Linked Watershed Marsh Assessment and Modeling to Determine Critical Nitrogen Thresholds and Loading for the Herring Brook Estuarine System, Falmouth MA

FINAL REPORT
June 2023

for the

Town of Falmouth

Prepared by:

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Prepared for

Town of Falmouth
Department of Public Works
Water Quality Management Committee

Prepared By

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The authors also remember with fondness and admiration the foundational work completed by Brian Howes to protect and restore Falmouth's waters and most of the surface waters of Cape Cod. Brian had a long and illustrious career in coastal and estuarine ecology, was a Chancellor Professor at the University of Massachusetts Dartmouth School for Marine Science and Technology, and founding Director of the Coastal System Program at SMAST. But, probably more importantly, Brian was a friend and mentor whose insights and guidance are woven throughout every report produced by the Coastal Systems Program, including this one. Brian passed in December 2022.

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EXECUTIVE SUMMARY

Herring Brook Marsh is a small 11 hectare (27.5 acre) salt marsh on the Buzzards Bay coast of Falmouth, Massachusetts. It is bracketed by two estuarine systems that were previously assessed during the Massachusetts Estuaries Project (MEP): Wild Harbor to its north and West Falmouth Harbor to its south. The Herring Brook Marsh system is a typical New England salt marsh dominated by a central tidal creek and emergent marsh colonized by low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) with some more brackish marsh plants found in the uppermost regions and limited bordering patches of *Phragmites*. Tidal exchange with the high quality waters of Buzzards Bay is high, given the ~45 foot wide tidal inlet that passes under Quaker Road, and ~5 ft tidal range with near complete drainage at low tide. As with most small tidal salt marshes, Herring Brook does not retain significant water volume at low tide. As part of the Town of Falmouth commitment to appropriate nitrogen management for its coastal systems, the Town asked the Coastal Systems Program, School of Marine Science and Technology at the University of Massachusetts Dartmouth (CSP/SMAST) to complete an MEP-style assessment of Herring Brook Marsh.

During the course of the MEP, CSP/SMAST and the rest of the MEP Technical Team reviewed a number of salt marshes, including Little Namskaket Marsh and Namskaket Marsh in Orleans, Scorton Creek and Sandwich Harbor in Sandwich, Cockle Cove Creek in Chatham, and salt marsh portions of other embayment systems, including Mashapaquit Creek Marsh in the West Falmouth Harbor estuary system and the upper portions of the Centerville River. All of these systems had characteristics that traditionally label embayments as impaired, but are consistent with healthy salt marshes, including nutrient-enrichment (with a complementary infauna population), occasional hypoxia, and lack of eelgrass.

The Herring Brook Marsh assessment was completed by the same technical team that completed all the MEP assessments. The Herring Brook effort included:

a. Watershed delineation, determination of groundwater discharge rates, and development of a watershed nitrogen loading model
b. Gauging and regular water quality and flow monitoring (~2X per month; 2021-2022) of the two streams that discharge into the marsh
c. Collection and incubation of eight (8) sediments cores along the central tidal creek to measure nitrogen regeneration
d. Collection of bathymetry throughout the marsh
e. Collection of tide measurements for over 30 days to capture the whole lunar cycle
f. Development of a hydrodynamic model integrating the bathymetry and tidal measurements and calibrated and validated with different portions of the tidal record

g. Collection of water column data at five locations within the system during three summers (2020-2022)
h. Deployment of a continuous water quality sensor platform for over 30 days to measure temperature, depth, chlorophyll a, dissolved oxygen, and salinity every 15 minutes
i. Collection of replicate infauna sampling at eight (8) locations along the central tidal creek
j. Development of a water quality model integrating hydrodynamics, water quality, sediment regeneration, stream and watershed inputs; model calibrated and validated with different datasets (*i.e.*, salinity and nitrogen).

As a result of synthesis of all of the site-specific information, Herring Brook system was determined to be a healthy salt marsh system. Comparison of its current status and characteristics to >20 other salt marsh systems showed that nitrogen concentrations in Herring Brook were relatively low, but as with most salt marsh systems, could conservatively receive additional nitrogen load while maintaining its healthy conditions. Based on the Herring Brook assessment and lessons learned from other salt marsh assessments completed by the MEP team, it was determined that an appropriate threshold concentration to be protective of Herring Brook is 1.0 mg/L total nitrogen (TN) at the border of the upper and lower reaches of the system (at water quality monitoring station HB3). Water quality data collected at HB3 during the summers of 2020-2022 had an average TN concentration of 0.478 mg/L (n=21).

Since the Herring Brook water quality model was validated and reliably predicted measured TN concentrations throughout the system (97% match), it can be used to predict the TN impact of changes in watershed inputs through a variety of scenarios (Table EX-1). As such, the project team completed two standard MEP scenarios and a municipal wastewater scenario. The two standard MEP scenarios were: 1) watershed buildout based on current Town zoning and Town Assessor parcel classifications and 2) no anthropogenic watershed loading. The project team buildout assessment showed that current zoning and lot classifications could result in 80 new parcels, 72 of which would be single family residences. There were no projected additional commercial parcels and only one additional industrial property. The projected impact of the buildout scenario would raise the system-wide attenuated watershed nitrogen load by 15% and increase the modeled average TN concentration to 0.546 mg/L, which is well below the 1.0 mg/L TN threshold concentration. The no anthropogenic scenario provides an assessment of what background nitrogen concentrations would be within an estuary if there was only atmospheric deposition of nitrogen and natural forests within the watershed. The no anthropogenic scenario results had a TN concentration of 0.206 mg/L at HB3 and showed how in the absence of significant watershed nitrogen loads, TN concentrations throughout the Herring Book system were spatially-dependent, diluted Buzzards Bay background levels with higher concentrations closer to the system inlet and lower concentrations further inland.

The Town of Falmouth also asked the project team to use the validated Herring Brook water quality model to evaluate the potential impact of discharging 0.76 million gallons per day (MGD) of treated wastewater (3.0 mg/L TN) from the Town's existing treatment facility within the watershed. This discharge would occur at open sand beds 14-15, which are located within the Herring Brook watershed, but adjacent to the watershed boundary between Herring Brook and West Falmouth Harbor. Groundwater modeling by GHD, Inc. using a localized portion of the same USGS regional groundwater model used in MEP watershed delineations shows that

41% of nitrogen load from the 0.76 MGD flow will flow through Crocker Pond (and be reduced by 50% attenuation) before flowing into Herring Brook, while 14% will flow directly to Herring Brook. The remaining 45% of the discharge and load will flow directly to Buzzards Bay. The scenario nitrogen loading additions within the Herring Brook watersheds will increase the attenuated system-wide nitrogen loading rate by 28% compared to existing conditions. Using these results, the project team added these loads at their appropriate locations to the existing conditions watershed loads and used the water quality model to determine the estimated TN concentrations in Herring Brook. Under this scenario, the TN concentration at the sentinel station (HB3) increases to 0.518 mg/L, but remains well below the 1.0 mg/L threshold. The water quality impact of the municipal discharge is less than the buildout scenario largely because most of the nitrogen load from the municipal discharge enters the system in the lower portion of the Herring Brook system, closer to the inlet whereas the buildout loading additions enter the system mostly at its most inland location, furthest from the inlet. Although an additional modeling scenario combining buildout and the municipal discharge was not completed, it is reasonable to assume that the combined impact would also have a TN concentration below the 1 mg/L threshold at the sentinel station.

Table EX-1. Summary of Herring Brook scenario results: modeled total nitrogen concentrations (mg/L). After collecting and reviewing available system data, project staff determined that water quality monitoring station HB3 was an appropriate threshold station for the Herring Brook system. Monitoring in 2020-2022 showed the average TN concentration at HB3 was 0.48 mg/L (±0.17 stdev) and based on review of similar wetland marsh systems reviewed during the Massachusetts Estuaries Project (MEP), project staff selected 1 mg/L TN as a threshold concentration to conservatively ensure that the system remains healthy. Background TN concentration in Buzzards Bay is 0.282 mg/L. Synthesis of watershed and sediment N inputs with system hydrodynamics resulted in excellent match (R^2=0.97) between measured and modeled TN concentrations throughout the system and a reliable basis for projected future impacts and alternative scenarios. At the request of the Town of Falmouth, project staff completed analysis of three scenarios: a) watershed buildout based on current Town zoning and Town Assessor land use classifications, b) no-anthropogenic loading (a standard MEP scenario), and c) a treated wastewater discharge scenario, using groundwater modeling results to assess the distribution of 0.76 MGD discharge at a parcel within the watershed. None of the scenarios exceeded the 1 mg/L TN threshold for Herring Brook at the sentinel station (shown in **bold**).

Sub-Embayment	Upper Herring Brook	Upper Herring Brook	**Lower Herring Brook**	Lower Herring Brook	Lower Herring Brook
monitoring station (MEP ID)	HB01	HB02	**HB03**	HB04	HB05
Present	0.85	0.648	**0.501**	0.393	0.398
Buildout scenario	0.927	0.725	**0.546**	0.415	0.421
% change from present	9%	12%	9%	6%	6%
No-anthropogenic loading	0.088	0.151	**0.206**	0.248	0.25
% change from present	-90%	-77%	-59%	-37%	-37%
Municipal Discharge scenario	0.857	0.663	**0.518**	0.412	0.426
% change from present	1%	2%	**3%**	5%	7%

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I. INTRODUCTION

Herring Brook Marsh is a small 11 hectare (27.5 acre) salt marsh on the Buzzards Bay coast of Falmouth, Massachusetts (**Figure I-1**). Wild Harbor is to its north and West Falmouth Harbor is to its south. It is similar to other small Cape Cod salt marsh systems reviewed during the Massachusetts Estuaries Project (MEP), including Little Namskaket Marsh[1] and Namskaket Marsh[2] in Orleans, and portions of other embayment systems, including Mashapaquit Creek Marsh in the West Falmouth Harbor estuary system[3] and the upper portions of the Centerville River.[4] None of these systems retain significant water volume at low tide. Each of these estuarine systems is predominantly tidal salt marsh with a central tidal creek and smaller tributary tidal creeks. As part of the Town of Falmouth commitment to appropriate nitrogen management for its coastal systems, the Town has asked the Coastal Systems Program, School of Marine Science and Technology at the University of Massachusetts Dartmouth (CSP/SMAST) to complete an MEP-style assessment of Herring Brook Marsh.

The Herring Brook Marsh system is a typical New England salt marsh dominated by a central tidal creek and emergent marsh colonized by low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) with some more brackish marsh plants found in the uppermost regions and limited bordering patches of *Phragmites*. Tidal exchange with the high quality waters of Buzzards Bay is high, given the ~45 foot wide tidal inlet that passes under Quaker Road, and ~5 ft tidal range with near complete drainage at low tide. Review of historical US Geologic Survey maps shows that the road and bridge over the inlet was built between 1893 and 1915. Tidal exchange is through a single inlet that is now protected to the north by a jetty and reinforced with stone revetments on the north and south sides. These structures appear to have been in place since he early 1960's.[5] Given these structures, the tidal inlet is unlikely to become significantly occluded by sediment transport. Overall, these characteristics result in the type of coastal system which has a relatively high tolerance for nitrogen inputs from its watershed. Observations by the project team indicate Herring Brook is healthy functioning New England Salt Marsh.

The primary ecological threat to Herring Brook Marsh resources is degradation resulting from nutrient enrichment. As with all coastal ecosystems in this region, watershed loading of the critical eutrophying nutrient, nitrogen, has been increasing over the past few decades. These increases primarily result from on-site disposal of wastewater through septic systems. The Town

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[1] Howes B.L., E. Eichner, S.W. Kelley, J. S. Ramsey, R.I. Samimy, D.R. Schlezinger (2007). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Little Namskaket Marsh Estuarine System, Orleans, MA. SMAST/DEP Massachusetts Estuaries Project, MassDEP. Boston, MA. 116 pp.

[2] Howes B.L., S.W. Kelley, J. S. Ramsey, R.I. Samimy, E.M. Eichner, D.R. Schlezinger, (2007). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Namskaket Marsh Estuarine System, Orleans, MA. SMAST/DEP Massachusetts Estuaries Project, MassDEP. Boston, MA. 125 pp.

[3] Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for West Falmouth Harbor, Falmouth, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 161 pp.

[4] Howes B., H.E. Ruthven, J. S. Ramsey, R. Samimy, D. Schlezinger, J. Wood, E. Eichner (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Centerville River System, Barnstable, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 172 pp.

[5] Bourne Consulting Engineering. 2009. Massachusetts Coastal Infrastructure Inventory and Assessment Project: Falmouth. Massachusetts Department of Conservation and Recreation, Office of Waterways. Franklin, MA. 296 pp.

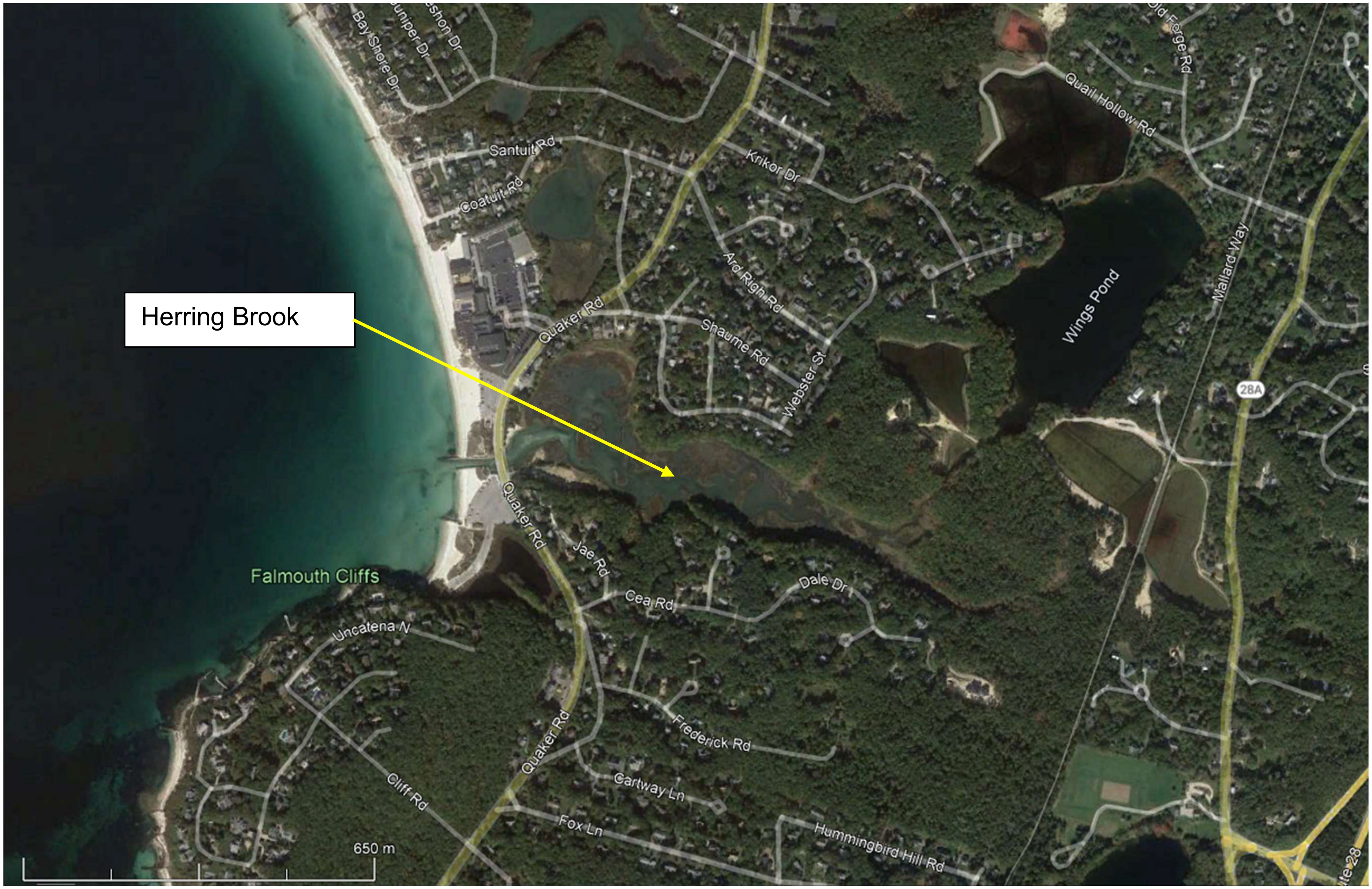

Figure I-1. Herring Brook Marsh study area. Tidal waters enter the system through one inlet under Quaker Road. Tidal flood waters enter the system from Buzzards Bay. Freshwater enters the head of the system from the watershed primarily through surface water discharge points, as well as direct groundwater discharge.

of Falmouth has been working to quantify the watershed loading and coastal water quality impacts for all their estuaries for a number of decades, including the development of the PondWatchers citizen water quality sampling program, participation in the MEP for more than 10 estuarine systems, and development and implementation of a Comprehensive Wastewater Management Plan over the past decade.

Fortunately for the resource protection of Herring Brook Marsh, its function as a tidal salt marsh makes it more tolerant of watershed nitrogen inputs than coastal embayments, like nearby West Falmouth Harbor or Squeteague Harbor. The greater sensitivity of embayments versus wetlands results from their lower tidal exchange rates, the fact that there is limited to no exposure of the sediments to the atmosphere at low tide (like the marsh plain), and the fact that these systems have evolved under much lower levels of productivity and organic matter loading than wetlands. For example, the organic carbon content of New England Salt Marsh vegetated sediments can frequently reach 20%, while embayment sediments are generally in the 1%-5% range. Similarly, oxygen depletion in the creeks of *pristine* wetlands can occur on summer nights, while embayment bottom waters become hypoxic generally as a result of *eutrophic* conditions.

Some additional insight into the nitrogen response by salt marshes can be garnered from long-term chronic nitrogen addition experiments. These have been conducted at multiple sites along the Atlantic coast and specifically in a nearby New England salt marsh, Great Sippewissett Marsh. This latter project was started by WHOI scientists in 1970 and has been overseen solely by current CSP/SMAST staff since 1985. These studies reveal that nitrogen additions to low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) areas, typically results in increased plant production and biomass and secondary production as well. Nitrogen dynamics have been quantified, which show that as nitrogen is added the initial increased nitrogen available is taken up by the plants, but this plant demand is rapidly satisfied and additional load is denitrified *in situ* by soil bacteria. In the Great Sippewissett Marsh, fertilization experiments the denitrification capacity of the sediments has not been exhausted in 30 years of N additions and at levels about 7X the natural background N input (75.6 g N m^{-2} each growing season).

Salt marsh creek bottoms and creek banks (such as those found in Herring Brook Marsh, Namskaket Marsh and the Little Namskaket Marsh areas) have developed under nutrient and organic matter rich conditions, as have the organisms that they support. It is the creek bottoms rather than the emergent marsh which are the primary receptors of increased watershed derived nitrogen in Cape Cod salt marshes. Watershed nitrogen predominantly enters these salt marshes through groundwater or small headwater streams, as is the case in all three systems. Both surface and groundwater entry focusses on the tidal channels. Even groundwater entry through seepage at the upland interface is channeled to creek bottoms. As the tide ebbs in these New England salt marshes (like Herring Brook and Namskaket Creek) the freshwater inflow "freshens" the waters and the nitrogen levels in the tidal creeks increase due to the nitrogen entry from the watershed. At low tide, the nitrogen levels in the tidal creeks are dominated by watershed inputs.

Since the predominant form of nitrogen entering from the watershed is inorganic nitrate, the effect on the creek bottom is to stimulate denitrification, hence nitrogen removal. For example, in a salt marsh in West Falmouth Harbor, Mashapaquit Creek, ~40% of the entering watershed nitrogen is denitrified by the creek bottom sediments on an annual basis. This stimulation of denitrification does not negatively affect the salt marsh, but does result in a reduction of nitrogen loading to the adjacent nitrogen sensitive coastal waters. However, analysis by MEP Staff of salt marsh areas receiving wastewater discharges indicates that at very high nitrogen loads (inputs relative to tidal flushing), macroalgal accumulations can occur. These accumulations are generally found in the creek bottoms and flats and also may drift and settle on the creek banks. Large macroalgal accumulations in tidal creeks can cause impairment of benthic animal communities. In the latter case, negative effects on creek bank grasses can occur, which may lead to bank erosion and negative effects on organisms. A part of the focus of the present analysis of the Herring Brook Marsh System, relates to potential macroalgal issues.

The watershed to the Herring Brook Marsh is somewhat geologically complex, being composed primarily of Falmouth Moraine and sand and gravel outwash glacial deposits. The watershed to the Herring Brook Marsh is comprised primarily of deposits of the Buzzards Bay Moraine, which include boulders and till with lenses of stratified sand and gravel, while areas around the marsh are coarse deposits sand and gravel. These formations consist of material deposited during the retreat and readvance of Laurentide Ice sheet. The material is highly permeable and as such, rainwater typically infiltrates rather than generating runoff. Portions of rainwater that infiltrate recharge the aquifer and flow with groundwater toward the Marsh. Originally the Herring Brook Marsh was isolated from the sea, but as a result of rising sea level following the last glaciation, they began to serve as sediment depositional areas. Studies of Cape Cod salt marsh sediments tend to show they began to be deposited 4,000 to 6,000 years ago as sea level rise began to slow.

The common focus of the water quality monitoring efforts undertaken by the Town of Falmouth has been to gather site-specific data on the current nitrogen related water quality throughout the Herring Brook Marsh system and many others including Great Pond, Green Pond, Bournes Pond, Little Pond, and West Falmouth Harbor. These site-specific data were then utilized to determine the relationship between observed water quality and watershed nitrogen loads. This multi-year effort has provided the baseline information required for determining the link between upland loading, tidal flushing, and estuarine water quality. The combined water quality data sets from the Falmouth PondWatch Program form a baseline from which to gauge long-term changes as watershed nitrogen management moves forward. This data has already proven to be of high quality and adequate for the development of management thresholds for each of the Town's coastal systems, as was demonstrated in the nine MEP nitrogen threshold analyses completed for systems in the Town of Falmouth. The Falmouth PondWatch Program efforts allowed the MEP to prioritize all of the Falmouth systems for the next step in the restoration/protection and management process.

The critical nitrogen targets and the link to specific ecological criteria form the basis for the nitrogen threshold limits necessary to complete wastewater master planning and nitrogen management alternatives development needed by the Town of Falmouth for restoration of its impaired embayment habitats. While the completion of this complex multi-step process of rigorous scientific investigation to support watershed based nitrogen management has taken place under the umbrella of the MEP Technical Team, the results stem directly from the efforts of large number of Town staff and volunteers over many years. The modeling tools developed as part of this program provide the quantitative information necessary for the Town of Falmouth to develop and evaluate the most cost effective nitrogen management alternatives to restore those valuable coastal resources of Falmouth that have been degraded by nitrogen overloading.

I.1 THE MASSACHUSETTS ESTUARIES PROJECT APPROACH

Coastal embayments throughout the Commonwealth of Massachusetts (and along the U.S. eastern seaboard) are becoming nutrient enriched. The nutrients are primarily related to changes in watershed land-use associated with increasing population within the coastal zone over the past half century. Many of Massachusetts' embayments have nutrient levels that are approaching or are currently over this assimilative capacity, which begins to cause declines in their ecological health. The result is the loss of fisheries habitat, eelgrass beds, and a general disruption of benthic communities. At its higher levels, enhanced loading from surrounding watersheds causes aesthetic degradation and inhibits even recreational uses of coastal waters. In addition to nutrient related ecological declines, an increasing number of embayments are being closed to swimming, shellfishing and other activities as a result of bacterial contamination. While bacterial contamination does not generally degrade the habitat, it restricts human uses. However like nutrients, bacterial contamination is related to changes in land-use as a watershed becomes more developed. The regional effects of both nutrient loading and bacterial contamination span the spectrum from environmental to socio-economic impacts and have direct consequences to the culture, economy, and tax base of Massachusetts's coastal communities.

The primary nutrient causing the increasing impairment of the Commonwealth's coastal embayments is nitrogen and the primary sources of this nitrogen are wastewater disposal, fertilizers, and changes in the freshwater hydrology associated with development. At present there is a critical need for state-of-the-art approaches for evaluating and restoring nitrogen sensitive and impaired embayments. Within southeastern Massachusetts alone, almost all of the municipalities (as is the case with the Town of Falmouth) are grappling with Comprehensive Wastewater Planning and/or environmental management issues related to the declining health of their estuaries.

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

The MEP represented the next generation of watershed-based nitrogen management approaches. Through the MEP, CSP/SMAST and MassDEP have undertaken the task of providing a quantitative tool for watershed-embayment management for communities throughout Southeastern Massachusetts.

The MEP was founded upon science-based management. The MEP Technical Team used 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 MEP is to provide the municipalities and MassDEP with technical guidance to support policies on nitrogen loading to embayments. In addition, the technical reports prepared for each embayment system served 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. To date, MassDEP has used MEP findings to produce nitrogen TMDLs for over 130 estuarine segments.

The core of the MEP method is the Linked Watershed-Embayment Management Modeling Approach. This approach represents the "next generation" of nitrogen management strategies. It fully links watershed nitrogen loading inputs with embayment circulation and nitrogen characteristics. The Linked Model includes:

- requires site specific measurements within each watershed and embayment;
- uses realistic "best-estimates" of nitrogen loads for each parcel within an individual watershed, including parcel-specific water use;
- spatially distributes the watershed nitrogen loading to the embayment;
- accounts for nitrogen attenuation during transport to the embayment with flow through ponds or streams;
- 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 from the bottom sediments;
- is validated by both independent hydrodynamic, nitrogen concentration, and ecological data; and
- is calibrated and validated with field data, so that it can be used reliably for generation of "what if" scenarios.

The Linked Model approach has been applied for watershed nitrogen management in over 70 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 Model, when properly parameterized, calibrated and validated for a given embayment, becomes a nitrogen management planning tool, which fully supports TMDL analysis. The Model suggests "solutions" for the protection or restoration of nutrient related water quality and allows testing of "what if" management scenarios to support evaluation of resulting water quality impact versus cost (*i.e.*, "biggest ecological bang for the buck"). In addition, once a model is fully functional it can be "kept alive" and corrected for continuing changes in land-use or embayment characteristics (at minimal cost). In addition, since the Model uses a holistic approach (the entire watershed, embayment and tidal source waters), it can be used to evaluate all projects as they relate directly or indirectly to water quality conditions within its geographic boundaries.

Linked Watershed-Embayment Model Overview: The Linked 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 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Linked Watershed-Embayment Management Modeling Approach to the Herring Brook Marsh in the Town of Falmouth. A review of existing studies related to habitat health or nutrient related water quality and current regulatory status is provided in Chapter II. The development of the watershed delineations and associated detailed land use analysis for watershed-based nitrogen loading and nitrogen input parameters to the water quality model are described in Chapters III and IV. Since nitrogen recycling associated with the 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 and are also summarized in Chapter IV. Results of hydrodynamic modeling of embayment circulation are discussed in Chapter V. Analysis of how the measured nitrogen levels correlate to observed estuarine water quality is described in Chapter VI. Collection and review of water quality monitoring data and its use in the calibration and validation of the linked-watershed embayment modeling is discussed in Chapter VII. In addition, this chapter also includes a summary of the marsh ecological assessment. The modeling and assessment information is synthesized and nitrogen threshold levels developed for restoration in Chapter VIII. This chapter also includes modeling of current conditions, watershed build-out conditions, and conditions with removal of anthropogenic nitrogen sources. Additional modeling is currently planned once the model is calibrated and validated to review management options and alternative watershed loading scenarios.

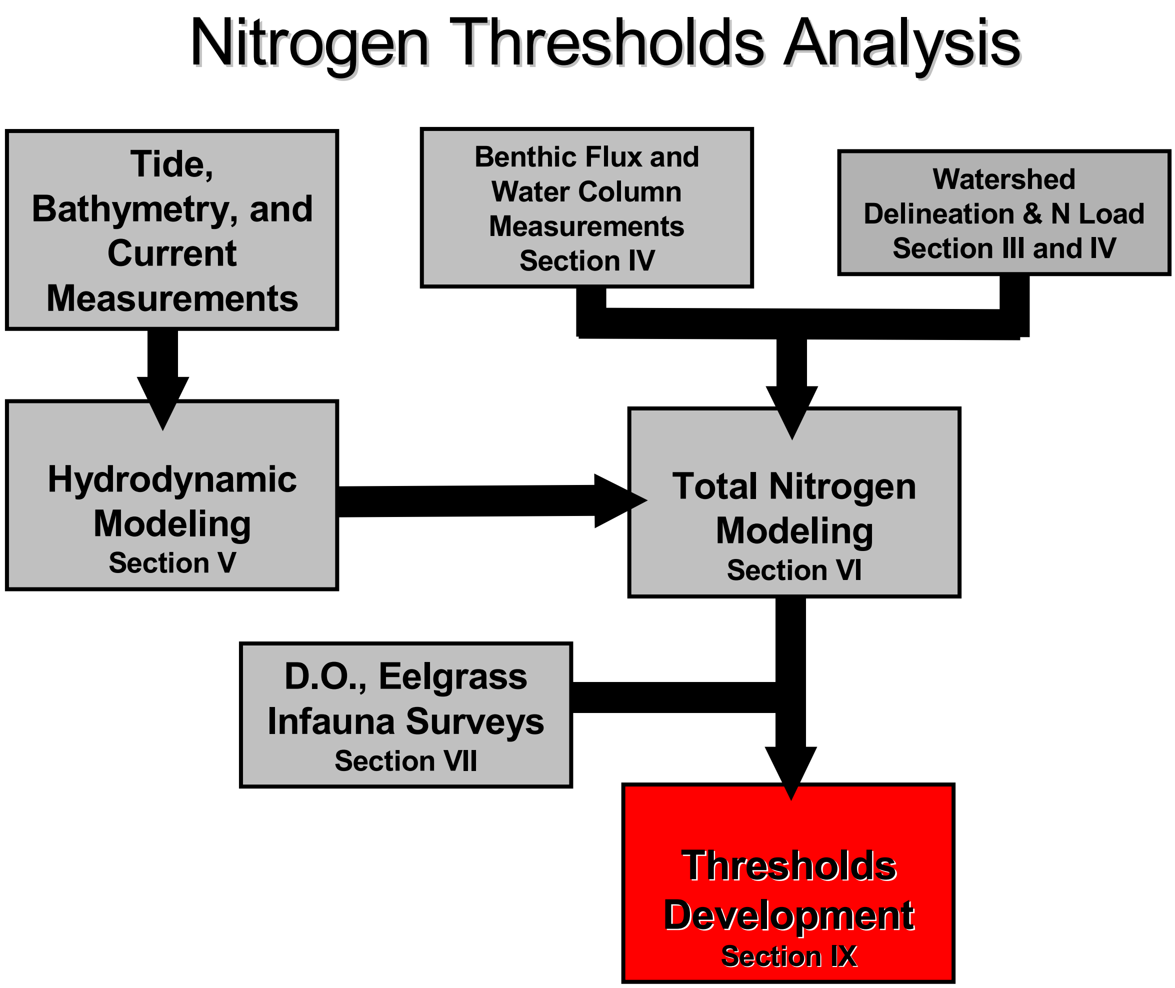

Figure I-2. Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach.

II. PREVIOUS STUDIES AND REGULATORY STATUS

The Town of Falmouth, as the primary stakeholder to the Herring Brook Marsh system, has been concerned over the resource quality of the Town's significant coastal resources for nearly 40 years. In the mid-1980's the Town enacted an innovative Nutrient Overlay By-law that tied permitting of watershed development to estuarine water quality standards. In 1987, the Town initiated the Falmouth PondWatch Program that was the initial regular, citizen volunteer-based, water quality monitoring of surface waters on Cape Cod.[6] As originally conceived, the PondWatch program focused on data collection in three original ponds, Oyster Pond, Little Pond and Green Pond, but gradually expanded to include additional estuaries. Since 1997, technical aspects of the Falmouth PondWatch Program have been coordinated through Coastal Systems Program, School of Marine Science and Technology at the University of Massachusetts Dartmouth (CSP/SMAST).

In addition, the Town of Falmouth has supported the Buzzard Bay Coalition (*né* Coalition for Buzzard Bay) Water Quality Monitoring Program which, through its original association with CSP/SMAST, collected data on nitrogen related water quality within the Falmouth estuaries that exist adjacent Buzzards Bay. The collaborative CBB/SMAST water quality monitoring effort covered systems such as Wild Harbor and Megansett Harbor, Fiddlers Cove and Rands Harbor System beginning in 1992. The BayWatchers is a citizen-based water quality monitoring program with technical and analytical assistance from CSP/SMAST until 2008. PondWatch water quality data has been used as input to MEP assessments in Falmouth, as well as regular reviews by the Town to check the status of water quality in the systems and any trends.[7]

The specific objectives of the PondWatch Program continue to be:

- to provide a long-term data base of nutrient levels and environmental conditions on Falmouth's coastal salt ponds required for data-based management;
- to form the basis for the development and evaluation of various potential management and remediation options;
- to provide a high quality independent evaluation of the impacts of both natural and man induced alterations (ex. changes to nutrient inputs or circulation) to pond water quality;
- to evaluate the effectiveness of implemented management programs aimed at protecting or improving nutrient related water quality;
- to provide necessary data to evaluate impacts of the Falmouth Wastewater Treatment Facility on West Falmouth Harbor, and potential impacts from nutrient plumes emanating from the Mass Military Reservation on Bournes, Green and Great Ponds;
- to develop heightened public awareness of the cumulative impact of human activities on these ponds through interactive partnerships between citizens, scientists and resource managers to preserve the ecological health of these fragile coastal ecosystems.

