# Linked Watershed Assessment and Modeling to Determine Critical Nitrogen Loading Thresholds for the Sesuit Harbor Estuarine System, Dennis MA

## FINAL REPORT
### May 2024

for the

## Town of Dennis

Prepared by:

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Prepared By

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# Acknowledgements

## Recommended Citation

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# EXECUTIVE SUMMARY

Sesuit Harbor is a 75 hectare (187 acre) salt marsh with a dredged harbor basin on the Cape Cod Bay coast of Dennis, Massachusetts. The combination of a dredged harbor in a salt marsh system is similar to other estuarine systems reviewed during the Massachusetts Estuaries Project (MEP, 2001-2017). These similar systems were once typical New England salt marshes dominated by a central tidal creek with tributary tidal creeks and emergent marsh colonized by low marsh (*Spartina alterniflora*) and high marsh (*Spartina patens, Distichlis spicata*). Each of these systems had a deeper and larger boat basin dredged from some portion of the salt marsh. Sesuit Harbor had historical boat building dating back to before the Revolutionary War, but its current boat basin configuration was created by dredging/removing a portion of its salt marsh in 1958 and then removing an additional portion in 1982. As part of the Town of Dennis commitment to appropriate ecological 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 ecosystem and water quality assessment of Sesuit Harbor, consistent with the MEP Linked Watershed Embayment Model approach used to set the nitrogen restoration thresholds in the majority of estuaries in southeastern Massachusetts.

Since the Sesuit Harbor estuary system has been modified in a number of ways, it includes a variety of habitat types, a range of water quality conditions, and different sensitivities to watershed inputs. This mix of habitats is similar to other systems reviewed during the course of the MEP, including Rock Harbor in Orleans[1] and Saquatucket Harbor in Harwich.[2] The Sesuit Harbor assessment was completed by the same MEP technical team that previously completed all (>50) of the prior MEP assessments. Using standard MEP procedures, the Sesuit Harbor evaluation included:
   a. Watershed delineation, determination of groundwater discharge rates, and development of a watershed nitrogen loading model based on current land use
   b. Collection and incubation of 16 sediments cores from 12 sites to measure nitrogen regeneration in the primary habitats in the system: inlet, boat basin, and salt marsh
   c. Collection of tide measurements for over 30 days to capture the tidal changes throughout a lunar cycle
   d. Stream gauging and regular water quality and flow monitoring (~2X per month; 2005-2006) of the stream that discharges into the marsh from Scargo Lake

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[1] Howes B., S. Kelley, J. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner. 2007. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Rock Harbor Embayment System, Orleans, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 132 pp.

[2] Howes B., H. Ruthven, J. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner. 2010. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Allen, Wychmere, and Saquatucket Harbor Embayment Systems, Harwich, MA. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 191 pp.

e. Review of long-term water column data at eight locations within the system, including comparison of averages measurements from two time periods: 2005-2010 and 2017-2022

f. Deployment of a continuous water quality sensor platform for over 30 days to measure near bottom temperature, depth, chlorophyll a, dissolved oxygen, and salinity every 15 minutes (completed in 2005 and 2006)

g. Collection of replicate benthic infauna sampling at seven locations in both 2005 and 2022

h. Collection of bathymetry throughout the system

i. Development of a hydrodynamic model integrating the bathymetry and tidal measurements and calibrated and validated with different portions of the tidal record

j. Development of a water quality model integrating hydrodynamics, water quality, sediment regeneration, stream and watershed inputs; model calibrated and validated so it can be used to make reliable predictions of management options.

MEP evaluations assess the health of an estuary system based on five key metrics: dissolved oxygen, chlorophyll concentrations, presence or extent of macroalgae, extent of historical and current eelgrass coverage, and the sediment infauna population and characteristics. Review of all Sesuit Harbor-specific information determined that:

1. Infauna communities throughout Sesuit Harbor were impaired with worse conditions in the inlet and salt marsh, but slightly better conditions in the boat basin.

2. Infauna impairments were worse in 2022 than in 2005. This change is consistent with notable recent increases in 2017-2022 average water column total nitrogen (TN) concentrations compared to 2005-2010 averages.

3. Eelgrass restoration is not a management concern for Sesuit Harbor. MassDEP has established restoration of historic eelgrass beds as one of the primary goals of nitrogen TMDLs.[3] Review of historical eelgrass coverages show that Sesuit Harbor generally has not had any significant eelgrass presence[4] and the largest patch of eelgrass noted during 2022 CSP/SMAST field work was only 21 sq ft (located near the inlet).

4. Since eelgrass has largely not been present, nitrogen threshold development for protection/restoration of the Sesuit Harbor system should be focused on infaunal habitat quality.

5. The appropriate TN threshold for restoring and maintaining high quality infaunal habitat throughout Sesuit Harbor is 0.50 mg/L TN at a sentinel station at the edge of the boat basin (current Town station SES-4). SES-4 had a 0.58 mg/L TN average in 2017-2022.

Since the Sesuit Harbor water quality model developed in this project was validated and reliably matched measured TN concentrations throughout the system (90% match), it can be used to predict the impact of alternative management options to attain the recommended threshold, as well as the impacts of three standard MEP scenarios (**Table EX-1**). One standard MEP scenario is to determine a set of watershed septic system nitrogen load reductions to attain the recommended TN threshold. This scenario had septic nitrogen load reductions of 50%-60% in the individual system subwatersheds and an overall watershed nitrogen loading reduction of 48%. The project team also completed two other standard MEP scenarios: 1) watershed buildout based on current Town zoning and Assessor parcel classifications and 2) no anthropogenic watershed loading to assess background concentrations/loads. The buildout

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[3] TMDL = Total Maximum Daily Load; maximum amount of a contaminant allowed to enter a waterbody while meeting water quality standards (33 U.S.C. §1313; Clean Water Act)

[4] There was estimated eelgrass within the system inlet in 1951, but this is prior to the dredging and reconfiguration of the inlet and boat basin.

assessment showed that current zoning and lot classifications could result in the addition of 72 new residential parcels and three new commercial parcels (total area of 107,867 sq ft) within the watershed. The projected impact of the buildout scenario would increase the system-wide attenuated watershed nitrogen load by 5% and TN concentration at the sentinel station by 6%. The no anthropogenic loading scenario used nitrogen additions from only atmospheric deposition and natural forests within the watershed; the resulting TN concentration at the sentinel station was 105% less than current conditions. The linked watershed/hydrodynamic model could be used to evaluate other management scenarios if requested by the Town of Dennis in the future.

It is recommended that the Town discuss the regulatory status and water quality goals for the various segments of the Sesuit Harbor system, especially if MassDEP chooses to develop a nitrogen TMDL for the system. Although attaining the recommended nitrogen threshold will restore the infaunal habitat throughout the Sesuit Harbor system, additional clarification is needed to resolve the regulatory standing of the various portions of the system. The inlet and boat basin are not listed in the most recent MassDEP Integrated List, although the Sesuit Creek segment upstream of the boat basin is included. It is unclear from this listing how MassDEP regards man-made basins/harbors.

**Table EX-1. Summary of Sesuit Harbor scenario results: modeled total nitrogen concentrations (mg/L).** After collecting and reviewing available system data, project staff determined that water quality monitoring station SES4 was an appropriate threshold station for the Sesuit Harbor system. Based on review of assessed ecosystem characteristics, project staff selected 0.50 mg/L TN as a threshold concentration to attain acceptable infauna habitat conditions throughout the Harbor system. Monitoring in 2017-2022 showed the average TN concentration at SES4 was 0.58 mg/L (±0.18 mg/L stdev). Synthesis of watershed and sediment N inputs with system hydrodynamics resulted in an excellent match ($R^2=0.90$) between current measured and projected modeled TN concentrations throughout the system, which means the model is reliable for assessing projected future impacts and alternative management scenarios. Project staff completed three standard MEP scenarios using the Sesuit Harbor linked water quality model: a) threshold scenario with staff-selected watershed nitrogen loading reductions to attain the threshold TN concentration, b) watershed buildout scenario based on current Town zoning and Assessor classifications and c) no-anthropogenic loading to establish background conditions. Modeled TN concentrations for existing conditions and the scenarios are shown; sentinel station SES4 results are shown in **bold**.

| Sub-Embayment | Inlet | Lower Harbor basin | Cold Storage Rd. Marsh | **Upper Harbor Basin** | West Sesuit Creek | Head of Sesuit Creek |
|---|---|---|---|---|---|---|
| monitoring station (MEP ID) | SES01 | SES02 | SES03 | **SES04** | SES06 | SES07 |
| Present | 0.460 | 0.470 | 0.509 | **0.563** | 0.968 | 1.009 |
| Threshold scenario | 0.447 | 0.451 | 0.471 | **0.496** | 0.651 | 0.888 |
| % change from present | -48% | -51% | -50% | **-52%** | -59% | -21% |
| Buildout scenario | 0.462 | 0.472 | 0.513 | **0.571** | 1.005 | 1.042 |
| % change from present | +7.4% | +5.4% | +5.3% | **+6.2%** | +6.9% | +5.7% |
| No-anthropogenic loading | 0.433 | 0.433 | 0.433 | **0.426** | 0.322 | 0.03 |
| % change from present | -100.0% | -100.0% | -100.0% | **-105.4%** | -120.7% | -170.0% |

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# I. INTRODUCTION

Sesuit Harbor is a 75 hectare (187 acre) salt marsh with a dredged harbor basin on the Cape Cod Bay coast of Dennis, Massachusetts (**Figure I-1**).  Quivett Neck is to the east of the Harbor and the Chase Garden portion of the Barnstable Great Marsh is to the west.  The combination of a dredged harbor in a salt marsh system is similar to other estuarine systems reviewed during the Massachusetts Estuaries Project (MEP), including Rock Harbor in Orleans[5] and Saquatucket Harbor in Harwich.[6]  All of these systems were predominantly tidal salt marshes with a central tidal creek, smaller tributary tidal creeks and a slightly wider inlet to the surrounding ocean, that was then expanded and deepened to create a harbor.  Each of these systems also had long histories of boating, but only recently had a deeper and larger boat basin created.

Sesuit Harbor was the site of a Revolutionary War-era salt works created by Captain John Sears.[7]  In the early 1800's, the Harbor was the site of a large shipyard (Shiverick Shipyard).[8]  The earliest United States Geological Survey (USGS) topographic maps of the area in 1893 show an approximately 80 m wide inlet to "Sursuit Creek" with marsh upstream of what is now Salt Works Road.[9]  The first more-refined 1943 USGS topographic map shows a similar system (renamed Sesuit Creek) with a central tidal creek of relatively constant width extending under Bridge Street to within approximately 100 m of Route 6A, but no headwater stream connection to Scargo Lake (**Figure I-2**).  The 1961 updated USGS topographic map shows the result of the initial 1958 dredging to complete a boat basin,[10] two jetties armoring the inlet and extending out into Cape Cod Bay, and a stream connecting Scargo Lake to Sesuit Creek.  This 1961 update also shows a notably thinner tidal creek upstream and under Bridge Street.  In 1982, the US Army Corps of Engineers led a dredging project that created a 2,400 ft long, six foot deep channel to Cape Cod Bay and expanded and deepened the boat basin that was created in 1958.[11]  In 2008, the Town and state partners replaced a restricted culvert under Bridge Street with the goal to create better tidal connection to the upstream marsh.[12]

All the changes to the Sesuit Harbor system have created a system with different responses to watershed inputs.  The Harbor basin area functions like a coastal embayment, while the inland portions upstream of the basin function like a traditional New England salt marsh.  The salt marsh portion of system is dominated by a central tidal creek and emergent marsh colonized by low marsh plants (*Spartina alterniflora*) and high marsh plants (*Spartina patens*, *Distichlis spicata*) with some more brackish marsh plants found in the uppermost regions and limited bordering patches of *Phragmites*.

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[5] Howes B., S. Kelley, J. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner.  2007.  Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Rock Harbor Embayment System, Orleans, MA.  SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection.  Boston, MA.  132 pp.

[6] Howes B., H. Ruthven, J. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner.  2010.  Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Allen, Wychmere, and Saquatucket Harbor Embayment Systems, Harwich, MA.  Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection.  Boston, MA.  191 pp.

[7] https://newenglandhistoricalsociety.com/the-rise-and-fall-of-cape-cod-salt/ (accessed 11/8/23).

[8] https://www.snpoa.org/SNPOA_History_Page.html (accessed 11/8/23).

[9] https://ngmdb.usgs.gov/topoview/ (accessed 11/9/23).

[10] https://dennisyc.com/club-history (accessed 11/8/23).

[11] https://www.nae.usace.army.mil/Missions/Civil-Works/Navigation/Massachusetts/Sesuit-Harbor/ (accessed 11/8/23).

