic loads*** (attenuated) used for modeling of present and threshold loading scenarios of the Slocums River and Little River Systems. The “threshold septic load” is insufficient to meet the threshold concentration at the sentinel station, without additional source reductions (see Table VIII-3, below). 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[2]
Slocums River[1]	2.855	0.690	-75.8%
Little River[1]	1.784	1.784	+0.0%
Surface Water Sources			
Paskamanset R & Destruction Brk	24.299	6.252	-74.3%
Barneys Joy River North	0.241	0.241	0.0%
Barneys Joy River South	0.808	0.808	0.0%

[1] Total estuarine reach which receives septic N inputs through direct groundwater discharge and from surface water (stream) inflows.
[2] A reduction of 100% of the nitrogen septic load from Slocums River groundwater sub-watersheds and Paskamanset River and Destruction Brook sub-watersheds would not achieve the required threshold nitrogen concentration within Slocums River System.

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 load reductions to meet the threshold and the removal of septic loads depicted in Table VIII-2. The total nitrogen loads for Slocums River and Little River are presented in Table VIII-4. Table VIII-4 shows the breakdown of threshold sub-embayment and surface water loads used for total nitrogen modeling. In Table VIII-4, loading rates are shown in kilograms per day, since benthic loading varies throughout the year and the values shown represent ‘worst-case’ summertime conditions. The benthic flux for this modeling effort is reduced from existing conditions based on the load reduction and the observed particulate organic nitrogen (PON) concentrations within each sub-embayment relative to background concentrations in Buzzards Bay.

Table VIII-3. Comparison of sub-embayment ***total attenuated watershed loads*** (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Slocums River and Little River 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)	threshold load (kg/day)	threshold % change
Slocums River[1]	8.488	2.121	-75.0%
Little River[1]	4.690	4.690	0.0%
Surface Water Sources			
Paskamanset R & Destruction Brk[2]	118.863	91.151	-23.3%
Barneys Joy River North	3.260	3.260	0.0%
Barneys Joy River South	5.485	5.485	0.0%

[1] Total estuarine reach which receives N inputs from the watershed through direct groundwater discharge and from surface water (stream) inflows.
[2] In this example, 30% of the total load from the combined Paskamanset River (equivalent to 23.5% of the combined River & Destruction Brook watersheds). Note that removing an equivalent total N mass amount distributed in any manner between the River and Brook would have the same result.

Table VIII-4. Threshold sub-embayment loads and attenuated surface water loads used for total nitrogen modeling of the Slocums River and Little River 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)
Slocums River[1]	2.121	5.395	-3.867
Little River[1]	4.690	1.186	8.898
Surface Water Sources			
Paskamansett R & Destruction Brk	91.151	-	-
Barneys Joy River North	3.260	-	-
Barneys Joy River South	5.485	-	-

[1] Total estuarine reach which receives N inputs through direct atmospheric deposition and through direct groundwater discharge and from surface water (stream) inflows.

Comparison of model results between existing loading conditions and the selected loading scenario to achieve the target TN concentrations at the sentinel station is shown in Table VIII-5. To achieve the threshold nitrogen concentrations at the sentinel station, a reduction in TN concentration of approximately 6% is required at station SRT-12. However, to meet secondary threshold requirement for station SRT-6 a greater reduction was required. With a reduction in TN concentration of approximately 7.3% at station SRT-12, the TN concentration of 0.5 mg/L was achieved at the secondary "check" station SRT-6. These reductions will restore eelgrass habitat in the lower estuary and infaunal animal habitat throughout almost all the estuary. It should be noted that while station SRT-6 still does not meet the secondary threshold, this option provides a reasonable and achievable goal for the Slocums River system, restoration of infaunal habitat quality for a majority of the upper reaches. The threshold analysis for the Slocums River System is similar to the major tidal river to Popponesset Bay (Mashpee River) where the narrow upper estuarine reach is strongly influenced by bordering wetlands and a higher TN threshold (0.500 – 0.600 mg/L) was found to be appropriate for infaunal animals. Salt marshes have a much greater tolerance for nitrogen loading than do open water basins, supporting a slightly higher acceptable threshold TN level for the upper estuarine reach of the Slocums River Estuary.

The basis for the watershed nitrogen removal strategy utilized to achieve the embayment thresholds was selected as the example for nitrogen remediation because it focuses on watersheds where groundwater is flowing directly into the estuary without attenuation of nitrogen in transport to the estuary. Removal of nitrogen sources from these sub-watersheds maximizes the load reduction to the estuary per unit of nitrogen managed at the source, which generally has positive implications relative to the cost of management. For nutrient loads entering the systems through surface water inflows, natural attenuation in freshwater bodies (i.e., streams and ponds) can significantly reduce the load that finally reaches the estuary. Presently, this attenuation is occurring due to natural ecosystem processes and the extent of attenuation being determined by the mass of nitrogen which is transported through to these freshwater systems. The nitrogen entering these surface water systems primarily results, under present conditions, from the widely distributed non-point nitrogen sources (e.g. septic systems, lawns, etc.). Future nitrogen management should take advantage of natural nitrogen attenuation, where possible, to ensure the most cost-effective nitrogen reduction strategies. However, if use of natural systems is to be part of a planning effort (i.e. planned source location) care has to be taken to ensure that degradation of these systems will not occur.

One clear finding of the MEP has been the need for analysis of the potential associated with restored wetlands or ecologically engineered ponds/wetlands to enhance nitrogen attenuation. Attenuation by ponds in agricultural systems has also been found to work in some cranberry bog systems, as well. Cranberry bogs, other freshwater wetland resources, and freshwater ponds provide opportunities for enhancing natural attenuation of their nitrogen loads. Restoration or enhancement of wetlands and ponds associated with the lower ends of rivers and/or streams discharging to estuaries are seen as providing a dual service of lowering infrastructure costs associated with wastewater management and increasing aquatic resources associated within the watershed and upper estuarine reaches.

Table VIII-5. Comparison of model average total N concentrations from present loading and the modeled threshold scenario, with percent change, for the Slocums River and Little River Systems. Sentinel threshold station are in bold print. The secondary "check" station in the Slocums River Estuary is SRT-6.

Sub-Embayment	monitoring station	present (mg/L)	threshold (mg/L)	% change
Head Slocums	SRT-3	1.499	1.152	-23.12%
Upper Slocums	SRT-4	0.994	0.789	-20.59%
Upper Slocums	SRT-5	0.826	0.671	-18.78%
Mid Slocums	SRT-6	0.690	0.576	-16.62%
Mid Slocums	SRT-7	0.586	0.503	-14.28%
Mid Slocums	SRT-10	0.450	0.405	-10.00%
Lower Slocums: Giles	SRT-11	0.398	0.368	-7.57%
Lower Slocums	**SRT-12**	**0.392**	**0.364**	**-7.34%**
Lower Slocums	SRT-13	0.337	0.323	-3.92%
Inner Little River	SRT-14	0.365	0.360	-1.34%
Basin Little River	**SRT-15**	**0.349**	**0.345**	**-1.32%**
Inlet - Little River	SRT-16	0.325	0.321	-1.14%
Outer Basin	SRT-17	0.290	0.289	-0.35%

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.

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