[6] Initiated in coordination with B. Howes at the Woods Hole Oceanographic Institution

[7] *e.g.*, CSP/SMAST Technical Memorandum. April 25, 2014. PondWatch Nutrient Related Water Quality West Falmouth Harbor, Bournes Pond, Little Pond: SMAST POST-MEP Sampling (2004-2012). From: B. Howes, S. Sampieri, D. Goehringer, and R. Samimy. To: Town of Falmouth, Wastewater Division/DPW, Water Quality Management Committee. 26 pp.

Herring Brook has been listed as an impaired water on the MassDEP Integrated List since 2012. Each state is required under the federal Clean Water Act to prepare a list of all surface water bodies within their boundaries (*i.e.*, the Integrated List) and update the list every two years. The list includes the current water quality status of each system, whether it is impaired, and the causes of impairment (*e.g.*, nitrogen, chlorophyll, fecal coliform). Herring Brook was listed in Category 4A ("All TMDLs are completed') in the 2010 Integrated List[8] for fecal coliform and the draft 2012 Integrated List, but was shifted to Category 5 ("Waters requiring a TMDL") in the 2012 final Integrated List.[9] The 2012 shift to the impaired category in the final Integrated List was in response to comments from the Buzzards Bay Coalition (BBC) suggesting that Herring Brook was impaired due to high chlorophyll-a and total nitrogen concentrations. All subsequent Integrated Lists since 2012, including the current list,[10] have assigned Herring Brook to the impaired Category 5.

BBC began monitoring on the Bay side of the Quaker Road bridge (HB2) in 2005 and added two sampling sites within the marsh beginning in 2013.[11] Review of the data on the BBC website shows that average annual total nitrogen (TN) concentrations at HB2 have varied between 0.39 mg/L (2015) and 0.67 mg/L (2007). The BBC has applied the Bay Health Index to collected data and these scores have generally been in the "Fair" category throughout the collection period (2005-2021).

The high end of the TN range at HB2 is consistent with TN concentrations at healthy salt marshes reviewed by the MEP. For example, TN concentrations at the inlet to Little Namskaket Marsh in Orleans averaged 0.60 mg/L during 2001-2006 for its MEP assessment[12] and 0.63 mg/L TN in regular annual monitoring through 2016.[13] Namskaket Marsh also in Orleans averaged 0.59 mg/L TN at the inlet to its system during 2001-2006 for it MEP assessment[14] and 0.57 mg/L TN from 2007-2016. Mashapaquit Creek marsh at its connection to West Falmouth Harbor averaged 0.742 mg/L TN during 1995-2004 data review for its MEP assessment.[15] This issue will be further discussed in the assessment of Herring Brook (Section VII).

Review of Massachusetts Natural Heritage & Endangered Species Program (NHESP) GIS databases show that none of the NHESP regulatory areas are located in the area around Herring Brook (**Figure II-2**). There are no NHESP natural communities, priority habitats for rare species or estimated habitats of rare wildlife in the immediate area except for the offshore priority habitat for rare species area that includes most of Buzzards Bay.

8 MassDEP. November 2011. Massachusetts Year 2010 Integrated List of Waters. Massachusetts Division of Watershed Management, Watershed Planning Program. CN: 360.1. Worcester, MA. 311 pp.

9 MassDEP. March 2013. Massachusetts Year 2012 Integrated List of Waters. Massachusetts Division of Watershed Management, Watershed Planning Program. CN: 400.1. Worcester, MA. 313 pp.

10 MassDEP. November 2021 Final Massachusetts Integrated List of Waters for the Clean Water Act 2018/2020 Reporting Cycle. Massachusetts Division of Watershed Management, Watershed Planning Program. CN: 505.1. Worcester, MA. 225 pp.

11 https://www.savebuzzardsbay.org/bay-health/waterway/herring-brook/ (accessed 3/1/23).

12 Howes B.L., E. Eichner, S.W. Kelley, J. S. Ramsey, R.I. Samimy, D.R. Schlezinger (2007).

13 Eichner, E and B. Howes. 2018. Town of Orleans Estuaries: Water Quality Monitoring Database Development and Review. Technical Report, Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 95 pp.

14 Howes B.L., S.W. Kelley, J. S. Ramsey, R.I. Samimy, E.M. Eichner, D.R. Schlezinger, (2007).

15 Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2006).

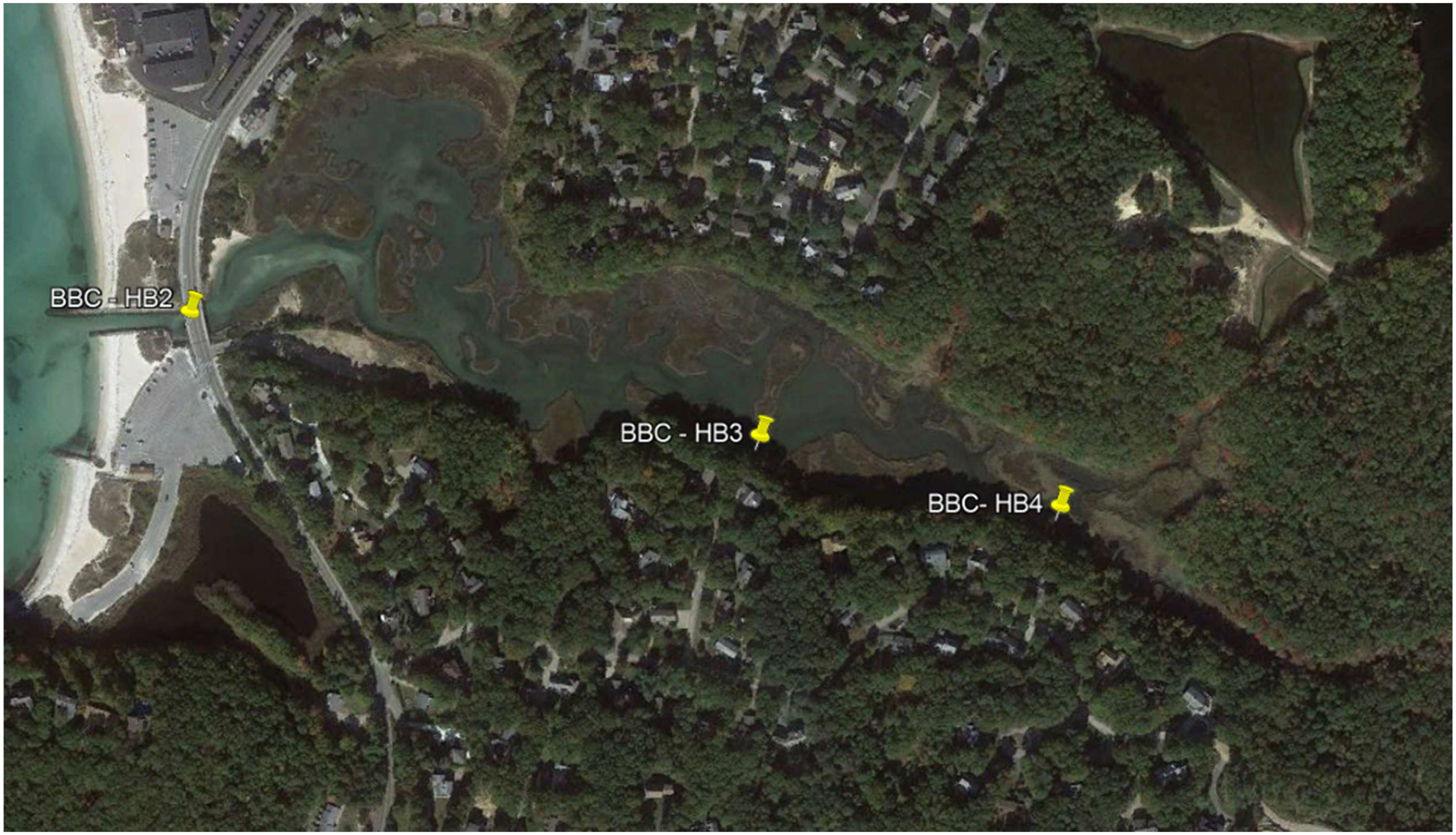

Figure II-1. Buzzards Bay Coalition Herring Brook Marsh monitoring locations. BBC has been collecting water quality samples at HB2, which is on the bayside of the Quaker Road inlet bridge since 2005, while marsh stations HB3 and HB4 were initially sampled in 2013. BBC notes that it "does not calculate a Bay Health Index score for Herring Brook – Marsh because it is a salt marsh" (https://www.savebuzzardsbay.org/bay-health/waterway/herring-brook/herring-brook-marsh/; accessed 3/1/23). BBC does use collected data to calculate a Bay Health Index score for HB2, which has generally been in the "Fair" category. The Bay Health Index is only used to measure the health of coastal waters, including harbors, coves, and tidal rivers. Base map: Google Earth, 10/23/21.

Figure II-2. Massachusetts Natural Heritage & Endangered Species Program Regulated Areas near Herring Brook. Based on information available through MassGIS, no NHESP natural communities, priority habitats for rare species or estimated habitats of rare wildlife in the immediate area except for the offshore priority habitat for rare species area that includes most of Buzzards Bay. Available through MassGIS MassMapper on-line GIS (downloaded 4/6/23).

III. WATERSHED DELINEATION

III.1 BACKGROUND

The MEP team, which developed watershed delineations for estuaries throughout Cape Cod, included technical staff from the United States Geological Survey (USGS). The USGS has a long history of developing regional models for the six-groundwater flow cells on Cape Cod. Through the years, advances in computing, lithologic information from well installations, water level monitoring, stream flow measurements, and reconstruction of glacial history have allowed the USGS to update and refine the regional groundwater models. The MODFLOW and MODPATH models utilized by the USGS to organize and analyze the available data use up-to-date mathematical codes and create better tools to answer the wide variety of questions related to watershed delineation, surface water/groundwater interaction, groundwater travel time, and drinking water well impacts that have arisen during the MEP analysis of southeastern Massachusetts estuaries, including all of the systems within the Town of Falmouth.

The transmissive sand and gravel deposits that comprise most of Cape Cod create a hydrologic environment where watershed boundaries are usually better defined by elevation of the groundwater and its direction of flow, rather than by land surface topography.[16,17,18] Freshwater discharge to estuaries is usually composed of two components: 1) surface water inflow from streams, which receive much of their water from groundwater base flow, and 2) direct groundwater discharge. For a given estuary, differentiating between these two water inputs and tracking the sources of nitrogen that each carry requires determination of the portion of the watershed that contributes directly to the stream and the portion of the groundwater system that discharges directly into the estuary as groundwater seepage.

III.2 REGIONAL GROUNDWATER MODEL DESCRIPTION

As part of the development of the updated Cape Cod regional groundwater system, the USGS delineated groundwater watersheds/contributing areas to selected estuaries, ponds and lakes, and drinking water supply wells for incorporation into the MEP. Since these contributing area/watershed delineations were completed using the same model and over the whole extent of Cape Cod, the watersheds were part of a consistent Cape-wide mosaic. Contributing areas to the Herring Brook Marsh system were delineated using a USGS regional model of the Sagamore Lens flow cell.[19]

The Sagamore Flow Model is based on the USGS three-dimensional, finite-difference groundwater model MODFLOW-2000.[20] The model outputs from this model were used as input to the USGS particle-tracking program MODPATH4 to delineate groundwater

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

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

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

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

[20] Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

watersheds/contributing areas.[21] The Sagamore Flow Model consists of 246 rows, 365 columns and 20 layers. The horizontal model discretization, or grid spacing, is 400 by 400 feet. The top 17 layers of the model extend to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft. The top of layer 8 resides at NGVD 29 with layers 1-7 stacked above and layers 8-20 below. Layer 18 has a thickness of 40 feet and extends to 140 feet below NGVD 29, while layer 19 extends to 240 feet below NGVD 29. The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics (up to 519 feet below NGVD 29 in the Sagamore Lens); since bedrock is approximately 150 feet below NGVD 29 in the Herring Brook area the lowest model layer was inactive in this area of the model with variable thickness in the layer directly above. The rewetting capabilities of MODFLOW-2000, which allows drying and rewetting of model cells, was used to simulate the top of the water table, which varies in elevation depending on the location within the lens.

The glacial sediments that comprise the aquifer of the Sagamore Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments. The Herring Brook marsh system watershed is mostly located in the Buzzards Bay Moraine, which includes boulders and till with lenses of stratified sand and gravel, while areas around the marsh are coarse deposits of sand and gravel. These formations consist of material deposited during the retreat and readvance of the Laurentide Ice sheet. Modeling and field measurements of contaminant transport at Joint Base Cape Cod have shown that similar materials are permeable with only slightly lower hydraulic conductivity than the outwash plains that comprise most of the Cape.[22] This distinction does not tend to impact groundwater flow direction and direct rainwater run-off is typically rather low due to the permeable soils as seen on most of the Cape. Lithologic data used to determine hydraulic conductivities used in the groundwater model were obtained from a variety of sources including well logs from USGS, local Town records and data from previous investigations. Final aquifer parameters in the groundwater models were determined through calibration to observed water levels and stream flows. Hydrologic data used for model calibration included historic water-level data obtained from USGS records and local Towns and stream flow data collected in 1989-1990 as well as 2003.

The USGS Sagamore Lens groundwater model simulates steady state, or long-term average, hydrologic conditions including a long-term average recharge rate of 27.25 inches/year and the pumping of public-supply wells at average annual withdrawal rates for the period 1995-2000 with a 15% consumptive loss. This recharge rate is based on the most recent USGS information. Large withdrawals of groundwater from pumping wells or discharge of treated effluent from wastewater treatment facilities may have a significant influence on water tables and watershed boundaries and therefore the flow and distribution of nitrogen within the aquifer. After accounting for the consumptive loss, water withdrawn from the modeled aquifer by public drinking water supply wells is evenly returned within residential areas designated as using on-site septic systems.

[21] Pollock, D.W., 1994, User's guide for MODPATH/MODPATH-PLOT, version 3—A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 234 p.

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

III.3 HERRING BROOK MARSH WATERSHEDS

The Herring Brook marsh watershed is between two MEP watersheds: Wild Harbor (north of Herring Brook) and West Falmouth Harbor (to the south). During the MEP, the USGS determined watershed and subwatershed boundaries to Wild Harbor and West Falmouth Harbor. Model outputs of both MEP watershed boundaries were "smoothed" to (a) correct for the grid spacing, (b) to enhance the accuracy of the characterization of the pond and coastal shorelines, and (c) to more closely match the sub-embayment segmentation of the tidal hydrodynamic model. The refinement step was a collaborative effort between the USGS and the rest of the MEP Technical Team. For Herring Brook marsh, project staff used the same techniques beginning with USGS model outputs. The Herring Brook watershed includes subwatersheds to the two freshwater stream inputs at the head of the system and subwatersheds to Wings Pond and Crocker Pond (**Figure III-1**). The watershed delineations also include 10 year time of travel boundaries. The Wings Pond watershed is the same watershed delineated in the Wild Harbor MEP assessment.[23]

Table III-1 provides the freshwater discharge volumes for various sub-watersheds. These volumes were used in the salinity calibration of the tidal hydrodynamic model, as well as for comparison to the directly measured surface water discharges. The overall estimated freshwater flow into the Herring Brook system from the delineated watershed is 9,099 m^3/d. This flow includes corrections for outflow from Wing Pond that is shared with Wild Harbor.

The delineations completed by this revised MEP analysis are the first watershed delineation completed in recent years for this estuary. The Cape Cod Commission's regional delineation of estuary/embayment watersheds, which was incorporated into the Commission's regulations through the 2018 Regional Policy Plan, did not include a watershed or subwatershed delineations for Herring Brook marsh.[24] The Herring Brook marsh watershed area is 1,421 acres and the majority of the watershed is within the Town of Falmouth; a small portion (6.2 acres) is in Bourne and an even smaller portion (0.3 acres) is in Sandwich. Bourne and Sandwich portions are within the boundary of Joint Base Cape Cod.

The watershed delineations for Herring Brook marsh are possible because of regional efforts to develop new hydrologic data and combine it with previously collected information. The groundwater model allows all this data to be organized and to be brought into congruence with data from adjacent watersheds. The evaluation of older data and incorporation of new data is important as it decreases the level of uncertainty in the final calibrated and validated linked watershed-embayment model used for the evaluation of nitrogen management alternatives. Errors in watershed delineations do not necessarily result in proportional errors in nitrogen loading as errors in loading depend upon the land-uses that are included/excluded within the contributing areas. Small errors in watershed area can result in large errors in loading if a large source is counted in or out. Conversely, large errors in watershed area that involve only natural woodlands have little effect on nitrogen inputs to the downgradient estuary. This project's watershed delineation was used to develop the watershed nitrogen loads to each of the aquatic systems and ultimately to the estuarine waters of the Herring Brook marsh system (Section IV).

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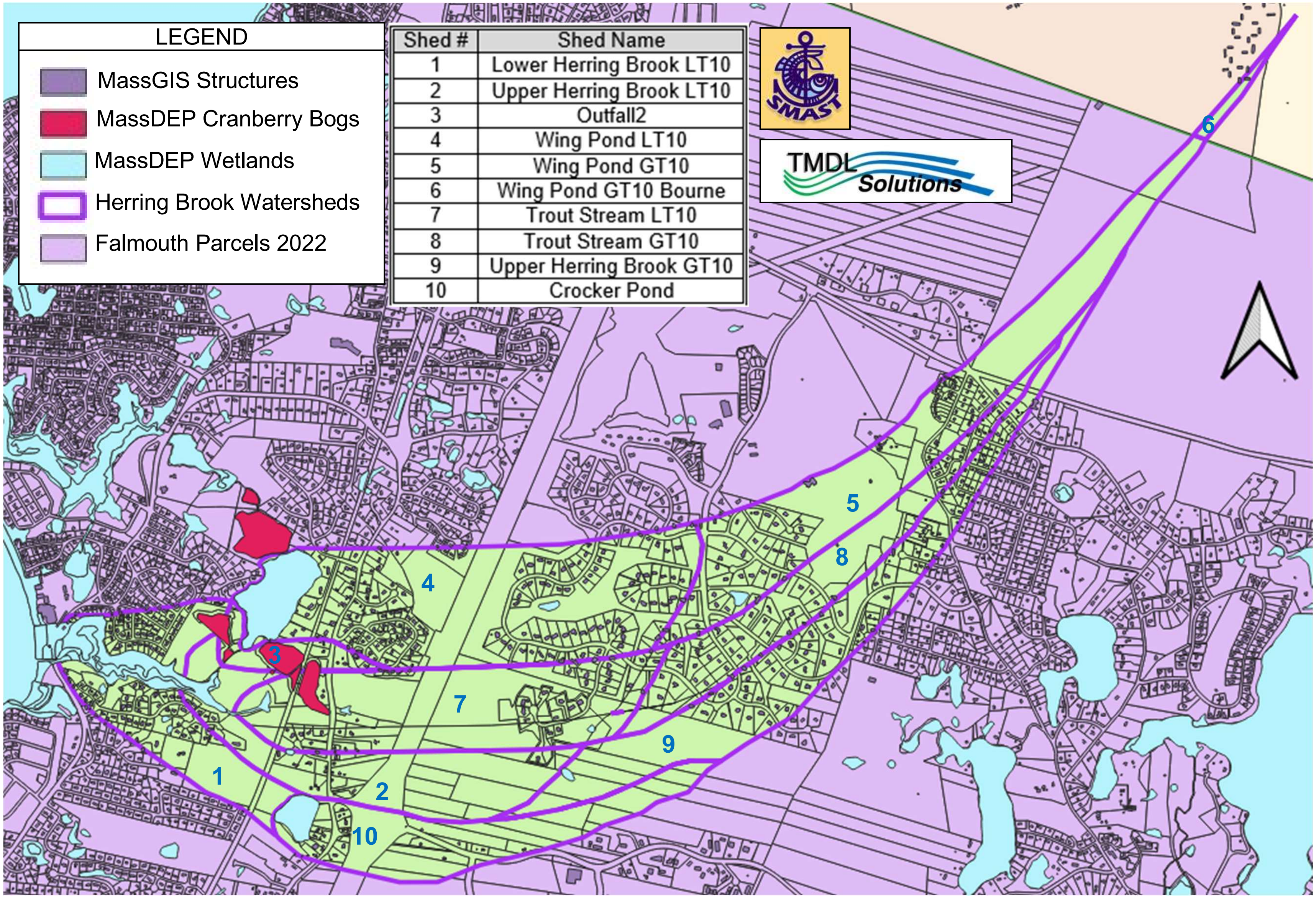
[23] Howes B., E.M. Eichner, S. Kelley, R.I. Samimy, J.S. Ramsey, D.R. Schlezinger, P. Detjens. 2011. Massachusetts Estuaries Project Linked Watershed-Embayment Modeling Approach to Determine Critical Nitrogen Loading Thresholds for the Wild Harbor Embayment Systems, Town of Falmouth, Massachusetts, Massachusetts Department of Environmental Protection. Boston, MA. 163 pp.

[24] Regional Policy Plan Data Viewer (https://www.capecodcommission.org/our-work/2018-rpp-data-viewer/; accessed 3/2/23).



Shed #	Shed Name
1	Lower Herring Brook LT10
2	Upper Herring Brook LT10
3	Outfall2
4	Wing Pond LT10
5	Wing Pond GT10
6	Wing Pond GT10 Bourne
7	Trout Stream LT10
8	Trout Stream GT10
9	Upper Herring Brook GT10
10	Crocker Pond

Figure III-1. Watershed Delineation for Herring Brook Marsh Estuary. Sub-watersheds to were delineated based upon the functional sub-units in the water quality model (see section VI). Delineations based on outputs from USGS regional groundwater model and are consistent with MEP watershed delineations in adjacent estuaries (Wild Harbor and West Falmouth Harbor).

Table III-1. Daily groundwater discharge to each of Herring Brook marsh estuary subwatersheds. Discharge is based on watershed areas and USGS model recharge rate (27.25 in/yr).					
Watershed	#	Watershed Area (acres)	% contributing to Brook	**Discharge**	
				m³/day	**ft³/day**
Lower Herring Brook LT10	1	133	100	1,023	36,112
Upper Herring Brook LT10	2	133	100	1,022	36,087
Outfall2	3	28	100	218	7,696
Wing Pond LT10	4	294	54	1,222	43,154
Wing Pond GT10	5	213	54	886	31,283
Wing Pond GT10 Bourne	6	6	54	27	954
Trout Stream LT10	7	192	100	1,473	52,020
Trout Stream GT10	8	119	100	912	32,206
Upper Herring Brook GT10	9	182	100	1,397	49,347
Crocker Pond	10	120	100	919	32,456
TOTAL		1,421		9,099	321,315
Totals may be slightly off due to rounding differences					

IV. WATERSHED NITROGEN LOADING: LAND USE, STREAMS, 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 watershed freshwaters (surface water flow, groundwater flow) 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 Herring Brook estuary system. Determination of watershed nitrogen inputs to these embayment systems requires the (a) identification and quantification of the nutrient sources and their loading rates to the land or aquifer, (b) confirmation that a groundwater transported load has reached the embayment at the time of analysis, and (c) quantification of nitrogen attenuation that can occur during travel through lakes, ponds, streams and marshes prior to reaching the estuary. This latter natural attenuation process results from biological processes that naturally occur within these ecosystems. Failure to account for attenuation of nitrogen during transport results in an over-estimate of nitrogen inputs to an estuary and an underestimate of the sensitivity of a system to new inputs (or removals). In addition to the nitrogen transport from land to sea, the amount of direct atmospheric deposition on each embayment surface must be determined as well as the amount of nitrogen recycling within the embayment, specifically nitrogen regeneration from sediments. Sediment nitrogen recycling results primarily from the settling and decay of phytoplankton and macroalgae (and eelgrass when present). During decay, organic nitrogen is transformed to inorganic forms, which may be released to the overlying waters or lost to denitrification within the sediments. Permanent burial of nitrogen in the sediments is generally small relative to the amount cycled. Sediment nitrogen regeneration can be a seasonally important source of nitrogen to embayment waters or, in some cases, a sink that removes nitrogen from the water column. Failure to include the nitrogen balance of estuarine sediments and the watershed attenuation generally leads to errors in predicting water quality, particularly in determination of summertime nitrogen load to embayment waters. Sediment nitrogen regeneration focused on summer months, the critical nitrogen management interval and the focal season of the MEP approach and application of the Linked Watershed-Embayment Management Model (Section IV.3).

In order to determine watershed nitrogen loading inputs to the Herring Brook estuary system, the project team developed nitrogen-loading rates (Section IV.1) to each component of the estuary and its watersheds (Section III) based on standard MEP factors. The Herring Brook watershed was sub-divided to define contributing areas or sub-watersheds to each of the major inland freshwater systems and to each major portion of the estuary. Further sub-divisions were made to identify watershed areas where a nitrogen discharge reaches estuary waters in less than 10 years or greater than 10 years. A total of ten sub-watersheds were delineated in the overall Herring Brook watershed, including watersheds to Crocker and Wing Ponds. The nitrogen loading effort also involved further refinement of watershed delineations to accurately reflect shoreline areas to freshwater ponds and each portion of the estuary (see Chapter III).

The initial task of standard MEP land use analysis is to gauge whether or not nitrogen discharges to the watershed have reached the estuary. This involves a temporal review of land use changes, the time of groundwater travel provided by the USGS watershed model, and review of data at natural collections points, such as streams and ponds. Evaluation and delineation of ten-year time of travel zones are a regular part of MEP watershed analysis. Ten-year time of travel sub-watersheds in the overall Herring Brook watershed have been delineated for ponds, streams and the estuary itself. Simple review of less than and greater than 10-year time of travel watersheds indicates that 67% of the unattenuated nitrogen load from the whole watershed is within less than 10 year travel time to the estuary (**Table IV-1**). If this review is refined by looking at the measured stream flows, outflow from the ponds, and adding in loads from precipitation on the estuary surface, the percentage that reaches the estuary within 10 years increases to 77%. The overall result of the timing of development relative to groundwater travel times is that the present watershed nitrogen load appears to accurately reflect the present nitrogen sources to the estuary (after accounting for natural attenuation, see below) and considering that the distinction between time of travel in the sub-watersheds is not important for modeling existing conditions. Based on the review of all this information, it was determined that the overall Herring Brook estuary is currently in balance with its watershed load.

In order to determine nitrogen loads from the watersheds, detailed individual lot-by-lot data are used for some portion of the loads, while information developed from other detailed site-specific studies is applied to other portions of the watershed. The MEP Linked Watershed-Embayment Management Modeling Approach uses a land-use watershed Nitrogen Loading Sub-Model based

Table IV-1. Percentage of unattenuated nitrogen loads in less than ten year time-of-travel sub-watersheds to Herring Brook.				
WATERSHED	LT10	GT10	TOTAL	% LT10
Name	kg/yr	kg/yr	kg/yr	
Lower Herring Brook	705		705	100%
Upper Herring Brook	170	887	1,057	16%
Outfall2	43		43	100%
Wing Pond	948	413	1,361	70%
Trout Stream	582	651	1,233	47%
Crocker Pond	212		212	100%
Herring Brook Whole System	2,659	1,300	3,959	67%
Note: If these loads are corrected to account for stream flows, outflow from the ponds, and input loads from precipitation on the estuary surface, the percentage of watershed nitrogen load within 10-year time-of-travel to estuary increases to 77% .				

upon sub-watershed specific land uses and pre-determined nitrogen loading rates based on regional analyses.[25] For the Herring Brook System, the model used land-use and water use data from the Town of Falmouth transformed into nitrogen loads using both regional nitrogen loading factors and local watershed-specific data. 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 unattenuated nitrogen loads to Herring Brook are then corrected with attenuation factors during transport based on measured loads at a later stage.

Natural attenuation of nitrogen during transport from land-to-sea within the Herring Brook watershed was determined based upon a site-specific study of stream flow (Section IV.2) and assumed attenuation in the upgradient freshwater ponds. Stream flow was characterized at the outlet immediately downstream of Wing Pond and Trout Stream, which enters at the headwaters of Herring Brook. Subwatersheds delineated to these stream discharge point allowed comparison between field collected data from the stream and estimates from the watershed nitrogen-loading sub-model. Nitrogen attenuation in individual ponds is generally estimated based on available information. Attenuation through the ponds is conservatively assumed to equal 50% unless available monitoring and pond physical data are reliable enough to calculate a pond-specific nitrogen attenuation factor.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to effect groundwater flow patterns (area and depth) was a standard part of the data collection effort of the MEP. In the present effort, two freshwater ponds have delineated sub-watersheds within

[25] Howes, B.L., J.S. Ramsey, S.W. Kelley. 2001. Nitrogen modeling to support watershed management: comparison of approaches and sensitivity analysis. Final Report to Massachusetts Department of Environmental Protection and U.S. Environmental Protection Agency, 94 pp.

the Herring Brook watershed: Crocker Pond and Wing Pond. If smaller aquatic features that have not been included in this analysis were providing additional attenuation of nitrogen, nitrogen loading to the estuary would only be slightly overestimated given the distribution of nitrogen sources within the watershed.

IV.1.1 Land Use and Water Use Database Preparation

The watershed to Herring Brook is mostly within the Town of Falmouth with a small portion in Joint Base Cape Cod (Towns of Bourne and Sandwich). As such, project staff obtained digital parcel and tax assessor's data from the Town of Falmouth[26] to serve as a base for the Herring Brook watershed nitrogen loading model. Digital parcels and land use/Town Assessor's data for Falmouth are from 2022. The land use database contains traditional information regarding parcel sizes and land use classifications.[27]

Figure IV-1 shows the land uses within the Herring Brook estuary watershed. Land uses in the study area are grouped into ten (10) land use categories: 1) residential, 2) commercial (golf course), 3) industrial, 4) mixed use, 5) agricultural (mostly cranberry bogs), 6) undeveloped – industrial, 7) undeveloped - residential, 8) public service/government, 9) open space, and 10) road rights-of-way. These land use categories are utilized by the Town Assessor and are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications.[28] "Public service" in the MADOR system represents tax-exempt properties, including lands owned by government (*e.g.*, conservation commission land, wellfields, schools, golf courses, open space, roads) and private groups like religious organizations and land trusts. It should be noted that the whole commercial land category in the Herring Brook watershed is the Sacconnesset Golf Club (land use code 380) and the whole agricultural category is cranberry bogs or associated lands. Public service lands are the largest percentage of the overall watershed area (38%) with residential lands as the second largest portion (37%) (**Figure IV-2**).

Residential land uses are the dominant parcel type in the overall Herring Brook watershed with 77% of the overall parcel count (total count = 794). Residential land uses are also the dominant parcel type in each of the sub-watershed groupings shown in Figure IV-2. Undeveloped or public service parcels are the second largest parcel count within the subwatersheds with undeveloped parcels the second largest parcel type (10% of total) in the overall watershed. Single family residences are 98% of the residential parcel count and 97% of the residential area.

In order to estimate wastewater flows within the Herring Brook study area, project staff obtained and linked parcel-by-parcel water use data from the Town of Falmouth[29] to the Town Assessor parcels. Four years of water use (2018-2021) was obtained from the town. Measured water use is used to estimate wastewater-based nitrogen loading from individual parcels; average water use for each parcel is used for parcels with multiple years of data.

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[26] Personal communication, S. Waid, Town of Falmouth GIS Coordinator

[27] Massachusetts Department of Revenue. April 2019. Property Type Classification Codes. 23 pp.