[12] Town of Dennis, 2008 Annual Report.
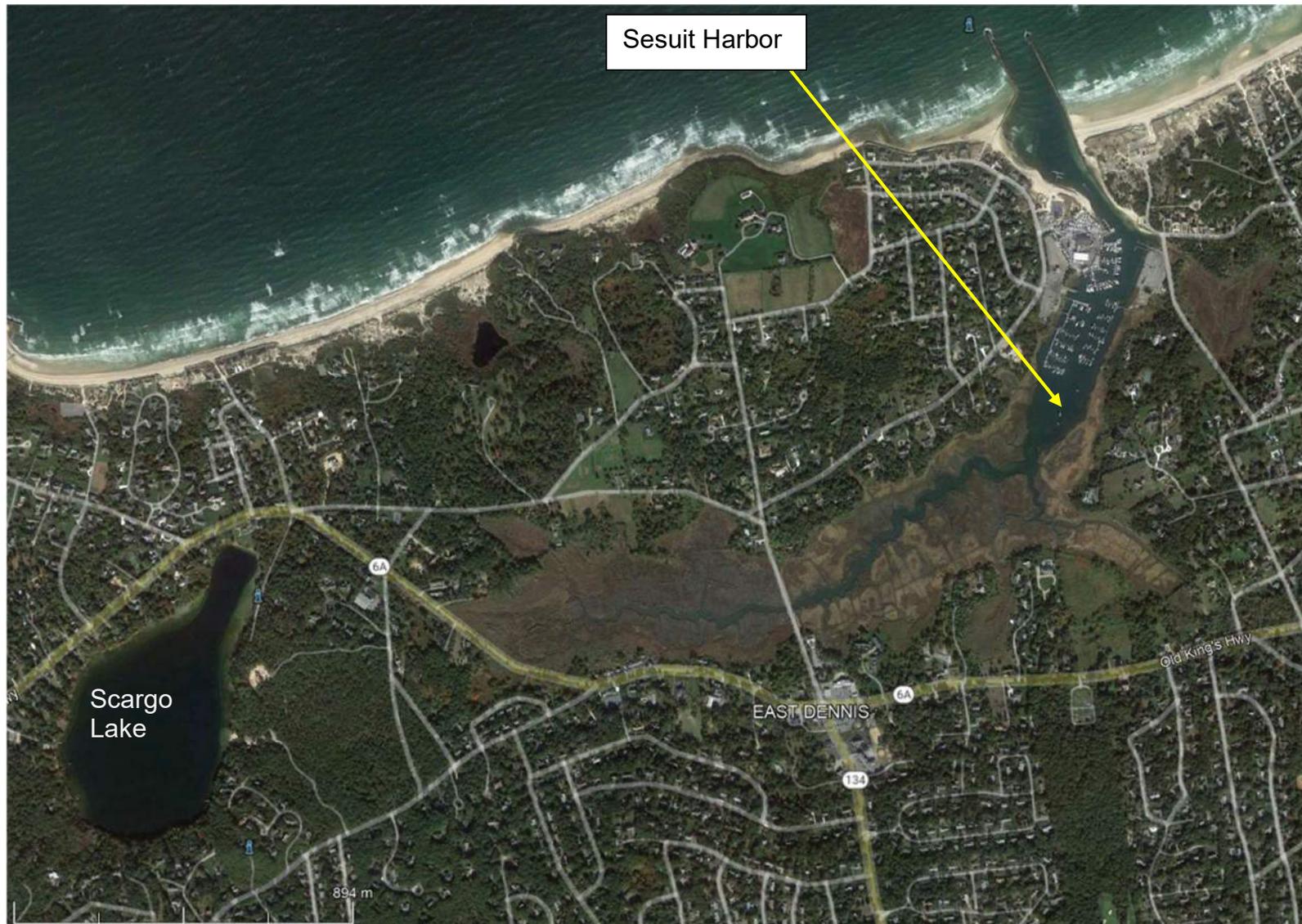
**Figure I-1.    Sesuit Harbor study area.**  Tidal waters from Cape Cod Bay enter the system through one inlet.  Upstream of the Harbor basin is an extensive salt marsh system and a stream input from Scargo Lake.  Freshwater enters the system primarily groundwater along its margins, as well as small collection streams along the marsh.
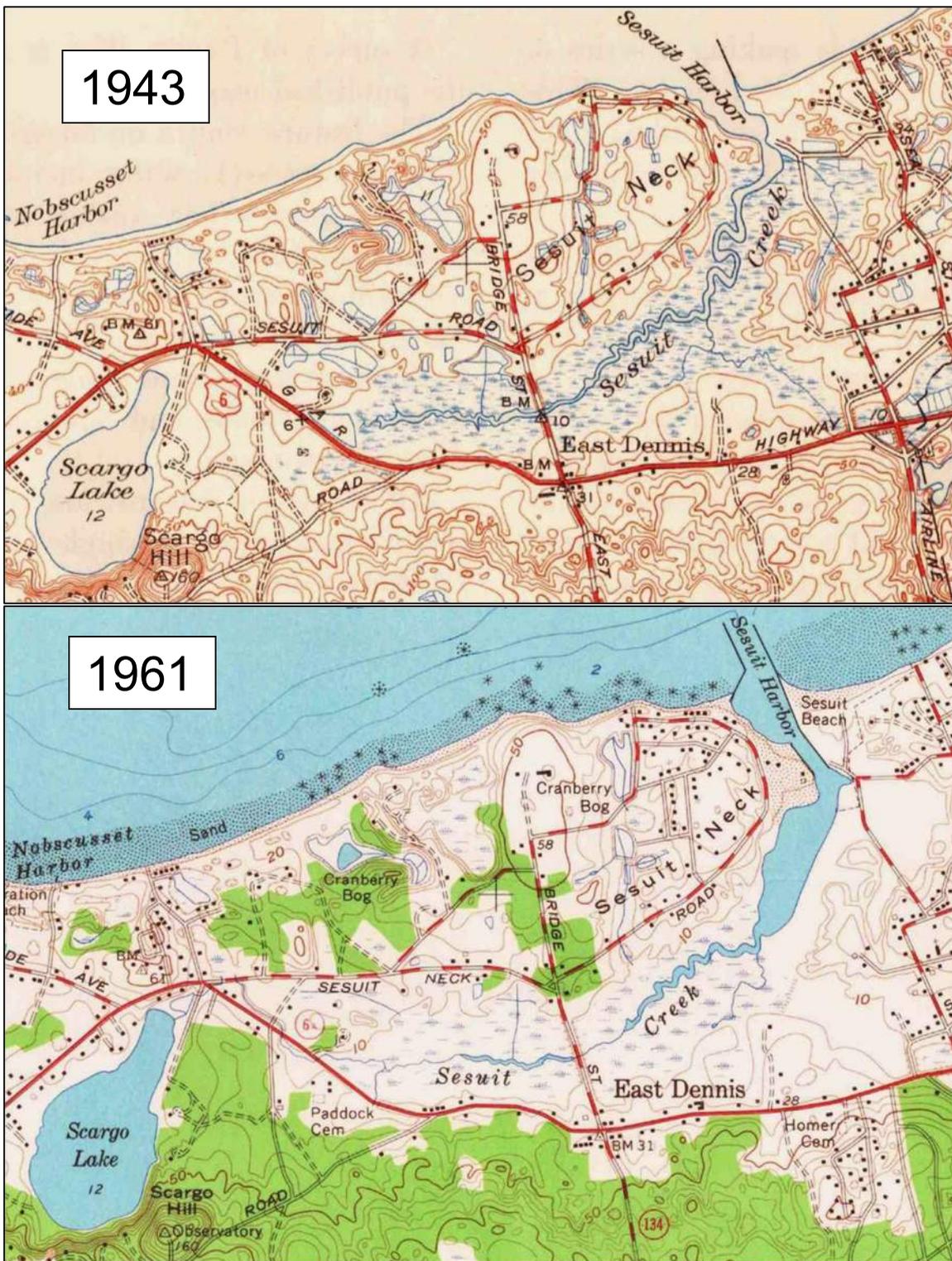
**Figure I-2. US Geological Survey Historical Topographic Maps of Sesuit Harbor study area: 1943 and 1961.** 1943 map shows a small harbor area and a central tidal creek of relatively constant width extending under Bridge Street to within approximately 100 m of Route 6A, but no headwater stream connection to Scargo Lake. 1961 map shows a significantly expanded Harbor after the initial 1958 dredging of the Harbor boat basin, two jetties armoring the inlet, a notably thinner tidal creek upstream of the boat basin, and a stream connecting Scargo Lake to Sesuit Creek.

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The primary ecological threat to the Sesuit Harbor 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 increased development density and reliance on on-site disposal of wastewater through septic systems. The Town of Dennis has been working to quantify and assess the watershed loading and coastal water quality impacts for all their estuaries for a number of decades, including regular water quality monitoring[13] and development and implementation of a Comprehensive Wastewater Management Plan. As part of the Town of Dennis 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 assessment of the ecosystem and water quality in Sesuit Harbor consistent with the MEP Linked Watershed Embayment Model approach used to set the nitrogen restoration thresholds in the majority of estuaries in southeastern Massachusetts.

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 development of nitrogen management alternatives needed by the Town of Dennis 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 was undertaken by the same technical team that developed and completed the MEP, the results stem directly from the efforts of a 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 Dennis to develop and evaluate the most cost effective nitrogen management alternatives to restore those valuable coastal resources of Dennis 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 over their individual assimilative capacity, which causes declines in their ecological health. The ecological impacts include 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.

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[13] CSP/SMAST Technical Memorandum. January 11, 2022. Integrated Estuarine Water Quality Database and Review: Swan Pond, Bass River, and Sesuit Harbor. From: B. Howes and E. Eichner. To: D. Young, CDM Smith and T. Andrade, Town Engineer, Town of Dennis. 20 pp.

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 (including the Town of Dennis) 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, such as hydrodynamics and sediment nitrogen regeneration. 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 develop, results must be understandable to the regulatory community, town officials, and the general public in order for appropriate implementation. The MEP represented the next generation of watershed-based nitrogen management approaches. Through the MEP, CSP/SMAST and MassDEP provided quantitative tools for community-based watershed-embayment management 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 provided technical expertise and guidance to the municipalities and regulatory agencies tasked with management, protection, and restoration of each individual embayment system. 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, which MassDEP implements. TMDLs must identify sources of the pollutant of concern (in this case nitrogen) from both point and non-point sources and the allowable load to meet the state water quality standards with 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:

- site specific measurements within each watershed and embayment;
- realistic "best-estimates" of nitrogen loads for each parcel within a system watershed, including parcel-specific water use;
- spatially distributes the watershed nitrogen loading to the embayment;
- accounts for watershed 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;

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- includes nitrogen regenerated within the embayment from the bottom sediments;
- is calibrated and validated by both independent hydrodynamic, nitrogen concentration, and ecological embayment-specific data; and
- can be used reliably for evaluation of "what if" management options 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-3**). 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
  - Dissolved Oxygen (DO) record
  - Macrophyte survey
  - Infaunal survey

# Nitrogen Thresholds Analysis
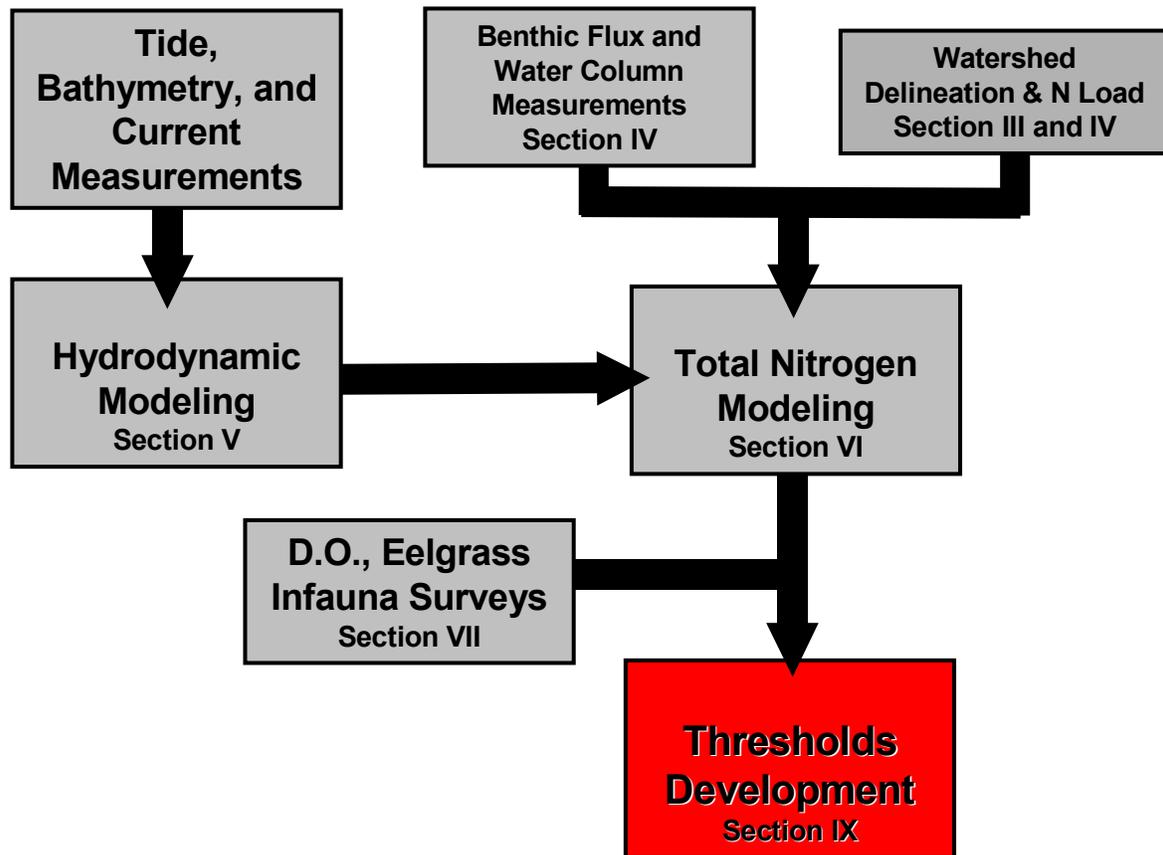


**Figure I-3.    Massachusetts Estuaries Project Critical Nutrient Threshold Analytical Approach.**  General MEP assessment approach and associated sections of this report.

## I.2 REPORT DESCRIPTION

This report presents the results generated from the implementation of the Linked Watershed-Embayment Management Modeling Approach to the Sesuit Harbor system in the Town of Dennis. 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 the hydrodynamic modeling of embayment circulation are discussed in Chapter V. 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 VI. Chapter VII discusses the findings from the system ecological assessment. The modeling and assessment information is synthesized and a nitrogen threshold level was developed for restoration of acceptable ecological conditions is included in Chapter VIII. Chapter IX includes modeling of two prospective scenarios: past conditions with removal of anthropogenic nitrogen sources and future conditions with complete watershed build-out based on current zoning. Additional modeling may be completed to evaluate other options to attain the recommended threshold concentration to restore acceptable ecological condition throughout the Sesuit Harbor system.

## II. PREVIOUS STUDIES AND REGULATORY STATUS

The Town of Dennis, as the primary stakeholder to the Sesuit Harbor system, has been concerned over the resource quality of the Town's significant coastal resources for at least 20 years. In 2002, the Cape Cod Commission created the first Cape-wide delineation of coastal embayment watersheds, which included a watershed to Sesuit Harbor.[14] This watershed delineation was utilized in the 2005 Needs Assessment completed by the Town for the initial Comprehensive Wastewater Plan (CWMP).[15] During the same period, the Town began collecting coastal water quality data according to the procedures necessary for inclusion of data in Massachusetts Estuaries Project assessments. This water quality data collection has continued to this day with coordination through Coastal Systems Program, School of Marine Science and Technology at the University of Massachusetts Dartmouth (CSP/SMAST).

CSP/SMAST recently reviewed Dennis coastal water quality data collected from 2005-2020.[16] This review compared and contrasted 2005-2010 data with 2015-2020 data and completed trend analyses over the whole timeframe. Average TN concentrations at the Sesuit Harbor main basin stations and the mid-marsh were all slightly higher in 2015-2020, but were not statistically different from averages measured in 2005-2010. The average TN concentration at the head of the marsh was significantly higher than the 2005-2010 average, while the TN average at the Cold Storage stream input close to the inlet was significantly lower than the 2005-2010 average. Average TN concentrations at the inlet, both just outside and just inside, were significantly

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[14] Cape Cod Water Resources Classification Map II (Marine Water Recharge Areas) from 2002 Regional Policy Plan. https://www.capecodcommission.org/our-work/past-rpp-editions/ (accessed 11/10/23).

[15] Figure 4-3 Town of Dennis, Massachusetts Comprehensive Wastewater Management Plan, Stearns and Wheler, LLC. 2005.

[16] CSP/SMAST Technical Memorandum. January 11, 2022. Integrated Estuarine Water Quality Database and Review: Swan Pond, Bass River, and Sesuit Harbor.

higher. Trend analysis of the TN data from 2005 to 2019/2020 showed no statistically significant trends at the main basin and mid-marsh stations, but all other stations had significant, mostly increasing, trends. Collectively, this data review showed that the system has changed from the initial conditions measured in 2005-2010. Further discussion of these findings is included in Sections VI and VII.

The most recent MassDEP Integrated List (2022) does not include the Sesuit Harbor boat basin, but does include the estuarine creek segment from the boat basin to within approximately 650 ft of Route 6A (**Figure II-1**).[17] 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 (*i.e.*, requires a TMDL), and the causes of impairment (*e.g.*, nitrogen, chlorophyll, fecal coliform). The Sesuit Creek segment is listed in Category 4A ("TMDL is completed') in the 2022 Integrated List for fecal coliform. Sesuit Creek has been classified in Category 4A since the 2010 MassDEP Integrated List. This classification occurred after MassDEP developed a region-wide Cape Cod Pathogen TMDL in 2009.[18]

Review of Massachusetts Natural Heritage & Endangered Species Program (NHESP) GIS databases show that none of the NHESP regulatory areas are located within the main portion of Sesuit Harbor, but there are some overlapping habitat areas near the inlet (**Figure II-2**). There are no NHESP natural communities, priority habitats for rare species or estimated habitats of rare wildlife in the main portion of the Sesuit Harbor system. There are overlapping priority and estimated habitat areas that extends into the system inlet from larger rare species offshore priority habitat area that includes large portions of Cape Cod Bay. Scargo Lake, which is in the Sesuit Harbor system watershed, is also listed as a priority habitat for rare species.

Recent management activities within the Sesuit Harbor area have included enlarged culverts at Bridge Street and dredging of the system inlet channel. In 2008, the Bridge Street culvert between the upper and lower portions of the Sesuit Creek salt marsh was replaced with two 9-foot wide box culverts. Subsequent marsh monitoring upstream of the new culverts showed that there are extensive mudflats created upstream of the new culverts and there have be subsequent attempts in 2019 to vegetate these areas with *Spartina alterniflora* (low marsh plants).[19] The Town also completed a 2022 dredging project with Barnstable County for the inlet channel between Cape Cod Bay and the Harbor Boatyard to maintain a depth of -6 ft at mean low low water (MLLW).[20]

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[17] MassDEP. 2023. Final Massachusetts Integrated List of Waters for the Clean Water Act 2022 Reporting Cycle. CN 568.1, Massachusetts Department of Environmental Protection, Bureau of Water Resources, Division of Watershed Management, Watershed Planning Program. Worcester, MA. 224 pp wo/appendices.

[18] MassDEP. 2009. Final Pathogen TMDL for the Cape Cod Watershed (Control Number: CN: 252.5). 153 pp.

[19] Wobst, A. May, 2019. Sesuit Creek Salt Marsh Pilot Planting, Association to Preserve Cape Cod. Presentation to the Massachusetts Ecosystem Climate Adaptation Network's Salt Marsh Working Group (SMWG). https://www.umass.edu/ses/sites/default/files/Wobst_SMWG%20LightningTalk_SesuitCrk_16may2019.pdf (accessed 11/28/23).

[20] https://www.capecod.gov/2022/02/26/project-summary-sesuit-harbor-dennis-dredging-project/ (accessed 11/28/23)
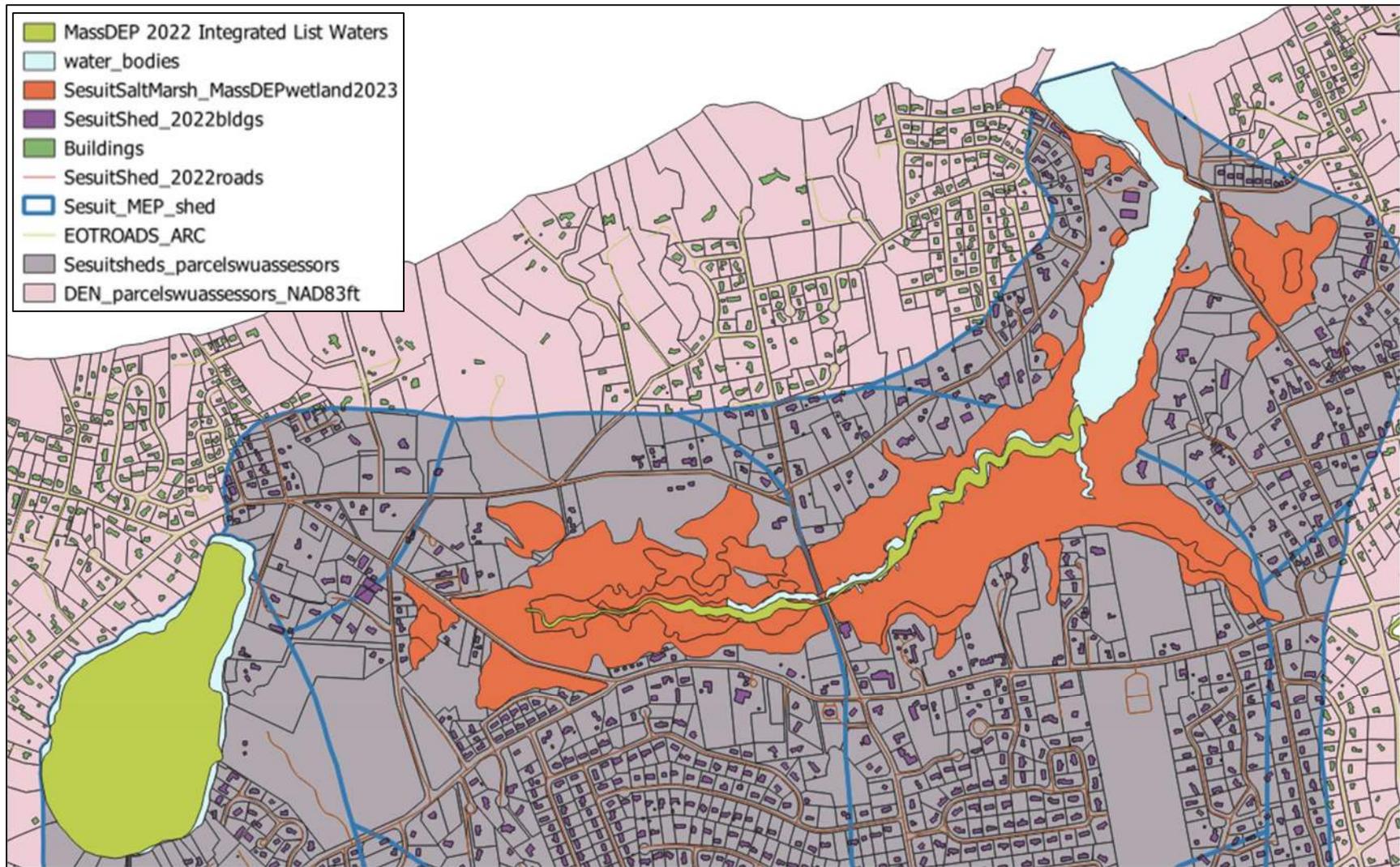
**Figure II-1. Sesuit Harbor Area: 2022 MassDEP Integrated List Waters.** The most recent MassDEP Integrated List (2022) does not include the Sesuit Harbor boat basin, but does include the estuarine creek segment (colored light green) from the boat basin to within approximately 650 ft of Route 6A. The Sesuit Creek segment is listed in Category 4A ("TMDL is completed") in List for fecal coliform. Scargo Lake, which is also in the watershed, is listed in Category 3 ("No uses assessed").
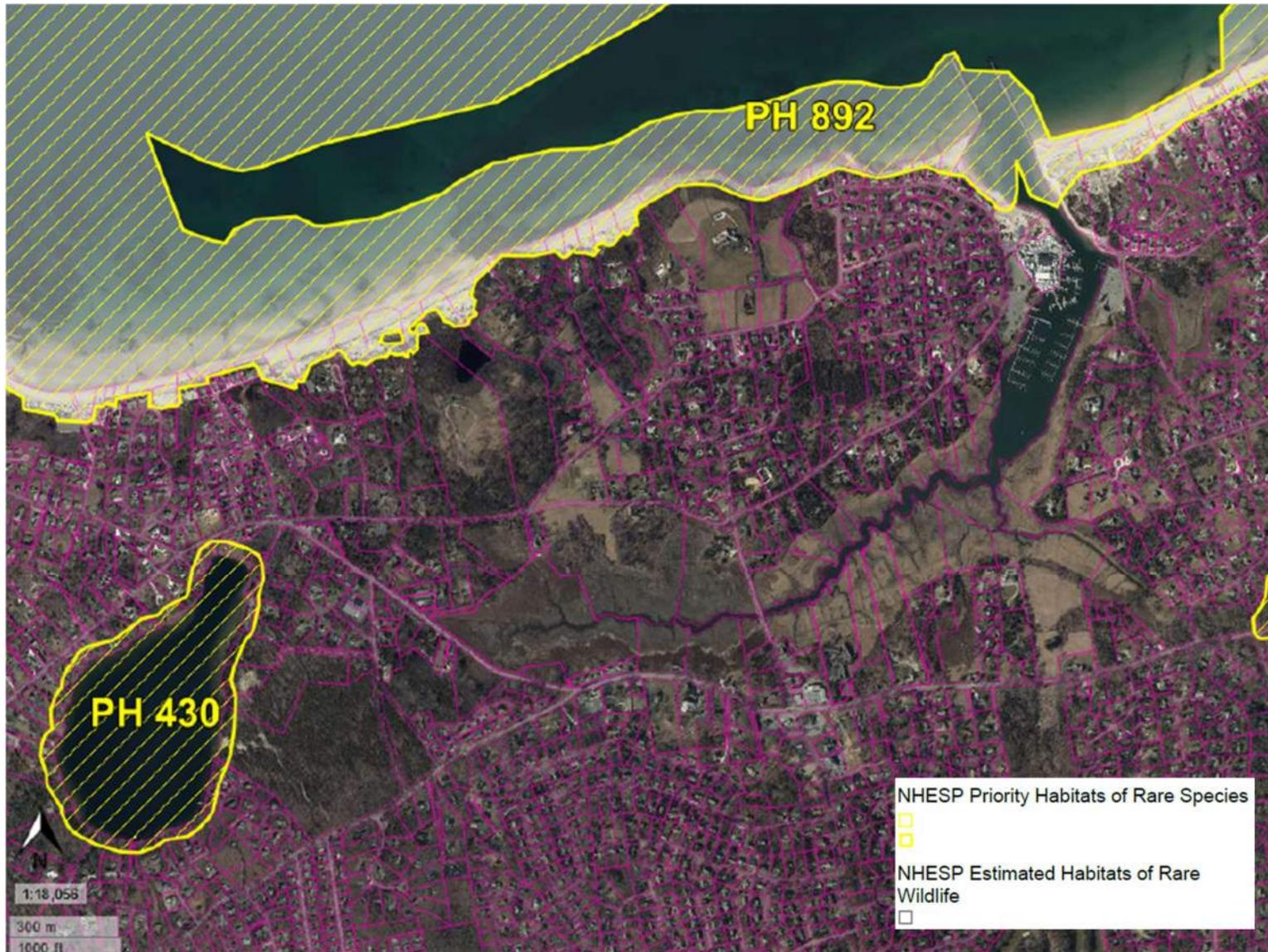
**Figure II-2. Massachusetts Natural Heritage & Endangered Species Program Regulated Areas near Sesuit Harbor system.** Based on information available through MassGIS, no NHESP natural communities, priority habitats for rare species or estimated habitats of rare wildlife are in the main portion of Sesuit Harbor except for the offshore priority habitat for rare species area that includes large portions of Cape Cod Bay. Available through MassGIS MassMapper on-line GIS (downloaded 11/9/23).

# 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 groundwater models for the six Cape Cod groundwater flow cells. 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 these 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 Dennis.

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.[21,22,23]  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 input carries 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 Sesuit Harbor system were delineated using a USGS regional model of the Monomoy Lens flow cell.[24]

The Monomoy Flow Model is based on the USGS three-dimensional, finite-difference groundwater model MODFLOW-2000.[25]  The model outputs from this model were used as input to the USGS particle-tracking program MODPATH4 to delineate groundwater

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

[22] 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.

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

[24] 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.

[25] 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.[26]  The Monomoy Model consists of 164 rows, 220 columns, and 20 layers.  The horizontal model discretization, or grid spacing, is 400 by 400 feet.  The vertical discretization of the model has the top 17 layers of the model extending to a depth of 100 feet below NGVD 29 and have a uniform thickness of 10 ft.  The top of layer 8 resides at NGVD29 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 NGVD29, while layer 19 extends to 240 feet below NGVD29.  The bottom layer, layer 20, extends to the bedrock surface and has a variable thickness depending upon site characteristics (up to 525 feet below NGVD29 in the Monomoy Lens); since bedrock is approximately 200 feet below NGVD29 in the Sesuit Harbor watershed 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 Monomoy Lens consist of gravel, sand, silt, and clay that were deposited in a variety of depositional environments.  Sesuit Neck, which is located on the north side of the Sesuit Creek portion of the Sesuit Harbor system, is composed of young Lake Deposits created during the formation of Glacial Lake Cape Cod when the continental ice sheet had withdrawn to a more northern location in what is now Cape Cod Bay.[27]  On the south side of the creek are older Ice Contact Deposits created when colder global temperatures caused the continental ice sheet to advance south and pushed into previously deposited sands and gravel. Scargo Hill is located within these Ice Contact Deposits.  In between the Lake and Ice Contact Deposits is the Sesuit Creek salt marsh that likely is situated on top of older lake-bottom deposits from Glacial Lake Cape Cod.

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.  The Kame Deposits generally are assigned a lower hydraulic conductivity (*i.e.*, 80 ft/d) in the upper layer of the Monomoy Lens model than the other portions of the Sesuit Harbor watershed (180-250 ft/d).  Modeling and field measurements of contaminant transport at Joint Base Cape Cod have shown similar differences in hydraulic conductivity do not tend to have any impact groundwater flow direction.[28]  Land surface runoff and direct stormwater discharge to surface waters is typically rather low in most areas of Cape Cod due to these permeable soils.  Final aquifer parameters throughout all layers of the regional USGS 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 Monomoy 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 at the

[26] 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.

[27] Oldale, R.N. and R.A. Barlow.  1986.  Geologic Map of Cape Cod and the Islands.  Miscellaneous Investigations Series, Map I-1763.  U.S. Geological Survey.  Reston, VA.

[28] 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.

time.  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.

## III.3  SESUIT HARBOR ESTUARY WATERSHEDS

The Sesuit Harbor system watershed abuts two MEP watersheds:  Bass River (south of the Sesuit Harbor watershed) and Barnstable Great Marshes (to the west).  USGS 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 the Sesuit Harbor system watershed delineation, project staff used the same techniques beginning with USGS model outputs.  The Sesuit Harbor system watershed includes subwatersheds to Scargo Lake and Cedar Pond, a stream gauge location adjacent to Route 6A, the Bridge Street marsh crossing, and the southern edge of the Harbor boat basin (**Figure III-1**).  The watershed delineations also include 10 year groundwater time of travel boundaries.

**Table III-1** provides the freshwater discharge volumes for the 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 Sesuit Harbor system from the delineated watershed is 11,496 m$^3$/d.  This flow includes corrections for outflow from Scargo Lake and Cedar Pond, since they are situated on the system boundaries and also have discharge to adjacent watersheds.

The watershed delineations completed by this revised analysis are the same watershed delineations completed by Cape Cod Commission (CCC) staff in coordination with USGS staff in 2012.  These delineations were previously completed in anticipation of a Sesuit Harbor MEP assessment.  A previous watershed delineation was completed by CCC staff for the first 2002 Regional Policy Plan, but it did not include subwatershed delineations.[29]  The Sesuit Harbor system watershed area is 1,498 acres and all of the watershed is within the Town of Dennis.

The watershed delineations for the Sesuit Harbor system 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 areas 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 Sesuit Harbor marsh system (Section IV).