[28] *Ibid.*

[29] Personal communication, A. Lowell, Town of Falmouth Wastewater Superintendent, 8/30/22

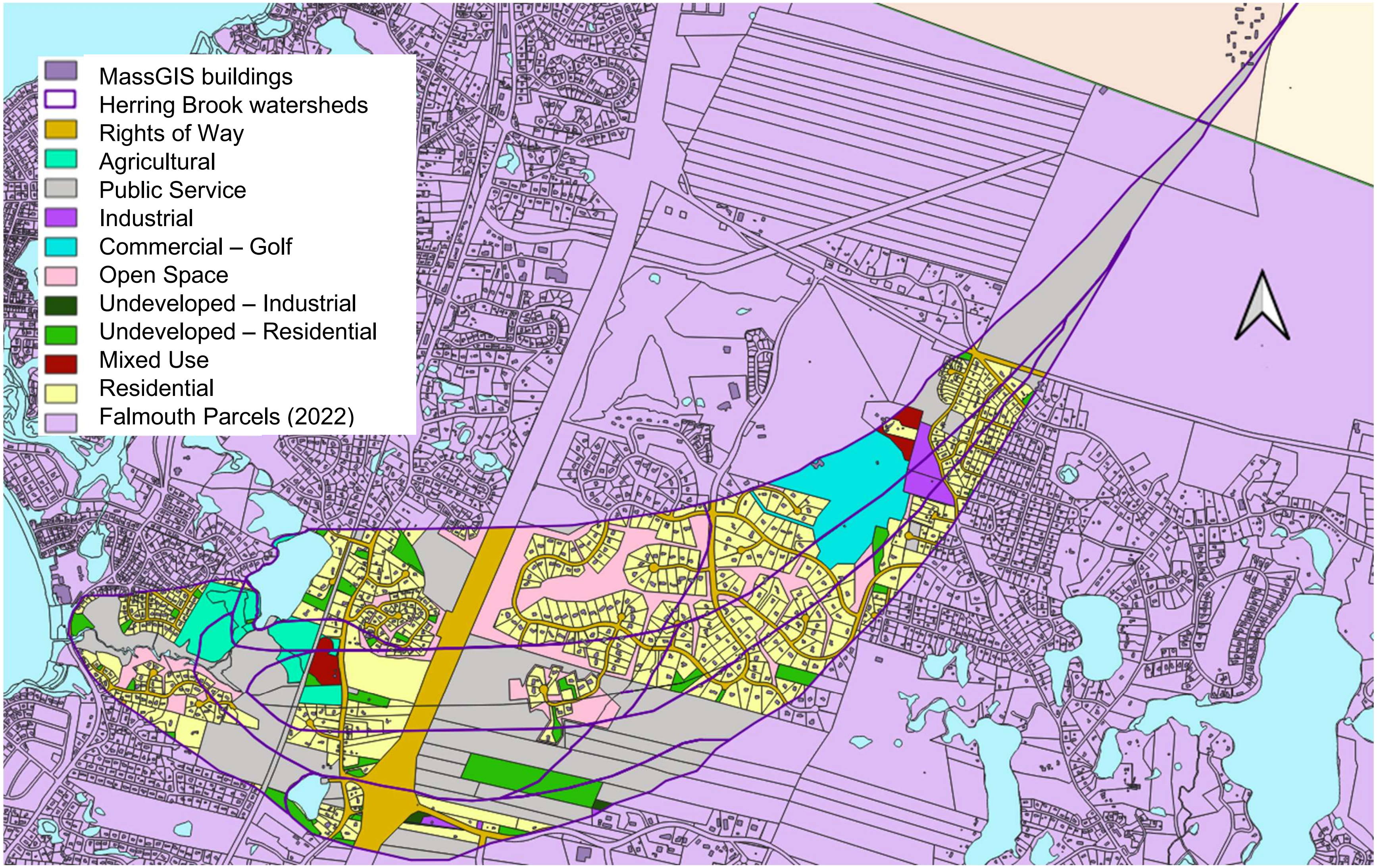

Figure IV-1. Land-use in the Herring Brook system watershed and sub-watersheds. The total system watershed is mostly within the Town of Falmouth, but a small portion extends into the Bourne and Sandwich portions of Joint Base Cape Cod. Land use classifications are based on Town Assessor's classifications and MADOR (2019) categories. Base assessor and parcel data for Falmouth are from the year 2022.

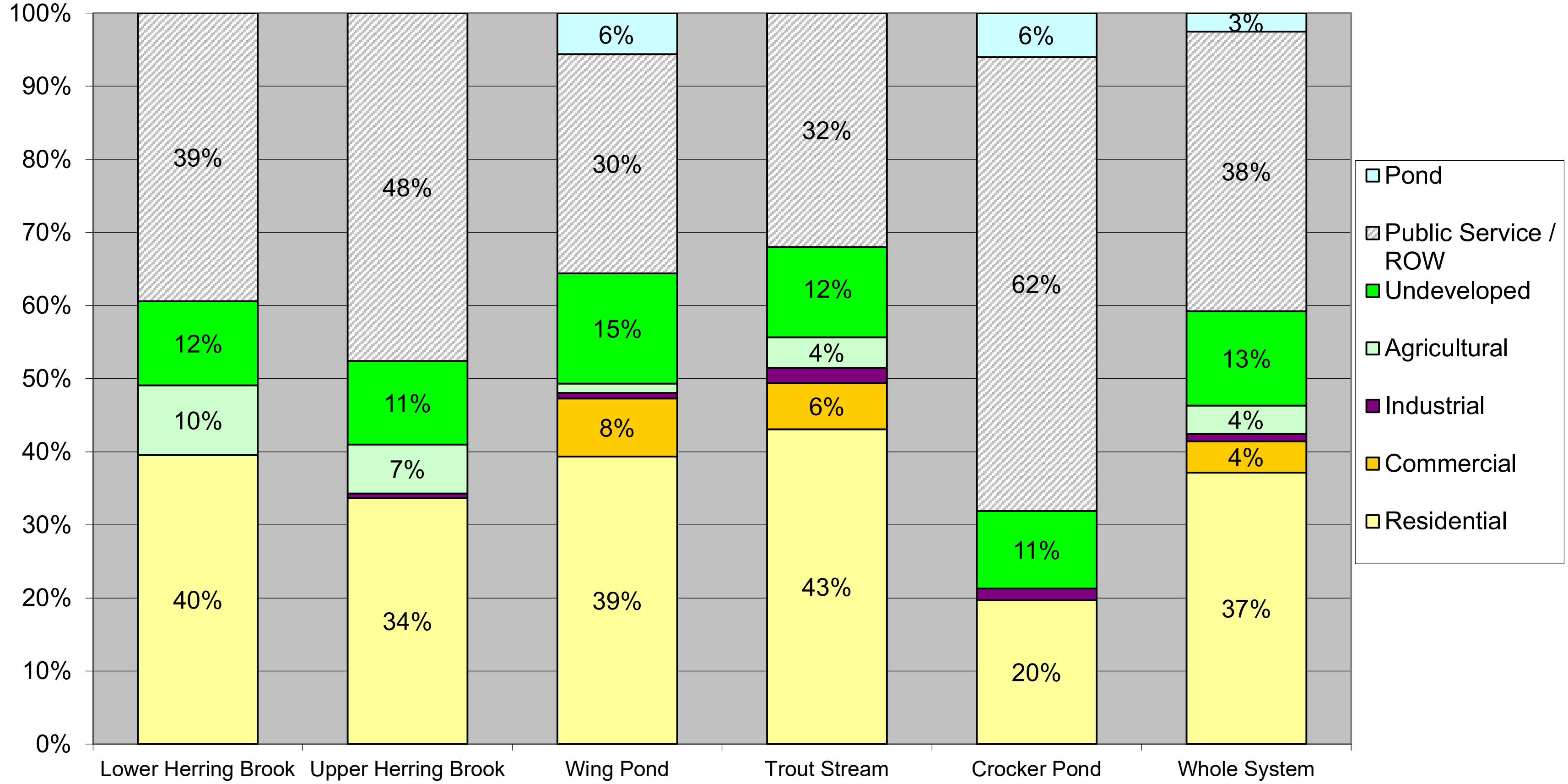

Figure IV-2. Distribution of land-uses by area within the Herring Brook system watershed and five component sub-watersheds. Land use categories are generally based on town assessor's land use classification and groupings recommended by MADOR (2019). Undeveloped category includes land currently classified by the Town Assessor's as developable and undevelopable. Lands in the Public Service category include those owned by the Town, the Commonwealth of Massachusetts (various agencies), and various non-profits, including charities and religious groups. Only land-uses comprising 4% or more of the watershed area have percent labels.

IV.1.1 Nitrogen Loading Input Factors

The Herring Brook watershed nitrogen loading is based on Massachusetts Estuaries Project (MEP) techniques, which relied on watershed-specific factors, such as individual parcel water use, and factors derived from studies in similar sandy aquifer conditions or those developed in MEP evaluations of other estuaries. The MEP Technical Team developed watershed nitrogen loads for over 70 estuaries in southeastern Massachusetts with an approach that was approved by MassDEP and USEPA, and was found to be reasonable in a number of peer-reviews, including a National Science Foundation-level review by Barnstable County in 2011.[30]

Wastewater/Water Use

The MEP septic system nitrogen loading rate is fundamentally based upon a *per capita* nitrogen load to the receiving aquatic system. 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 changes in population 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 used water use adjusted for consumptive use as a proxy for wastewater generation. The water-use approach is applied on a parcel-by-parcel basis within a watershed and parcel-specific water use data are converted to septic system nitrogen discharges by adjusting for consumptive use and applying a wastewater nitrogen concentration.

All nitrogen losses within a septic system are incorporated into standard MEP analysis. For example, information developed at the MassDEP Alternative Septic System Test Center at Joint Base Cape Cod has shown nitrogen removals between 21% and 25% for standard Title 5 septic systems. Multi-year monitoring at 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.[31] Downgradient studies of septic system plumes in similar soils indicate that further nitrogen loss during aquifer transport is negligible.[32,33]

During the development of the MEP wastewater nitrogen loading factors, MEP staff relied on the well-constrained *per capita* septic load and reviewed options for consumptive use to develop a reasonable N concentration. As a result of extensive discussions with MassDEP, MEP staff derived a combined term for an effective N Loading Coefficient (consumptive use times N concentration) of 23.63 mg/L to convert water use to nitrogen loads. This coefficient relies on a *per capita* annual nitrogen load of 2.1 kg N. 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, including over

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30 Bierman, V.J, Jr., P. Shanahan, L.E. Band, B.H. Johnson, W.J. Kenworthy, and P.E. Stacey. 2011. Massachusetts Estuary Project (MEP) Linked Watershed Embayment Model Peer Review. Scientific Peer Review Panel Report. 54 pp.

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

32 Robertson, W.D., J.D. Cherry, and E.A. Sudicky. 1991. Ground-Water Contamination from Two Small Septic Systems on Sand Aquifers. *Groundwater*. 29(1): 82-92.

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

65 streams measured during the MEP (including Mashapaquit Creek in West Falmouth Harbor) and pre-MEP assessments of watershed/stream tube analysis.[34,35]

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

In order to provide an independent validation of the average residential water use within the Herring Brook watersheds, project staff reviewed available US Census information and focused on the North Falmouth census-designated place (CDP) that includes the northern portion of the Herring Brook watershed. According to the 2020 US Census, the North Falmouth CDP has 2,644 housing units with approximately 37% occupied year-round and 992 households. This information would translate to 2.39 people per house year-round, but the low percentage of year-round occupancy means that there is likely a large seasonal inflow, as there is for many areas of Cape Cod with some anecdotal information of conversions of seasonal houses to year-round residences during the initial COVID outbreak. The state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5) assume that each person generates 55 gpd of wastewater. Based the average occupancy in the North Falmouth CDP, this flow would be 119 gpd after accounting for consumptive use. Average recorded water use for the single-family residences within the Herring Brook watershed based on 2018-2021 water use was 228 gpd. If the population within the North Falmouth CDP doubled, the average daily water use would be 237 gpd. Given that past reviews of other Cape Cod data (*e.g.*, traffic counts, garbage generation, WWTF flows) suggest average population increases from two to three times year-round residential populations, this suggests that the water use measured in the Herring Brook watershed is a reasonable estimate of wastewater.

Water use information exists for 79% of the 448 developed parcels in the Herring Brook watershed. Developed parcels without water use accounts are assumed to utilize private wells for drinking water. These are properties that were classified with land use codes that should be developed (*e.g.*, 101 or 325), have been confirmed as having buildings on them through a review of aerial photographs or town assessor valuations, and do not have a listed account in the water

[34] Weiskel, P.K. and B.L. Howes, 1991. Quantifying Dissolved Nitrogen Flux Through a Coastal Watershed. *Water Resources Research*. 27(11): 2929-2939.

[35] Weiskel, P.K. and B.L. Howes, 1992. Differential Transport of Sewage-Derived Nitrogen and Phosphorous through a Coastal Watershed. *Environmental Science and Technology*. 26: 352-360.

use databases. Of the 96 developed parcels without water use accounts, 92 (96%) are classified as single-family residences (land use code 101). These parcels are assumed to utilize private wells and were assigned the Herring Brook study area average water use of 253 gpd in the watershed nitrogen loading modules. Of the four remaining developed parcels, all are other residential land uses. Given the preponderance of residential land uses among developed parcels without water use accounts, all of these parcels were also assigned 253 gpd as their water use in the watershed nitrogen loading model.

In addition to standard septic systems, project staff also consulted with the Barnstable County Department of Health and the Environment (BCDHE) to see if any alternative, denitrifying septic systems were monitored within the Herring Brook watershed. None were listed in the BCDHE database.[36] No groundwater discharge permits were listed for any properties within the watershed either.[37]

Nitrogen Loading Input Factors: Fertilized Areas

The second largest watershed source of nitrogen loading to estuaries is usually fertilized areas: lawns, golf courses, and cranberry bogs. Residential lawns are usually the predominant source within this category, but can golf course turf can also be a significant source. In order to add these sources to the nitrogen loading model for the Herring Brook system, project staff utilized standard lawn nitrogen loads used in all previous Falmouth MEP assessments, as well as the fertilizer application rates used for the Sacconnesset Golf Club in the Wild Harbor MEP assessment.[38] An estimated nitrogen load is also included for the cranberry bogs in the watershed based on monitoring of other similar bogs.

Prior to the MEP, residential lawn fertilizer use was rarely directly measured in watershed-based nitrogen loading investigations. Instead, lawn fertilizer nitrogen loads were estimated based upon a number of assumptions. During the development of the MEP, CSP/SMAST reviewed many of the key assumptions and developed MEP-specific residential lawn fertilizer factors for application rates, lawn sizes, and leaching rates. The initial effort in this review was determining nitrogen fertilization rates for residential lawns in the Towns of Falmouth, Mashpee and Barnstable. Based upon ~300 interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sqft, 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a nitrogen leaching rate of 20% results in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors were used in MEP nitrogen loading calculations. It is likely that this still represents a conservative estimate of nitrogen load from residential lawns. It should be noted that professionally maintained lawns in the three town survey were found to have the higher rate of fertilizer application and hence higher estimated annual contribution to groundwater of 3 lb/lawn/yr. Similar later surveys in the Town of Orleans largely confirmed these findings.

[36] Personal communication. Tracy Long, BCDHE. January 18, 2023.

[37] GWDP are MassDEP permits for wastewater discharges >10,000 gpd.

[38] Howes B., E.M. Eichner, S. Kelley, R.I. Samimy, J.S. Ramsey, D.R. Schlezinger, P. Detjens. 2011.

At the time of the Wild Harbor MEP assessment, project staff contacted Charles Passios, Chief Operating Officer of the Golf Club of Cape Cod (now Sacconnesset Golf Club) and Ballymeade Country Club to obtain site-specific fertilizer application rates for the various turf types at the golf course. In other MEP assessments, when site-specific golf course fertilizer application rates were not available, MEP staff assigned average application rates from the 19 courses that provided this information. Mr. Passios approved the use of the averages for the two courses in the Wild Harbor watershed and this was continued in the Herring Brook assessment. The MEP golf course turf nitrogen application rate averages (all in pounds per 1,000 square feet per year) based on reporting from 19 courses are: greens, 3.6; tees, 3.3; fairways, 3.3, and roughs, 2.5. As has been done in all MEP reviews, project staff reviewed the layout of the Sacconnesset Golf Club from aerial photographs, classified the various turf types, and, using GIS, assigned these areas to the appropriate Herring Brook subwatersheds. The MEP average golf course nitrogen application rates were then applied to the respective turf areas, a standard MEP 20% nitrogen leaching rate was applied, and annual nitrogen load from the golf course to each subwatershed was calculated.

Cranberry bog nitrogen loading was determined based on previous studies conducted in southeastern Massachusetts. Cranberry bog fertilizer application rate and percent nitrogen attenuation in the bogs is based on an annual study of nutrient cycling and loss from cranberry agriculture that was conducted in southeastern Massachusetts.[39] Based on this study, there were differences in how much nitrogen is released from cranberry bogs depending on whether water flows through the bog continuously or whether water is only pumped on to the bog during harvesting, irrigation, and frost prevention. After reviewing historical and current aerial photographs of the bogs in the Herring Brook watershed, they were assigned the pump-on loading rate and only for the bog surfaces, not the upland areas. For the watershed nitrogen loading analysis, the bog surface areas are based on a GIS coverage maintained by MassDEP for Water Management Act purposes. Cranberry bogs impact the Wing Pond subwatershed nitrogen loads, which means they are split between the Herring Brook and Wild Harbor nitrogen loads.

Nitrogen Loading Input Factors: Other

Other nitrogen loading factors included in the Herring Brook assessment are for atmospheric deposition, impervious surfaces and natural areas. These are the standard MEP factors[40] and are similar to those used in the Cape Cod Commission Nitrogen Loading Technical Bulletin[41] and the 1999 MassDEP Nitrogen Loading Computer Model.[42] The recharge rate for natural areas and lawn areas is the same as utilized in the watershed delineation effort (Section III). Factors used in the MEP nitrogen loading analysis for the Herring Brook watershed are summarized in **Table IV-2.**

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

[40] Howes, B.L., J.S. Ramsey and S.W. Kelley, 2001. Nitrogen modeling to support watershed management: comparison of approaches and sensitivity analysis. Final Report to MA Department of Environmental Protection and USEPA, 94 pp. Published by MADEP.

[41] Eichner, E.M. and T.C. Cambareri, 1992. Technical Bulletin 91-001: Nitrogen Loading. Cape Cod Commission, Water Resources Office, Barnstable, MA. 25 pp.

[42] https://www.mass.gov/service-details/nitrogen-loading-computer-model

Road areas are based on Massachusetts Department of Transportation (MassDOT) GIS information.[43] The MassDOT GIS coverage provides information on all road widths, rights-of-way width, and various other road characteristics within the state. The coverage was originally produced in 2018, but portions are regularly updated. MEP staff utilized the GIS to sum these road segments and their various widths by subwatershed. Project staff also checked this information against Town parcel-based rights-of-way.

Building areas are based on MassGIS information.[44] This information is building footprints digitized from interpretation of aerial photos and LiDAR data collect state-wide. The most recent update that included Falmouth was 2021 aerial imagery.

IV.1.2 Watershed Nitrogen Loads

Standard MEP procedures were followed to develop the nitrogen loads once all the factors were assigned. Land and water use information is linked to the parcel coverages, parcels are assigned to various watersheds based initially on whether at least 50% or more of the land area of each parcel is located within a respective subwatershed. Following the assigning of boundary parcels, all large parcels are examined individually and are split (as appropriate) in order to obtain less than a 2% difference between the total land area of each subwatershed and the sum of the parcel areas.

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

Following the assignment of all parcels, sub-watershed modules were generated for each of the ten (10) subwatersheds in the Herring Brook study area. These subwatershed modules summarize, among other things: water use, parcel area, parcel frequency by land use category, private wells, and road area. All relevant nitrogen loading data are assigned to each subwatershed. Individual subwatershed information is then integrated to create the Herring Brook Watershed Nitrogen Loading summary module with summaries for each of the individual eight sub-watersheds. The subwatersheds are generally paired with functional embayment/estuary units for the Linked Watershed-Embayment Model's water quality component.

[43] https://www.mass.gov/info-details/massgis-data-massachusetts-department-of-transportation-massdot-roads
[44] https://www.mass.gov/info-details/massgis-data-building-structures-2-d

Table IV-2. Primary Nitrogen Loading Factors used in the Herring Brook assessment. General factors are consistent with other MEP assessments, while other factors are based on Falmouth-specific data.

Nitrogen Concentrations:	**mg/l**	**Recharge Rates:**	**in/yr**
Road Run-off	1.5	Impervious Surfaces	40
Roof Run-off	0.75	Natural and Lawn Areas	27.25
Natural Area Recharge	0.072	**Water Use/Wastewater:**	
Direct Precipitation on Embayments and Ponds	1.09	Existing developed parcels wo/water accounts and buildout single-family residential parcels:	253 gpd[3]
Wastewater Coefficient	23.63		
Fertilizers:			
Average Residential Lawn Size (sq ft)[2]	5,000	Existing developed parcels w/water accounts:	Measured annual water use
Residential Watershed Nitrogen Rate (lbs/lawn)[2]	1.08	Only commercial properties are golf course properties	
Cranberry Bogs Nitrogen Leaching (kg/ha/yr)[1]	6.9	No denitrifying I/A septic systems in the watershed listed in Barnstable County Department of Health and the Environment monitoring database	
Average footprint of buildings on Single Family Residence parcels (sq ft)	2,681		

Notes:
1) MEP pump on-pump off cranberry bog factor
2) Data from MEP lawn study
3) Based on average flow of all single-family residences in the watershed

The aggregated watershed nitrogen loads are partitioned by the major types of nitrogen sources in order to focus development of nitrogen management alternatives. Within the Herring Brook marsh system watershed, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), fertilizers, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (**Table IV-3**). The annual watershed nitrogen input to the watershed of an estuary is then adjusted for natural nitrogen attenuation by streams or ponds during transport to the estuarine system before use in the embayment water quality sub-model (details discussed below). 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-3**).

Table IV-3. Herring Brook Existing Conditions Watershed Nitrogen Loads. Nitrogen loads are initially developed as unattenuated nitrogen loads that are the sum of loads from individual parcels after applying nitrogen loading factors. These loads are then modified to reflect natural attenuation that occurs in freshwater ponds and streams. Stream attenuation factors are based on measured loads (see Section IV.2), while pond attenuation factors are assigned a standard MEP nitrogen attenuation rate of 50% based on water quality monitoring from the Cape Cod Pond and Lake Stewards program or a modified factor if sufficient monitoring data are available. All nitrogen loads are kg N yr^{-1}.

PRESENT		Herring Brook N Loads by Input (kg/yr):					% of Pond Outflow	Present N Loads		
Name	Watershed ID#	Wastewater	Fertilizers (Residential, Cran bogs, GCs, Agric)	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces		UnAtten N Load	Atten %	Atten N Load
HERRING BROOK SYSTEM		**3,614**	**387**	**297**	**103**	**209**		**4,610**		**3,905**
Lower Herring Brook LT10	1	582	52	49	-	22		705		705
Crocker Pond	10	106	12	40	32	21		212	50%	106
Upper Herring Brook Total		2,926	323	208	71	166		3,694		3,094
Upper Herring Brook LT10	2	101	17	25	-	26		170		170
Upper Herring Brook GT10	9	768	42	44	-	33		887		887
Wing Pond Outfall Total		1,048	161	73	71	50		1,404		928
Wing Pond Outfall	3	24	12	4	-	4		43		43
Wing Pond Total		1,024	149	70	71	47	54%	1,361	35%	884
Trout Stream Total		1,008	103	65	-	57		1,233	10%	1,110
Trout Stream LT10	7	489	23	34	-	36		582		582
Trout Stream GT10	8	519	80	31	-	21		651		651
Lower Herring Brk LT10 Estuary Surface					11					11
Wing Pond TOTAL		1,891	275	129	131	86		2,512	35%	1,633
Wing Pond LT10	4	1,381	104	87	131	47		1,750		1,750
Wing Pond GT10 + shed 6 JBCC	5/6	510	171	41	-	39		762		762

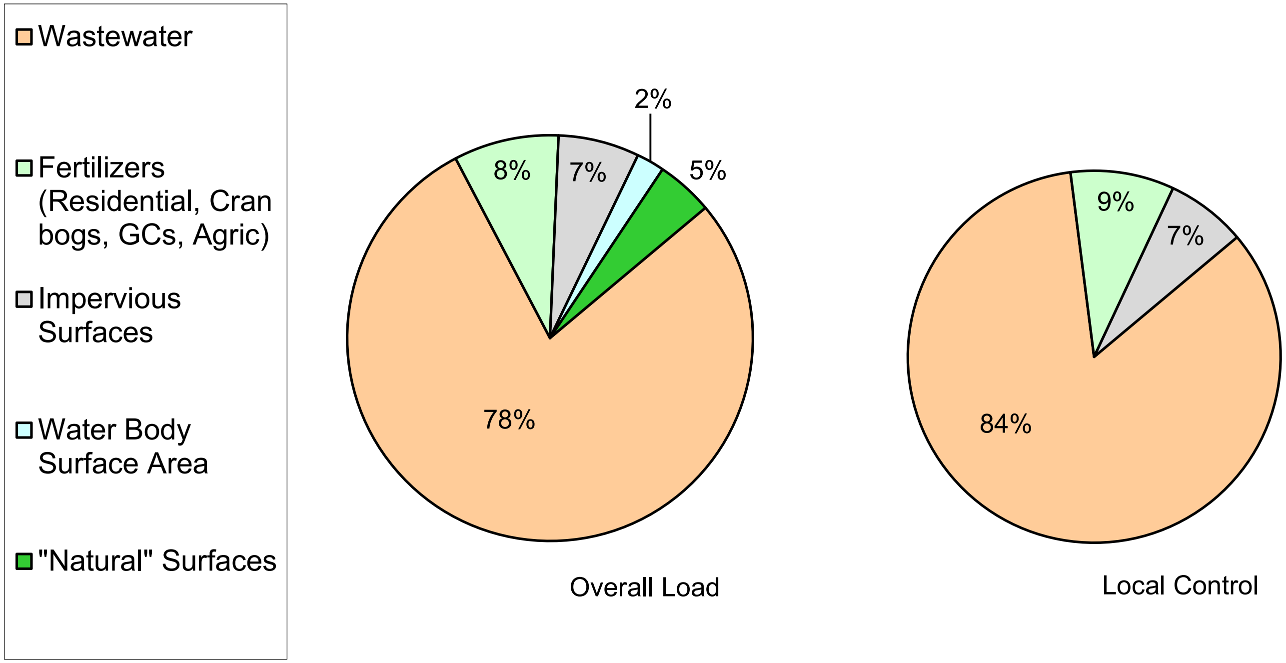

Figure IV-3. Land use-specific unattenuated nitrogen loads (by percent) to the whole Herring Brook watershed. "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control. Wastewater is the predominant source of nitrogen within the Herring Brook marsh watershed.

Freshwater Pond Nitrogen Loads

Freshwater ponds and lakes on Cape Cod are generally watershed sites of natural nitrogen reduction (or attenuation) prior to the watershed nitrogen reaching an estuary. Ponds and lakes may have different configurations; some are true kettle-hole ponds with no stream inflows or outflows, while others may have either an inflow or outflow or both. Ponds and lakes in the Cape Cod Ecoregion are generally depressions in the land surface that intercept the surrounding groundwater table, so groundwater will flow into the ponds along the upgradient shoreline, then lake/pond water flows back into the groundwater system along the downgradient shoreline. If a pond has a stream outflow, the stream can act as a path of least resistance and outflow can be focused toward the stream, but this impact can vary from pond to pond.

Since the nitrogen loads usually flow into a pond with the groundwater, the relatively more productive pond ecosystems incorporate some of the nitrogen, retain some nitrogen in the sediments, and change the nitrogen among its various oxidized and reduced forms. As a result of these interactions and transformations, some of the nitrogen in the pond watershed is removed from the estuary watershed system, mostly through burial in pond sediments and denitrification that returns it to the atmosphere. Following these reductions, the remaining (attenuated) loads flow back into the groundwater system along the downgradient side of the pond and eventually discharge into the downgradient embayment or through a stream outlet directly to the estuary. The nitrogen load summary in Table IV-3 includes both the unattenuated (nitrogen load to each subwatershed) and attenuated nitrogen loads.

At the time of the MEP started, nitrogen attenuation in freshwater ponds had generally been found to be at least 50% in available studies. So a conservative attenuation rate of 50% was generally assigned to all nitrogen from freshwater pond watersheds in MEP watershed models unless more detailed pond monitoring or studies were available. Detailed studies of nitrogen in Cape Cod ponds since the MEP was initiated have generally shown that a 50% attenuation rate is reasonable if no further information is available. Nitrogen attenuation calculated after extensive monitoring attenuation in the following ponds has generally ranged from 50% to 80%, but some exceptions have been measured:

- Shubael Pond, Barnstable: 76% attenuation[45]
- Long Pond, Barnstable: 83% attenuation[46]
- Crystal Lake, Orleans: 35% to 53% attenuation[47]
- Pilgrim Lake, Orleans: 50% attenuation[48]

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[45] Eichner, E., B. Howes, and D. Schlezinger. 2022. Shubael Pond Management Plan and Diagnostic Assessment. Town of Barnstable, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 119 pp.

[46] Eichner, E., B. Howes, and D. Schlezinger. 2022. Long Pond Management Plan and Diagnostic Assessment. Town of Barnstable, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 110 pp.

[47] Eichner, E., B. Howes, and D. Schlezinger. 2021. Crystal Lake Management Plan and Diagnostic Assessment. Town of Orleans, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 104 pp.

[48] Eichner, E., B. Howes, and D. Schlezinger. 2019. Pilgrim Lake Management Plan and Diagnostic Assessment. Town of Orleans, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 114 pp.

- Baker Pond, Orleans: 52% attenuation[49]
- Mystic Lake, Barnstable: 87% attenuation[50]
- Middle Pond, Barnstable: 40% attenuation[51]
- Hamblin Pond, Barnstable: 52% attenuation[52]

During the course of the MEP, the technical team reviewed the available data for each pond to determine whether it was sufficient to support a pond-specific nitrogen attenuation rate rather than assigning the MEP 50% standard rate. This review usually included reviews of water column data, temperature and dissolved oxygen profiles, whether sediment regeneration was likely, and bathymetric information. Bathymetric information is generally a prerequisite for determining the level of enhanced attenuation, since it provides the volume of the pond and, with appropriate pond total nitrogen concentrations, a measure of the nitrogen mass in the water column. Combined with the watershed recharge, this information can provide a residence or turnover time that is necessary to gauge nitrogen attenuation. In addition to bathymetry, temperature profiles are useful to help understand whether temperature stratification is occurring in a pond. If the pond thermally stratifies, the stability and volume of the layers must be accounted for in the nitrogen attenuation calculations. In stratified lakes, the upper epilimnion is usually the primary discharge for watershed nitrogen loads during the summer, while the deeper hypolimnion generally does not interact with the upper layer. However, deep lakes with hypolimnions often also have significant sediment regeneration of nitrogen and in lakes with impaired water quality this regenerated nitrogen can impact measured water column nitrogen concentrations in the upper epilimnion and this impact should also be considered when estimating nitrogen attenuation.

Many Cape Cod ponds and lakes have been sampled through the regional Cape Cod Pond and Lake Stewards (PALS) Snapshots, which have occurred annually for more than 20 years. The PALS Snapshots are regional volunteer pond one-time sampling in August/September that has been supported with free laboratory services provided by the Coastal Systems Program Laboratory at SMAST. Samples were analyzed provided they were collected according to the PALS sampling protocols.[53] The Snapshot was developed to help towns gather some useful information for prioritization of more extensive sampling and development of pond management plans, has created local volunteer pond sampling programs, and led to creation of town-based advocacy groups. Sampling protocols developed through the PALS program have also been used for more extensive citizen-based pond sampling programs in many communities.

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49 Eichner, E., B. Howes, and D. Schlezinger. 2022. Baker Pond Management Plan and Diagnostic Assessment. Town of Orleans, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 106 pp.

50 Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Three Bays, Barnstable, Massachusetts. Massachusetts Estuaries Project, Massachusetts. Department of Environmental Protection. Boston, MA. 183 pp.

51 *Ibid.*

52 *Ibid.*

53 Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas. Cape Cod Commission. Barnstable, MA. 280 pp.

Within the Herring Brook watershed, there are two freshwater ponds with delineated watersheds: Crocker Pond and Wing Pond. Crocker Pond has a bathymetric map completed in 2012,[54] while Wing Pond does not. Neither pond has sufficient water quality data collection outside of the MEP or PALS. Crocker Pond has been sampled five times through PALS Snapshots and Wing Pond has not been sampled through the PALS Program. Given that neither of the ponds with delineated watersheds in the Herring Brook watershed have sufficient information to assign alternative nitrogen attenuation rates, both Crocker Pond and Wing Pond were assigned the MEP standard rate of 50% nitrogen attenuation.

IV.2 STREAM MEASUREMENTS: ATTENUATION OF WATERSHED NITROGEN

Modeling and predicting changes in coastal embayment nitrogen related water quality is based, in part, on reasonable determination of the inputs of nitrogen from the surrounding contributing land or watershed. Part of making sure that watershed nitrogen loads are reasonable is determining all of the watershed loads that reach the estuary and which are removed by natural processes in lakes, ponds, streams, and marshes prior to discharge into the estuary. As was mentioned in the discussion of pond attenuation, these resources can remove nitrogen loads through burial in pond sediments and denitrification that returns nitrogen to the atmosphere. During the MEP one of the additional ways this nitrogen attenuation was directly measured was in stream discharges. Since streams are natural drains and can collect flow from large portions of the watershed, measurements of stream nitrogen loads can directly measure a portion of the watershed nitrogen load to the estuary. In the Herring Brook system, two streams were gauged to directly measure nitrogen inputs: Wing Pond outfall and Trout Stream (**Figure IV-4**).

Gauges were installed to continuously measure water levels and instantaneous flow readings and water quality samples were collected at both gauge locations on 25 dates between August 4, 2021 through September 16, 2022 using standard MEP measurement and sampling techniques. Higher frequency of sampling and measurements occurred during the summer (June-September) and monthly during the rest of the year. The gauges were programmed to record water level data every 10 minutes.