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[29] Cape Cod Water Resources Classification Map II (Marine Water Recharge Areas) from 2002 Regional Policy Plan. https://www.capecodcommission.org/our-work/past-rpp-editions/ (accessed 11/10/23).
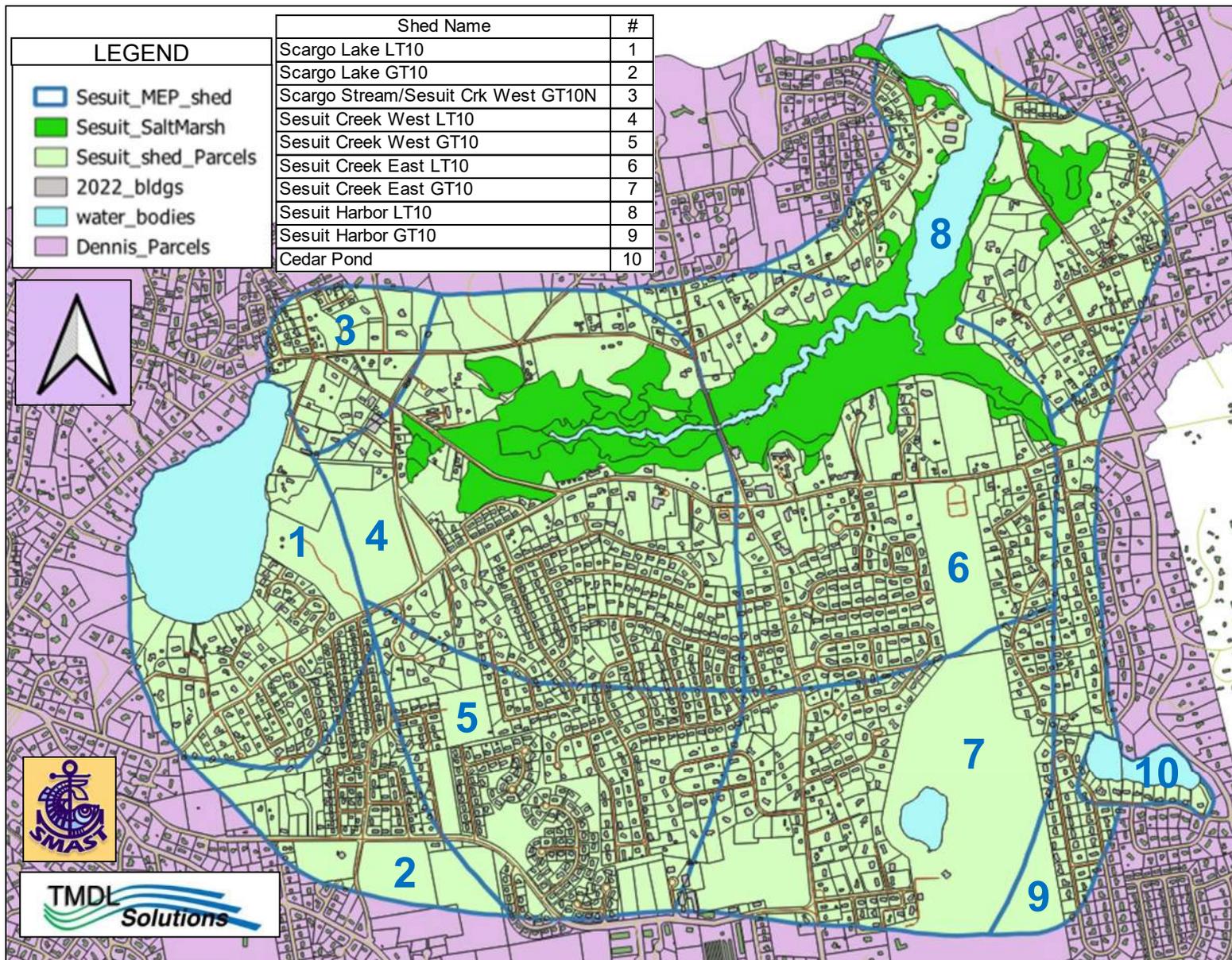
**Figure III-1. Watershed Delineation for Sesuit Harbor System Estuary.** Sub-watersheds to were delineated based upon the functional sub-units in the water quality model (see section VI). Delineations based on outputs from USGS regional groundwater model and are consistent with MEP watershed delineations to adjacent estuaries (Bass River and Barnstable Great Marshes).

| Table III-1. **Daily groundwater discharge to each of Sesuit Harbor estuary subwatersheds.** Groundwater discharge is based on watershed areas and USGS model recharge rate (27.25 in/yr). Scargo Lake and Scargo Stream adjusted to reflect measured flow at gauge discussed in Section IV. | | | | | |
|---|---|---|---|---|---|
| **Watershed** | **#** | **Watershed Area (acres)** | **% contributing to Sesuit Harbor** | **Groundwater discharge** | |
| | | | | **m³/day** | **ft³/day** |
| Scargo Lake LT10 | 1 | 176 | 46 | 613 | 21,653 |
| Scargo Lake GT10 | 2 | 83 | 46 | 292 | 10,295 |
| Scargo Stream/Sesuit Creek West GT10N | 3 | 53 | 100 | 404 | 14,251 |
| Sesuit Creek West LT10 | 4 | 341 | 100 | 2,617 | 92,417 |
| Sesuit Creek West GT10 | 5 | 187 | 100 | 1,433 | 50,619 |
| Sesuit Creek East LT10 | 6 | 318 | 100 | 2,441 | 86,191 |
| Sesuit Creek East GT10 | 7 | 224 | 100 | 1,721 | 60,792 |
| Sesuit Harbor LT10 | 8 | 179 | 100 | 1,370 | 48,385 |
| Sesuit Harbor GT10 | 9 | 75 | 100 | 578 | 20,403 |
| Cedar Pond | 10 | 18 | 28 | 37 | 1,306 |
| TOTAL | | 1,653 | | 11,505 | 406,311 |
| 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 Sesuit Harbor estuary system. Determination of watershed nitrogen inputs to these embayment systems requires: (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 Sesuit Harbor estuary system, the project team developed nitrogen-loading rates to each component of the estuary and its watersheds (Section III) based on standard MEP factors. The Sesuit Harbor 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 Sesuit Harbor watershed, including watersheds to Scargo Lake and Cedar Pond.

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 upon sub-watershed specific land uses and pre-determined nitrogen loading rates based on regional analyses.[30] For the Sesuit Harbor System, the watershed nitrogen loading model used land-use and water use data from the Town of Dennis 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.

Natural attenuation of nitrogen within key subwatersheds during transport from land-to-sea within the Sesuit Harbor watershed was determined based upon a site-specific study of stream flow and attenuation in the upgradient freshwater ponds. Stream flow was characterized at the head of the Sesuit Creek salt marsh, collecting flow from Scargo Lake and the small subwatershed to the gauge location (Section IV.2). This stream discharge point subwatershed allows a 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%, but can be adjusted if available monitoring and pond physical data are reliable enough to calculate a pond-specific nitrogen attenuation factor. Both Scargo Lake and Cedar Pond have sufficient water quality data to determine pond-specific nitrogen attenuation rates.

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[30] 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.

Natural attenuation during stream transport or in passage through fresh ponds of sufficient size to affect 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 the Sesuit Harbor watershed: Scargo Lake and Cedar 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 Sesuit Harbor is completely within the Town of Dennis. As such, project staff obtained digital parcel and tax assessor's data from the Town of Dennis[31] to serve as a base for the Sesuit Harbor watershed nitrogen loading model. Digital parcels and land use/Town Assessor's data for Dennis are from 2022. The land use database contains traditional information regarding address, parcel sizes and land use classifications.

**Figure IV-1** shows the land uses within the Sesuit Harbor estuary watershed. Land uses in the study area were grouped into six (6) land use categories: 1) residential, 2) commercial (golf course), 3) industrial, 4) mixed use, 5) undeveloped, and 6) government/non-profit. Right of way areas for roads are also shown. The land use categories are those utilized by the Town Assessor and are generally aggregations derived from the major categories in the Massachusetts Assessors land uses classifications.[32] "Government/non-profit" 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 there are four commercial clusters in the watershed: 1) the Harbor area near the Dennis Yacht Club, 2) a larger area near the Route 6A/Route 134 interchange that extend along Route 6A, 3) a small cluster near the Route 6A/Sesuit Neck Road interchange, and 4) portions a small area along Hokum Rock Road at the edge of the watershed. Residential land uses are the largest percentage of the overall watershed area (52%) with government/non-profit lands as the second largest portion (31%) (**Figure IV-2**).

Residential land uses are the dominant parcel type in the overall Sesuit Harbor watershed with 85% of the overall parcel count (total count = 1,371). Residential land uses are also the dominant parcel type in each of the sub-watershed groupings shown in Figure IV-2. Undeveloped parcels are the second largest parcel count within the subwatersheds with government/non-profit parcels the third largest parcel type. Single family residences are 96% of the residential parcel count and 90% of the residential area.

In order to estimate wastewater flows within the Sesuit Harbor study area, project staff obtained and linked parcel-by-parcel water use data from the Town of Dennis[33] to the Town Assessor parcels. Five years of water use (2018-2022) for individual parcels were 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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[31] Personal communication 12/8/22, K. Johnston, CDM Smith

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

[33] Personal communication 12/8/22, K. Johnston, CDM Smith
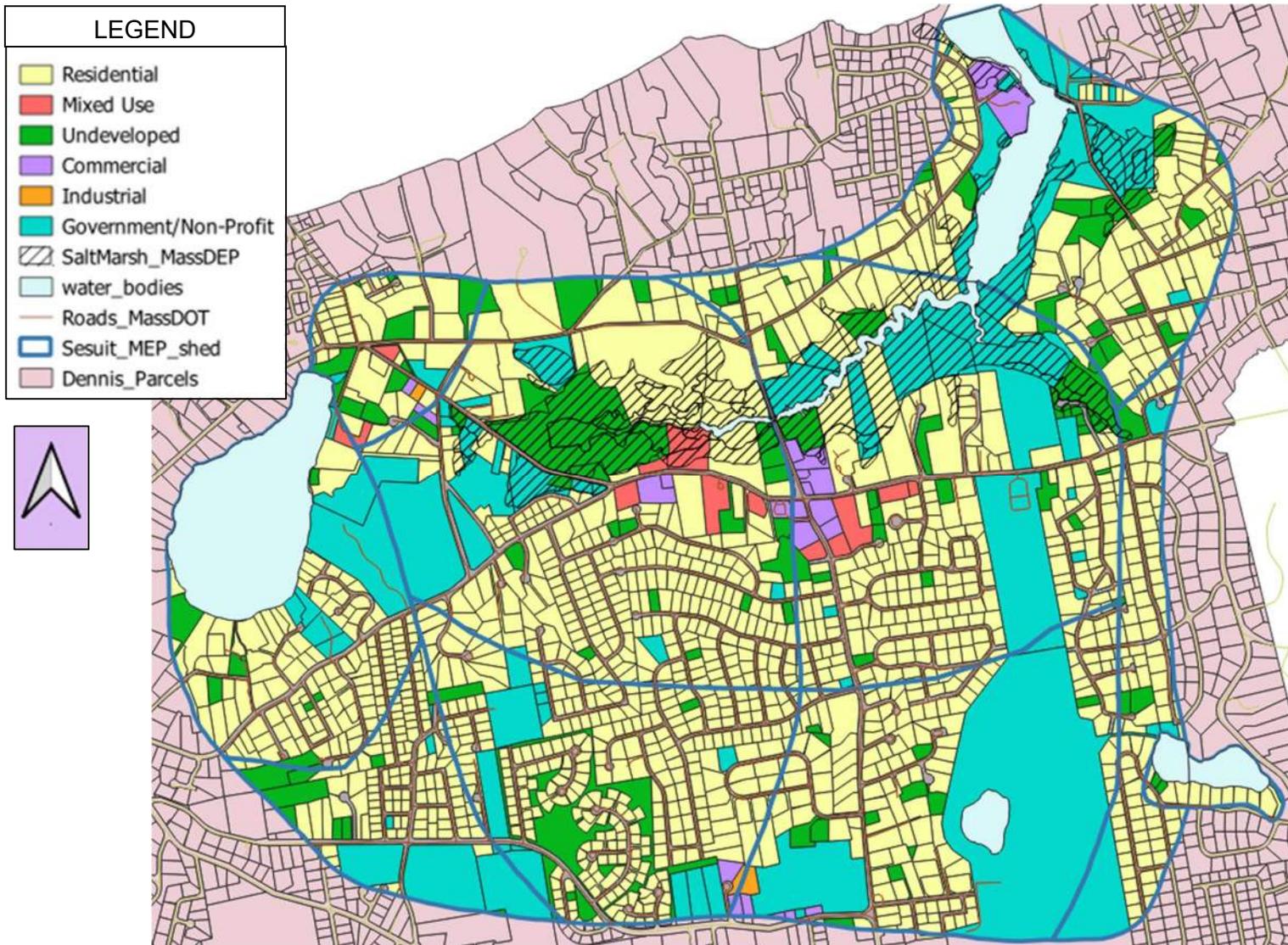
**Figure IV-1. Land-use in the Sesuit Harbor system watershed and sub-watersheds.** The system watershed is completely within the Town of Dennis. Land use classifications are based on Town Assessor's classifications and MADOR (2019) categories. Base assessor and parcel data for Dennis are from the year 2022. Residential land uses are 85% of parcel types and 52% of the overall watershed area. Single family residences are 96% of the residential parcel count and 90% of the residential area.
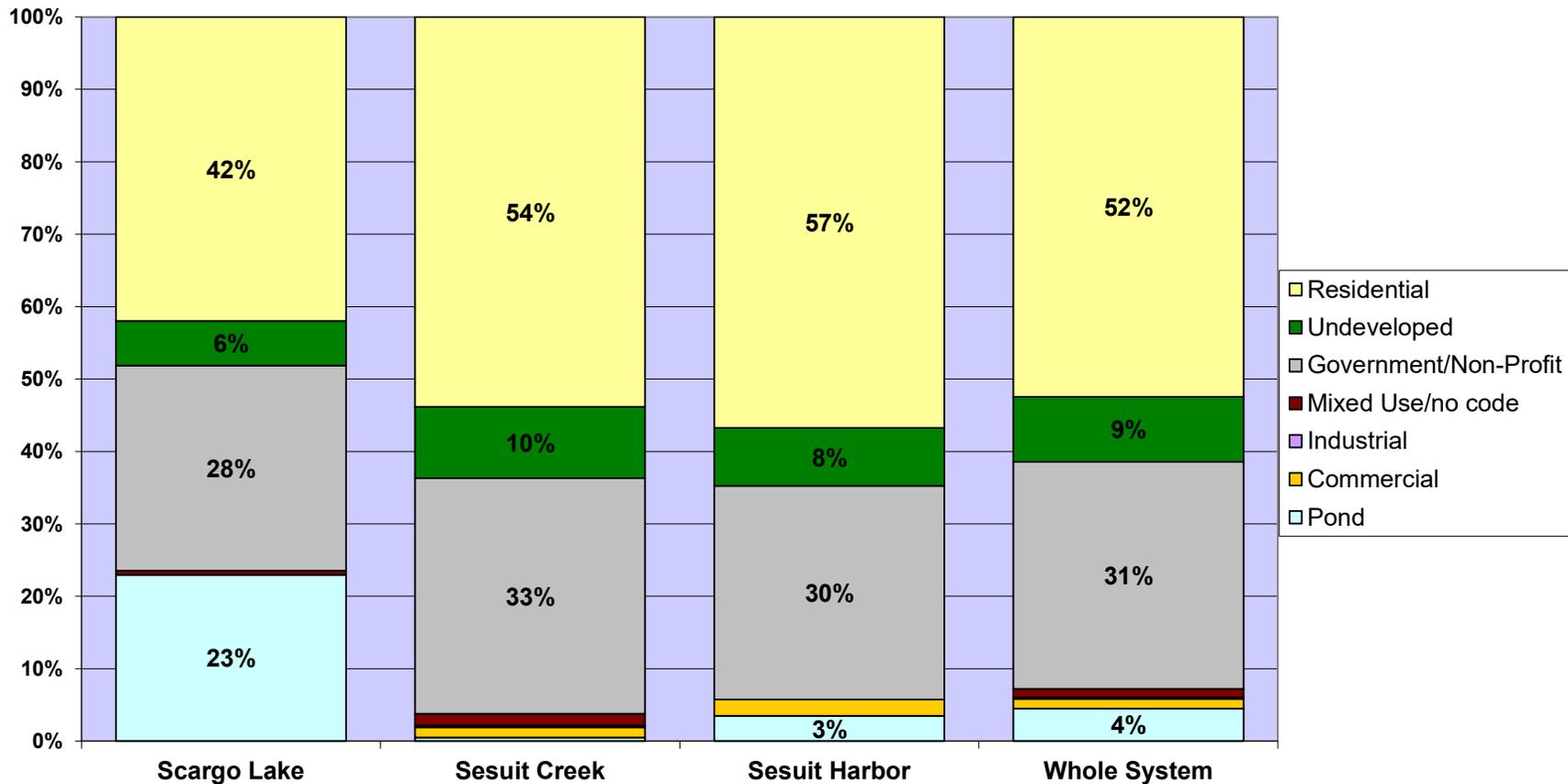
**Figure IV-2. Distribution of land-uses by area within the Sesuit Harbor system watershed and three component sub-watersheds.** Residential parcels compose the majority of the land area within the overall watershed and are the largest area in all of the component subwatersheds. Parcels with government/Non-profit classifications (land use codes in the 900's) are the second largest land use area within the watershed and each of the subwatersheds. Lands classified as undeveloped are 9% of the overall watershed area and a smaller portion of this area is classified as developable. Land use categories/groupings are generally based on town assessor's land use classifications (MassDOR, 2019). Only land use categories comprising 3% or more of the watershed area have percent labels.

### IV.1.1  Nitrogen Loading Input Factors

The Sesuit Harbor watershed nitrogen loading is based on Massachusetts Estuaries Project (MEP) techniques, which rely 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.[34]

#### *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 the 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.[35]  Downgradient studies of septic system plumes in similar soils indicate that further nitrogen loss during aquifer transport is negligible.[36,37]

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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[34] 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.

[35] 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.

[36] 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.

[37] 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 and pre-MEP assessments of watershed/stream tube analysis.[38,39]

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 another independent validation of the average residential water use within the Sesuit Harbor watersheds, project staff reviewed available US Census information and focused on the East Dennis census-designated place (CDP) that includes most of the Sesuit Harbor watershed. According to the 2020 US Census estimates, the East Dennis CDP has 2,352 housing units with approximately 56% occupied year-round and a total population of 3,068. This information would translate to 2.32 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 recent anecdotal information of conversions of seasonal houses to year-round residences during the initial COVID outbreak. In order to compare this to water use values, the project team began with state on-site wastewater regulations (*i.e.*, 310 CMR 15, Title 5), which assume that each person generates 55 gpd of wastewater. Based the average occupancy in the East Dennis CDP, the average household flow would be 127 gpd, which would include some consumptive use. Average recorded water use for the single-family residences within the Sesuit Harbor watershed based on 2018-2022 water use was 207 gpd, which would be 186 gpd with 10% consumptive use. This average is nearly the same as the 212 gpd average developed by MEP staff in 2009. If the population within the East Dennis CDP doubled during the summer, the average annual daily water use would be 159 gpd and if it tripled, the average would increase to 191 gpd. Given that past reviews of other Cape Cod data (*e.g.*, traffic counts, garbage generation, WWTF flows) suggest average regional population increases from two to three times year-round residential populations, this suggests that the average water use measured in the Sesuit Harbor watershed is a reasonable estimate of wastewater.

Water use information exists for all but four of the 1,344 developed parcels in the Sesuit Harbor watershed. The four developed parcels without water use accounts are assumed to utilize private

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

[39] 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.

wells for drinking water. These are properties that were classified by the Town Assessor with land use codes that should be developed (*e.g.*, 101 or 325), have been confirmed as having buildings on them through a review of aerial photographs or town assessor valuations, and do not have a listed account in the water use databases. Of the four properties, three are classified as single-family residences (land use code 101). All these parcels are assumed to utilize private wells and were assigned the Sesuit Harbor study area average water use for single-family residences of 207 gpd in the watershed nitrogen loading modules.

In addition to standard septic systems, alternative, denitrifying septic systems are also utilized in the Sesuit Harbor watershed. Project staff consulted with the Barnstable County Department of Health and the Environment (BCDHE) to see if any alternative, denitrifying septic systems were monitored within the Sesuit Harbor watershed. BCDHE provided a database of all reported monitoring of alternative, denitrifying septic systems within the Town of Dennis[40] and project staff reviewed the database to identify systems within the Sesuit Harbor watershed and those with three or more monitoring results. Based on this review, project staff identified 14 alternative, denitrifying septic systems within the Sesuit Harbor watershed with three or more sampling dates. Wastewater nitrogen loads were adjusted for each of the systems based on the average total nitrogen concentrations in the monitoring database: ranged from 10.1 mg/L to 46.8 mg/L TN. No groundwater discharge permits (*i.e.*, flows >10,000 gpd) were listed for any properties within the watershed.

### *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 golf course turf can also be a significant source. In order to add these sources to the nitrogen loading model for the Sesuit Harbor system, project staff utilized standard residential lawn nitrogen loads used in all previous MEP assessments, as well as recent nitrogen fertilizer application rates from the Town for the Dennis Pines Golf Course. 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 homeowner interviews and over 2,000 site surveys, a number of findings emerged: 1) average residential lawn area is ~5000 sq ft, 2) half of the residences did not apply lawn fertilizer, and 3) the weighted average application rate was 1.44 applications per year, rather than the 4 applications per year recommended on the fertilizer bags. Integrating the average residential fertilizer application rate with a nitrogen leaching rate of 20% resulted in a fertilizer contribution of N to groundwater of 1.08 lb N per residential lawn; these factors were used in MEP watershed nitrogen loading calculations. It is likely that this still represents a

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[40] Personal communication. T. Long and B. Baumgaertel, BCDHE. 12/12/22.

conservative estimate of nitrogen load from residential lawns.  It should also 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.

As has been done for golf courses in all MEP reviews, project staff reviewed the layout of the Dennis Pines Golf Course from aerial photographs, classified the various turf types (*i.e.*, greens, fairways, etc.), and, using GIS, assigned these turf areas to the appropriate Sesuit Harbor subwatersheds.  Staff received updated nitrogen fertilizer application rates from Maryellen Fabiano, Acting Director of Golf, Town of Dennis.[41]  Supplied rates showed that nitrogen fertilizer application rates (all in pounds per 1,000 square feet per year) by turf type for the Dennis Pines Golf Course were:  greens, 3.5; tees, 2.0; fairways, 2.0, and roughs, 2.0.  These nitrogen application rates were then applied to the respective turf areas, a standard MEP 20% fertilizer nitrogen leaching rate was applied, and annual nitrogen load from the golf course to each subwatershed was calculated.

### *Nitrogen Loading Input Factors: Other*

Other nitrogen loading factors included in the Sesuit Harbor assessment are for atmospheric deposition, impervious surfaces and natural areas.  These are the standard MEP factors[42] and are similar to those used in the Cape Cod Commission Nitrogen Loading Technical Bulletin[43] and the 1999 MassDEP Nitrogen Loading Computer Model.[44]  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 Sesuit Harbor watershed are summarized in **Table IV-1.**

Road areas are based on Massachusetts Department of Transportation (MassDOT) GIS information.[45]  The MassDOT GIS coverage provides information on selected 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 the areas of these road segments by subwatershed.  Project staff also checked this information against Town parcel-based rights-of-way.

Building areas were also included in the nitrogen loading analysis and are based on MassGIS information.[46]  This information is building footprints digitized from interpretation of aerial photos and LiDAR data collected state-wide.  The most recent update that included Dennis was based on 2021 aerial imagery.

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[41] Personal communication.  M. Fabiano, Acting Director of Golf, Town of Dennis.  12/9/22.

[42] 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.

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

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

[45] https://www.mass.gov/info-details/massgis-data-massachusetts-department-of-transportation-massdot-roads

[46] https://www.mass.gov/info-details/massgis-data-building-structures-2-d

**Table IV-1.    Primary Nitrogen Loading Factors used in the Sesuit Harbor assessment.** General factors are consistent with other MEP assessments, while other factors are based on Dennis-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: | 207 gpd[2] |
| Wastewater Coefficient | 23.63 | | |
| **Fertilizers:** | | Existing developed parcels w/water accounts: | Measured average annual water use (2018-2022) |
| Average Residential Lawn Size (sq ft)[1] | 5,000 | | |
| Residential Watershed Nitrogen Rate (lbs/lawn)[1] | 1.08 | 14 denitrifying I/A septic systems in the watershed listed in Barnstable County Department of Health and the Environment monitoring database (n ≥3 monitoring results) | |
| **Impervious Surfaces** | | | |
| • Road areas based on MassDOT MassGIS database<br>• Building areas based on MassGIS interpretation of aerial photographs | | | |
| Average footprint of buildings on Single Family Residence parcels town-wide (sq ft) | 1,552 | | |

Notes:
1) Data from MEP lawn study
2) Based on average 2018-2022 water use of all single-family residences in the watershed [only 4 of the 1,371 developed properties within the watershed (0.3%) did not have water use accounts and available water use]

## IV.1.2 Watershed Nitrogen Loads

Standard MEP procedures were followed to develop watershed nitrogen loads once all appropriate factors were assigned. Land and water use information is linked to the parcel coverages, parcels are assigned to various subwatersheds 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 determined from the watershed delineations 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 Sesuit Harbor 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 Sesuit Harbor study area. These subwatershed modules summarize, among other things: water use, parcel area, parcel frequency by land use category, private wells, and road areas. All relevant nitrogen loading data are assigned to each subwatershed. Individual subwatershed information is then integrated to create the Sesuit Harbor Watershed Nitrogen Loading summary module with summaries for each of the individual sub-watersheds. The subwatersheds are generally paired with functional embayment/estuary units for the Linked Watershed-Embayment Model's water quality component.

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 Sesuit Harbor marsh system watershed, the major types of nitrogen loads are: wastewater (*e.g.*, septic systems), turf fertilizers, impervious surfaces, direct atmospheric deposition to water surfaces, and recharge within natural areas (**Table IV-2**). The annual watershed nitrogen input to the 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 (*i.e.*, attenuated nitrogen load; 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-2.    Sesuit Harbor Existing and Buildout Watershed Nitrogen Loads.** Existing 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 and the portion of flow that leaves the watershed from ponds on the watershed boundary.  Stream attenuation factors are based on measured loads (see Section IV.2), while pond attenuation factors are based on measured water column data collected by Town volunteers, including water quality monitoring from the Cape Cod Pond and Lake Stewards (PALS) program.  All nitrogen loads are kg N yr$^{-1}$.

| Name | Watershed ID# | Sesuit Harbor N Loads by Input (kg/yr): | | | | | | % of Pond Outflow | Present N Loads | | | Buildout N Loads | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Wastewater | Fertilizers | Impervious Surfaces | Water Body Surface Area | "Natural" Surfaces | Buildout | | UnAtten N Load | Atten % | Atten N Load | UnAtten N Load | Atten % | Atten N Load |
| Sesuit Harbor System | 1 to 10 | 8,990 | 887 | 543 | 323 | 236 | 562 | | 10,979 | | 10,118 | 11,541 | | 10,633 |
| Sesuit Harbor subwatershed | 8,9 + CL | 1670 | 112 | 100 | 144 | 42 | 98 | | 2068 | | 2040 | 2165 | | 2138 |
| Sesuit Harbor LT10 | 8 | 1013 | 51 | 62 | 0 | 31 | 90 | | 1157 | | 1157 | 1247 | | 1247 |
| Sesuit Harbor GT10 | 9 | 637 | 59 | 37 | 0 | 11 | 8 | | 744 | | 744 | 751 | | 751 |
| Cedar Lake | CL | 20 | 1 | 1 | 12 | 0 | 0 | 28% | 34 | 79% | 7 | 34 | 79% | 7 |
| Sesuit Harbor Estuary surface deposition | | | | | 132 | | | | 132 | | 132 | 132 | | 132 |
| Sesuit Creek East | 6,7 | 2875 | 449 | 171 | 54 | 86 | 150 | | 3635 | | 3635 | 3785 | | 3785 |
| Sesuit Creek East LT10 | 6 | 1885 | 105 | 110 | 0 | 54 | 90 | | 2154 | | 2154 | 2245 | | 2245 |
| Sesuit Creek East GT10 | 7 | 989 | 344 | 62 | 24 | 31 | 60 | | 1450 | | 1450 | 1510 | | 1510 |
| Sesuit Creek East Estuary surface deposition | | | | | 31 | | | | 31 | | 31 | 31 | | 31 |
| Sesuit Creek West | 3,4,5 + SL | 4446 | 326 | 272 | 125 | 107 | 314 | | 5276 | | 4442 | 5590 | | 4710 |
| Sesuit Creek West LT10 | 4 | 1913 | 126 | 128 | 0 | 57 | 180 | | 2224 | | 2224 | 2405 | | 2405 |
| Sesuit Creek West GT10 | 5 | 1680 | 133 | 82 | 0 | 27 | 58 | | 1922 | | 1922 | 1979 | | 1979 |
| Scargo Stream Total | 3 + SL | 853 | 67 | 63 | 120 | 23 | 76 | | 1126 | | 291 | 1201 | | 321 |
| Sesuit Creek West Estuary surface deposition | | | | | 5 | | | | 5 | | 5 | 5 | | 5 |
| Scargo Lake (SL) | | 1180 | 105 | 88 | 267 | 31 | 68 | | 1672 | 83% | 287 | 1740 | 83% | 299 |
| Scargo Lake LT10 | 1 | 808 | 58 | 49 | 267 | 18 | 45 | | 1201 | | 1201 | 1246 | | 1246 |
| Scargo Lake GT10 | 2 | 372 | 47 | 39 | 0 | 13 | 23 | | 471 | | 471 | 494 | | 494 |
| Cedar Pond | 10 | 75 | 5 | 2 | 42 | 1 | 0 | | 125 | 79% | 27 | 125 | 79% | 27 |
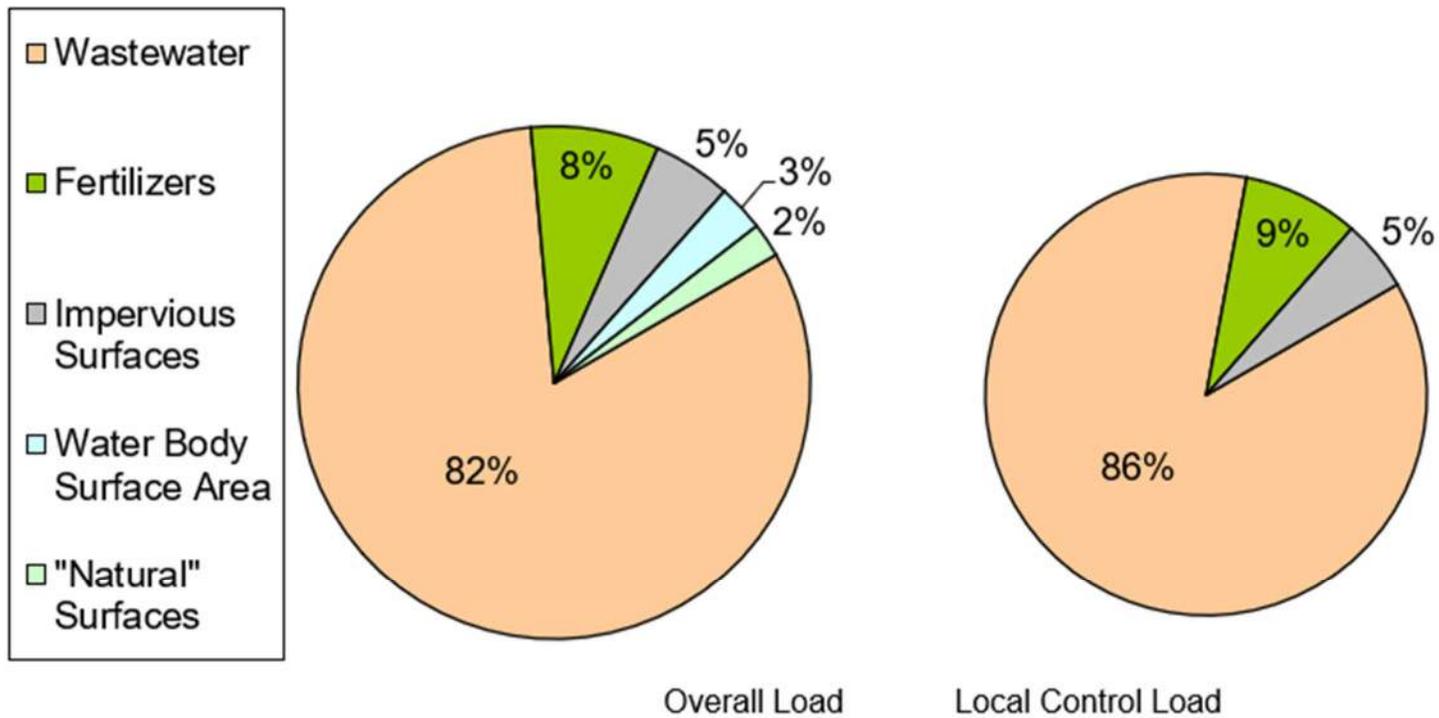
**Figure IV-3. Land use-specific unattenuated nitrogen loads (by percent) to the whole Sesuit Harbor watershed.** "Overall Load" is the total nitrogen input within the watershed, while the "Local Control Load" represents only those nitrogen sources that could potentially be under local regulatory control. Wastewater is the predominant source of nitrogen within the Sesuit Harbor 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 a stream 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 function as a path of least resistance and outflow can be focused toward the stream, but the magnitude of 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 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 in the following ponds has generally ranged from 50% to 80%, but some exceptions have been measured:

- Shubael Pond, Barnstable: 76% attenuation[47]
- Long Pond, Barnstable: 83% attenuation[48]
- Crystal Lake, Orleans: 35% to 53% attenuation[49]
- Pilgrim Lake, Orleans: 50% attenuation[50]

[47] 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.