During MEP stream gauging, the Technical Team typically used stage recordings and the instantaneous flow readings to develop stage-discharge relationships (*i.e.*, rating curves) that could then be used with the stage recording record to develop hourly and daily measurements of flow volumes, which could then, in turn, be used to determine a refined annual flow. After reviewing the stream recordings at the two Herring Brook locations, project staff determined that the stage-discharge relationships were not reliable (**Figure IV-5**). The flow readings were inconsistent with each other (*e.g.*, flow readings at one gauge would increase while other decreased), were inconsistent with precipitation events, and stage and flow recordings had low correlations ($R^2<0.4$). Project staff believe that these differences are likely due to water use and transfers at the cranberry bogs that are located nearby (see Figure IV-4). After correcting measured flows to remove outliers/spikes, the annual daily flows at the two gauges were: 2,354 m^3/d at the Wing Pond outfall and 2,359 m^3/d at Trout Stream (**Table IV-4**). The project team used the individual corrected individual readings with the corresponding TN concentrations to determine that the annual daily loads were 2.55 kg TN/d and 2.98 kg TN/d, respectively.

[54] EcoLogic LLC Technical Memorandum. August 8, 2013. Crocker Pond, Falmouth: Potential Soil Attenuation of Phosphorus Migration from Infiltrating Treated Wastewater at Site 7. To: GHD, Inc. 21 pp.

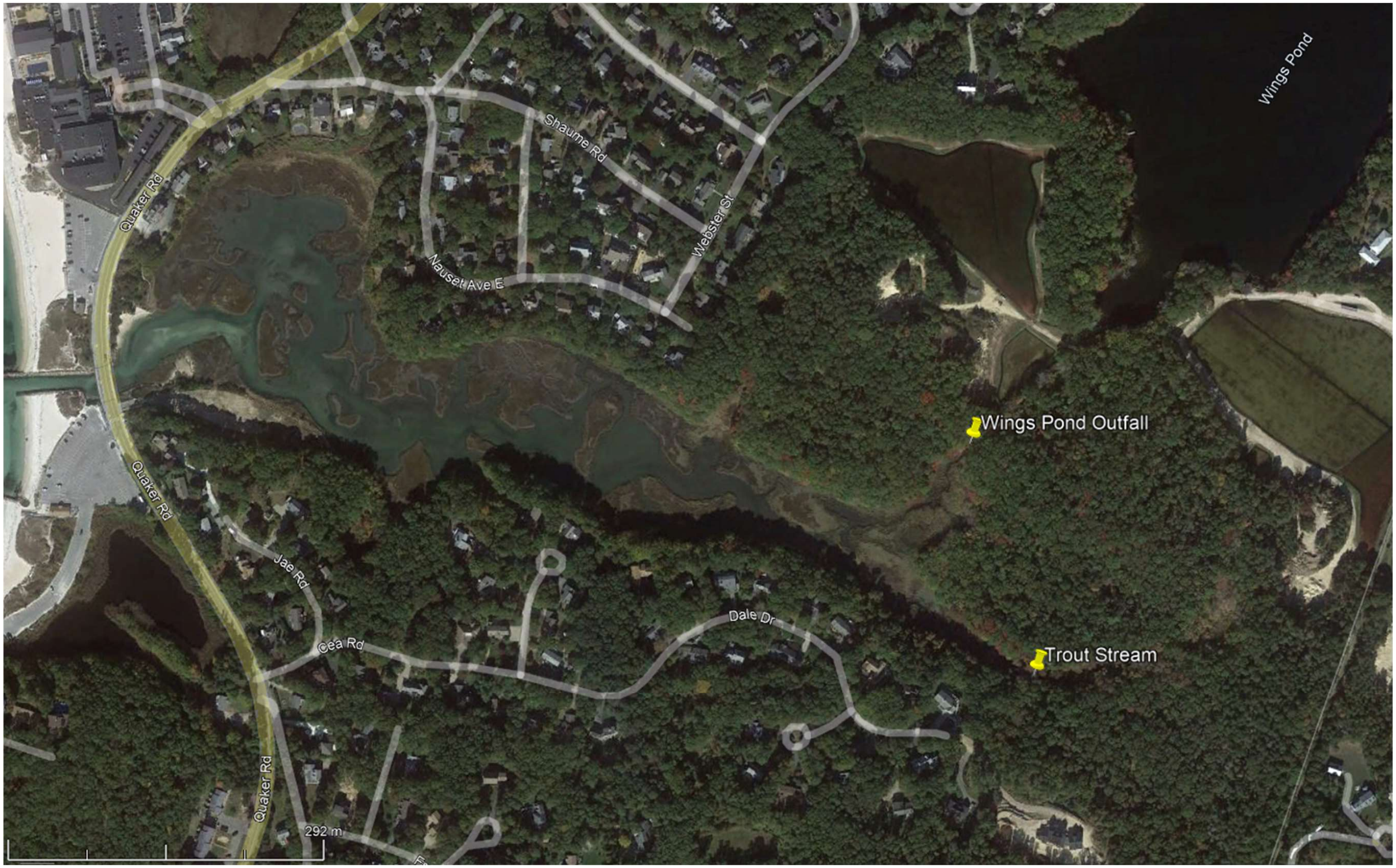

Figure IV-4. Location of Herring Brook marsh stream gauges. Gauges were located just upstream of tidal influences and were in place from August 4, 2021 through September 16, 2022. Instantaneous flow readings and water quality samples were collected at gauge locations on 25 dates with higher frequency during the summer (June-September) and monthly during the rest of the year.

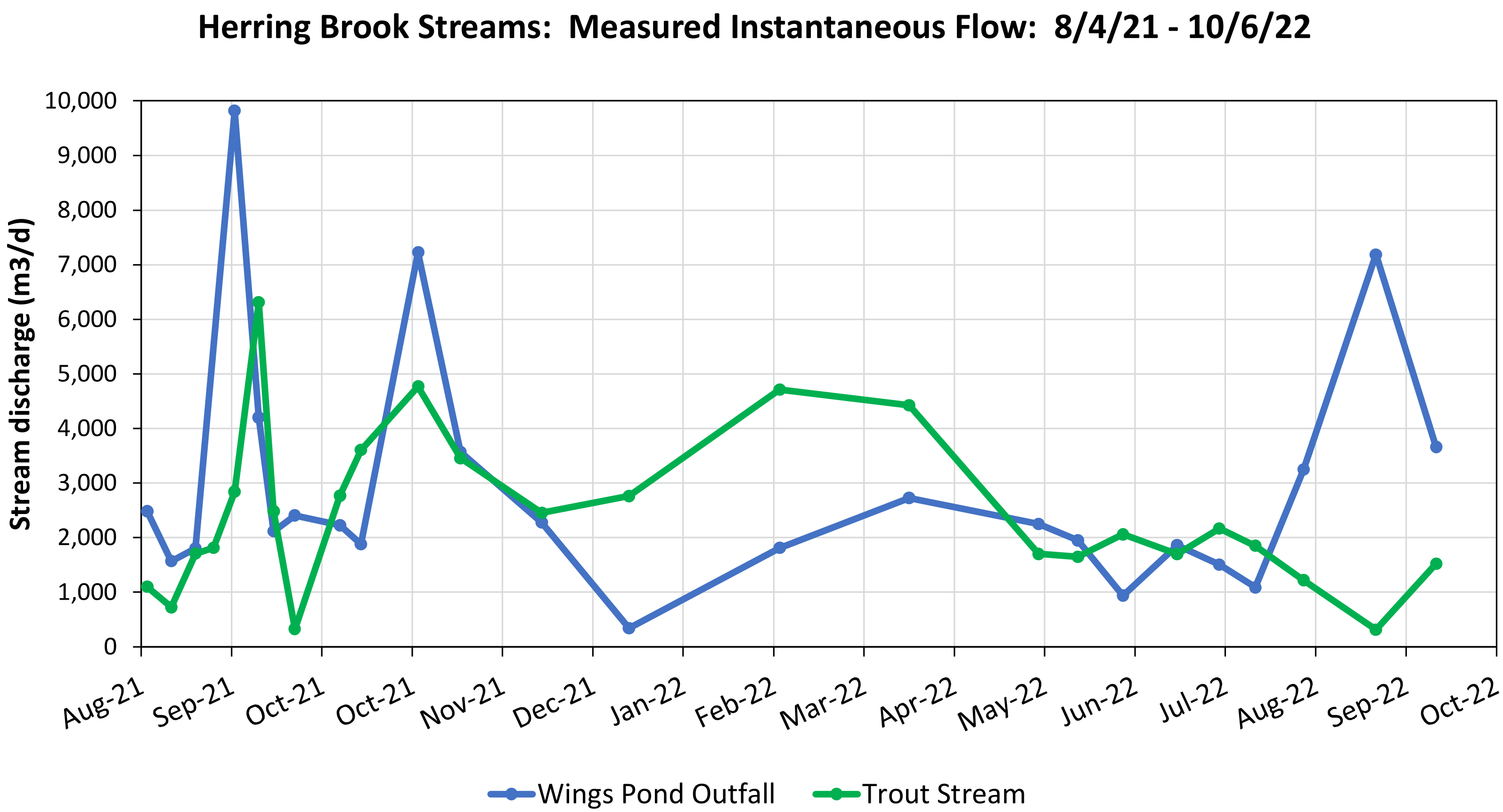

Figure IV-5. Measured Flow at Herring Brook marsh stream gauges. Instantaneous flow readings collected between August 4, 2021 and October 6, 2022 at the two Herring Brook stream gauges are shown. Even though the two gauges are <250 m apart, flow at the two locations have different patterns (*i.e.*, low correlation), likely due to the cranberry bogs, which are directly upstream, moving water and Wing Pond impacts. Water level gauges were installed at both locations, but review of stage-discharge relationships at both locations showed low predictive ability. Instantaneous readings were used for estimating annual flow and nitrogen inputs to Herring Brook marsh.

Table IV-4. Herring Brook Stream Summary: Wing Pond Outfall and Trout Stream				
	Units	Wing Pond Outfall	Trout Stream	Notes
Period of Record		Sept 2, 2021 – Aug 23, 2022	Sept 2, 2021 – Aug 23, 2022	1
Flow Characteristics				
Average Discharge	m^3/d	2,330	2,181	
Contributing Area Discharge	m^3/d	2,353	2,385	2
Difference		1%	9%	3
Nitrogen Characteristics				
Average Nitrate + Nitrite Concentration	mg N/L	0.15	0.91	4
Average Total Nitrogen	mg N/L	0.69	1.17	4
Nitrate+Nitrite as percent of TN	%	21%	78%	5
Average TN Discharge	kg N/d	2.55	2.98	
Average Unattenuated subwatershed N load	kg N/d	3.85	3.38	6
Stream/Pond N Attenuation	%	34%	12%	7

Notes:

1) Gauge data was collected from August 4, 2021 to October 6, 2022. The data shown is for one water year.
2) Contributing area discharge is based on USGS groundwater model contributing areas and model recharge rate. Flow into Wing Pond is split between Herring Brook and Wild Harbor.
3) Flow record at both stations is highly variable with spikes in flow suggesting the nearby cranberry bog was altering the flows.
4) Results from water quality samples collected at gauge locations.
5) The lower % of NOx in Wing Pond outfall reflects the N transformations in Wing Pond, while Trout Stream is a more typical aquifer drain, where most N in in DIN forms.
6) Unattenuated N loads are estimated subwatershed loads in Table IV-3.
7) Higher attenuation in Wing Pond outfall reflects impact of attenuation occurring in Wing Pond.

IV.3 BENTHIC REGENERATION OF NITROGEN IN BOTTOM SEDIMENTS

The overall objective of a benthic nutrient flux survey is to quantify the summertime exchange of nitrogen, between the sediments and overlying waters throughout the Herring Brook system. Concentrations measured in the water column are impacted by both watershed inputs and sediment interactions. These sediment nutrient 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. As such, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

IV.3.1 Sediment-Water Column Exchange of Nitrogen

Nitrogen enters the Herring Brook system predominantly in highly bio-available forms from the surrounding upland watersheds (*i.e.*, inorganic forms) and more refractory forms (*i.e.*, organic 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 watershed nitrate-N enters the embayment, it and other bio-available forms are rapidly taken up by phytoplankton for growth and nitrogen is converted into organic forms. Most of converted N remains in the water column for sufficient time to be flushed out to 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 sediments. In longer residence time systems (greater than 8 days), these nitrogen-rich phytoplankton particles may die and settle to the bottom. In both cases (grazing or senescence), a fraction of the phytoplankton with their associated nitrogen load becomes incorporated into the surficial sediments of the estuary.

In some systems that were investigated during the MEP, recycled nitrogen accounted for one-third to one-half of the nitrogen supply to phytoplankton blooms during the primary management period of the warmer summer months. It is during these warmer months that estuarine waters are most sensitive to nitrogen loadings. In contrast in some systems, with deep depositional basins or salt marsh tidal creeks, the sediments can be a net sink for nitrogen even during summer (*e.g.,* Mashapaquit Creek salt marsh in West Falmouth Harbor; Centerville River salt marsh or Sesachacha Pond on Nantucket). Embayment basins can also be net sinks for nitrogen to the extent that they support relatively oxidized surficial sediments, for example in the margins of the main basin to Lewis Bay (shared between Barnstable and Yarmouth). In contrast, embayments may show low rates of nitrogen release throughout most of a basin area, but portions with high deposition and anoxic sediments may support high release rates during summer months. The consequence of high deposition rates is that the basin sediments are unconsolidated, organic rich and sulfidic. The diversity of these spatial differences may become important in the overall system water quality and ecosystem function.

In general the fraction of the phytoplankton population which enters the surficial sediments of a shallow embayment will increase with: (1) decreased hydrodynamic flushing, (2) low velocity settings, (3) 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 or anoxic conditions and can vary by season. It is through the decay of the organic matter that bio-available nitrogen is returned to the 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, especially during summer months. 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. 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. Failure to account for the site-specific nitrogen input from the sediments and its spatial variation from the tidal creeks and embayment basins will result in significant errors in determination of the threshold nitrogen loading.

IV.3.2 Method for Determining Sediment-Water column Nitrogen Exchange

In order to determine the contribution of sediment regeneration to nutrient levels in the Herring Brook estuary system, sediment samples were collected during the most sensitive summer interval (August 2021), and incubated under *in situ* conditions using the same methods as during the MEP. A total of 8 cores were collected from eight sites (**Figure IV-6**), focusing on obtaining an areal distribution that would be representative of nutrient fluxes throughout the system.

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.

Sediment-water column exchange follows the methods of Jorgensen[55], Klump and Martens[56], and Howes *et al.*[57] for nutrients and metabolism. Upon return from the field laboratory, 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[58] and orthophosphate[59] assays were conducted within 24 hours and the remaining samples frozen (-20°C) for assay of

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

[56] Klump, J. and C. Martens. 1983. Benthic nitrogen regeneration. In: *Nitrogen in the Marine Environment*, (Carpenter & Capone, eds.). Academic Press. 900 pp.

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

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

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

nitrate + nitrite (Cd reduction: Lachat Autoanalysis), and DON.[60] Chemical analyses were performed by the SMAST Coastal Systems Analytical Facility at the University of Massachusetts Dartmouth. The laboratory follows standard methods for saltwater analysis and sediment geochemistry. Nitrogen flux rates were determined from linear regression of analyte concentrations through time.

Figure IV-6. Herring Brook sediment core sample sites. Cores were collected August 24, 2021 and were incubated to determine nitrogen fluxes using standard MEP methods. Numbers are for reference in Table IV-6. Map is 10/23/21 aerial available from Google Earth.

IV.3.3 Rates of Summer Nitrogen Regeneration from Sediments

In order to determine the net nitrogen flux between water column and sediments, all of the factors discussed above 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 Nitrogen Release by Standard MEP Core Approach: Sediment sampling was conducted throughout the embayment basins of the Herring Brook System and the distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core, the nitrogen flux rates (described in the section above) were evaluated relative to measured sediment organic carbon and nitrogen content, as well as sediment type and an analysis of each site's tidal flow velocities. Flow velocities are generally high in the main channel of the

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

Herring Brook System with near draining of the system during low tide, but slower in the adjoining marsh. 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 the various portions of the system.

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). Based upon previous evaluations of low velocities, a water column particle residence time of ~8 days was used (based upon phytoplankton and particulate carbon studies of poorly flushed basins). Adjusting the measured sediment releases was essential in order not to over-estimate the sediment nitrogen source and to account for those sediment areas that are net nitrogen sinks for the aquatic system.

This approach has been previously validated in outer Cape Cod embayments (*e.g.*, Chatham) by examining the relative fraction of the sediment carbon turnover (total sediment metabolism) which would be accounted for by daily particulate carbon settling. This analysis indicated that sediment metabolism in the highly organic rich sediments of the wetlands and depositional basins is driven primarily by stored organic matter (~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 (~33% to 67%). This range of values and their distribution is consistent with ecological theory and field data from shallow embayments. Additional validation has been conducted on other enclosed basins (with little freshwater inflow), where the fluxes can be determined by multiple methods. In this case the rate of sediment regeneration determined from incubations was comparable to that determined from whole system balance.

Rates of net nitrogen release or uptake from the sediments within the Herring Brook embayment system were comparable to measurements in the main channels of other salt marshes reviewed during the MEP. Typically, salt marshes have a net water column addition in the upper reaches, a transitional area with net addition or uptake, and then a gradient of net uptake with rates that decrease as the main channel moves closer to the inlet. This pattern, however, can vary from system to system with much higher rates, differing degrees of gradient, and altogether different patterns. In Herring Brook, there was high spatial variability, likely due to the how much the system drains during regular tides and the flux of sand brought into the system from Buzzard Bay (a sand delta was noted as far into the system as the C6 station). The sediments were sandy at C1, the innermost station, with soft mud at subsequent stations closer to the system inlet, mixing in of sands and silt at stations C6 and C7, and sand again at C8. Net nitrogen fluxes were 7.6 mg N m^{-2} d^{-1} at the upper stations and 5.8 N m^{-2} d^{-1} at the lower stations, meaning that nitrogen was added to the water column at relatively low levels throughout the sediments along the main channel (**Table IV-5**). These rates are similar to other organic rich tributary creeks and systems: Herring River in Harwich (9.7-10.5 mg N m^{-2} d^{-1}),[61] Wild Harbor River (1.4 mg N m^{-2}

[61] Howes, B., H. Ruthven, J. Ramsey, R. Samimy, D. Schlezinger, E. Eichner. 2012. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Herring River System, Harwich, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 181 pp.

d^{-1}),[62] and portions of Back River in Bourne (6.5 mg N m^{-2} d^{-1}) and Slocums and Little River in Dartmouth (4.6-9 mg N m^{-2} d^{-1}).[63] Slocums and Little River, Wild Harbor and Back River are all tributary to Buzzards Bay.

Table IV-5. Rates of net nitrogen return from sediments to the overlying waters throughout the Herring Brook System. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July - August rates.

Location	Sediment Nitrogen Flux (mg N m^{-2} d^{-1})			Station IDs
	Mean	S.E.	# of sites	
Herring Brook Embayment System				
Herring Brook Upper	7.6	1.7	2	1,2
Herring Brook Lower	5.8	2.9	6	3,4,5,6,7,8

* Station numbers refer to Figure IV-6.

[62] Howes B., E.M. Eichner, S. Kelley, R.I. Samimy, J.S. Ramsey, D.R. Schlezinger, P. Detjens (2011). Massachusetts Estuaries Project Linked Watershed-Embayment Modeling Approach to Determine Critical Nitrogen Loading Thresholds for the Wild Harbor Embayment Systems, Town of Falmouth, Massachusetts, Massachusetts Department of Environmental Protection. Boston, MA. 163 pp.

[63] Howes B.L., N.P. Millham, S.W. Kelley, J. S. Ramsey, R.I. Samimy, D.R. Schlezinger, E.M. Eichner (2012). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Slocum's and Little River Estuaries, Dartmouth, Massachusetts. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 237 pp.

V. HYDRODYNAMIC MODELING

V.1 INTRODUCTION

This hydrodynamic study was performed for the Herring Brook marsh system, located on the western coast of Falmouth, Massachusetts, near Old Silver Beach. It is the receiving basin of groundwater flow from the Silver Beach neighborhood and the northern extent of West Falmouth. A topographic map detail in **Figure V-1** shows Herring Brook and the general study area. Herring Brook is a shallow salt marsh-tidal creek system with a structured inlet maintaining a direct hydraulic connection to Buzzards Bay (**Figure V-2**). The average elevation of the marsh plain is +1.8 feet NAVD88 and the mean depth of Herring Brook (excluding marsh plain) is only -1.0 feet. The lowest elevations of the system exist in the main channel, east of the Quaker Road bridge, where maximum depths of approximately -4.2 feet, NAD88, occur. The total surface coverage of the Herring Brook system (not including Wings Pond) is approximately 30 acres, which includes about 17 acres of the marsh plain (**Figure V-3**).

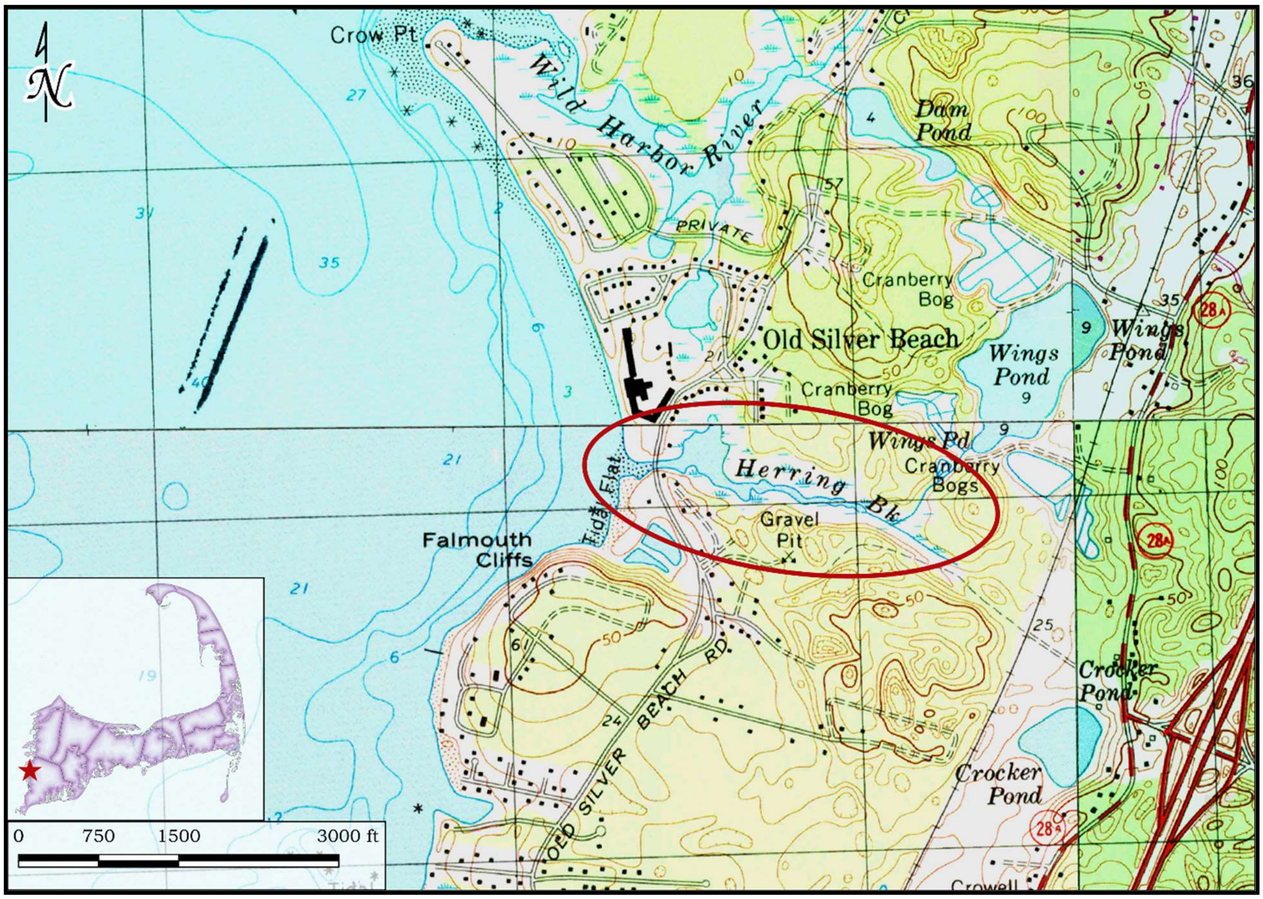

Figure V-1. Topographic map detail of the Herring Brook marsh system and the surrounding coastal area.

Figure V-2. View of the armored inlet channel to Herring Brook.

Figure V-3. View of marsh areas in Herring Brook.

Tidal exchange with Buzzards Bay dominates circulation in the Marsh. From measurements made in the course of this study, the average offshore tide range is 3.6 feet. As indicated by the lack of attenuation of high tide elevations across the inland extents of the marsh creeks of Herring Brook, tidal flushing appears very efficient throughout the tidal reaches of the system. Tidal flow is mainly distributed within the main channel of the system, however, there also exists several short secondary and tertiary channels that branch from the main channel.

The hydrodynamic study of the Herring Brook system proceeded as two component efforts. In the first portion of the study, bathymetry and tide data were collected in order to accurately characterize the physical system, and to provide data necessary for the modeling portion of the study. The bathymetry survey of Herring Brook was performed to determine the variation of depths throughout the system. This survey addressed the previous lack of adequate bathymetry data for these areas. In addition to the bathymetry survey, tides were recorded offshore of Old Silver Beach and within the marsh system for 31 days. These tide data were necessary to run and calibrate the hydrodynamic model of the system.

A numerical hydrodynamic model of Herring Brook and the associated marsh system was developed in the second portion of this study. Using the bathymetry survey data, a model grid mesh was generated for use with the RMA-2 hydrodynamic code. The tide data from Buzzards Bay were used to define the open boundary condition that drives the circulation of the model. Data measured within the system were used to calibrate and verify model performance to ensure that it accurately represents the dynamics of the real, physical system.

The calibrated hydrodynamic model of the Herring Brook system is an integral piece of the water quality model developed in Section VI of this report. In addition to its use as the hydrodynamic basis for the TN and salinity models, the calibrated hydrodynamic model is a useful tool that can be used to investigate the tidal properties of the system.

V.2 DATA COLLECTION AND ANALYSIS

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

V.2.1 Bathymetry Data

A detailed bathymetric survey of Herring Brook was performed May 27 and June 14, 2005 as an extension of the Wild Harbor MEP assessment.[64] A fathometer was used to take continuous soundings of the bottom as the survey vessel moved through the water (**Figure V-4**). Positioning data were collected using a differential GPS. Collected bathymetry data was tide-corrected to account for the change in water depths as the tide level changed over the survey period. The tide-correction is performed using tide data collected while the survey was run. Additional bathymetric data was gathered from the NOAA National Ocean Service (NOS) data archive

[64] Howes B., E.M. Eichner, S. Kelley, R.I. Samimy, J.S. Ramsey, D.R. Schlezinger, P. Detjens. 2011. Massachusetts Estuaries Project Linked Watershed-Embayment Modeling Approach to Determine Critical Nitrogen Loading Thresholds for the Wild Harbor Embayment Systems, Town of Falmouth, Massachusetts, Massachusetts Department of Environmental Protection. Boston, MA. 163 pp.

which provide the 2013-2014 US Geological Study (USGS) Coastal and Marine Geology Program (CMGP) Topographic and Bathymetric LiDAR dataset for the region, which covers the marsh plain and much of the main channel, and the 2017 USGS Coastal National Elevation Database (CoNED) topobathymetric digital elevation model (TBDEM) for the New England sub-region, which covers areas further offshore as well as areas in the main channel not covered by the 2013-2014 flights. Field staff also spot checked system-specific bathymetry during 2021 data collection. The compiled elevation dataset, including elevations from the bathymetry survey, is shown in **Figure V-5**.

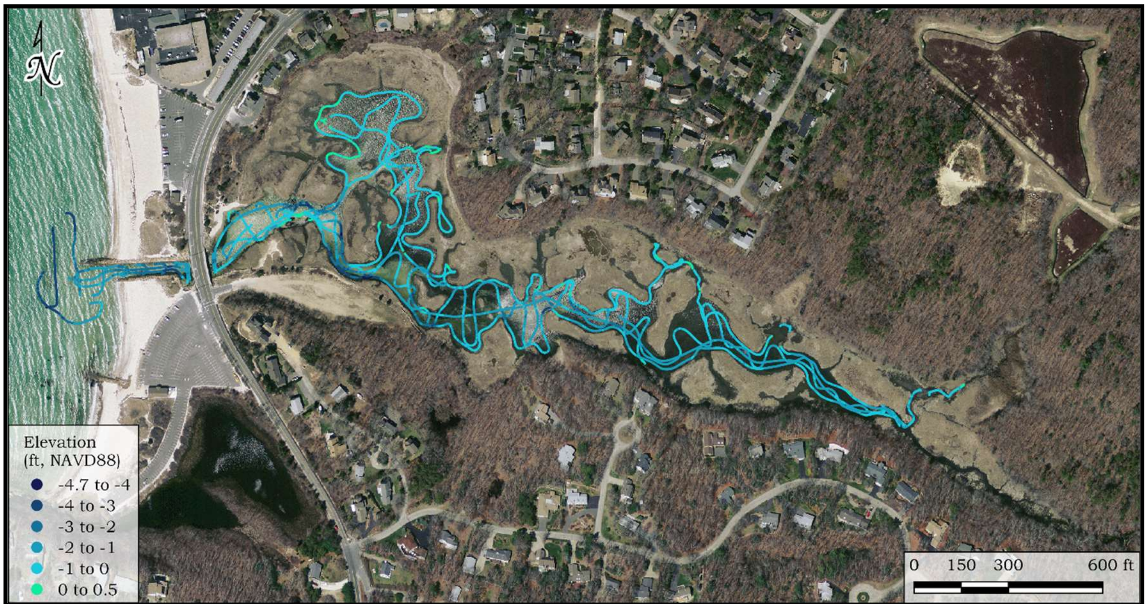

Figure V-4. Transects from the May and June 2005 bathymetry survey of Herring Brook.

Figure V-5. Bathymetric/Topographic data used to develop the RMA-2 hydrodynamic model. Data are colored to represent the bottom elevation relative to NAVD88. The primary data sources used to develop the grid mesh are from: a) the 2005 bathymetric survey, b) 2013-2014 USGS LiDAR data, and c) 2017 USGS DEM data.

V.2.2 Tide Data Collection and Analysis

Tide data records were collected concurrently at two gauging stations, located offshore in Buzzards Bay and at the inner region of the Herring Brook system. The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 30-day period between May 17 and June 17, 2005.[65] The elevation of each gauge was surveyed relative to the NAVD88 vertical datum. The Buzzards Bay tide record was used as the open boundary condition of the hydrodynamic model. Data from inside the system was used to calibrate the model.

Tide records longer than 29 days are necessary for a complete evaluation of tidal dynamics within the marsh system. Although a one-month record likely does not include extreme high or low tides, it does provide an accurate basis for typical tidal conditions governed by both lunar and solar motion. For numerical modeling of hydrodynamics, the typical tide conditions associated with a one-month record are appropriate for driving tidal flows with the system.

Plots of the tide data from the two gauges are shown in **Figure V-6** for the entire 30-day deployment. The spring-to-neap variation in tide range is discernable in these plots. The data record begins during a period of neap tides, where the minimum range is approximately 2 feet. A week later there is a period of spring tides, where the minimum range of 5.4 feet occurs on May 23, the day before the full moon. Following this spring tide is a continuing cycle of neap and spring tides, though the transition is more muted than at the beginning of the month. The visual comparison between tide elevations offshore and within the system shows that the tide amplitude does not change significantly , even in the inner reaches of the system.

To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from the 30-day records. These datums are presented in **Table V-1**. For most NOAA tide stations, these datums are computed using 19 years of tide data, the definition of a tidal epoch. For this study, a significantly shorter time span of data was available; however, these datums still provide a useful comparison of tidal dynamics within the system. The Mean Higher High Water (MHHW) and Mean Lower Low Water (MLLW) levels represent the mean of the daily highest and lowest levels. The Mean High Water (MHW) and Mean Low Water (MLW) levels represent the mean of all the high and low tides of a record, respectively. The Mean Tide Level (MTL) is simply the mean of MHW and MLW.

Frictional damping can be observed in the reduction of the mean tide range in Herring Brook compared to the mean range offshore. The tide range in the Herring Brook system is 3.3 feet, or approximately 90% of the mean offshore range. Damping not only affects the range of the observed tide, but it also causes a time lag in the time of high and low tide. **Figure V-7** shows how the time of low tide in Herring Brook lags 40 minutes from the low tide measured offshore. The time lag for low tides within marsh systems are generally larger than time lags between high tides.