[48] 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.

[49] 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.

[50] 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[51]
- Mystic Lake, Barnstable:  87% attenuation[52]
- Middle Pond, Barnstable:  40% attenuation[53]
- Hamblin Pond, Barnstable:  52% attenuation[54]

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 may 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 in August/September for more than 20 years.  The PALS Snapshots are regional once a year, volunteer pond sampling  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.[55]  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.

Within the Sesuit Harbor watershed, there are two freshwater ponds with delineated watersheds: Scargo Lake and Cedar Pond.  CSP/SMAST completed a water quality assessment of Scargo

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[51] 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.

[52] 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.

[53] *Ibid.*

[54] *Ibid.*

[55] 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.

Lake in 2012 that included collection of water quality data from April through November, collection and incubation of sediment cores, a freshwater mussel survey, and determination of an overall phosphorus budget for evaluation of management options.[56] Also in 2012, CSP/SMAST addressed some identified data needs for Cedar Pond by completing surveys of bathymetry, submerged aquatic vegetation, freshwater mussels, and water birds.[57] CSP/SMAST also completed a 2016 comprehensive review of Town 2001-2015 freshwater pond data that determined the current water quality status of all ponds, including Scargo and Cedar.[58]

For the current Sesuit Harbor Project assessment, project staff updated the water quality database data for Scargo Lake and Cedar Pond and determined pond-specific nitrogen attenuation rates. Scargo Lake has had 36 sampling runs, including a couple of years (*i.e.*, 2003 and 2010) where data was collected from spring through fall. Review of various groupings, including averages of all data, spring only, and summer only, showed that water column nitrogen mass varied within a relatively small range between years and seasons, likely due to its relatively long residence time (~2 years). Based on this review, project staff selected a conservative nitrogen attenuation rate of 80% for Scargo Lake and this value was incorporated into the Sesuit Harbor watershed nitrogen loading module. Cedar Pond has had 29 sampling runs, but has not had regular sampling throughout a summer season like Scargo Lake. Among the 29 Cedar Lake sampling runs are, however, six rounds of April/May samplings that provide a sense of whether different conditions exist in the spring compared to the late summer PALS sampling window. Comparisons of results from the various runs showed that the amount of nitrogen in Cedar Pond water column also varies within a relatively small range. Based on this review, project staff selected a conservative nitrogen attenuation rate of 75% for Cedar Pond and this value was incorporated into the Sesuit Harbor watershed nitrogen loading module.

### *Travel Time Check of Nitrogen Loads*

Once the watershed nitrogen loads are developed, one of the standard tasks of the MEP land use analysis is to gauge whether or not nitrogen discharges within the watershed have reached the estuary or if there are significant groundwater travel-time lags. This check 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 Sesuit Harbor watershed have been delineated for Scargo Lake and the portions of the estuary. Simple review of less than and greater than 10-year time of travel watersheds indicates that 61% of the unattenuated nitrogen load from the whole watershed is within less than 10 year travel time to the estuary (**Table IV-3**). If this review is refined by looking at the measured stream flows, outflow from the ponds,

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[56] Eichner, E., B. Howes, and D. Schlezinger. 2012. Scargo Lake Water Quality Management Report. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 65 pp.

[57] CSP/SMAST Technical Memorandum. December 18, 2012. Eagle Pond and Cedar Pond Technical Support Project: Bathymetry, Submerged Aquatic Vegetation and Mussel Surveys, Water Bird Survey. From: E. Eichner, B. Howes and D. Schlezinger. To: S. Brock, Chair, Water Quality Advisory Committee, Town of Dennis and K. Johnson, Director of Natural Resources, Town of Dennis. 19 pp.

[58] Eichner, E and B. Howes. 2016. Status of Town of Dennis Freshwater Ponds, 2001-2015 Water Quality Database Development. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 132 pp.

and adding in loads from precipitation on the estuary surface, the percentage that reaches the estuary within 10 years increases to 65%. Further review of the average age of the single family residences within the greater than 10 year time of travel subwatersheds showed that the average in all of the GT10 subwatersheds was greater than 30 years old (range 33 to 70 year averages). 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 that groundwater travel time within the sub-watersheds is not important for modeling existing conditions. Based on the review of all this information, it was determined that the overall Sesuit Harbor estuary is currently in balance with its watershed load.

**Table IV-3.    Percentage of unattenuated nitrogen loads in less than ten year time-of-travel sub-watersheds to Sesuit Harbor.**

| WATERSHED | LT10 | GT10 | TOTAL | % LT10 |
|---|---|---|---|---|
| Name | kg/yr | kg/yr | kg/yr | |
| Scargo Lake | 1,201 | 471 | 1,672 | 72% |
| Sesuit Creek West | 2,597 | 1,922 | 4,519 | 57% |
| Sesuit Creek East | 2,154 | 1,450 | 3,605 | 60% |
| Sesuit Harbor | 1,157 | 778 | 1,935 | 60% |
| Sesuit Harbor Whole System | 7,110 | 4,621 | 11,731 | 61% |

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 65% .  Further review of the age of single family residences with the GT10 subwatersheds, shows that the minimum average age is greater than 30 years.

## 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 groundwater 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 Sesuit Harbor system, one stream just upstream of the western salt marsh was gauged to directly measure nitrogen inputs (**Figure IV-4**).

A gauge was installed to continuously measure water levels and instantaneous flow readings and from June 5, 2005 through November 15, 2006 (18 months) using standard MEP measurement

and sampling techniques (**Figure IV-5**).  River flow (volumetric discharge) was measured every 4 to 6 weeks using a Marsh-McBirney electromagnetic flow meter and a rating curve was developed based upon these flow measurements and measured water levels at the gauge site.  The rating curve was then used for conversion of the continuously measured stage data (collected every 10 minutes) to obtain daily freshwater flow volume.  Water samples were collected weekly for nitrogen analysis (see Figure IV-5).  This effort was part of the initial MEP effort to prepare for an assessment of Sesuit Harbor and was not replicated in the current project.

Average daily flow based on annual measurements was 1,309 m3/d, which matched estimated groundwater discharge from the upstream watersheds after accounting for watershed flow out of Scargo Lake (**Table IV-4**).  It is notable that the measured flow shows that more of the Scargo Lake watershed flow exits the pond via the stream outlet than would be estimated based on the percentage of downgradient shoreline within the watershed (*i.e.*, the stream is a path of lower resistance for water leaving Scargo Lake).  Based on the measured nitrogen concentrations and streamflow, the watershed nitrogen load to the gauge is reduced by 75% by natural attenuation within Scargo Lake and stream functions.  The measured nitrogen load at the stream gauge location was 0.79 kg/d.

**Figure IV-4. Location of Sesuit Harbor stream gauge**. The gauge was located just upstream of tidal influences and was in place from June 5, 2005 through November 15, 2006. Instantaneous flow readings were collected at the gauge location every 4 to 6 weeks in order to develop a stage-discharge relationship. Water quality samples were collected weekly for nitrogen analyses.
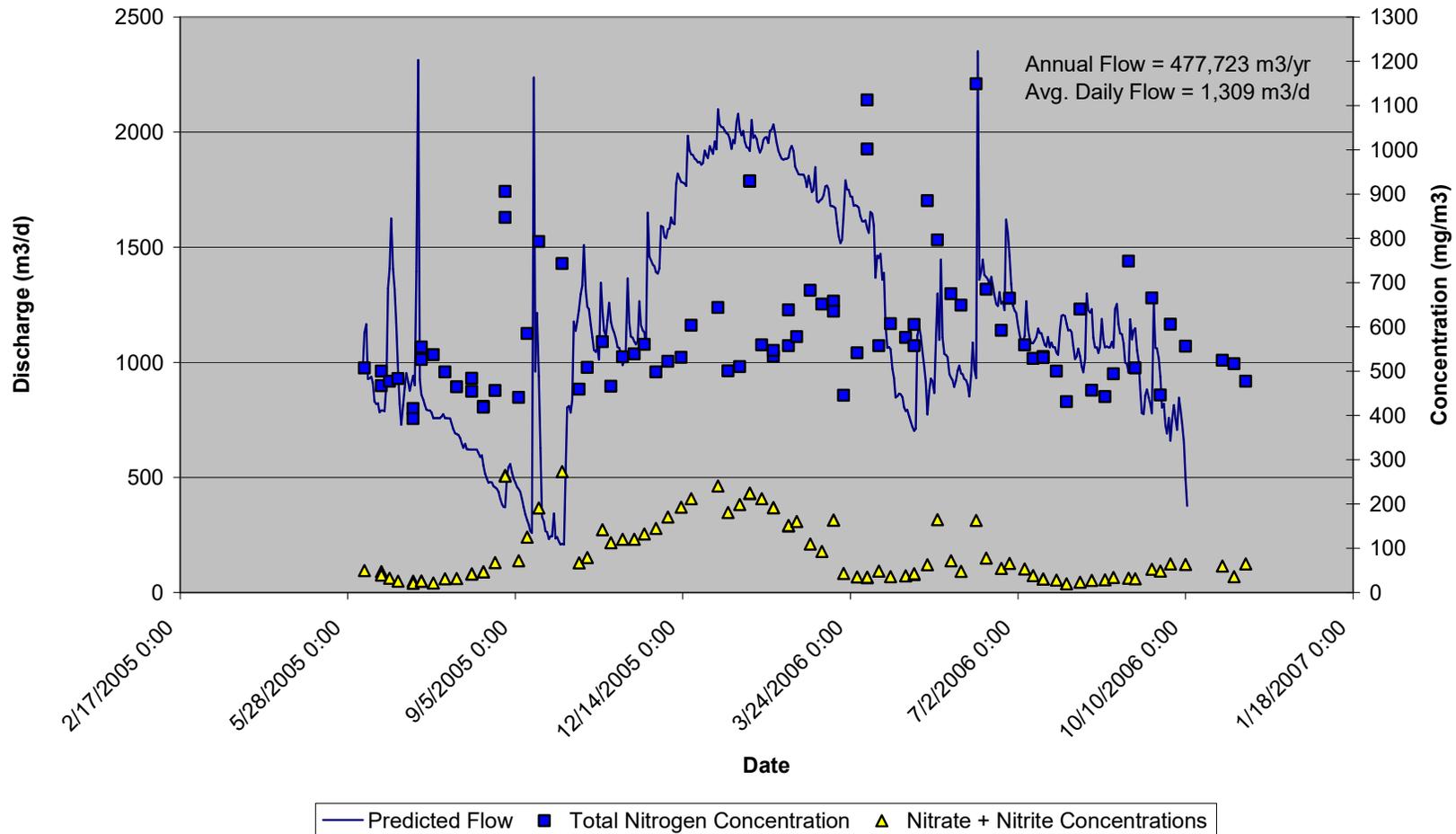
**Figure IV-5. Measured Flow and Nitrogen Concentrations at Sesuit Harbor stream gauge: 2005-2006**. The gauge collected stage recordings every 10 minutes between June 5, 2005 and November 15, 2006. These stage readings were compared to regular instantaneous flow readings to develop a predictive stage-discharge relationship and an estimated annual flow (477,723 m$^3$/yr; average daily flow = 1,309 m$^3$/d). Water quality samples were collected weekly and assayed for nitrate+nitrite (yellow triangles) and total nitrogen (blue squares) concentrations. Flow and N concentration data were used to estimate an annual nitrogen load of 0.79 kg per year to Sesuit Harbor marsh at the gauge location.

**Table IV-4. Sesuit Harbor Stream Summary.** The stream gauge was located at the headwaters of the western salt marsh and recorded stage readings for 16 months (June 5, 2005 and November 15, 2006). Instantaneous flow readings were collected every 4 to 6 weeks and stage and flow readings were synthesized to develop a predictive stage discharge relationship. Water quality samples were collected weekly and assayed for various nitrogen species. Flow readings and water quality results were synthesized to develop an annual nitrogen load at the gauge location.

| | Units | Sesuit Creek Discharge | Notes |
|---|---|---|---|
| Period of Record Reviewed | | September 1, 2005 - August 31, 2006 | 1 |
| Flow Characteristics | | | |
| Average Discharge | $m^3/d$ | 1,309 | |
| Contributing Area Discharge | $m^3/d$ | 1,308 | 2 |
| Difference | | 0% | |
| Nitrogen Characteristics | | | |
| Average Nitrate + Nitrite Concentration | mg N/L | 0.121 | 3 |
| Average Total Nitrogen | mg N/L | 0.605 | 3 |
| Nitrate+Nitrite as percent of TN | % | 20% | 4 |
| Average TN Discharge | kg N/d | 0.79 | |
| Average Unattenuated subwatershed N load | kg N/d | 3.11 | 5 |
| Stream/Pond N Attenuation | % | 75% | 6 |

Notes:
1) Gauge was in place from June 5, 2005 and November 15, 2006, but annual water year flow and N load based on gauge data from September 1, 2005 through August 31, 2006.
2) Contributing area discharge is based on USGS groundwater model contributing areas and model recharge rate. Scargo Lake discharges 46% of its watershed flow through the gauge location.
3) Results from water quality samples collected at gauge locations.
4) The relatively low % reflects the relatively large contribution of Scargo Lake water, which would tend to have higher concentrations of organic N forms. Direct watershed inputs would tend to be mostly dissolved inorganic nitrogen forms.
5) Unattenuated N loads are estimated subwatershed loads in Table IV-3.
6) Nitrogen attenuation at the gauge location reflects the cumulative impact of attenuation in Scargo Lake and the stream wetlands upstream of the gauge location. Comparison of water quality at the gauge location and in Scargo Lake showed that most of the attenuation occurs in Scargo Lake.

## 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 Sesuit Harbor system. Nitrogen 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 water quality modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

### IV.3.1  Sediment-Water Column Exchange of Nitrogen

Nitrogen enters the Sesuit Harbor 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 the converted N remains in the water column for sufficient time to be flushed out to Cape Cod 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 water column 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 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, so it is best management practice to directly measure the sediment impact on water column nitrogen.

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 within 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 Sesuit Harbor estuary system, sediment samples were collected during the most sensitive summer interval (July 31, 2022), and incubated under *in situ* conditions using the same methods as during the MEP. A total of 16 cores were collected from 12 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[59], Klump and Martens[60], and Howes *et al.*[61] 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[62] and orthophosphate[63] assays were conducted within 24 hours and the remaining samples frozen (-20°C) for assay of

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

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

[61] 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.

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

[63] 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.[64]  Chemical analyses of headspace water 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.  Sesuit Harbor sediment core sample sites.**  Cores were collected July 31, 2022 and were incubated to determine nitrogen fluxes using standard MEP methods.  Site numbers are for reference in Table IV-6.  Duplicate cores were collected at sites of cores 3 and 13.  The figure base map is a US Geological Survey topographic map.

### 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 Sesuit Harbor System, in the inlet channel, the main basin, and along

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[64]  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.

the salt marsh creek with the distribution of cores 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 inlet channel, significantly reduced in the main boat basin, and variable in the saltwater marsh and Bridge Street culvert. 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 at 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 to not 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 Sesuit Harbor embayment system were comparable to measurements in the main channels of other basins with upstream 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 Sesuit Harbor, there was high spatial variability, likely due to the how much the marsh system drains during regular tides (something that can be seen in slightly deeper pools within the marsh creek) and the different characteristics in the deeper basin and higher flow rates in the inlet. The sediments tended to be sandy and well-oxidized near the inlet (stations SES 1, 2, 3, 4), but even within these areas were settling areas with soft mud (SES14). Sediments in the main boat basin were soft mud with oxidized surface (SES 5, 6), but stations within the marsh creek tended to have the greatest heterogeneities with sand or mud, sand covering sticky mud, peat and sand over peat. Net nitrogen fluxes were -32.0 mg N m$^{-2}$ d$^{-1}$ near the inlet (*i.e.*, removing N from the water

column), 72.9 N m$^{-2}$ d$^{-1}$ in the main boat basin (adding N to the water column), -20.7 N m$^{-2}$ d$^{-1}$ in the eastern portion of the salt marsh, and 7.0 N m$^{-2}$ d$^{-1}$ in the western portion of the salt marsh (**Table IV-5**). The western marsh rate is similar to other organic rich tributary creeks and systems: Herring River in Harwich (9.7 - 10.5 mg N m$^{-2}$ d$^{-1}$),[65] 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$^{-1}$).[66] The nitrogen removal by the sediments in the eastern salt marsh creek is likely due to the greater depths (2.5 m – 4.6 m vs. 0.9 m – 1.9 m in the western marsh creek) allowing N/water to reside longer and approach N flux rates similar to some embayments (*e.g.*, Chatham Harbor, Westport Harbor). The main basin had a N flux rates similar to Meetinghouse Pond (79.5 mg N m$^{-2}$ d$^{-1}$) in Pleasant Bay[67] or the boat basin in Rock Harbor in Orleans (80.8 mg N m$^{-2}$ d$^{-1}$).[68] The inlet N flux was comparable to rates measured near other inlets subject to Cape Cod Bay tidal ranges: -17.9 mg N m$^{-2}$ d$^{-1}$ in Lower Old Harbor Creek in Sandwich Harbor[69] and -19.9 mg N m$^{-2}$ d$^{-1}$ in Long Hill Tidal Creek in Scorton Creek.[70]

| Table IV-5. Rates of net nitrogen return from sediments to the overlying waters throughout the Sesuit Harbor 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** | |
| **Sesuit Harbor Embayment System** | | | | |
| Sesuit Harbor - Inlet | -32.0 | 5.9 | 4 | 1, 2, 3, 4, 14 |
| Sesuit Harbor – Basin | 72.9 | 59.7 | 2 | 5, 6 |
| Sesuit Harbor – East Marsh | -20.7 | 2.4 | 3 | 8, 10, 11 |
| Sesuit Harbor – West Marsh | 7.0 | 6.8 | 3 | 12, 13, 15, 16 |
| * Station numbers refer to Figure IV-6. | | | | |

[65] 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.

[66] 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.

[67] Howes B., S. Kelley, J. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2006). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Pleasant Bay, Chatham, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 245 pp.

[68] Howes B., S. Kelley, J. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2007). Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Rock Harbor Embayment System, Orleans, MA. SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 132 pp.

[69] Howes B., T. Ruthven, E. Eichner, R. Samimy, J. Ramsey, D. Schlezinger, P. Detjens (2015). Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Sandwich Harbor Estuary, Town of Sandwich, Massachusetts. Massachusetts Department of Environmental Protection. Boston, MA. 173 pp.

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

# V. HYDRODYNAMIC MODELING

## V.1 INTRODUCTION

A hydrodynamic analysis was performed for the Sesuit Harbor estuary system, located on the Cape Cod Bay shoreline of Dennis, Massachusetts.  It is the receiving basin of groundwater flow from East Dennis and Sesuit Neck, as well as surface water flows from Scargo Lake via Scargo Stream .  A topographic map detail in **Figure V-1** shows the Harbor's geographic setting and the general study area.  The Sesuit Harbor system is composed of a main harbor basin with a highwater surface area of about 33 acres and about 145 acres of salt marsh plain.  The Harbor has a direct hydraulic connection to Cape Cod Bay via a jettied inlet (**Figure V-2**).  The west and east harbor jetties are 1,075 and 1,700 feet long, respectively.  The average elevation of the marsh plain is +4.8 feet NAVD88, while the mean depth of the main harbor basin is 7.5 feet at mean tide level.  Sesuit Harbor has a federally authorized navigation channel that is maintained by the US Army Corps of Engineers (USACE).  The channel is 2,970 feet long and is maintained at its -6 ft MLLW authorized depth to a width of 100 feet between the jetties and 80 feet at North Side Marina.



**Figure V-1.    Topographic map detail of the Sesuit Harbor system and the surrounding coastal area.**

**Figure V-2.     The west jetty of Sesuit Harbor.**

Internal to the system, there are two flow control structures, 1) a group of three 30" plastic corrugated pipes that allow tidal flows to a 10-acre marsh east of Cold Storage Road (**Figure V-3**), and a two-barrel box culvert at Bridge Street (**Figure V-4**).  Both Bridge Street culvert barrels are 35 feet long, 12 feet wide and 10 feet high.  The culvert invert is at -4.5 feet NAVD88, which roughly corresponds to mean low water (MLW) measured in 2004.  This culvert was constructed in 2008 to replace a much smaller single barrel culvert.  Both culvert barrels have tracks that allow weir boards to be added in order to raise the minimum water levels in the marsh area west of Bridge Street, but at the time of this study, no weir boards were in place.  Though the bottom of the culvert barrels is visible in some areas, shoaling has occurred at the entrances, middle and exits of the culverts, leading to a limiting channel bottom elevation that is about -3 feet NAVD at the culverts.



**Figure V-3.     Three 30-inch plastic corrugated pipes that provide tidal flows to the marsh area east of Cold Storage Road.**  These are located just to the north of the Sesuit Harbor East parking area.

**Figure V-4.    View of the two 12-foot-wide box culverts under Bridge Street.**  Bridge Street is a dividing line between the eastern and western portions of the Sesuit Creek marsh.

Tidal exchange with Cape Cod Bay dominates circulation in the Harbor.  From measurements made in the course of this study, the average offshore tide range is 9.5 feet.  As indicated by the limited amount of attenuation of high tide elevations across the inland extents of the marsh creeks, tidal flushing appears very efficient throughout the tidal reaches of the system, including the upper area of Sesuit Creek that is west of Bridge Street.  Tidal flow in the marsh areas of the system is mainly distributed within the main channel of Sesuit Creek, however, there also exists several short secondary and tertiary channels that branch from the main channel.

The hydrodynamic study of the Sesuit Harbor 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 modelling portion of the study.  A bathymetry survey of the harbor basin and main channel of Sesuit Creek was performed to determine the variation of depths throughout the system.  This survey was used to complement and confirm other sources of elevation data from USACE and NOAA.  Tides were recorded offshore of Sesuit Harbor and at four stations inside the estuary for 41 days in October and November 2022.  These tide data were necessary to run and calibrate the hydrodynamic model of the system.  In addition, an ADCP survey of tidal flows at the system inlet was conducted in June 2023 over the course of a single tide cycle.  The ADCP data provided an independent source of data used to corroborate and verify the performance of the calibrated hydrodynamic mode of the Sesuit Harbor system.

A numerical hydrodynamic model of Sesuit Harbor and the associated marsh was developed in the second portion of this study.  Using the bathymetry survey data and LiDAR topography from NOAA, a model grid mesh was generated for use with the RMA-2 hydrodynamic code.  The tide data record from Cape Cod Bay was 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 Sesuit Harbor system is an integral piece of the water quality model discussed 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, including performance of the inlet.

## V.2 DATA COLLECTION AND ANALYSIS

The field data collection portion of this study was performed to characterize the physical properties of Sesuit Harbor. 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 and velocity data were also collected in 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 Sesuit Harbor was performed in 2015, and a post-dredge update survey was done in 2022. In each survey, a fathometer was used to make continuous soundings of the bottom as the survey vessel moved through the water. Positioning data were collected using a differential GPS. The actual survey paths followed in the 2015 survey by the survey boat are shown in **Figure V-5**. 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 conducted. Additional elevation data was gathered from a 2018 topographic and bathymetric (topobathy) LiDAR dataset for the region performed by USACE (**Figure V-6**). This LiDAR survey was the primary source of elevation data for the marsh plain and the region offshore of the inlet. A 2019 single beam survey of the federal navigation channel is also available from the New England District of USACE.



**Figure V-5.** **Transects from the 2015 bathymetry survey of Sesuit Harbor.**

**Figure V-6.** **Bathymetric/Topographic Elevations from the 2018 USACE LiDAR flight of the Sesuit Harbor area**. Elevations in feet NAVD are indicated by the color shaded gradient. The location of the five tide gauges deployed in October/November 2022 are indicated using the yellow markers, while the two ADCP survey transects followed in June 2023 (inner and outer) are indicated by the labeled red lines. The area at or below the elevation of the maximum tide level recorded during the 2022 deployment is indicated by the solid-black contour line.

## V.2.2 Tide Data Collection and Analysis

Tide data records were collected concurrently at five gauging stations (see Figure V-6), located offshore in Cape Cod Bay and inside Sesuit Harbor. The Temperature Depth Recorders (TDR) used to record the tide data were deployed for a 41-day period between October 7 and November 16, 2022. The elevation of each gauge was surveyed relative to the NAVD88 vertical datum. The Cape Cod 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 that are at least 29 days long are necessary for a complete evaluation of tidal dynamics within the harbor/marsh system. Although a one-month record likely does not include the most extreme high or low tides of the whole year, 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-7** for the entire 41-day deployment. The spring-to-neap variation in tide range is discernable in these plots. The data record begins during a period of spring tides, where the maximum range is approximately 12 feet. A week later there is a period of neap tides, where the minimum range of 5.8 feet occurs on October 19, two days after the last quarter moon. Following this neap tide is a continuing cycle of spring and neap tides. The visual comparison between tide elevations offshore and within the system shows that the elevation of high tide changes minimally, even for the station west of Bridge Street, but the total tide range at the marsh stations becomes smaller as the tide level drops to the controlling elevation in the main marsh channel.

**Standard Tide Datums.** To better quantify the changes to the tide from the inlet to inside the system, the standard tide datums were computed from a 29-day segment of the complete 41-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.

Attenuation of the tide due to the elevation of the marsh creek bottom can be observed in the reduction of the mean tide range in the two marsh creek stations (SES4 and SES5) compared to the mean range offshore and in the main harbor basin. The mean tide range west of Bridge Street is 7.7 feet, or approximately 80% of the mean offshore range. The propagation of the tide across the length of the harbor also results in a slight delay of the arrival time of the tide signal, known as phase lag. The tide propagates through Sesuit Harbor efficiently, which leads to only a small amount of lag between the offshore and uppermost reaches of the system. A small delay is observed in the plot of **Figure V-8**, where the five tide gauge records are plotted together. The records from the offshore gauge and two gauges in the main harbor basin plot on top of each other, indicating minimal lag. Only with the two gauges at the Bridge Street culvert is the enough of a delay in the phasing of the tide to distinguish the traces of these records from the others.

**Harmonic Analysis of 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 the Harbor during the gauge deployment period.

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-9**. The amplitudes and phase of 21 known constituents result from this procedure. **Table V-2** presents the amplitudes of eight tidal constituents computed for the deployed Sesuit Harbor gauge record. The M2, or the
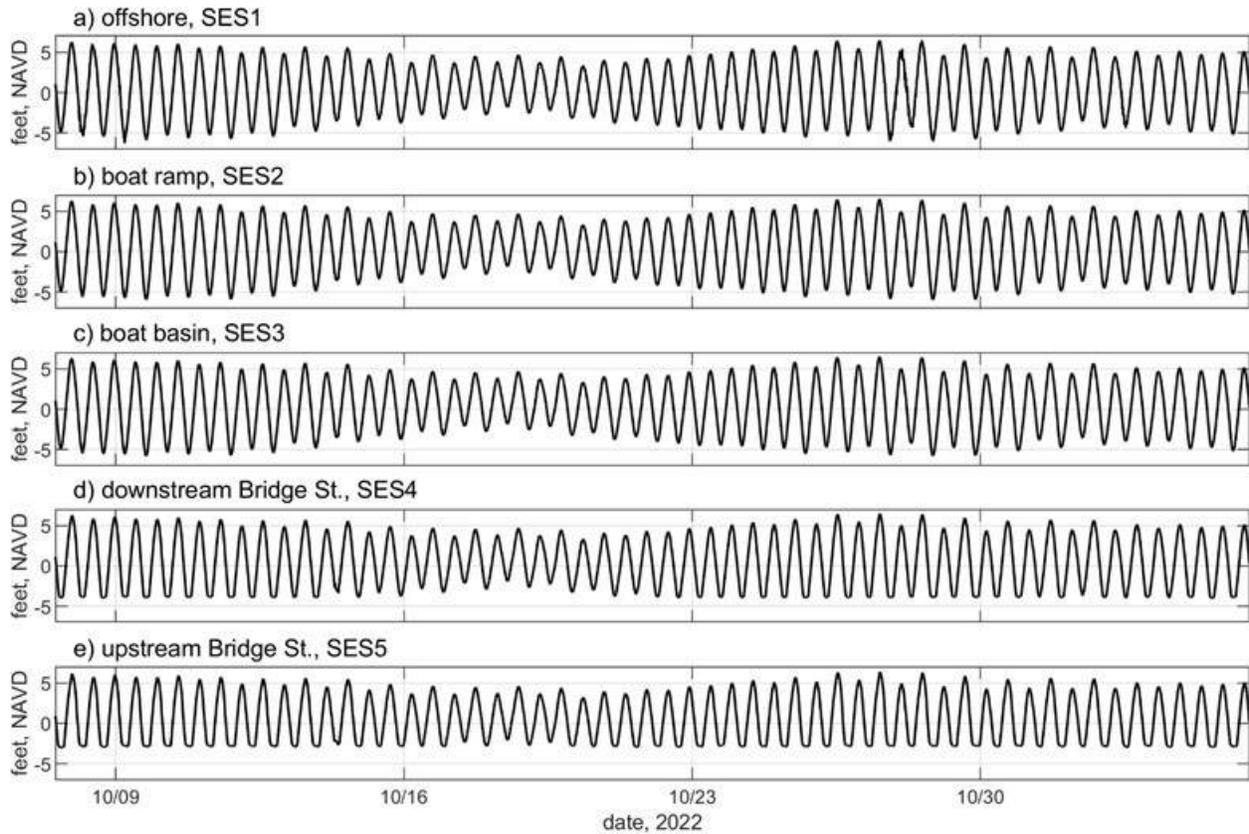
**Figure V-7. Plot of recorded tides at stations in Cape Cod Bay and Sesuit Harbor.** Recorders were deployed for the 41-day period between October 7 and November 16, 2022. All water levels are referenced to the NAVD88 vertical datum.

| Tide Datum | Offshore (feet) | Boat Ramp (feet) | Boat Basin (feet) | Downstream Bridge St. (feet) | Upstream Bridge St. (feet) |
|---|---|---|---|---|---|
| Maximum Tide | 6.5 | 6.5 | 6.5 | 6.5 | 6.4 |
| MHHW | 5.4 | 5.5 | 5.5 | 5.5 | 5.4 |
| MHW | 5.0 | 5.0 | 5.0 | 5.0 | 4.9 |
| MTL | 0.3 | 0.3 | 0.3 | 0.7 | 1.1 |
| MLW | -4.4 | -4.5 | -4.4 | -3.6 | -2.8 |
| MLLW | -4.8 | -4.8 | -4.7 | -3.8 | -2.9 |
| Minimum Tide | -6.3 | -5.9 | -5.8 | -4.0 | -3.0 |
| Mean Range | 9.5 | 9.5 | 9.4 | 8.7 | 7.7 |