A more thorough harmonic analysis of the tidal time series was also performed to produce tidal amplitude and phase of the major tidal constituents, and provide assessments of hydrodynamic 'efficiency' of the 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.

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[65] Original tidal data collection occurred as an extension of the Wild Harbor MEP assessment. Project staff also collected 2021 tidal data, which matched the 2005 data, but the 2005 data had a more complete tidal recording.

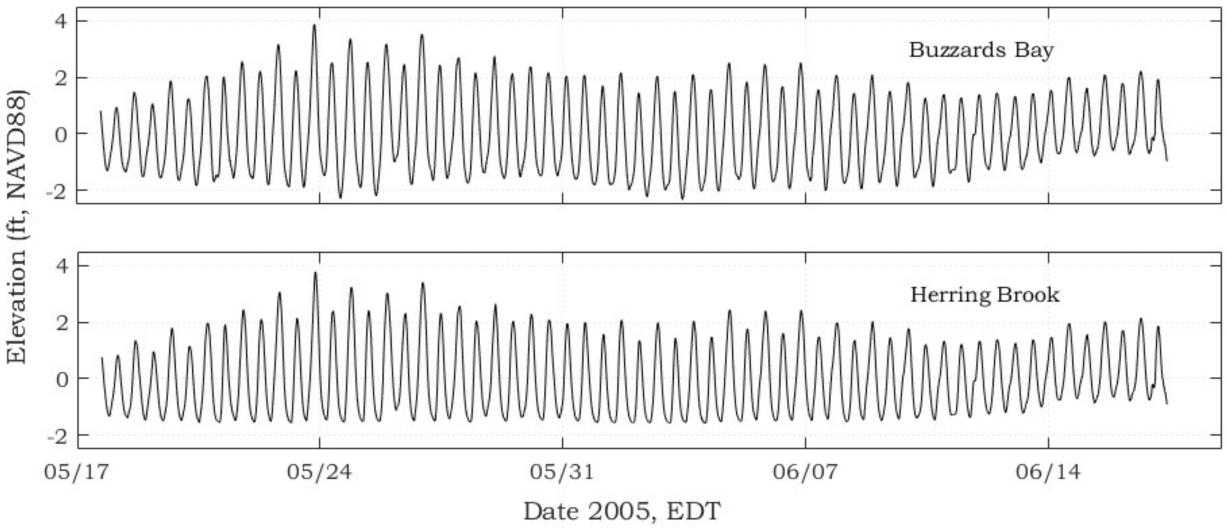

Figure V-6. Plot of observed tides for stations in the vicinity of the Herring Brook system, for the 30-day period between May 17 and June 17, 2005. All water levels are referenced to the NAVD88 vertical datum. These tidal measurements largely matched 2021 data, but were more robust.

Table V-1. Tide datums computed from data records collected offshore in Buzzards Bay and in the upper regions of Herring Brook (May 17, 2005 to June 17, 2005). Datum elevations are given relative to NAVD88.

Tide Datum	Buzzards Bay (feet)	Herring Brook (feet)
Maximum Tide	3.9	3.8
MHHW	2.3	2.2
MHW	2.0	1.9
MTL	0.2	0.3
MLW	-1.6	-1.4
MLLW	-1.7	-1.4
Minimum Tide	-2.3	-1.6
Range	3.6	3.3

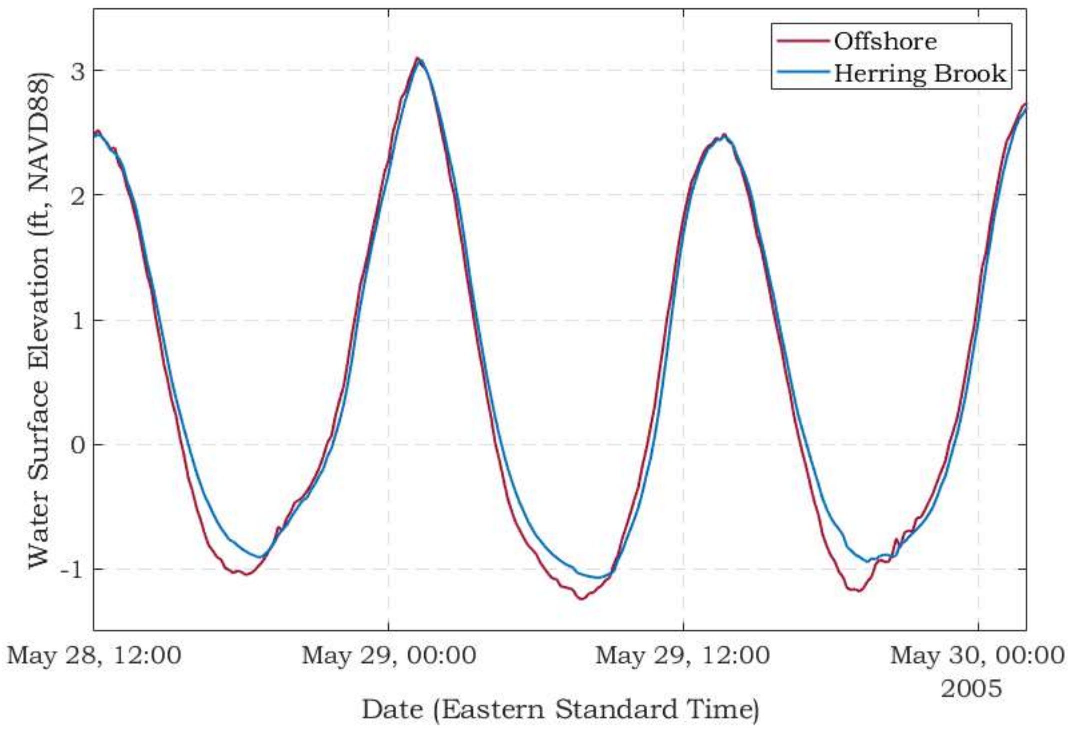

Figure V-7. Two-day tide plot showing tides measured in Buzzards Bay and in the Herring Brook system. Demonstrated in this plot is the frictional damping effect caused by flow restriction through the inlet of the system. The damping effects are seen as a reduction in tidal amplitude, as well as the lag in time of high and low tides from the offshore tide.

A harmonic analysis was performed on the time series from each gauge station location. Harmonic analysis is a mathematical procedure that fits sinusoidal functions of known frequency to the measured tide signal. The observed astronomical tide is the sum of several individual tidal constituents, with a particular amplitude and frequency. For demonstration purposes a graphical example of how these constituents add together is shown in **Figure V-8**. The amplitudes and phases of 22 known constituents result from this procedure. **Table V-2** presents the amplitudes of seven tidal constituents computed for the Herring Brook station records. The M_2, or the familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an offshore amplitude of 1.7 feet. The total range of the M_2 tide is twice the amplitude, or 3.4 feet.

The diurnal tides (once daily), K_1 and O_1, possess amplitudes of approximately 0.3 and 0.2 feet, respectively. Other semi-diurnal tides, the S_2 (12.00-hour period) and N_2 (12.66-hour period) tides, also contribute to the total tide signal, with amplitudes of 0.3 feet and 0.4 feet, respectively. The M_4 and M_6 tides are higher frequency harmonics of the M2 lunar tide (exactly half the period of the M2 for the M4, and one third of the M2 period for the M6), results from frictional attenuation of the M2 tide in shallow water.

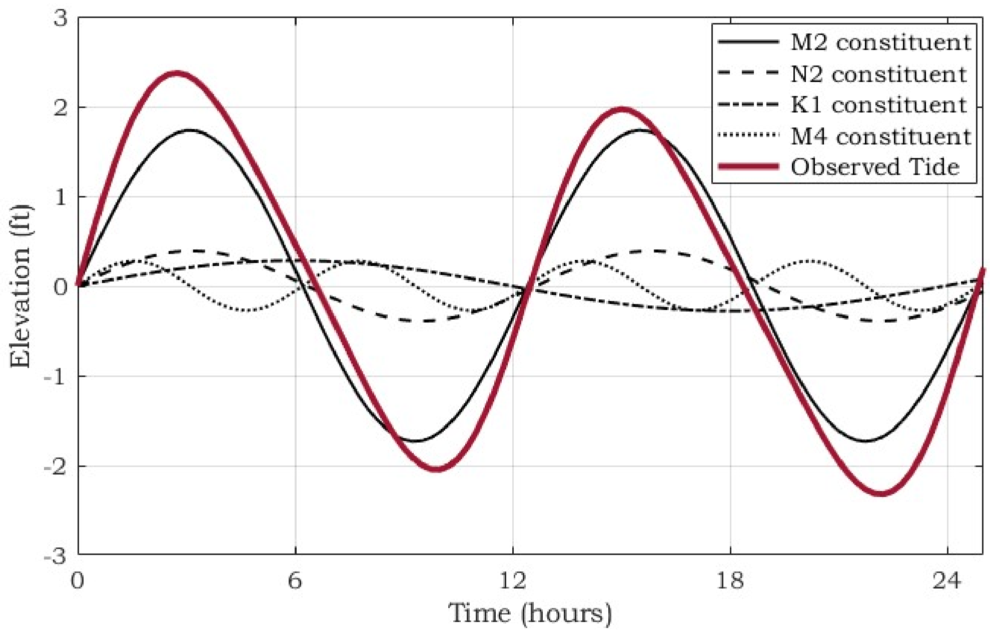

Figure V-8. Example of an observed astronomical tide as the sum of its primary constituents.

Table V-2. Tidal Constituents computed for tide stations in the Herring Brook System and offshore in Buzzards Bay, May to June 2005.

	Amplitude (feet)						
Constituent	M2	M4	M6	S2	N2	K1	O1
Period (hours)	12.42	6.21	4.14	12	12.66	23.93	25.82
Buzzards Bay	1.73	0.28	0.03	0.27	0.39	0.28	0.23
Herring Brook	1.59	0.30	0.03	0.23	0.37	0.28	0.22

Generally, it can be seen that as the total tide range is attenuated within the system there is a corresponding reduction in the amplitude of the individual tide constituents. One exception is the M4 and M6 amplitudes within the Herring Brook System, which are larger than for the offshore station. Again, this is due to energy transferring from the M2 to these overtides due to frictional losses across the system.

Though there is little change in constituent amplitudes between the offshore gauge station and the inner region of the marsh, the phase change of the tide is easily seen from the results of the harmonic analysis. Between the offshore and the upper river, there is only a 13-minute delay in the M2. This is not a large delay, considering that the period of this constituent is more than 12 hours.

In addition to the tidal analysis, the data were further evaluated to determine the importance of tidal versus non-tidal processes to changes in water surface elevation. These other processes include wind forcing (set-up or set-down) within the estuary, as well as sub-tidal oscillations of the sea surface. Variations in water surface elevation can also be affected by freshwater discharge into the system, if these volumes are relatively large compared to tidal flow.

The results of an analysis to determine the energy distribution (or variance) of the measured water elevation records for the gauge record in Herring Brook compared to the energy content the astronomical tidal signal (re-created by summing the contributions from the 22 constituents determined by the harmonic analysis) is presented in **Table V-3**. 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. **Figure V-9** shows the comparison of the measured tide from Buzzards Bay, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

Table V-3 shows that the variance of tidal energy was largest in the offshore signal, as should be expected. The analysis also shows that tides are responsible for approximately 95% of the water level changes in Buzzards Bay and Herring Brook. This indicates that the hydrodynamics of the system are influenced predominantly by astronomical tides.

Table V-3. Percentages of Tidal versus Non-Tidal energy for the Herring Brook system and Buzzards Bay, May to June 2005.

TDR Location	Total Variance (ft^2)	Tidal (%)	Non-Tidal (%)
Buzzards Bay	1.77	94.8	5.2
Herring Brook	1.52	95.3	4.7

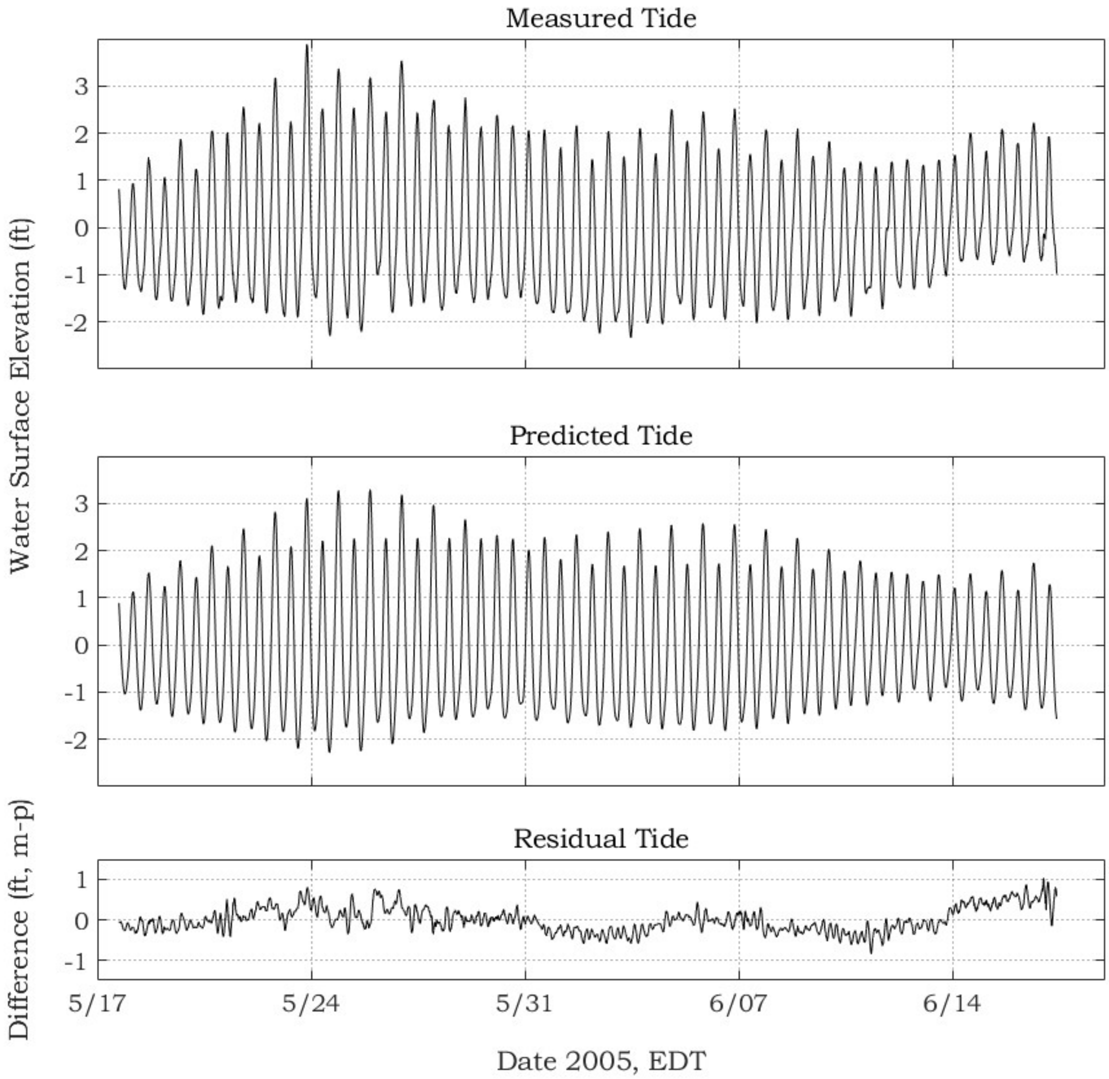

Figure V-9. Measured vs. Predicted Tides in Herring Brook area. Comparison between the measured tide time series (top plot) and the predicted astronomical tide (middle plot) computed using the 22 individual tide constituents determined in the harmonic analysis of the Buzzards Bay gauge data, collected offshore Herring Brook. The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (residual = measured - predicted).

V.3 HYDRODYNAMIC MODELING

For the modeling of the Herring Brook system, Sustainable Coastal Solutions utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in the marsh. 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 evaluated for analyses of estuaries, rivers, and marshes. RMA-2 has been utilized for numerous flushing studies through the MEP, including Falmouth estuaries: West Falmouth Harbor, Waquoit Bay, Wild Harbor, Little Pond, Megansett-Squeteague Harbor, Quissett Harbor, Fiddlers Cove and Rands Harbor, Salt Pond, and Great, Green and Bournes Ponds.

V.3.1 Model Theory

In its original form, RMA-2 was developed by William Norton and Ian King under contract with the U.S. Army Corps of Engineers.[66] Further development included the introduction of the one-dimensional elements, state-of-the-art pre- and post-processing data programs, and the use of elements with curved borders. Recently, the graphic pre- and post- processing routines were updated by Brigham Young University through a package called the Surfacewater Modeling System or SMS.[67] Grid development and bathymetry interpolation in support of this report primarily were generated within the SMS modeling package.

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

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

V.3.2 Model Setup

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

- Grid Generation
- Boundary condition specification
- Calibration

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

[67] Brigham Young University (1998). "User's Manual, Surfacewater Modeling System."

The extent of each finite element grid was generated using 2014 and 2021 digital aerial photographs from the MassGIS online orthophoto database. A time-varying water surface elevation boundary condition (measured tide) was specified at the entrance of the Herring Brook grid based on the tide gauge data collected offshore in Buzzards Bay. 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 model calibration simulations for the system, to obtain agreement between measured and modeled tides. The calibrated model provides the requisite information for future detailed water quality modeling.

V.3.2.1 Grid generation

The grid generation process was aided by the use of the SMS package. 2014 and 2021 digital aerial orthophotos and the compiled topographic and bathymetric data were imported to SMS, and a finite element grid was generated to represent the estuary. The aerial photograph was used in conjunction with the topographic data to determine the land boundary of the system, as well as determine the surface coverage of salt marsh. The elevation data were interpolated to the developed finite element mesh of the system. The computed grid consists of 13918 nodes, which describe 6683 total 2-dimensionsal (depth averaged) quadratic elements. The maximum nodal depth is -9.37 ft (NAVD88) along the open boundary of the grid in Buzzards Bay, and the typical modeled marsh plain elevation is 1.4 ft. The completed grid mesh of the Herring Brook system is shown in **Figure V-10**.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Herring Brook. Areas of marsh plain were included in the model because they represent a significant portion of the total surface area of this system. The SMS grid generation program was used to develop quadrilateral and triangular two-dimensional elements throughout the estuary. Grid resolution is generally governed by two factors: 1) expected flow patterns, and 2) the bathymetric variability of the system. Relatively fine grid resolution is employed where complex flow patterns are expected, generally near the inlet. Appropriate implementation of wider node spacing and larger elements reduces computer run time with no sacrifice of accuracy.

V.3.2.2 Boundary condition specification

Three types of boundary conditions were employed for the RMA-2 model of the Herring Brook system: 1) “slip” boundaries, 2) tidal elevation boundaries, and 3) constant flow input boundaries. All of the elements with land borders have “slip” boundary conditions, where the direction of flow was constrained shore-parallel. The model generated all internal boundary conditions from the governing conservation equations. A tidal boundary condition was specified at the inlet from Buzzards Bay. TDR measurements provided the required data. The rise and fall of the tide in the Bay are the primary driving forces for estuarine circulation in the system. Dynamic (time-varying) model simulations specified a new water surface elevation at the open boundary of the Herring Brook grid every model time step. The model runs of Herring Brook used a 10-minute time step, which is the same as the 10-minute sampling rate of the measured tide data. Details concerning the constant flow input boundary conditions included in the hydro model are discussed in Chapter VI.

V.3.2.3 Calibration

After developing the finite grids, and specifying boundary conditions, the model for the Herring Brook 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 typically required for an estuary model, specifying a range of friction and eddy viscosity coefficients, to calibrate the model.

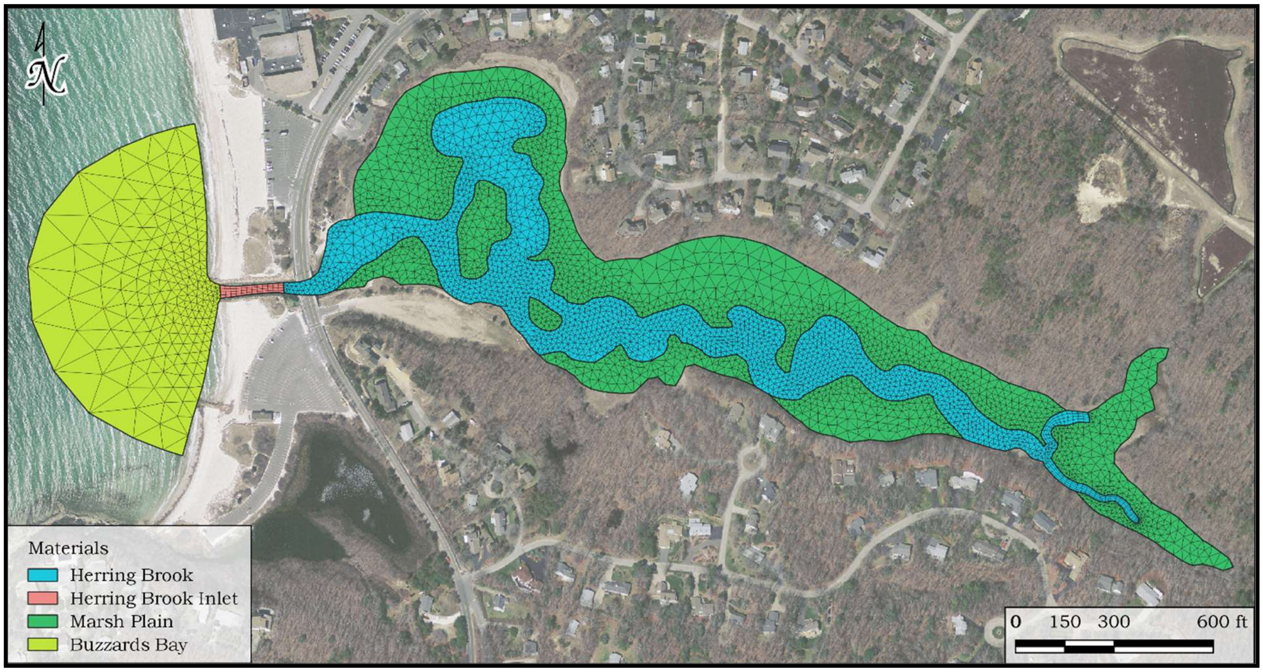

Figure V-10. Hydrodynamic model grid mesh for Herring Brook. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

Calibration of the hydrodynamic model required a close match between the modeled and measured tides from within the system (*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, a 14-day period (28 tide cycles) was modeled to calibrate the model based on dominant tidal constituents discussed in Section 2. The 14-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 14-day period beginning May 23, 2005 at 2050 EDT.[68] This representative time period included a full cycle between spring and neap periods.

After the model was calibrated, an additional verification run was made in order to test the model performance in a time period outside of the calibration period. The model verification was performed for the eight-day period beginning June 7, 2005 at 2130 EDT.

[68] Original tidal data collection occurred during the MEP; tidal data collected in 2021 generally showed same characteristics but the recording was not as robust as 2005.

The calibrated model was used to analyze existing detailed flow patterns and compute residence times. The flushing analysis is based on the 14-day period beginning May 23, 2005 at 2050 EDT. The ability to model a range of flow conditions is a primary advantage of a numerical tidal flushing model. For instance, average residence times were computed over the entire seven-day simulation. Other methods, such as dye and salinity studies, evaluate tidal flushing over relatively short time periods (less than one day). These short-term measurement techniques may not be representative of average conditions due to the influence of unique, short-lived atmospheric events.

V.3.2.3.a Friction coefficients

Friction inhibits flow along the bottom of estuary channels or other flow regions where velocities are relatively high. Friction is a measure of the channel roughness, and can cause both significant amplitude damping and phase delay of the tidal signal. Friction is approximated in RMA-2 as a Manning coefficient, and is applied to grid areas by user specified material types. Initially, Manning's friction coefficients between 0.025 and 0.070 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.[69]

To improve model accuracy, friction coefficients were varied throughout the model domain. First, the Manning's coefficients were matched to bottom type. For example, lower friction coefficients were specified for the main channel of Herring Brook, versus the marsh plain areas, which provides greater flow resistance. Final model calibration runs incorporated various specific values for Manning's friction coefficients, depending upon flow damping characteristics of separate regions within each estuary. Manning's values for different bottom types were initially selected based on ranges provided by the Civil Engineering Reference Manual,[70] and values were incrementally changed when necessary to obtain a close match between measured and modeled tides. Final calibrated friction coefficients are summarized in **Table V-4**.

Table V-4. Mannings Roughness and eddy viscosity coefficients used in simulations of the Herring Brook system. These embayment delineations correspond to the material type areas shown in Figure V-10.

System Regions	Bottom Friction	Eddy Viscosity lb-sec/ft^2
Herring Brook	0.025	50.0
Herring Brook Inlet	0.025	50.0
Marsh Plain	0.070	95.0
Buzzards Bay	0.025	85.0

V.3.2.3.b Turbulent exchange coefficients

Turbulent exchange coefficients approximate energy losses due to internal friction between fluid particles. The significance of turbulent energy losses increases where flow is swifter, such as inlets and bridge constrictions. According to King (1990, 1996), these values are proportional to

[69] Henderson, F. M. (1966). Open Channel Flow. Macmillan Publishing Company, New York. pp. 96-101.

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

element dimensions (numerical effects) and flow velocities (physics). In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 50 and 85 lb-sec/ft^2 (see **Table V-4**). Higher values were used for the marsh plain areas.

V.3.2.3.c Marsh porosity processes

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

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

A best-fit of model output for the measured data was achieved using the aforementioned values for friction and turbulent exchange. **Figures V-11 and V-12** illustrate sections of the 14-day simulation periods for the calibration model. Modeled (blue line) and measured (black line) tides are illustrated at the model location of the Herring Brook 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 system embayments. Four tidal constituents were selected for constituent comparison: the K_1, M_2, M_4, and M_6. Measured tidal constituent amplitudes are shown in **Table V-5** for the calibration and verification simulations. The constituent amplitudes shown in this table differ from those in **Table V-2** because constituents were computed for only the separate 14-day sub-sections of the 30-days represented in **Table V-2**. In **Tables V-5 and V-6**, error statistics are shown for the calibration and verification.

The constituent calibration resulted in excellent agreement between modeled and measured tides. The errors associated with tidal constituent amplitude for both the calibration and verification simulations were on the order of 0.01 ft, which is of the same order of magnitude as the accuracy of the tide gauges (0.032 ft). Time lag errors for the marsh system were within two timesteps of the time increment resolved by the model and tide data (10 minutes), indicating good agreement between the model and collected data. The skill of the model calibration is also demonstrated by the high degree of correlation (R^2) and the low RMS error shown in **Table V-7** for all stations.

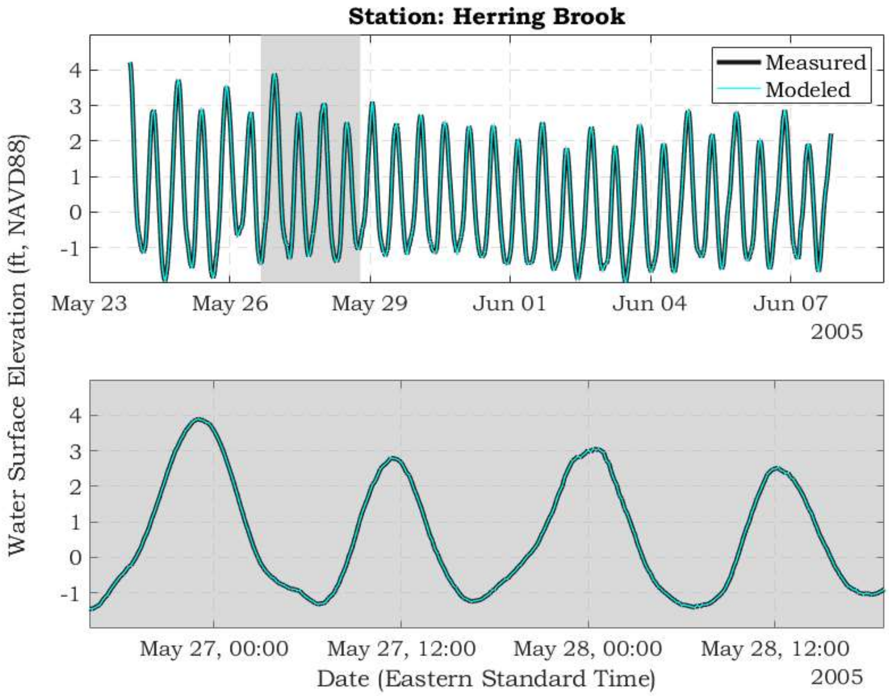

Figure V-11. Comparison of model output and measured tides for the offshore TDR location. This data collected in Buzzards Bay was used for the final calibration model run (May 23, 2005 at 2050 EDT). The bottom plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the top plot.

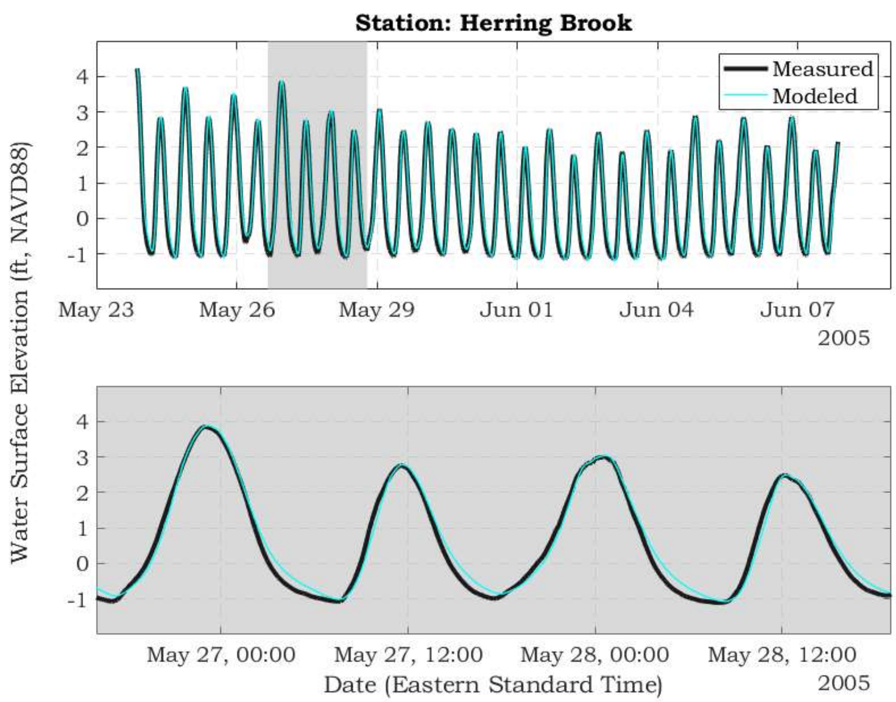

Figure V-12. Comparison of model output and measured tides for the Herring Brook TDR location. This data collected within the Herring Brook system was used for the final calibration model run (May 23, 2005 at 2050 EDT). The bottom plot is a 50-hour sub-section of the longer segment of the total modeled time period shown in the top plot.

Table V-5. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for the Herring Brook system, during modeled calibration time period.

Location	Constituent Amplitude (ft)				Phase (deg)	
Measured tide during calibration period						
	M_2	M_4	M_6	K_1	φM_2	φM_4
Buzzards Bay	1.93	0.30	0.02	0.32	5.02	24.10
Herring Brook	1.75	0.36	0.02	0.31	12.01	16.13
Modeled calibration run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	φM_2	φM_4
Buzzards Bay	1.93	0.30	0.02	0.32	4.92	23.87
Herring Brook	1.68	0.38	0.05	0.29	20.69	17.15
Error (measured - modeled)						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	M_6	K_1	φM_2	φM_4
Buzzards Bay	0.00	0.00	0.00	0.00	0.20	0.24
Herring Brook	0.08	-0.02	-0.03	0.01	-17.98	-1.06

Table V-6. Tidal constituents for measured water level data and calibrated model output, with model error amplitudes, for the Herring Brook system, during modeled verification time period.

Location	Constituent Amplitude (ft)				Phase (deg)	
Measured tide during verification period						
	M_2	M_4	M_6	K_1	φM_2	φM_4
Buzzards Bay	1.38	0.25	0.02	0.20	-22.94	8.02
Herring Brook	1.29	0.21	0.02	0.21	-16.72	0.11
Modeled verification run						
Location	Constituent Amplitude (ft)				Phase (deg)	
	M_2	M_4	M_6	K_1	φM_2	φM_4
Buzzards Bay	1.38	0.25	0.02	0.20	-27.89	-1.46
Herring Brook	1.25	0.20	0.05	0.20	-12.82	-11.31
Error (measured - modeled)						
Location	Constituent Amplitude (ft)				Phase (minutes)	
	M_2	M_4	M_6	K_1	φM_2	φM_4
Buzzards Bay	0.00	0.00	0.00	0.00	10.26	9.81
Herring Brook	0.05	0.01	-0.01	0.01	-8.08	11.82

Table V-7. Error statistics for the Herring Brook hydrodynamic model, for model calibration and verification.

	Calibration		Verification	
	R^2	RMSE	R^2	RMSE
Buzzards Bay	1.000	0.000	1.000	0.000
Herring Brook	0.996	0.043	0.997	0.026

V.3.4 Model Circulation Characteristics

The final calibrated model serves as a useful tool in investigating the circulation characteristics of the Herring Brook 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 particularly 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 physical data record exists. As an example, **Figure V-13** shows color contours and vectors that indicate velocity during a single model time step, during a period of maximum flood currents at the inlet.

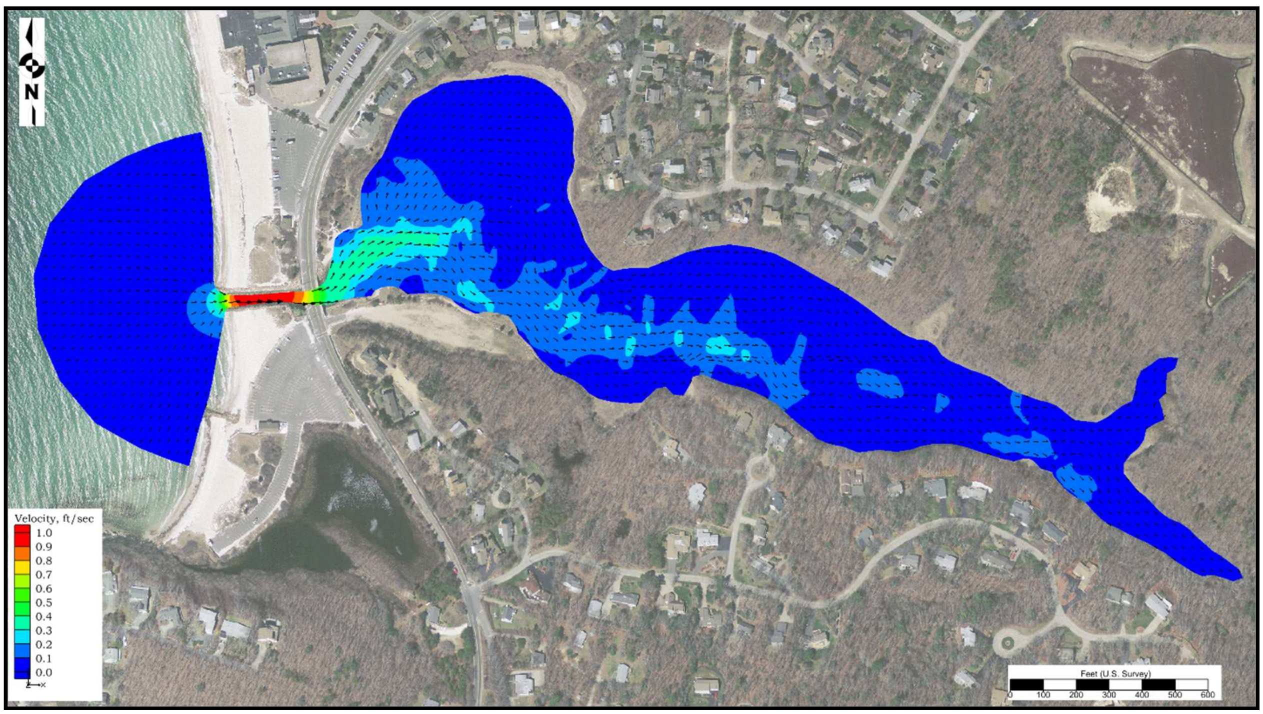

Figure V-13. Example of Herring Brook hydrodynamic model output for a single time step during a flooding tide at the Herring Brook inlet. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

As another example, from the calibration model run of the Herring Brook system, the total flow rate of water flowing through the inlet can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs is seen in the plot of system flow rates in **Figure V-14**. During spring tides, the maximum flood flow rates reach 400 ft^3/sec at the Herring Brook inlet. Maximum ebb flow rates during spring tides are generally smaller by approximately 100 ft^3/sec.

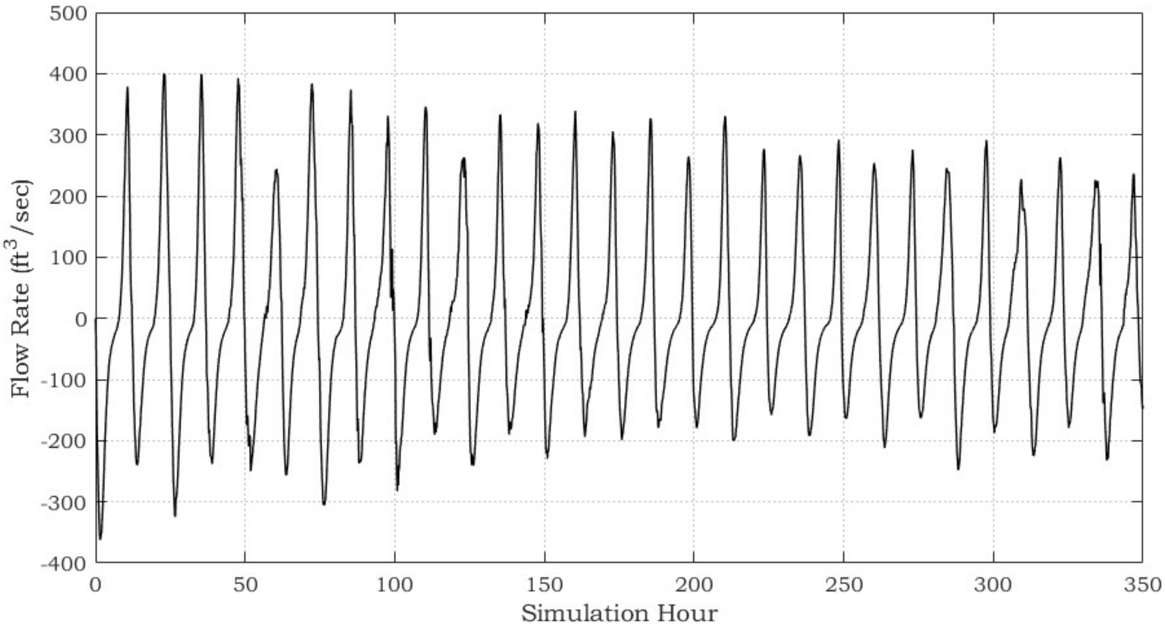

Figure V-14. Time variation of computed flow rates at the Herring Brook inlet. The model period shown corresponds to spring tide conditions, where the tide range is largest, and resulting flow rates correspondingly large compared to neap tide conditions. Positive flow indicates flooding tide flows, while negative flow indicates ebbing tide flows.

Using velocities computed in the model, an investigation of the flood or ebb dominance of the Herring Brook system can be performed. Marsh systems are typically flood dominant, meaning that maximum flood tide velocities are greater than during the ebb portion of the tide. Flood dominance indicates a tendency to collect and trap sediment, which is required to maintain healthy marsh resources.

Flood or ebb dominance in channels of a tidal system can be determined by performing a harmonic analysis of tidal currents. A discussion of the method of relative phase determination is presented in Friedrichs and Aubrey (1988). For this method, the M_2 and M_4 tidal constituents of a tidal velocity time series are computed, similar to the tidal elevation constituents presented in Section V.2.

The relative phase difference is computed as the difference between two times the M_2 phase and the phase of the M_4, expressed as $\Phi=2M_2-M_4$. If Φ is between 270 and 90 degrees ($-90<\Phi<90$), then the channel is characterized as being flood dominant, and peak flood velocities will be greater than for peak ebb. Alternatively, if Φ were between 90 and 270 degrees ($90<\Phi<270$), then the channel would be ebb dominant. If Φ is exactly 90 or 270 degrees, neither flood nor ebb dominance occurs. For Φ equal to exactly 0 or 180 degrees, maximum tidal distortion occurs and the velocity residuals of a channel are greatest. This relative phase relationship is presented graphically in **Figure V-15**.

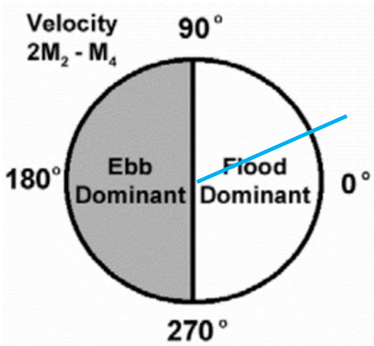

Figure V-15. Relative velocity phase relationship of M_2 and M4 tidal velocity constituents and characteristic dominance, indicated on the unit circle. Relative phase is computed as the difference of two times the M_2 phase and the M_4 phase ($2M_2$-M_4). A relative phase of exactly 90 or 270 degrees indicates a symmetric tide, which is neither flood nor ebb dominant. The computed value of $2M_2$-M_4 for within the Herring Brook system is 24 degrees (blue line) placing the system in the flood dominant phase.

Though this method of tidal constituent analysis provides similar results to a visual inspection of a velocity record (e.g., by comparing peak ebb and flood velocities), it allows a more exact characterization of the tidal processes. By this analysis technique, a channel can be characterized as being strongly, moderately, or weakly flood or ebb dominant.

The results of this velocity analysis of the Herring Brook model output show that the system (starting at the inlet) is indeed flood dominant, as expected for a marsh. The computed value of $2M_2$-M_4 for within the system is 24 degrees, making the estuary classified as moderately flood dominant.

V.3.5 Flushing Characteristics

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through the inlet, the primary mechanism controlling estuarine water quality within the modeled Herring Brook system is tidal exchange. A rising tide offshore in Buzzards Bay creates a slope in the water surface from the ocean into the upper-most reaches of the modeled system. Consequently, water flows into (floods) the system. Similarly, the estuary drains into the open waters of the Bay on an ebbing tide. This exchange of water between the system and the ocean is defined as tidal flushing. The calibrated hydrodynamic model is a tool to evaluate quantitative tidal flushing of the marsh 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 different points within the marsh to the entrance of the system. System residence times are computed as follows:

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

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

In addition to system residence times, a second residence, the local residence time, was defined as the average time required for a water parcel to migrate from a location within a sub-embayment to a point outside the sub-embayment. Using the inner region of Herring Brook as an example, the system residence time is the average time required for water to migrate from the inner reaches of the brook, through the main marsh channel, out through the inlet and into Buzzards Bay. Alternatively, the local residence time is the average time required for water to migrate from the inner reaches of the brook to the main channel within the marsh (not all the way to Buzzards 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-embayments 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 small systems or 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 Herring Brook system this approach is applicable, since the marsh is relatively small and has lower 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. It is impossible to evaluate an estuary's health based solely on flushing rates. 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 is obtained from the calibrated hydrodynamic model in the following section of this report (Section VI) by extending the model to include pollutant/nutrient dispersion. The water quality model provides an additional valuable tool to evaluate the complex mechanisms governing estuarine water quality in the marsh system.

Since the calibrated RMA-2 model simulated accurate two-dimensional hydrodynamics in the system, model results were used to compute residence times. 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 Buzzards Bay over a flood tide cycle (tidal prism) for system residence times (**Tables V-8 and V-9**). Units then were converted to days. The volume of the entire estuary was computed as cubic feet. Only volumes for the whole system were considered in this analysis since the nature of the Herring Brook system does not allow for convenient or meaningful subdivisions with regard to residence time calculation.

Table V-8. Herring Brook mean volume and average tidal prism during simulation period.		
Embayment	Mean Volume (ft^3)	Tidal Prism Volume (ft^3)
Herring Brook	888,800	2,498,800

Residence times were averaged for tidal cycles comprising a representative 14-day period (27 tide cycles). The modeled time period used to compute the flushing rates started May 23, 2005, similar to the model calibration period, and included the transition from neap to spring tide conditions. The RMA-2 model calculated flow crossing specified grid lines spanning across the inlet to the system to compute the tidal prism volume. Since the 14-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.

Table V-9. Computed System and Local residence times for the Herring Brook system		
Embayment	System Residence Time (days)	Local Residence Time (days)
Herring Brook	0.2	0.2

Computed flushing rates for the entire system show that the system flushes very well. A flushing time of 0.2 days for the entire estuary shows that on average, water is resident in the system for less than one day. The low local residence times for the whole Herring Brook system show that water quality in the system is not impacted negatively by tidal flushing. This is a typical result for marsh dominated estuaries, where the tide prism volume is larger than the mean volume of the system.

Based on our knowledge of estuarine processes, we estimate that the combined errors associated with the method applied to compute residence times are within 10% and 15% of “true” residence times, for the Herring Brook system. Possible errors in computed residence times can be linked to two sources: 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 mesh, which was the basis for all the flushing volumes used in this analysis. In addition, the dynamic nature of these estuarine systems may result in morphologic changes that are not represented in previously collected bathymetric data.

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 along the shoreline Buzzards Bay typically is strong because of the effects of the local winds and tidal induced mixing, the “strong littoral drift” assumption only will cause minor errors in residence time calculations.

VI. WATER QUALITY MODELING

VI.1 MODEL OVERVIEW

A two-dimensional finite element water quality model, RMA-4,[71] was employed to study the effects of nitrogen loading in the Herring Brook estuarine system. The RMA-4 model has the capability for the simulation of advection-diffusion processes in aquatic environments. It is the constituent transport model counterpart of the RMA-2 hydrodynamic model used to simulate the fluid dynamics of Herring Brook. Like the 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. Sustainable Coastal Solutions staff have utilized this model in water quality studies of most MEP systems, including all of those assessed in Falmouth. 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 and water quality conditions tend to be lowest. Total nitrogen modeling is based upon various data collection efforts and analyses presented in previous sections of this report.

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

Extensive field measurements and hydrodynamic modeling of the system were an essential preparatory step to the development of the water quality model. The result of this work, among other things, was a calibrated and validated hydrodynamic model representing the transport of water within the Herring Brook system (Section V). Files of node locations and node connectivity for the RMA-2 model grids were transferred to the RMA-4 water quality model; therefore, the computational grid for the hydrodynamic model was also the computational grid for the water quality model. Each modeled scenario required the model be run for a 28-day spin-up period, to allow the model to reach a dynamic "steady state," and ensure that model spin-up would not affect the final model output.

Three primary nitrogen loads to the system 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 (all summarized in Section IV). Additionally, there is a fourth load to the Herring Brook system, 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.1.1 Model Formulation

The formulation of the water quality model is for two-dimensional depth-averaged systems in

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

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 Herring Brook. 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 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 nitrogen 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.

VI.1.2 Water Quality Model Setup and Calibration: Salinity

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 Herring Brook also were used for the water quality constituent modeling portion of this study. Based groundwater recharge rates determined from the watershed delineations and measured stream inputs, the hydrodynamic model was set-up to include the latest estimates of freshwater inflows. Initial total N concentration and salinity were equal to the concentrations at the open boundary data from a long-term monitoring station in Buzzards Bay was applied to the entire model domain: 0.282 mg/L TN and 31.6 ppt, respectively.

Freshwater groundwater inputs to Herring Brook and average direct rainfall to the estuary's surface were applied to the model using values developed for this analysis. Stream inputs of freshwater are based on measurements at Trout Stream and the Wing Pond outlet, summarized in Section IV. Groundwater inputs of freshwater to the upper and lower portion of Herring Brook are based the delineated watersheds and average annual recharge (Section III).

For model calibration and verification, the water quality model was run for a simulated full lunar month for model spin-up, followed by a two-week period used for model calibration. Tidally averaged salinity output from the model was compared to the measured averaged at each of the water quality monitoring stations (**Figure VI-1**). The objective of the model calibration is to minimize RMS error and maximize the R^2 correlation between the measured salinity data and model output at the monitoring stations by adjusting the diffusion coefficients set for the model (final values in **Table VI-1**). The final calibrated salinity model has an R^2 of 0.97 and RMS errors of 1.7 ppt compared to measured salinities at each of the Herring Brook monitoring stations (**Figures VI-2 and VI-3**). Modeled salinity concentrations throughout Herring Brook are shown in **Figure VI-4**.

VI.2 MODEL VALIDATION AND CURRENT CONDITIONS TN CONCENTRATIONS

Once the water quality model was calibrated with the salinity data, nitrogen inputs were added (**Table VI-2**) and the model was subjected to validation testing. This testing resulted in a strong verification of model performance with a R^2 of 0.97 and RMS error of 0.026 mg/L (**Figures VI-5 and VI-6**) compared to the measured TN data at the Herring Brook monitoring stations (**Table VI-3**). Modeled Total Nitrogen concentrations throughout Herring Brook are shown in **Figure VI-7**. Given that the water quality model predicts existing TN concentrations well, it can be used to reliably predict nitrogen concentrations from potential changes in watershed nitrogen loads. Scenarios for watershed buildout and no anthropogenic loads are discussed in Section IX.

Figure VI-1. Estuarine water quality monitoring station locations in the Herring Brook estuary system. Station labels correspond to those provided in Table VI-1.

Table VI-1. Diffusion coefficient values specified for the material type subdivisions of the Herring Brook hydrodynamic model.	
mesh material type	Diffusion coefficient (D) m^2/sec
Offshore	5.0
Inlet	1.0
Marsh Plain	0.1
Marsh Creek	0.5

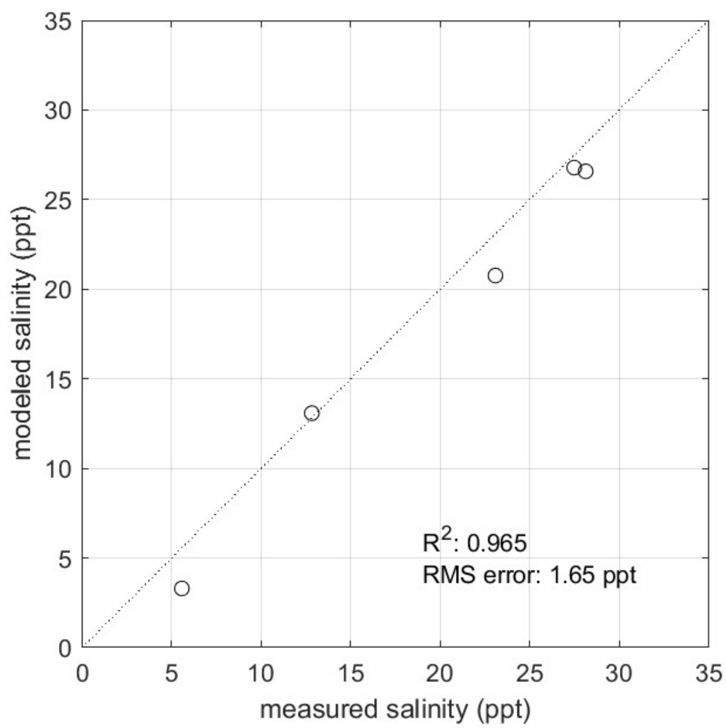

Figure VI-2. Herring Brook water quality model comparison of modeled and measured salinity concentrations. Modeled salinity values at Herring Brook monitoring stations are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) is 0.97 and RMS error for this model verification run is 1.65 ppt.

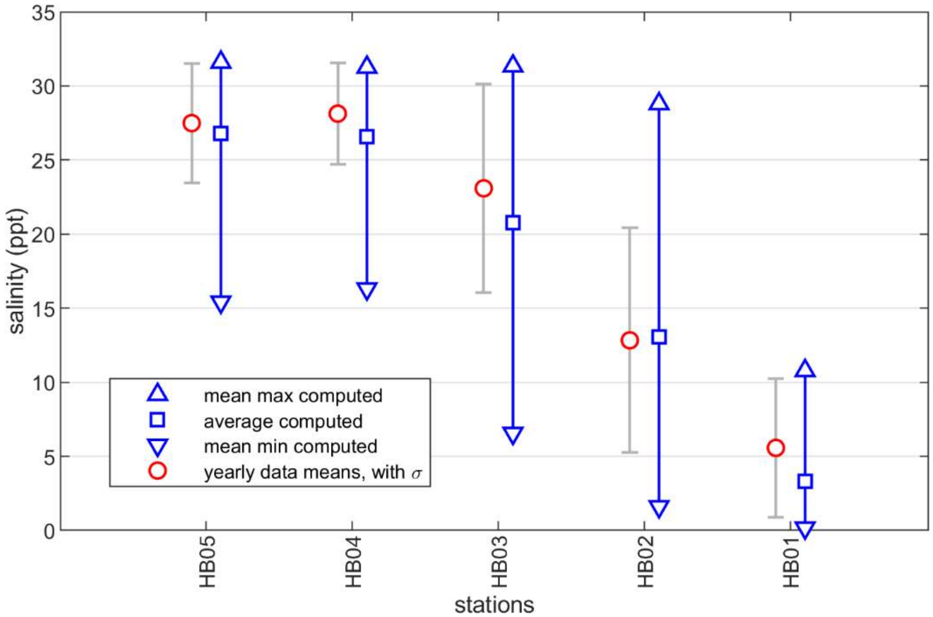

Figure VI-3. Comparison of measured mid-ebb salinity (with standard deviation) and tidally-averaged model output in Herring Brook. Also plotted are means of modeled tide cycle maximum and minimum concentrations.

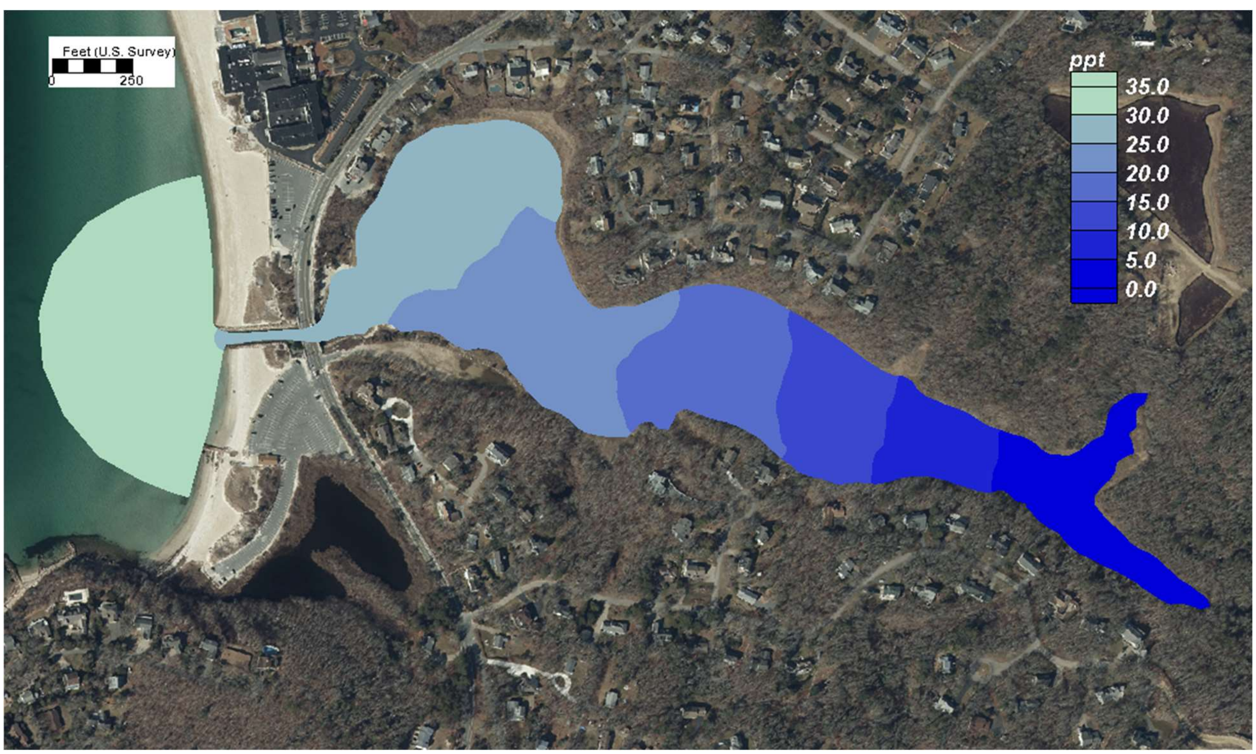

Figure VI-4. Modeled color contours of tidally-averaged salinity from the calibration run of the Herring Brook RMA4 water quality model.

Table VI-2. *Present* sub-embayment loads used for total nitrogen modeling of the Herring Brook system, with total watershed N loads, atmospheric N loads, and benthic flux. Watershed loads are summary of attenuated N loads, while stream N loads and benthic flux loads are based on measured stream outflow and sediment core incubations, respectively (all summarized in Section IV).

sub-embayment / surface water discharge	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
lower Herring Brook	2.148	0.074	0.214
upper Herring Brook	2.767	0.126	0.023
Wing Pond outlet	2.542	-	-
Trout Stream	3.041	-	-
System Total	**10.499**	**0.200**	**0.237**

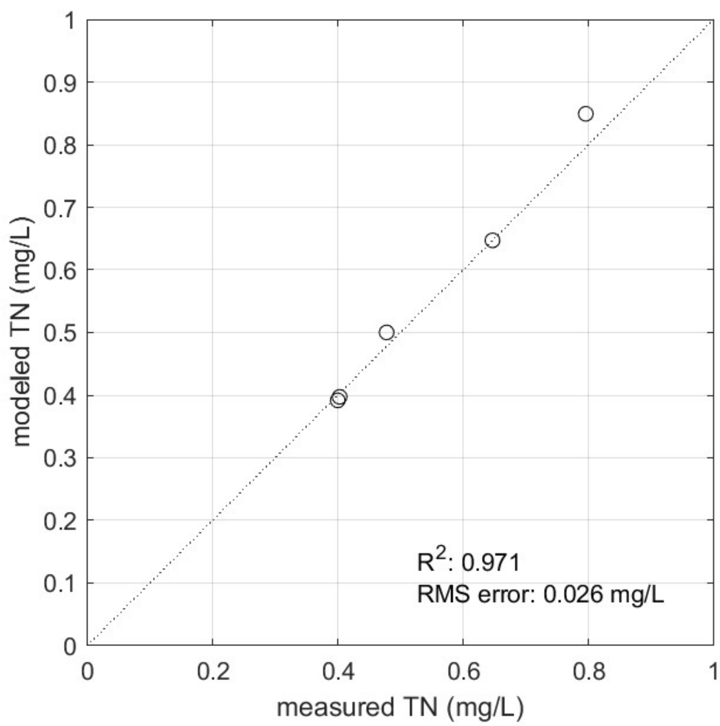

Figure VI-5. Herring Brook water quality model comparison of modeled and measured total nitrogen concentrations. Modeled TN values at Herring Brook monitoring stations are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) is 0.97 and RMS error for this model verification run is 0.026 mg/L.

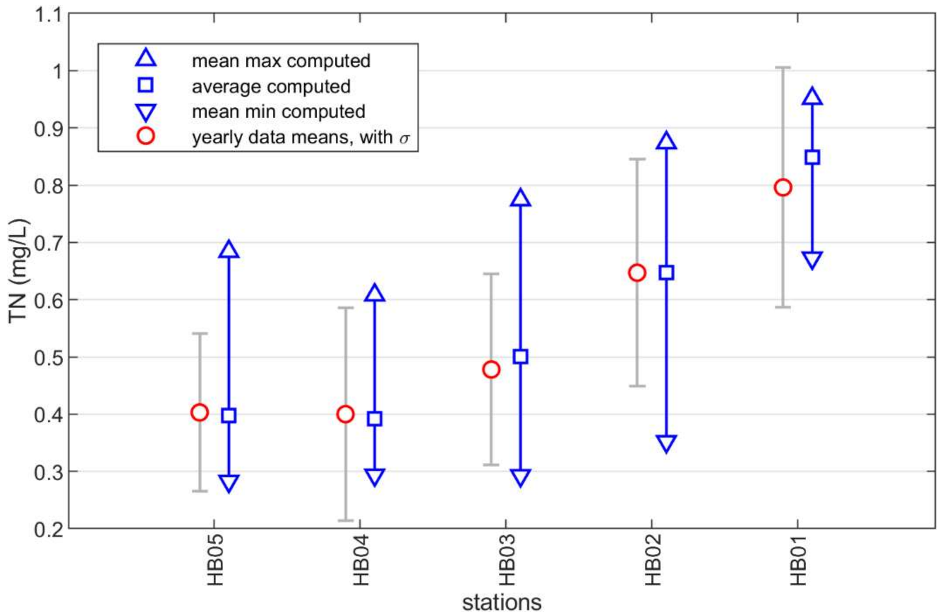

Figure VI-6. Comparison of mean measured mid-ebb TN concentrations (with standard deviation) and tidally averaged model output. Also plotted are modeled means of tide cycle maximum and minimum concentrations.

Table VI-3. Measured data and modeled nitrogen concentrations for the Herring Brook estuarine system. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of all samples. Measured data in this table were collected in the summers of 2020 and 2022.

monitoring station	data mean	s.d. all data	N	model min	model max	model average
Wings Pond Outfall	0.686	0.250	26	-	-	-
Trout Stream	1.184	0.140	25	-	-	-
HB1	0.796	0.209	21	0.547	0.956	0.849
HB2	0.647	0.198	21	0.314	0.887	0.647
HB3	0.478	0.167	21	0.289	0.820	0.500
HB4	0.400	0.186	21	0.289	0.665	0.392
HB5	0.403	0.138	21	0.283	0.752	0.397

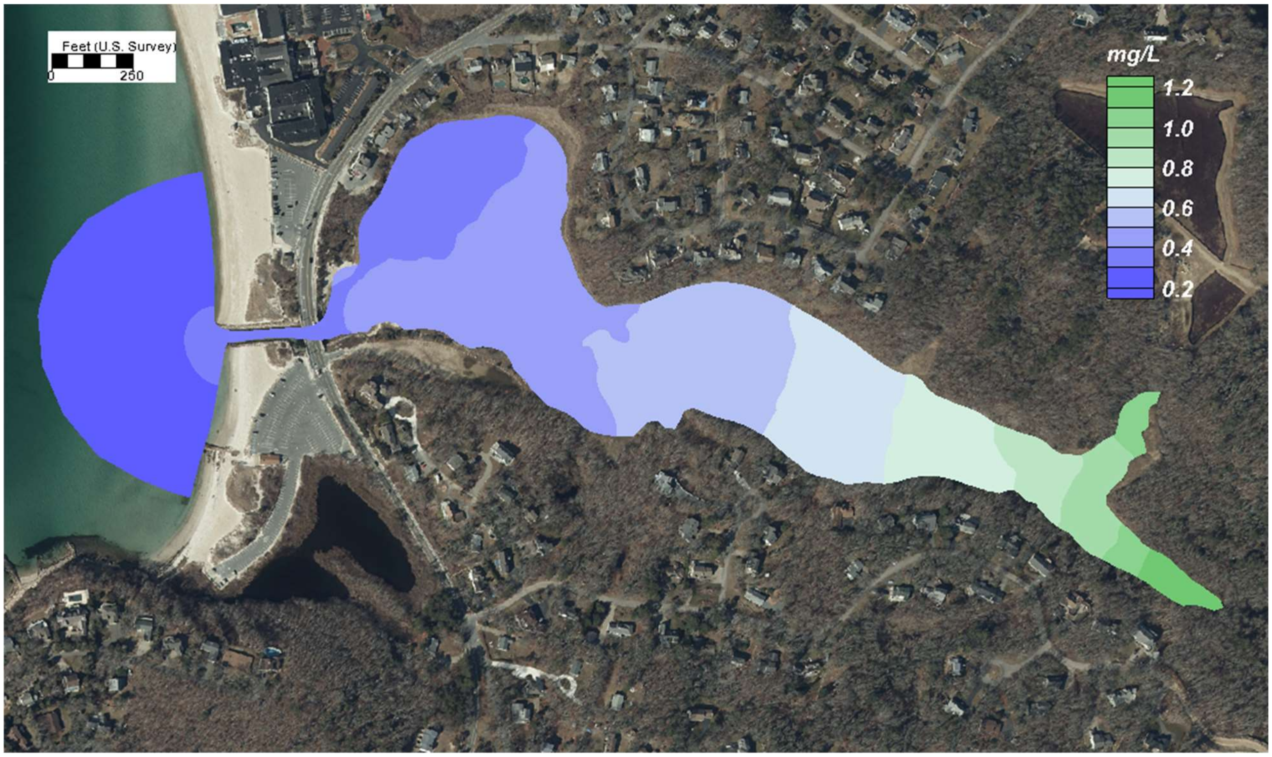

Figure VI-7. Modeled color contours of tidally-averaged TN concentration (mg/L) in Herring Brook for present/current conditions N loading.

VII. ASSESSMENT OF NUTRIENT-RELATED ECOLOGICAL HEALTH

The nutrient related ecological health of an estuary can be gauged by the nutrient, chlorophyll, and oxygen levels of its waters and the plant (eelgrass, macroalgae) and animal communities (fish, shellfish, infauna) which it supports. For the Herring Brook marsh estuarine system in the Town of Falmouth, MA, the project assessment of its ecological health was based upon data from the water quality monitoring discussed above and surveys of eelgrass distribution, benthic animal communities and sediment characteristics, and dissolved oxygen records conducted during 2020-2022. These data form the basis of an assessment of this system's present health, and when coupled with a full water quality synthesis and projections of future conditions based upon the water quality modeling effort, will support complete nitrogen threshold development for these systems (Chapter VIII).

VII.1 OVERVIEW OF BIOLOGICAL HEALTH INDICATORS

There are a variety of indicators that can be used in concert with water quality monitoring data for evaluating the ecological health of estuary systems. The best biological indicators are those species which are non-mobile and persist over relatively long periods, especially in systems where 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 during the MEP, the Technical Team/current project staff focused on major habitat quality indicators: 1) bottom water dissolved oxygen (DO) and chlorophyll-*a*, 2) eelgrass distribution over time, and 3) benthic animal communities. DO depletion is frequently the proximate cause of habitat quality decline in coastal embayments, but DO conditions can change rapidly and show strong tidal and diurnal patterns frequently. In coastal marshes, DO patterns can naturally vary significantly in healthy marshes to the point of becoming anoxic, because of the natural abundance of organic compounds. MEP habitat assessments also focused on eelgrass as a sentinel species for indicating nitrogen over-loading in coastal embayments. Eelgrass is a fundamentally important species in the ecology of shallow coastal systems, providing both habitat structure and sediment stabilization. Temporal trends in the distribution of eelgrass beds were used during the MEP to assess the stability of the embayment habitat and to determine trends potentially related to water quality. However, eelgrass is rarely found in coastal marshes and, for those systems, MEP assessments relied on benthic animal indicators to assess the level of habitat health.

In areas that do not support eelgrass beds, certain benthic animal species or species assemblages reflect the quality of the habitat. In these types of systems, the MEP team identified benthic animal species from sediment samples and the habitats were ranked based upon the fraction of healthy, transitional, and stressed indicator species. This type of analysis is based upon life-history information of the various species and a wide variety of field studies within southeastern Massachusetts waters, including the 1969 Wild Harbor oil spill, benthic population studies in Buzzards Bay and Nantucket Harbor (Woods Hole Oceanographic Institution) and New Bedford (SMAST).

VII.2 BOTTOM WATER DISSOLVED OXYGEN

DO 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. Given the importance of this indicator, various regulatory and planning efforts have defined DO minimums for acceptable water quality although these vary depending on the habitat (*e.g.*, marshes vs. embayments) and species (*e.g.*, fish vs. shellfish). For example, in Chesapeake Bay it was determined that restoration of nutrient degraded habitat requires that instantaneous oxygen levels not drop below 3.8 mg/L. MassDEP surface water regulations[72] require that DO concentrations shall not be less than 6 mg/L in high quality coastal and marine waters, but these regulations also acknowledge that natural background concentrations may be lower even in high quality waters. Herring Brook is not listed in the current MassDEP surface water regulations.

DO levels in embayments and marshes have notably different patterns. DO levels in both vary seasonally, due to changes in oxygen solubility, which varies inversely with temperature. Biological processes also vary by season, with water column respiration (consuming DO) several fold higher rates in summer than winter. It is not surprising that the largest levels of oxygen depletion (departure from atmospheric equilibrium) and lowest absolute levels are found during the summer when water column respiration rates are greatest and solubility is lower. The impact of respiration decreasing DO can be somewhat countered by wind-driven water column mixing and atmospheric replenishment. In embayments, which have lower nutrient levels than marshes, low DO levels generally occur only periodically in the deepest basins, while in nutrient and organic-enriched marshes, low DO will occur regularly as part of their ecological design.

Since DO levels can change rapidly, several mg/L in a few hours, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen conditions within shallow embayments.[73] In order to address this, a part of regular MEP procedures was the deployment of autonomous recording oxygen sensor and this was included in the Herring Brook marsh assessment. The sensor was moored 30 cm above the creek bottom at the upper margin of the lower reach of the central tidal creek from August 18, 2021 to September 29, 2021 (**Figure VII-1**). As a result of creek bottom oxygen uptake, this site should have among the lowest oxygen levels for this marsh system on the ebbing tide. The sensor (YSI 6600) was 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. The instrument mooring was serviced and calibration samples collected at least biweekly and sometimes weekly during its deployment.

Similar to other estuary marshes assessed during the MEP, the Herring Brook marsh sensor deployment showed high frequency variation, apparently related to diurnal and sometimes tidal influences (**Figures VII-2 and VII-3**). 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

[72] 314 CMR 4

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

dissolved oxygen concentration underscores the need for continuous monitoring within these systems. Dissolved oxygen and chlorophyll-*a* records were examined both for temporal trends and to determine the percent of the 25-28 day deployment period that these parameters were above/below various benchmark concentrations (**Tables VII-1, VII-2**).

The level of oxygen depletion and the magnitude of daily oxygen excursion and chlorophyll-*a* levels are consistent with other organic and nutrient enriched tidal marsh systems assessed during the MEP. The DO pattern had occasional concentrations <1 mg/L and these primarily occurred while the marsh was draining (*i.e.*, 86% of DO concentrations <1 mg/L occurred when salinity levels were <25 ppt). On the other hand, 89% of DO concentrations when the salinity was >30 ppt were >6 mg/L (avg = 6.3 mg/L), consistent with the flood portion of the tide. The average DO concentration during deployment was 5.17 mg/L or naturally lower than the MassDEP regulatory standard for SA waters. DO saturation levels were also consistent with typical marshes: only 13% of readings >110% and had an average of 75% saturation during the deployment period. Chlorophyll-*a* concentrations were low with an average of 3.78 µg/L, only 23% of readings >5 µg/L and only 1% of readings greater than 10 µg/L. The absence of elevated oxygen levels within Herring Brook marsh is consistent with tidal salt marsh systems; oxygen variations respond to the naturally organic rich qualities, rather than processes related to nutrient-driven phytoplankton effects. In salt marsh systems, the oxygen dynamic is primarily driven by consumption within the tidal creeks, with re-oxygenation through phytoplankton production being limited. The creeks drain nearly completely at low tide and the rise in oxygen levels is primarily through the entry of oxygen rich coastal waters on the flooding tide. These readings indicate that oxygen dynamics within these tidal creeks are driven by salt marsh processes, rather than by watershed nitrogen loading.

The Herring Brook system functions primarily as a tidal salt marsh throughout its estuarine reach. The upper reach has deeply incised narrow creeks surrounded by extensive emergent marsh vegetated with typical New England high and low marsh plants. The lower reach is transitional from the highly organic sediments of the upper marsh to the nearshore sediments of adjacent Buzzards Bay. The salt marsh areas are regularly flooded at high tide. Additionally, the salt marsh creeks drain nearly completely with each ebb tide.

The large diurnal shifts in dissolved oxygen, with periodic depletion to <2 mg/L are consistent with the high productivity within the marsh, high levels of oxygen uptake by the organic matter rich marsh sediments, and tidal changes in salinity and temperature which influence oxygen solubility. The low chlorophyll-*a* concentrations reflect the offshore waters, as the near complete exchange of tidal waters on each tide in the creeks, does not allow for chlorophyll levels to build within the marsh. The absence of a strong diurnal oxygen cycle, which is typically found in nitrogen enriched embayments (due to stimulation of phytoplankton), supports the concept that the marsh processes are the primary control on oxygen dynamics at this site. Further evidence for the dominance of marsh processes is the lack of linkage between the observed variations in chlorophyll (see **Table VII-2**) and the extent of oxygen depletion. In embayments, oxygen minima are typically observed as a bloom declines (senesces), a pattern not seen at this site. However, chlorophyll levels at the mooring site were consistently very low, averaging <4 µg/L. In embayment systems, on Cape Cod, this level of chlorophyll is not associated with significant oxygen depletion and especially not in systems with the low oxygen levels observed in the salt marsh creeks of the Herring Brook estuary. With the pattern of oxygen depletion, both in timing and magnitude, and consistency with other salt marsh systems assessed by the MEP (*e.g.*, Little Namskaket Marsh, Namskaket Marsh), the contention that oxygen dynamics in Herring Brook are being driven by the organically rich salt marsh creeks is supported.

Figure VII-1. Location of Continuous Water Quality Sensor Deployed in Herring Brook. A sonde device was deployed from August 18 to September 29, 2021 at the indicated location (white marker). The sonde had sensors for temperature, depth, chlorophyll-*a*, dissolved oxygen, and salinity and readings were recorded every 15 minutes. Periodic water quality samples were collected at the sensor depth for QA/QC purposes.

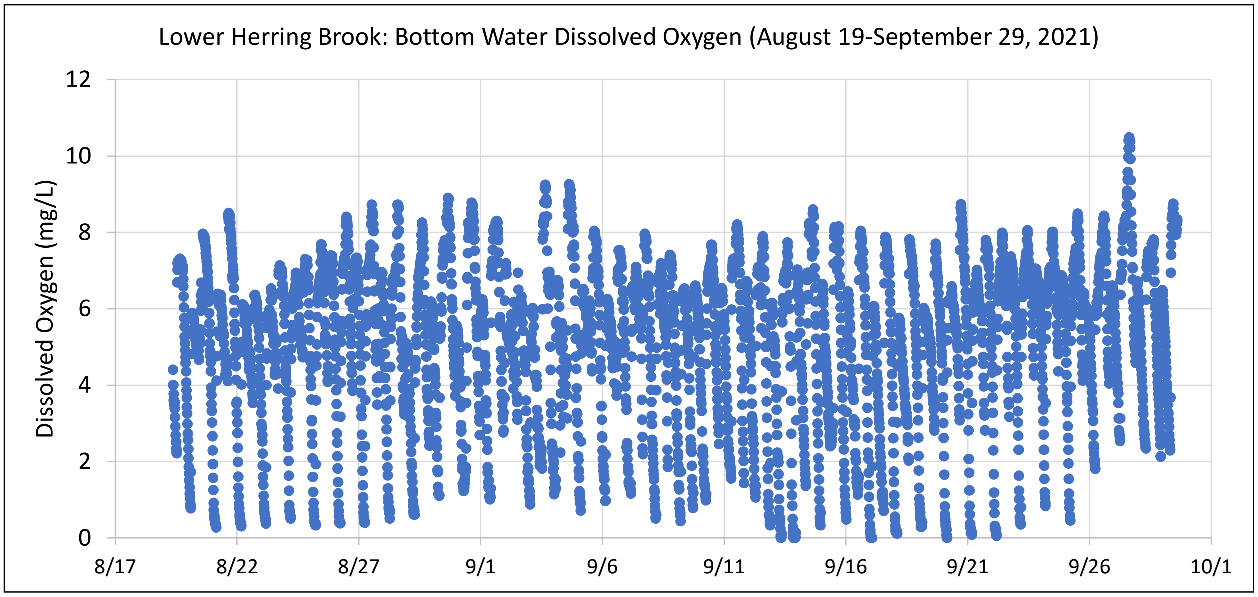

Figure VII-2. Continuous bottom water record of dissolved oxygen at the Herring Brook station. Sensor was deployed from August 19 through September 29, 2021 with measurements every 15 minutes.

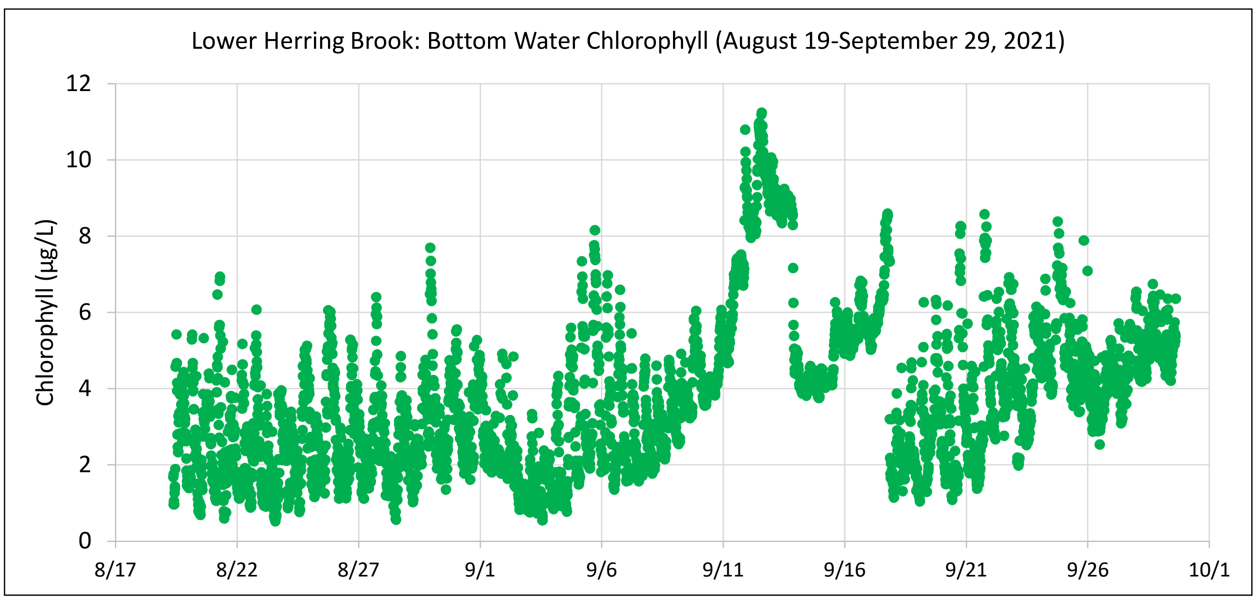

Figure VII-3. Continuous bottom water record of Chlorophyll-a at the Herring Brook station. Sensor was deployed from August 19 through September 29, 2021 with measurements every 15 minutes.

Table VII-1. Continuous dissolved oxygen readings in Herring Brook and similar marshes: percent of time bottom water oxygen levels were below various benchmark oxygen levels. MassDEP regulations establish 6 mg/L as a minimum concentration for SA waters, but allow lower concentrations if they are natural conditions. Namskaket Creek and Little Namskaket Creek are in the Town of Orleans, while Sandwich Harbor and Scorton Creek are in the Town of Sandwich. All systems are healthy marshes similar to Herring Brook. All data collected by the Coastal Systems Program, SMAST and reported in corresponding MEP reports.					
	Dissolved Oxygen: Continuous Record				
System	**Deployment Days**	**< 6 mg/L (% of days)**	**< 5 mg/L (% of days)**	**< 4 mg/L (% of days)**	**< 3 mg/L (% of days)**
Herring Brook	41.9	58%	39%	27%	19%
Other MEP Salt Marshes					
Namskaket Creek	38.6	55%	34%	18%	16%
Little Namskaket Creek	40.8	62%	43%	25%	9%
Sandwich Harbor 1	38.1	21%	12%	4%	14%
Sandwich Harbor 4	38.0	39%	22%	9%	2%
Scorton Creek 2	37.1	33%	21%	12%	17%
Scorton Creek 3	37.2	40%	22%	2%	0%

Table VII-2. Continuous chlorophyll-*a* readings in Herring Brook and similar marshes: percent of time bottom chlorophyll a levels were below various benchmark levels. Namskaket Creek and Little Namskaket Creek are in the Town of Orleans, while Sandwich Harbor and Scorton Creek are in the Town of Sandwich. All systems are healthy marshes similar to Herring Brook. All data collected by the Coastal Systems Program, SMAST and reported in corresponding MEP reports.								
Embayment System	**Start Date**	**End Date**	**Total Deployment (Days)**	**> 5 µg/L (%)**	**> 10 µg/L (%)**	**> 15 µg/L (%)**	**> 20 µg/L (%)**	**> 25 µg/L (%)**
Herring Brook	8/19/21	9/29/21	41.9	23%	1%	0%	0%	0%
Other MEP Salt Marshes								
Namskaket	8/3/03	9/11/03	38.8	63%	18%	4%	2%	1%
Little Namskaket	8/1/03	9/11/03	40.7	2%	0%	0%	0%	0%
Sandwich Harbor 1	6/20/06	7/28/06	30.5	43%	8%	3%	1%	0%
Sandwich Harbor 4	6/20/06	7/28/06	19.4	6%	0%	0%	0%	0%
Scorton Creek 2	6/28/06	8/4/06	37.0	100%	2%	0%	0%	0%
Scorton Creek 3	6/28/06	8/4/06	29.0	100%	67%	29%	10%	2%

VII.3 EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

Eelgrass surveys and analysis of historical eelgrass coverage data are key parts of the MEP approach given the important ecological role that eelgrass has in coastal embayments. Surveys have been conducted in the vicinity of the Herring Brook marsh system by the MassDEP, but none of these surveys have indicated eelgrass near the marsh inlet or within the marsh itself (**Figure VII-4**). The primary use of the eelgrass survey data during the MEP was to indicate (a) estuarine regions that have historically or presently support eelgrass habitat and (b) if large-scale system-wide shifts have occurred. Integration of these datasets provides a view of temporal trends in eelgrass distribution and the stability of its coverage.

Eelgrass surveys have not been undertaken within Herring Brook by the MassDEP Eelgrass Mapping Program,[74] as this "basin" is the central tidal creek of a salt marsh, similar to Namskaket Creek and Little Namskaket Creek in Orleans, which also were not surveyed by MassDEP. Tidal creeks do not generally support eelgrass habitat, particularly when the creek nearly drains completely during each ebb tide. There is no evidence of eelgrass colonizing Herring Brook in any of the available surveys. The project team confirmed the lack of eelgrass in the tidal creeks to the Herring Brook System while undertaking the various field surveys as part of the benthic regeneration and infauna studies and during the deployment and recovery of the sonde instrument moorings.

Based upon all available information, it appears that the Herring Brook Estuary is not structured to support eelgrass habitat. Therefore, threshold development for protection/restoration of this system will focus on infaunal habitat quality. This is typical for New England salt marshes, which are naturally organic and nutrient rich and generally contain little water in the creeks at low tide. This conclusion has been confirmed in a wide range of salt marsh dominated basins throughout southeastern Massachusetts by the MEP Technical Team.

VII.4 BENTHIC INFAUNA ANALYSIS

In areas that do not support eelgrass beds, benthic animal indicators are a key measure to assess the level of habitat health. 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.[75] 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, although there are no eelgrass beds in the Herring Brook marsh system, this is due more to the structure of the system than its health. As such, to the extent that Herring Brook marsh can support healthy infaunal communities given specific nutrient conditions in the water column, the benthic infauna analysis is important for determining the level of impairment (healthy→moderately impaired→significantly impaired→severely degraded). This assessment is also important for the establishment of site-specific nitrogen thresholds (Chapter VIII).

[74] https://www.mass.gov/guides/eelgrass-mapping-project

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

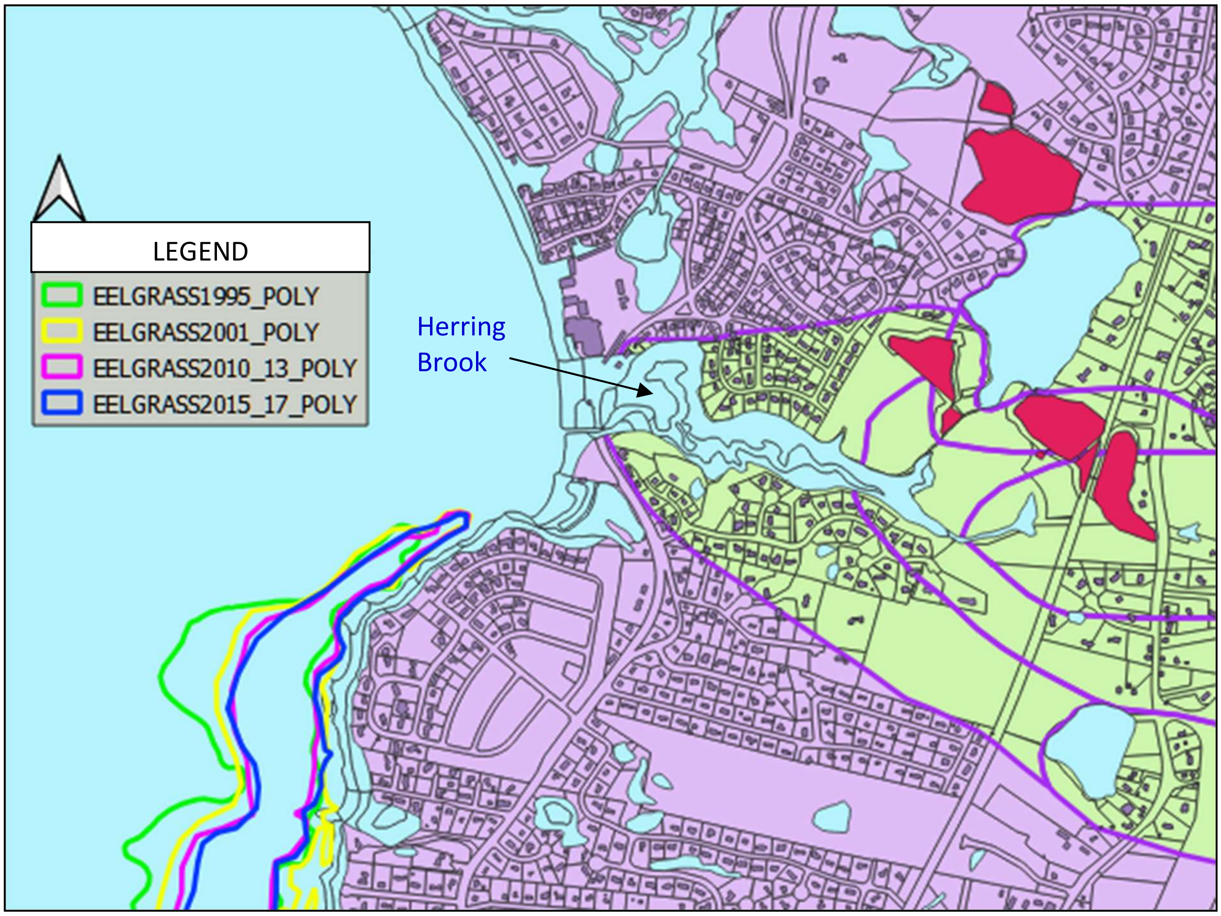

Figure VII-4. Eelgrass bed distribution immediately offshore of Herring Brook system. Delineation of eelgrass beds mapped by MassDEP in 1995, 2001, 2013, and 2017 based on aerial interpretation show the same general area of coverage to the south of Herring Brook. None of these reviews showed any eelgrass within Herring Brook. Review of eelgrass in Buzzards Bay based on 1974-1981 aerial photos noted eelgrass in approximately the same areas as noted on this map (Costa, 1988). There is no evidence that Herring Brook has ever supported eelgrass habitat, as it is primarily a tidal salt marsh.

Aside from determining the species present in the infaunal community, analysis of the evenness and diversity of the benthic animal communities was also used to support the density data and the natural history information. Evenness is a measure of the balance among individuals in each species that are present, while diversity is a measure of the number and quantities of the species. The evenness statistic can range from 0-1 (one being most even), while the diversity index does not have a theoretical upper limit. In MEP assessments of embayments, highest quality habitat areas, as shown by the oxygen and chlorophyll records and eelgrass coverage, have the highest diversity (index generally >3) and evenness (~0.7). The converse is also true, with poorest habitat quality is generally found where diversity is <1 and evenness is <0.5. High quality salt marsh systems, which are significantly different than embayments, typically have diversity indices between 1.5 and 2.5, while evenness is usually in the 0.6-0.8 range.

In the Herring Brook Marsh System, quantitative sediment infauna sampling was conducted at eight (8) locations along the central tidal creek, with replicate assays at all sampling sites (**Figure VII-5 and Table VII-3**). The infauna survey indicated that the tidal creeks of the Herring Brook Estuary are presently supporting a typical salt marsh infaunal habitat. Infauna communities within the tidal creek were indicative of the organic-rich environment typical of salt marshes and consistent with the measured levels of oxygen depletion and water column TN concentrations. The benthic infauna in Herring Brook are similar to the communities found in other wetland creeks assessed during the MEP, including Little Namskaket (Orleans), Namskaket (Orleans), Scorton Creek (Sandwich), and Sandwich Harbor. Animals were mostly polychaetes throughout the system, though amphipods/crustaceans were an important part of the infaunal population in the mid-system stations (C5 and C6). Polychaetes are typically found in high carbon settings (most of the terminal ponds of Pleasant Bay, for example). Amphipods generally dominate in slightly lower carbon settings tend to increase aeration of sediments.

Species counts in Herring Brook are closer to the numbers found in the creeks near the inlets of other salt marshes reviewed, suggesting that the Herring Brook creeks are subject to higher flow rates and regular periodic drying. Diversity indices are also consistent with other salt marshes reviewed, though the higher numbers in the mid-portion are among the highest measured. The lower diversity readings at the uppermost station (station C1) and lowermost stations (C8, near the inlet) are consistent with the instability of their settings. Station C1 has brackish conditions (*i.e.*, average salinity at mid-ebb = 5.6 ppt) which means it is a relatively unstable setting with wide variation in water quality (*e.g.*, flood tide salinities are likely >25 ppt), while Station C8 has unstable sediment conditions due to regular sand inputs (the sand delta from the higher flow flood tides is clearly seen in aerial photos). Overall, the observed communities in the bulk of Herring Brook were typical of New England salt marsh creek bottom environments.

Overall, the infauna survey indicated that Herring Brook marsh is supporting healthy infauna habitat typical of organic rich New England salt marshes. This is also supported by the absence of macroalgal accumulations and algal mats within the creek bottoms, which can result if there is "excessive" external nitrogen loading. The absence of macroalgal accumulations is consistent with the relatively low total nitrogen levels within this salt marsh, 0.4-0.6 mg N L^{-1} (mid-marsh stations HB2-HB4), compared to a similar marsh, Cockle Cove Creek (Chatham), which supports high quality habitats, both emergent marsh and creek bottom, with TN levels of ~2 mg TN L^{-1}. Based upon all lines of evidence it appears that the Herring Brook Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment.

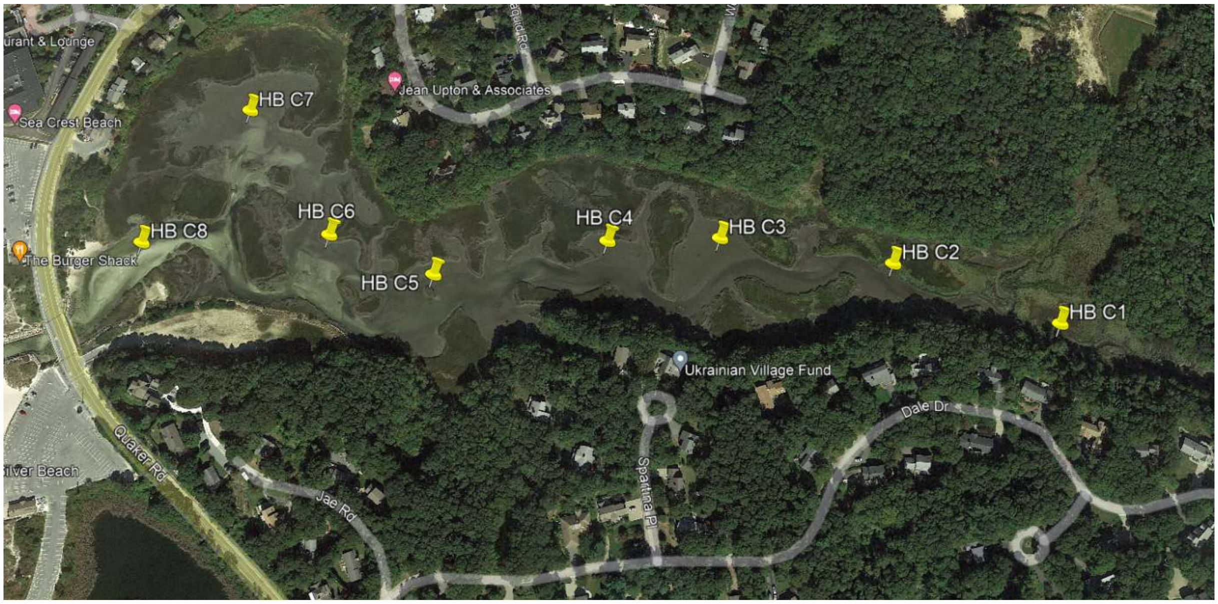

Figure VII-5. Herring Brook 2021 benthic infaunal sampling stations. Samples were collected on October 25 at the stations indicated by the yellow pushpin symbols.

Table VII-3. Benthic infaunal community data for Herring Brook Creek, Town of Falmouth, MA. 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 0.018 m2). Stations refer to map in Figure VII-5, (N) is the number of samples per site.

Station ID	N	Total Actual Species	Total Actual Individuals	Species Calculated @75 Indiv.	Weiner Diversity (H')	Evenness (E)
C1	1	3	7	N/A	1.15	0.72
C2	2	5	51	2	1.50	0.67
C3	2	6	80	2	1.58	0.66
C4	2	6	121	2	1.59	0.61
C5	2	15	171	12	2.94	0.76
C6	2	7	109	3	2.39	0.85
C7	2	11	63	4	2.57	0.74
C8	2	5	108	5	1.44	0.65

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 estuary requires integration of key habitat parameters (infauna and eelgrass), sediment characteristics and nutrient-related water quality information (particularly dissolved oxygen and chlorophyll-*a*). Additional information on temporal changes within each portion of the system and its watershed further strengthens the analysis. These data were collected during this project to support threshold development for the Herring Brook Creek estuarine/marsh system and were discussed in Section VII. Nitrogen threshold development builds on this data and links habitat quality to summer water column nitrogen levels.

The Herring Brook estuary is showing high habitat quality throughout its salt marsh reach. The uppermost reach appears to be a fully functional tidal salt marsh with deeply incised narrow creeks surrounded by extensive emergent marsh. This reach is typical of New England marshes, with smaller tidal creeks and a marsh plain dominated by low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*) plant communities with patches of fringing brackish marsh vegetation (*Juncus, Phragmites*). As the main channel and tidal creeks widen closer to the system inlet, the fringing brackish water species decrease and the marsh plain widens (~2X wider). The main tidal channel splits closer to the inlet and the marsh plain expands again (~2X wider again) with expansion of the low marsh vegetation. The tidal reach closest to the inlet is also influenced by sand transport into the marsh via nearshore coastal processes associated with adjacent Buzzards Bay. The tide range in adjacent Buzzards Bay is relatively large (~4 ft Section V) and the salt marsh areas are regularly flooded at high tide and the salt marsh creeks drain nearly completely with each ebb tide.

All of the key habitat indicators support the assessment that Herring Brook Marsh, and particularly its tidal creeks, are supporting high quality habitat relative to the system's salt marsh structure and function (Section VII). Assessment of habitat quality must necessarily consider the natural function and tolerances of the specific estuarine ecosystem being evaluated, specifically:

Eelgrass: Eelgrass is not present within the estuarine reach of this system. Based upon all available information, it appears that the Herring Brook Estuary is not structured to support eelgrass habitat, as is also the case in similar marsh systems evaluated during the MEP (*e.g.*, Namskaket Creek and Little Namskaket Creek in Orleans, Scorton Creek and Sandwich Harbor in Sandwich). This is typical for New England salt marshes, which are naturally organic and nutrient-rich and generally contain little water in the creeks at low tide. Because eelgrass is not a primary management focus, threshold development for protection/restoration of this system will focus on infaunal habitat quality.

Water Quality: The dissolved oxygen records indicate that the central tidal salt marsh creek of the Herring Brook salt marsh system has periodic oxygen depletion to <2 mg L^{-1} (**Table VIII-1**). Such oxygen depletion is typical of organic and nutrient-rich estuarine systems and indicates impaired habitat quality in coastal embayments. However, salt marshes are naturally nutrient and organic matter enriched as part of their ecological design, with a natural consequence being that these systems experience periodic oxygen depletion during warmer summer months. The observed level of oxygen depletion in Herring Brook Creek is expected, and was comparable to data collected in other salt marsh dominated systems in southeastern Massachusetts assessed during the MEP (*e.g.*, Namskaket Creek and Little Namskaket Creek in Orleans).

The large diurnal shifts in dissolved oxygen within Herring Brook are consistent with the high plant productivity within the marsh, high levels of oxygen uptake by the organic matter-rich marsh sediments and tidal changes in salinity and temperature which influence oxygen solubility (*e.g.*, incoming tides transport oxygen-rich waters into the estuary). The low chlorophyll-*a* concentrations (continuous average = 3.8 µg/L) reflect the offshore waters, as the near complete exchange of tidal waters in the creeks during each tide does not allow for chlorophyll levels to build up. A number of observations/measurements support the concept that the marsh processes are the primary control on oxygen dynamics in this system (Section VII). These include: 1) the importance of tidal variations over diurnal cycles, 2) the lack of linkage between oxygen depletion and chlorophyll, and 3) TN levels (0.4-0.5 mg N/L in the lower marsh). As the oxygen dynamics are associated with the natural structure and function of this estuarine system, Herring Brook Creek is considered to be supporting high quality habitat throughout its tidal reach.

Infaunal Animal Communities: Infauna communities within the central tidal creek of the Herring Brook Estuary are presently supporting infaunal habitat typical of the organic-rich environment of New England salt marshes in summer. The communities are consistent with the observed levels of oxygen depletion and water column TN. The communities tended to have relatively consistent species count at the upper and lower reaches, but higher species and individual counts and greater diversity in the middle reaches. The uppermost reaches have brackish salinity levels (<6 ppt) while the lower reaches appear to have regular sand deposition through the inlet. This lower reach is a transitional environment affected by transport from the upper marsh and coastal processes characteristic of the dynamic nearshore areas of Buzzards Bay. The communities generally contained some organic enriched tolerant species (*i.e.*, polychaetes), similar to Namskaket Marsh in Orleans, although the middle reaches had greater predominance of amphipods, which are typically present in slightly lower carbon settings.

Overall, the Infauna Survey indicated that most areas within Herring Brook Marsh are supporting infauna habitat typical of organic rich New England salt marshes, hence high quality relative to this estuarine ecosystem type. This is also supported by the absence of macroalgal accumulations and algal mats within the creek bottoms, which can result if there is "excessive" external nitrogen loading. The absence of macroalgal accumulations is consistent with the relatively low total nitrogen levels within this salt marsh system, 0.4-0.5 mg N/L in the lower marsh. By comparison, Cockle Cove Creek which is a similarly structured marsh located in Chatham supports high quality habitats (both emergent marsh and creek bottom) at levels of >2 mg TN L^{-1}. Based upon all lines of evidence it appears that the Herring Brook Estuary is presently supporting high quality infaunal habitat and has not exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment.

Table VIII-1. Summary of Nutrient Related Habitat Health within the Herring Brook Marsh Estuary. The tidal reach of this estuary is a typical New England salt marsh with a large central tidal creek and nutrient and organic matter enrichment. Assessment data presented in Chapter VII is the basis for characterizations in this table.

Health Indicator	Herring Brook Marsh Estuary	
	Upper Salt Marsh	**Lower Salt Marsh**
Dissolved Oxygen	--[1]	H[1]
Chlorophyll	--[2]	H[2,3]
Macroalgae	H[4]	H[4]
Eelgrass	--[5]	--[5]
Infaunal Animals	H[6]	H[7]
Overall:	**H**	**H**

Notes:

1 - oxygen mooring placed at upper margin of the lower reach, within the central tidal creek, oxygen dynamics were consistent with a naturally organic matter and nutrient-rich New England salt marsh, oxygen depletions are typical of pristine salt marsh creeks. Periodic oxygen depletions to 2 mg/L and frequently <4 mg/L.

2 - tidal waters ebb nearly completely at low tide, chlorophyll levels reflect floodwaters.

3 - low levels, typically 3-5 µg/L, oxygen dynamics do not appear linked to chlorophyll levels

4 - *Ulva* and drift algae and surface algal mats absent

5 - no evidence that this estuary is supportive of eelgrass, consistent with status as a tidal salt marsh, which drains at low tide.

6 - moderate to high numbers of individuals, low species numbers, species typical of organic rich New England salt marshes in summer (polychaetes).

7 -- low numbers of individuals and species, species typical of organic rich New England salt marshes (polychaetes, some amphipods), physical processes associated with inlet also have influence in this estuarine reach (unstable substrate).

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

VIII.2. THRESHOLD NITROGEN CONCENTRATION

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

Determination of the critical nitrogen threshold for maintaining high quality habitat within the Herring Brook estuarine system is based primarily upon: 1) the systems structure and function as a salt marsh, 2) macroalgal distribution, 3) current benthic community indicators and 4) nitrogen levels. As a salt marsh dominated estuary, Herring Brook Marsh does not support eelgrass habitat. As a result, threshold development for protection/restoration of this system focuses on infaunal habitat quality. The primary mechanism for infaunal habitat quality decline in salt marsh creeks of this type is through stimulation of macroalgal production and accumulation. Given the system-specific assessment database, it is possible to develop a site-specific threshold.

A principal component of the high tolerance of salt marsh systems to nitrogen inputs from groundwater and surface water inflows is that unlike embayments, creek waters cannot accumulate nutrients over multiple tidal cycles as do embayments. In addition, increasing the nitrogen concentration in the tidal waters that flood the marsh plain will have a negligible or possibly a stimulatory effect on marsh primary and likely secondary production (*i.e.,* an enhancement of habitat). In addition, since the inflowing fresh waters flow downstream through the marsh creek and out to the adjacent offshore waters, the nitrogen level will never exceed the inflowing freshwater nitrogen level.

The Herring Brook Estuary is presently supportive of high quality salt marsh infaunal habitat throughout its tidal reach. While there is periodic summertime oxygen depletion of creek waters, the levels are consistent with other unimpaired New England salt marsh systems assessed during the course of the Massachusetts Estuaries Project (MEP). At present, significant macroalgal accumulations do not occur within this macro-tidal estuary at tidally averaged total nitrogen levels that have a gradient of 0.80 mg N L^{-1} at the headwaters to 0.40 mg N L^{-1} at the tidal inlet. Among the MEP salt marshes, this gradient is similar to Namskaket Marsh, which was 0.84 mg/L at its headwaters and 0.53 mg/L at its outlet.[76]

Since Herring Brook Marsh is presently below the level of nitrogen loading that would cause impairment to its infaunal habitats (*i.e.,* below its nitrogen threshold level), a conservative estimate of the threshold was established. The threshold was based upon the site-specific data mentioned above and comparison to other similar systems on Cape Cod where other detailed nitrogen threshold studies have been completed. This inter-estuarine comparison focused upon similar salt marshes which are presently experiencing higher nitrogen levels, with and without impairment.

[76] Howes B.L., S.W. Kelley, J. S. Ramsey, R.I. Samimy, E.M. Eichner, D.R. Schlezinger, (2007).

During the MEP, a number of salt marshes were assessed and most had nitrogen thresholds of 1 mg/L TN recommended at the border of upper and lower reaches and 2 mg/L TN in the headwaters. This recommendation was usually based on the lack of macroalgal accumulation, measured and modeled tidal velocities, and the infauna survey results. Among these systems, Little Namskaket Marsh in Orleans had higher TN concentrations (1.2 mg/L TN mid-marsh) than Herring Brook, but also lower chlorophyll-*a* levels and similar infaunal species counts.[77] Scorton Creek in Sandwich had similar TN concentrations (generally 0.3-0.6 mg/L), but varied chlorophyll-*a*, DO depletion, and infauna in different portions of a complex salt marsh system.[78] Sandwich Harbor is another large marsh system with slightly higher infaunal species counts, but similar diversity, and variable chlorophyll-*a* and DO characteristics. In each of these, the MEP Technical Team noted that the recommended thresholds (mid: 1 mg/L TN, headwaters: 2 mg/L TN) were conservative and should be highly protective of the quality of these marshes.

Aside from the detailed MEP review of each of salt marsh systems, the selected thresholds were also based on separate review of >20 salt marsh systems that was completed at the beginning of the MEP. During the initial MEP reviews of Chatham's estuaries, the Technical Team assessed Cockle Cove Creek, a salt marsh system that receives groundwater discharge impacted by the Town of Chatham wastewater treatment facility.[79] This system had much higher TN concentrations than Herring Brook (1.9 mg/L TN mid-marsh), but showed no signs of habitat impairment. Question arose whether Cockle Cove Creek could accept more nitrogen and were there key characteristics that would guide the resulting answers. As such, the MEP Technical Team reviewed similar data from 23 salt marsh areas and generally found that adequate tidal velocities were a key to sustaining acceptable salt marsh habitat even in exceptionally high nutrient level settings. High TN levels were supported in systems with tidal velocities of ≥1 ft/s, while systems with similar TN levels, but tidal velocities of <0.5 ft/s tended to have macroalgal accumulations. This relationship was generally supported in the subsequent MEP assessments: macroalgal accumulation was noted in salt marshes of Aucoot Cove in Marion and Mashapaquit Creek in West Falmouth where velocities are <0.5 ft/s, but no accumulation had been noted in systems with velocities >1 ft/s (*e.g.*, Little Namskaket Creek and Namskaket Creek in Orleans). Among these, Cockle Cove Creek had N levels 3-5X other systems (2-3 mg/L TN in the upper reaches) and no indication of impairments. The velocity data relates to the inability of drift algae to accumulate if there is no basin or low velocity areas to allow for settling. Note that the result is not that large drift algae are swept from the estuary, but that the tidal velocities make the marsh creeks inhospitable environments for their colonization and growth. This is also the case in Herring Brook creeks, along with the other factors that indicate its current healthy condition.

Putting all the assessment elements together, it appears that for Herring Brook Creek, the critical values are a total nitrogen level of 2 mg/L TN in the headwaters and a level of 1 mg/L TN at the

[77] Howes B.L., E. Eichner, S.W. Kelley, J. S. Ramsey, R.I. Samimy, D.R. Schlezinger (2007). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Little Namskaket Marsh Estuarine System, Orleans, MA. SMAST/DEP Massachusetts Estuaries Project, MassDEP. Boston, MA. 116 pp.

[78] Howes B., S. Kelley, J. Ramsey, E. Eichner, R. Samimy, D. Schlezinger, and P. Detjens (2013). Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Scorton Creek Estuarine System, Town of Sandwich, Massachusetts. MassDEP. Boston, MA. 167 pp.

[79] SMAST MEP Technical Memorandum. November 30, 2006. Cockle Cove Salt Marsh Nitrogen Threshold. From: B. Howes, D. White and R. Samimy. To: R. Dunn and S. Halterman, MassDEP. 44 pp.

border of the upper and lower reach. Based on the infauna, sediment flux, and water quality review, we selected water quality Station HB3 as the boundary area location for the upper and lower reach and, as such, the sentinel station for this system. The threshold level of 1 mg/L TN was determined to be appropriate for this sentinel station. As a point of comparison, it should be noted that the total nitrogen level at the middle marsh station in Cockle Cove Creek is currently 1.38 mg/L TN. This threshold for Herring Brook applies as long as the tidal creek maintains its present hydrodynamic characteristics (flushing and velocity). The nitrogen threshold for Herring Brook Marsh is intentionally conservative based upon all available data from comparable systems. This concentration indicates that additional nitrogen may enter this system without impairment of its habitat quality throughout the estuary.

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IX. WATER QUALITY SCENARIOS: BUILDOUT, NO ANTHROPOGENIC, AND REQUESTED MUNICIPAL WWTF DISCHARGE

During the MEP, each system water quality model was calibrated to match existing conditions and validated using an independent dataset so that it could be used to reliably predict water quality impacts of scenarios that altered watershed nitrogen inputs or characteristics of the tidal flushing (*e.g.*, changes in the inlet or interior system dredging). As part of the MEP process, MassDEP and USEPA requested that two standard scenarios be completed: 1) a no-anthropogenic watershed loading scenario and 2) a watershed buildout scenario based on existing zoning. Other alternative scenarios were usually completed at the request of watershed towns and often involved the initial stages of wastewater planning [*i.e.*, comprehensive wastewater management plans (CWMPs)]. The Town of Falmouth requested these two standard MEP scenarios plus an additional scenario to evaluate the impact of a potential discharge of 1.3 MGD of treated effluent from the municipal wastewater treatment facility.

IX.1. WATERSHED BUILDOUT LOADING

Part of the regular MEP watershed nitrogen load modeling is to prepare a buildout assessment of potential development and accompanying nitrogen loads within the study area watershed. The MEP buildout is relatively straightforward and is generally completed in three steps: 1) each residential parcel classified by the Town Assessor as developable is identified and divided by minimum lot sizes specified in Town zoning and the resulting number of new residential units is rounded down, 2) parcels classified as developable commercial and industrial parcels by the town assessor are identified, and 3) residential, commercial and industrial parcels with existing development and areas greater than twice zoning's minimum lot size are identified, divided by the minimum lot size and the resulting number of new units is rounded down.

It should be noted that the initial buildout approach is relatively simple and does not include any modifications/refinements for lot line setbacks, wetlands, road construction, frontage requirements, parcel shape requirements, or other more detailed zoning provisions. The MEP buildout approach also does not include potential impacts associated with the higher density development usually associated with 40B affordable housing projects. As an example of how the MEP approach might apply, assume an 81,000 square foot lot is classified by the Town Assessor as a developable residential lot (land use code 130). This lot is divided by the 40,000 square foot minimum lot size specified in town zoning and the result is rounded down to two. As a result, two additional residential lots would be added to the sub-watershed in the MEP buildout scenario.

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

Table IX-1 shows the total number of additional parcels within each of the Herring Brook subwatersheds. There is a total of 80 projected new parcels with 38 projected on existing developed single-family residence parcels (*i.e.*, land use code 101) and 34 projected on undeveloped parcels classified by the Town Assessor as developable for residential development (*i.e.*, land use codes 130 and 131). The remaining projected parcels are on properties with existing residential development, but large enough lot areas that more development could occur. There are no parcels in the watershed classified to accept additional or new commercial development. There is only one parcel classified for new industrial development (*i.e.*, land use code 440). Each additional residential or industrial property added at buildout is assigned nitrogen loads for wastewater and impervious surfaces. Residential additions also include lawn fertilizer nitrogen additions. All wastewater loads are assumed to come from standard on-site septic systems. Cumulative attenuated buildout loads used in the buildout scenario are indicated in **Table IX-2,** along with corresponding direct atmospheric nitrogen loads (from precipitation) and benthic flux rates (adjusted from measured sediment core rates to reflect larger watershed loads). Buildout additions within the Herring Brook watersheds will increase the attenuated system-wide nitrogen loading rate by 15%.

Under buildout conditions, the TN concentration at the sentinel station (HB3) increases to 0.546 mg/L or well below the 1 mg/L threshold (**Table IX-3**). Overall TN concentrations throughout the system increase by 6 to 12% at the water quality monitoring stations; at HB3 the TN concentration increases by 9%. Modeled TN concentrations throughout the system in the buildout scenario are shown in **Figure IX-1**.

IX.2. WATERSHED NO ANTHROPHOGENIC LOADING

Another part of the standard MEP watershed nitrogen load modeling is to develop projected nitrogen loads to a system based on no anthropogenic watershed nitrogen loads. This scenario provides an assessment of what background nitrogen concentrations would be within an estuary if there was only atmospheric deposition of nitrogen and natural forests within the watershed. **Table IX-4** shows the nitrogen loads for the no anthropogenic scenario.

Under no anthropogenic conditions, the TN concentration at the sentinel station (HB3) is 0.206 mg/L (**Table IX-5**). This concentration is lower than the Buzzards Bay background concentration because watershed freshwater inputs are diluting the tidal TN concentrations. Overall TN concentrations throughout the system decrease by 37% to 90% at the various water quality monitoring stations compared to existing conditions.

Table IX-1. Buildout Scenario: Developable Parcels in Herring Brook Watershed. Buildout is based on standard MEP procedures, including reviewing Town Assessor land use classifications and current town zoning. Developable parcels are based on Town Assessor's classifications, while additional development on currently developed parcels is largely based on whether additional parcels can be created if the existing lot area is divided by minimum lot sizes specified in zoning. Eighty (80) additional residential parcels are projected in the Herring Brook watershed distributed among the indicated subwatersheds. No additional future commercial development is project and one additional industrial property is projected (one 44,101 sqft lot).								
Watershed	**Shed ID#**	**Total New residential units**	**Land use Codes**					
			Residential					**Industrial**
			017	**101**	**104**	**109**	**130/ 131**	**440**
Lower Herring Brook LT10	1	11		6			5	
Upper Herring Brook LT10	2	14		5			9	
Wing Pond Outfall	3	1					1	
Wing Pond LT10	4	12		1		1	10	
Wing Pond GT10 + shed 6 JBCC	5/6	1	1					
Trout Stream LT10	7	32	4	23	2		3	
Trout Stream GT10	8	2					2	
Upper Herring Brook GT10	9	3					3	
Crocker Pond	10	4		3			1	1
TOTAL		80	5	38	2	1	34	1

Table IX-2. *Buildout* scenario sub-embayment N loads used for total nitrogen modeling of the Herring Brook system. Total watershed N loads, atmospheric N loads, and benthic flux are shown. Existing watershed load and benthic flux are shown for comparison. Direct atmospheric deposition is the same under existing and buildout conditions.					
sub-embayment / surface water discharge	Buildout watershed load (kg/day)	Existing watershed load (kg/day)	direct atmospheric deposition (kg/day)	Buildout benthic flux net (kg/day)	Existing benthic flux net (kg/day)
Lower Herring Brook	2.468	2.148	0.074	0.226	0.214
Upper Herring Brook	3.189	2.767	0.126	0.024	0.023
Wing Pond outlet	2.679	2.542	-	-	-
Trout Stream	3.797	3.041	-	-	-
System Total	**12.134**	**10.499**	**0.200**	**0.250**	**0.237**

Table IX-3. Herring Brook modeled average total N concentrations (mg/L) in *buildout* scenario. Scenario TN concentrations at water quality monitoring stations are shown compared to existing conditions TN concentrations and the % increases from existing conditions. Background TN concentration in Buzzards Bay is 0.282 mg/L. Buildout scenario TN concentration at the threshold station (HB03, bold print) is significantly less than the 1.0 mg/L TN threshold for Herring Brook.

Sub-Embayment	Upper Herring Brook	Upper Herring Brook	**Lower Herring Brook**	Lower Herring Brook	Lower Herring Brook
monitoring station (ID)	HB1	HB2	***HB3***	HB4	HB5
Present	0.850	0.648	**0.501**	0.393	0.398
Buildout scenario	0.927	0.725	**0.546**	0.415	0.421
% change from present	9%	12%	9%	6%	6%

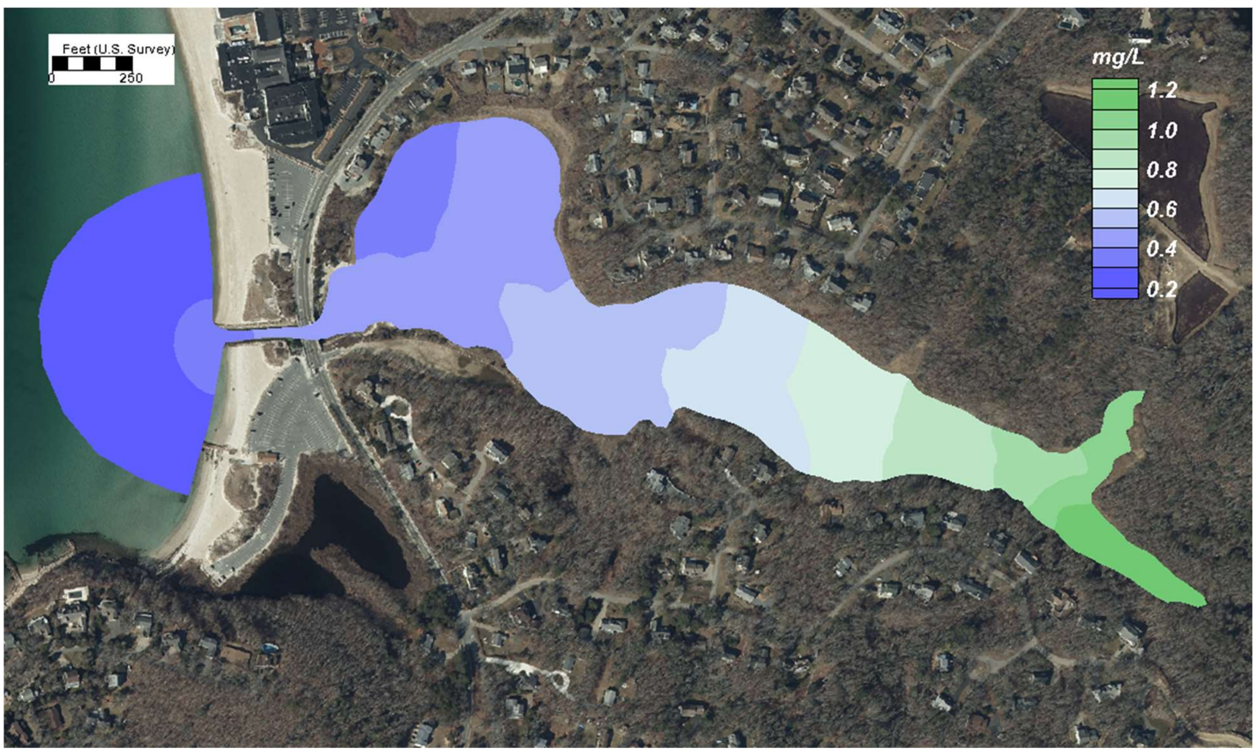

Figure IX-1. Color contours of tidally-averaged TN concentrations (mg/L) in Herring Brook for watershed buildout N loading scenario. Contours are based on water quality model output.

Table IX-4. *No-anthropogenic* scenario sub-embayment N loads used for total nitrogen modeling of the Herring Brook system. Total watershed N loads, atmospheric N loads, and benthic flux are shown. Existing watershed load and benthic flux are shown for comparison. Direct atmospheric deposition is the same under existing and no-anthropogenic conditions.

sub-embayment / surface water discharge	No Anthro watershed load (kg/day)	Existing watershed load (kg/day)	direct atmospheric deposition (kg/day)	No Anthro benthic flux net (kg/day)	Existing benthic flux net (kg/day)
Lower Herring Brook	0.058	2.148	0.074	0.142	0.214
Upper Herring Brook	0.036	2.767	0.126	0.012	0.023
Wing Pond outlet	0.219	2.542	-	-	-
Trout Stream	0.140	3.041	-	-	-
System Total	**0.452**	**10.499**	**0.200**	**0.154**	**0.237**

Table IX-5. Herring Brook modeled average total N concentrations (mg/L) in *no-anthropogenic* scenario. Scenario TN concentrations at water quality monitoring stations are shown compared to existing conditions TN concentrations and the % decreases from existing conditions. Background TN concentration in Buzzards Bay is 0.282 mg/L.

Sub-Embayment	Upper Herring Brook	Upper Herring Brook	**Lower Herring Brook**	Lower Herring Brook	Lower Herring Brook
monitoring station (ID)	HB1	HB2	***HB3***	HB4	HB5
Present	0.850	0.648	**0.501**	0.393	0.398
No Anthro scenario	0.088	0.151	**0.206**	0.248	0.250
% change from present	-90%	-77%	-59%	-37%	-37%

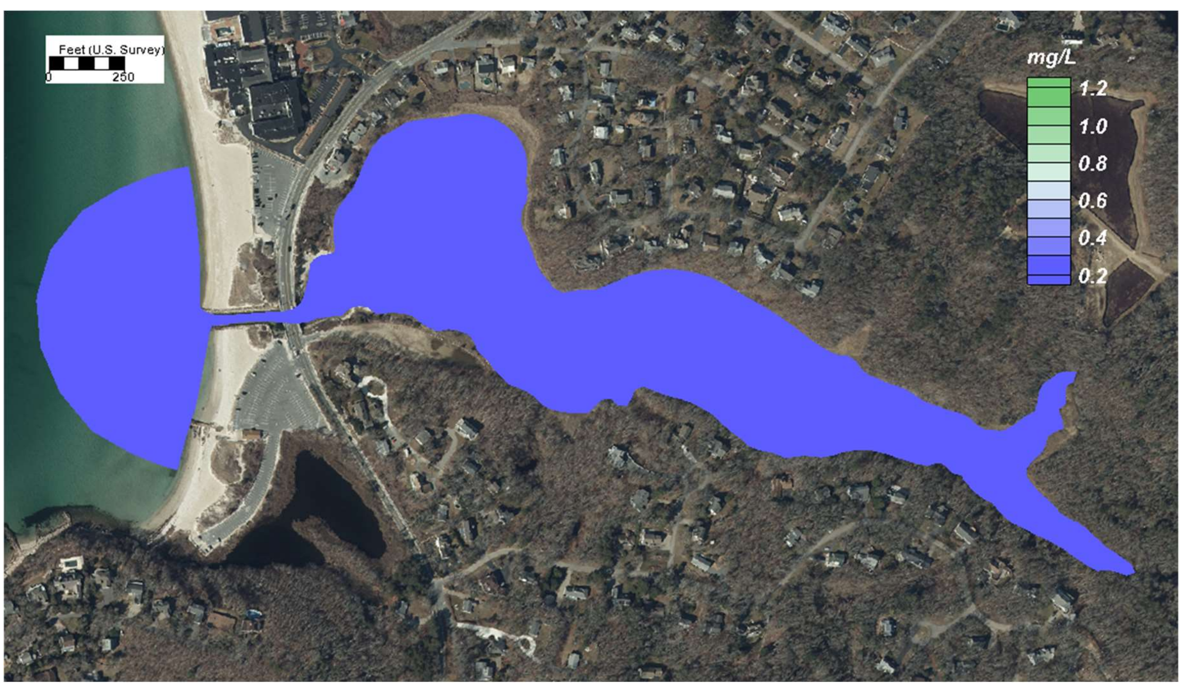

Figure IX-2. Color contours of tidally-averaged TN concentration (mg/L) in Herring Brook for watershed no-anthropogenic N loading scenario. Contours are based on water quality model output.

IX.3. WATERSHED MUNICIPAL WASTEWATER DISCHARGE LOADING

In addition to the standard MEP scenarios using the validated Herring Brook water quality model, the Town of Falmouth also requested a scenario to evaluate the impact of a potential wastewater discharge from the municipal wastewater treatment facility within the Herring Brook watershed. As part of current wastewater planning, the Town has been evaluating the impact of discharging 0.76 million gallon per day (MGD) annual average flow at open sand beds 14-15. These sand beds are located along the southern edge of the Herring Brook watershed (also the northern edge of the West Falmouth Harbor watershed) and partially upgradient of Crocker Pond. Groundwater modeling by GHD, Inc. using a localized portion of the USGS regional groundwater model shows that 41% of 0.76 MGD will flow through Crocker Pond and into Herring Brook, while 14% of the 0.76 MGD will flow directly to Herring Brook (of this 14%, 11% will flow under Crocker Pond and the remaining 3% will flow directly to Herring Brook). The remaining 45% of the 0.76 MGD will flow directly to Buzzards Bay.[80]

In order to prepare for the requested scenario, project staff used these groundwater modeling results and the findings from Herring Brook assessment discussed above to determine that 0.76 MGD at a town-specified treatment level of 3 mg/L TN would result in an annual nitrogen load of 3,150 kg discharged at open sand beds 14-15. Of this total, 41% would flow through Crocker Pond and be exposed to the 50% nitrogen attenuation in the pond resulting in an annual nitrogen load of 646 kg leaving Crocker Pond and discharging the Herring Brook along that flowpath. Another 14% of the total nitrogen load of 3,150 kg/yr (or 441 kg/yr) would reach Herring Brook without attenuation within the watershed. These nitrogen loads would then be added to the existing conditions watershed loads (**Table IX-6**). The scenario additions within the Herring Brook watersheds will increase the attenuated system-wide nitrogen loading rate by 28%.

Under the municipal discharge scenario conditions, the TN concentration at the sentinel station (HB3) increases to 0.518 mg/L or well below the 1 mg/L threshold (**Table IX-7**). Overall TN concentrations throughout the system increase by 1% to 7% at the water quality monitoring stations; at HB3 the TN concentration increases by 3%. The water quality impact of the municipal discharge is less than the buildout scenario largely because most of the municipal discharge enters the system in the lower portion, closer to the inlet. Modeled TN concentrations throughout the system in the municipal discharge scenario are shown in **Figure IX-3**.

Although an additional modeling scenario combining buildout and the municipal discharge was not completed, it is reasonable to assume that the combined impact would also have a TN concentration below the 1 mg/L threshold at the sentinel station. The increased watershed nitrogen inputs from the buildout scenario tended to have the greatest impacts at the upper Herring Brook monitoring stations and increased the TN concentration at the HB3 sentinel station by 0.045 mg/L to 0.546 mg/L. The increased watershed nitrogen inputs from the municipal discharge scenario tended to have their greatest impact at the lower Herring Brook monitoring station and increased the TN concentration at the HB3 sentinel station by 0.017 mg/L to 0.518 mg/L. A conservative combining of these additions at HB3 (+0.062 mg/L) without accompanying modeling (and sediment adjustments) would be notably less than the 1 mg/L TN threshold.

[80] GHD Technical Memorandum. March 9, 2023. Great Pond Targeted Watershed Management Plan, Open Sand Beds 14 / 15 Scenario A Simulation Summary – rev1. From: A. Rudenko. To: A. Lowell, Town of Falmouth, MA. 2 pp.

Table IX-6. *Municipal discharge* scenario sub-embayment loads used for total nitrogen modeling of the Herring Brook system. Total watershed N loads, atmospheric N loads, and benthic flux are shown. This scenario is based on 0.76 MGD of treated effluent from the municipal wastewater treatment facility located in the West Falmouth Harbor watershed being discharged at sand beds 14 and 15 located in the Herring Brook watershed with 55% of the effluent discharging into Herring Brook and most entering in the lower portion of the brook. Existing watershed load and benthic flux are shown for comparison. Direct atmospheric deposition is the same under existing and municipal discharge conditions.

sub-embayment / surface water discharge	Municipal Discharge watershed load (kg/day)	Existing watershed load (kg/day)	direct atmospheric deposition (kg/day)	Municipal Discharge benthic flux net (kg/day)	Existing benthic flux net (kg/day)
Lower Herring Brook	4.868	2.148	0.074	0.236	0.214
Upper Herring Brook	3.027	2.767	0.126	0.026	0.023
Wing Pond outlet	2.542	2.542	-	-	-
Trout Stream	3.041	3.041	-	-	-
System Total	**13.479**	**10.499**	**0.200**	**0.261**	**0.237**

Table IX-7. Herring Brook modeled average total N concentrations (mg/L) in *municipal discharge* scenario. Scenario TN concentrations at water quality monitoring stations are shown compared to existing conditions TN concentrations and the % increases from existing conditions. Background TN concentration in Buzzards Bay is 0.282 mg/L. Municipal discharge scenario TN concentration at the threshold station (HB03, bold print) is significantly less than the 1.0 mg/L TN threshold for Herring Brook.

Sub-Embayment	Upper Herring Brook	Upper Herring Brook	**Lower Herring Brook**	Lower Herring Brook	Lower Herring Brook
monitoring station (MEP ID)	HB01	HB02	***HB03***	HB04	HB05
Present	0.850	0.648	**0.501**	0.393	0.398
Municipal Discharge scenario	0.857	0.663	**0.518**	0.412	0.426
% change from present	1%	2%	**3%**	5%	7%

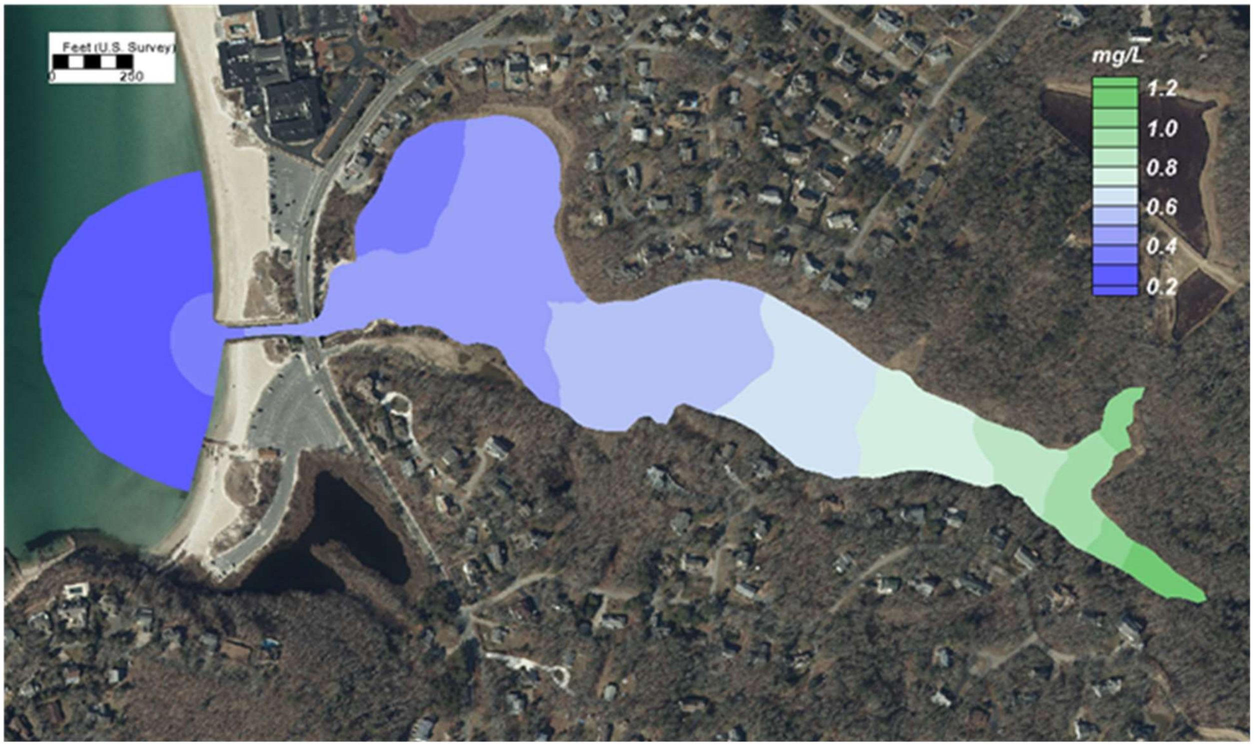

Figure IX-3. Color contours of tidally-averaged TN concentration (mg/L) in Herring Brook for watershed municipal discharge N loading scenario. Contours are based on water quality model output.

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