**Table V-1. Sesuit Harbor System Tide Datums.** Tide datums computed from data records collected in Cape Cod Bay and Sesuit Harbor, October 7 to November 5, 2022.
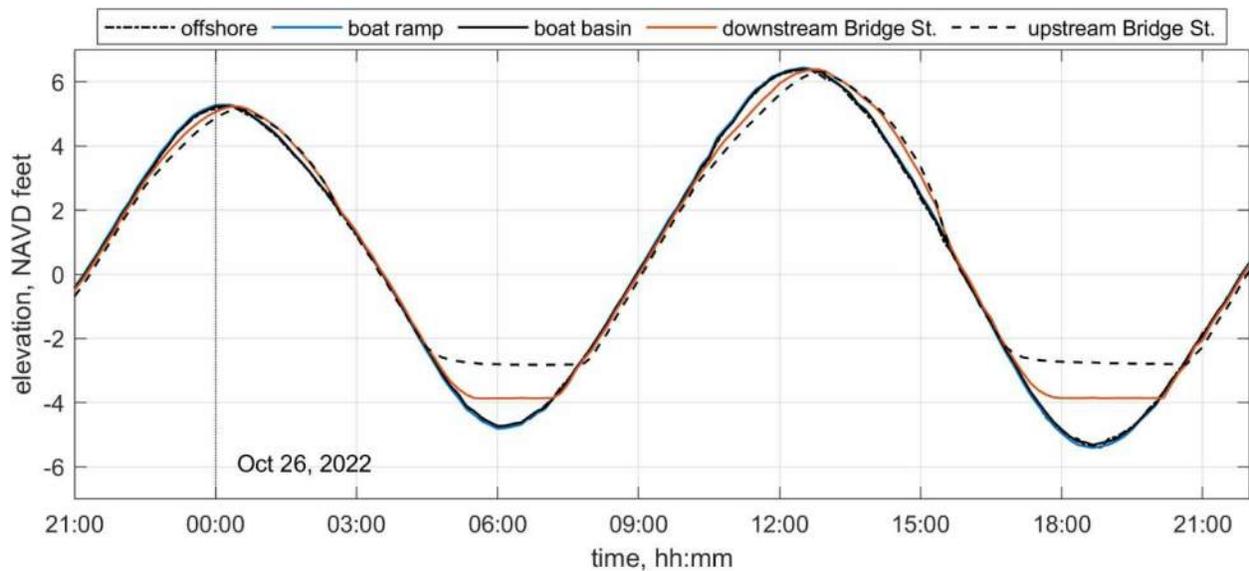
**Figure V-8. One-day tide plot showing tides measured in Cape Cod Bay and at stations in the Sesuit Harbor system.** Damping effects are seen as a reduction in tidal amplitude, as well as the lag in time of high and low tides from the offshore tide.
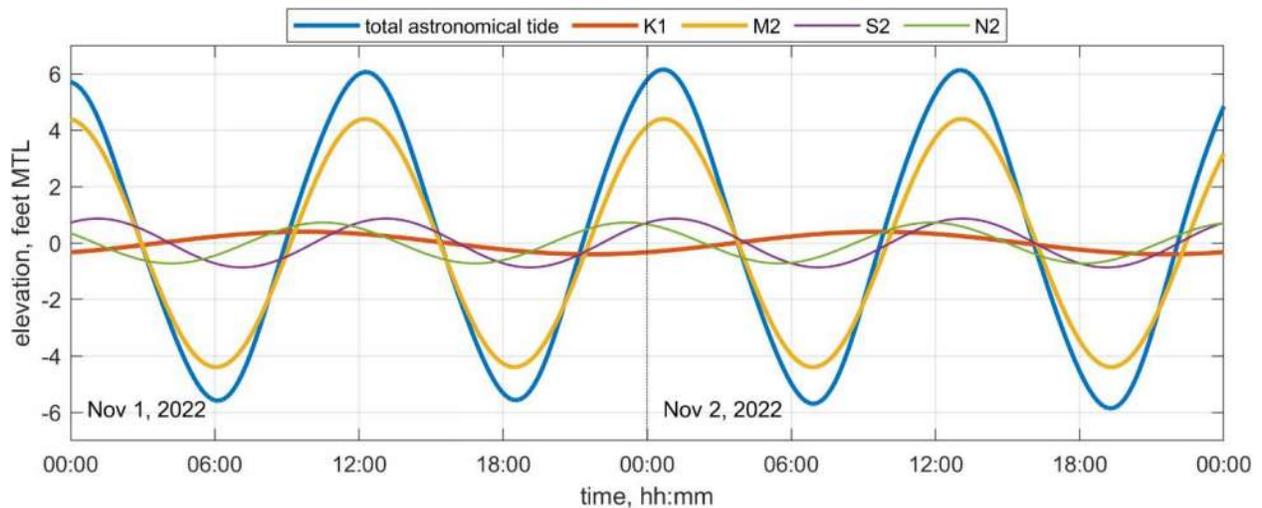


**Figure V-9. Example of tidal constituents.** Tides are the sum of 21 known constituents. This figure shows a portion of the observed astronomical tide (solid blue line) record at the Sesuit offshore tide gauge and its primary constituents, which are listed in Table V-2.

**Table V-2. Tidal Constituents computed for tide stations in Sesuit Harbor and offshore in Cape Cod Bay for October 2022.**

| | Amplitude (feet) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Constituent | M2 | N2 | K1 | O1 | S2 | L2 | M4 | M6 |
| Period (hours) | 12.42 | 12.66 | 23.93 | 25.82 | 12 | 12.19 | 6.21 | 4.14 |
| SES1 - Offshore | 4.40 | 0.72 | 0.40 | 0.42 | 0.86 | 0.12 | 0.08 | 0.17 |
| SES2 - Boat Ramp | 4.42 | 0.74 | 0.43 | 0.42 | 0.88 | 0.13 | 0.09 | 0.16 |
| SES3 – Harbor Basin | 4.41 | 0.73 | 0.40 | 0.42 | 0.87 | 0.12 | 0.08 | 0.17 |
| SES4 – downstrm Bridge St | 4.24 | 0.63 | 0.37 | 0.36 | 0.76 | 0.15 | 0.11 | 0.03 |
| SES5 – upstream Bridge St | 3.88 | 0.50 | 0.34 | 0.33 | 0.63 | 0.19 | 0.35 | 0.13 |

familiar twice-a-day lunar semi-diurnal tide, is the strongest contributor to the signal with an offshore amplitude of 4.4 feet. The total range of the M2 tide is twice the amplitude, or 8.8 feet.

The diurnal tides (once daily), K1 and O1, both have an amplitude of approximately 0.4 feet. Other semi-diurnal tides, the L2 (12.19-hour period), S2 (12.00-hour period), and N2 (12.66-hour period) tides, also contribute to the total tide signal, with amplitudes of 0.1, 0.9, and 0.7 feet, respectively. The M4 and M6 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.

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 amplitude at the two marsh creek stations (SES4 and SES5) which are larger than the offshore station. Again, this is due to energy transferring from the M2 due to frictional losses across the system.

Changes in the phasing of the tide across the length of the system can be quantified using the results of the harmonic analysis. Between the offshore and the station west of Bridge Street, there is only a 6-minute delay in the M2. This is not a large delay, considering that the period of this constituent is more than 12 hours.

**Flood Dominance.** Flood or ebb dominance in channels of a tidal system can be determined by using the results of the harmonic analysis of the water surface elevation records. A discussion of the method of relative phase determination is presented in Friedrichs and Aubrey (1988).

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 $\Phi$ is between 0 and 180 degrees, then the channel is characterized as being flood dominant, and peak flood velocities will be greater than for peak ebb. Alternatively, if $\Phi$ were between 180 and 360 degrees, then the channel would be ebb dominant. If $\Phi$ is exactly 0 or 180 degrees, neither flood nor ebb dominance occurs. For $\Phi$ equal to exactly 90 or 270 degrees, maximum tidal distortion occurs and the velocity residuals of a channel are greatest. This relative phase relationship is presented graphically in **Figure V-10**.
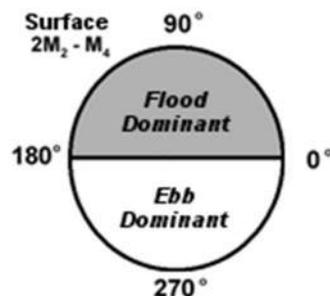


**Figure V-10. Relative velocity phase relationship of M2 and M4 tidal elevation constituents and characteristic dominance, indicated on the unit circle.** Relative phase is computed as the difference of two times the $M_2$ phase and the $M_4$ phase ($2M_2-M_4$). A relative phase of exactly 0 or 180 degrees indicates a symmetric tide, which is neither flood nor ebb dominant.

The water surface phase relationship of M2 and M4 determined for the five gauge stations in Sesuit Harbor system indicates that offshore and Harbor basin are moderately ebb dominant. The gauge just downstream of the Bridge Street culvert is also moderately ebb dominant. The

gauge just upstream of the Bridge Street culvert is balanced between flood and ebb dominance. The flood or ebb dominance of a tidal channel is indicative of the likely direction of net sediment transport. Flood dominance in a tidal channel would tend to have a net upstream transport of sediment. Tidal marshes tend to be flood dominant, which helps maintain and replenish material to build up the marsh plain. Ebb dominance tends to cause a net downstream transport of sediment. For a tidal marsh like Sesuit Creek, ebb dominance indicates tidal currents would lead to a net loss of material from the creeks and marsh plain over time, as sediment in the channels of the system tends to move toward and out of the inlet of the system, on balance.

**Tide Residual Analysis.** 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 energy distribution (or variance) of the measured water elevation records from the five gauge stations for Sesuit Harbor compared to the energy content of the astronomical tidal signal (re-created by summing the contributions from the 21 constituents determined by the harmonic analysis) is presented in **Table V-3**. Subtracting the tidal signal from the original elevation time series results in 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-11** shows the comparison of the measured tide in the main basin of Sesuit Harbor, with the computed astronomical tide resulting from the harmonic analysis, and the resulting non-tidal residual.

**Table V-3** results show that the variance of tidal energy was largest at the offshore and harbor basin stations. The analysis also shows that tides are responsible for 99% of the water level changes in Cape Cod Bay and the main harbor basin. This indicates that the hydrodynamics of the system were influenced overwhelmingly by astronomical tides during the deployment period.

| Table V-3. Percentages of Tidal versus Non-Tidal energy for the Sesuit Harbor system and Cape Cod Bay, October 2022. This analysis shows that the tides (rather than wind or other sources) are responsible for 99% of the changes in water levels. | | | |
|---|---|---|---|
| TDR Location | Total Variance ($ft^2$) | Tidal (%) | Non-Tidal (%) |
| SES1 - Offshore | 10.71 | 99.2% | 0.8% |
| SES2 - Boat Ramp | 10.82 | 99.3% | 0.7% |
| SES3 – Harbor Basin | 10.75 | 99.3% | 0.7% |
| SES4 – downstrm Bridge St | 9.80 | 99.2% | 0.8% |
| SES5 – upstream Bridge St | 8.25 | 98.9% | 1.1% |
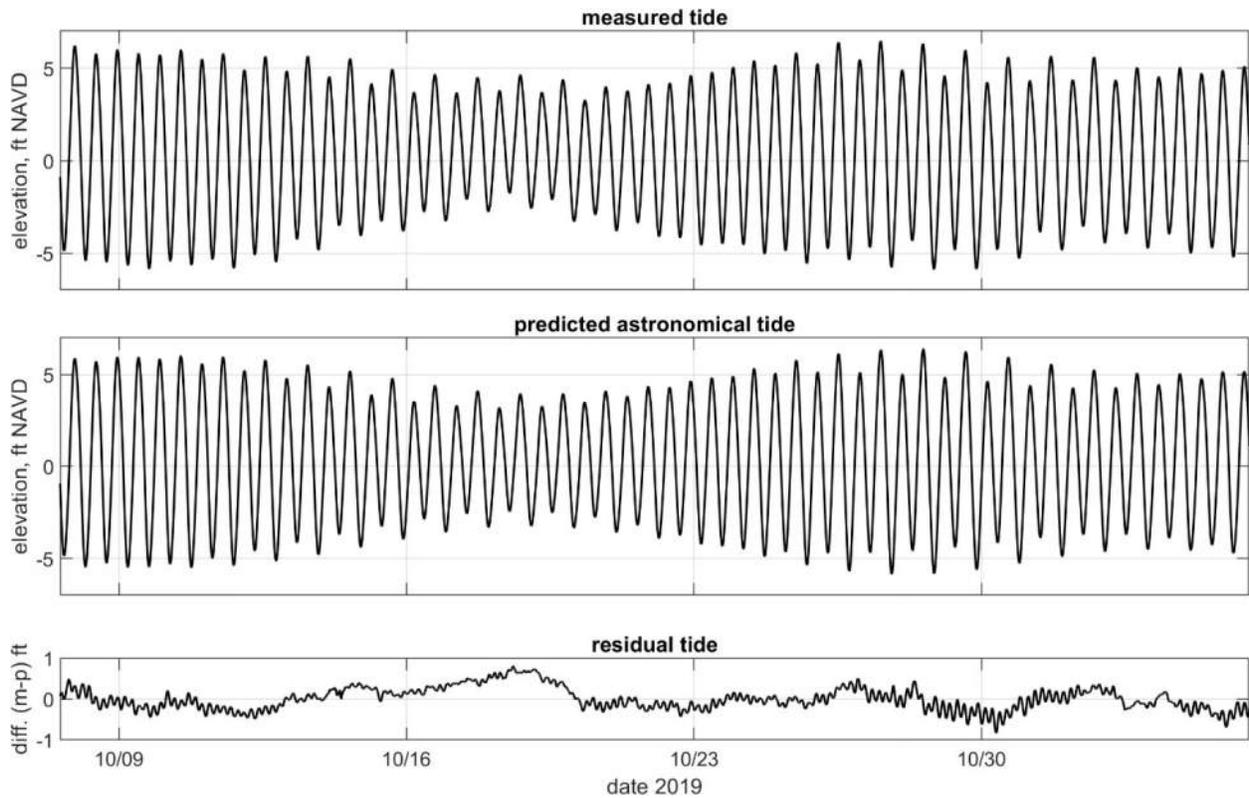
**Figure V-11. Plot showing the comparison between the measured tide time series (top plot), and the predicted astronomical tide (middle plot) computed using the 21 individual tide constituents determined in the harmonic analysis of the tide gauge record collected offshore at the Sesuit Harbor boat ramp (SES2).** The residual tide shown in the bottom plot is computed as the difference between the measured and predicted time series (residual = measured - predicted).

**Comparison of tides measured in past studies.** A comparison of tide datums determined for present (2022) conditions in the Harbor and from a previous deployment in 2004 (prior to the replacement of the Bridge Street culvert) are presented in **Table V-4**. Datums for the offshore gauge have slightly increased in elevation by about 0.1 to 0.2 feet between the two periods. The MTL increase of 0.2 feet is consistent with mean sea level rise (SLR) trends in the region of +2.89 mm/year (+0.17 feet over the 18-year period between deployments).

Larger differences in tide datums are seen in the gauge records upstream of the Bridge Street culvert (SES5). With the original culvert, the tide range in upper Sesuit Creek was only 1.6 feet. With the addition of the 2008 culvert, the mean range upstream of Bridge Street has increased to 7.7 feet, an increase of over 6 feet on average.

| Table V-4. Tide datums computed from data records collected in Cape Cod Bay (SES1) and upstream of the Bridge Street culvert (SES5), for 2004 (prior to the culvert replacement) and 2022 gauge deployments. | | | | |
|---|---|---|---|---|
| | **2004** | | **2022** | |
| Tide Datum | Offshore (feet) | Upstream of Bridge St. (feet) | Offshore (feet) | Upstream of Bridge St. (feet) |
| Maximum Tide | 7.3 | 3.3 | 6.5 | 6.4 |
| MHHW | 5.3 | 3.1 | 5.4 | 5.4 |
| MHW | 4.8 | 3.0 | 5.0 | 4.9 |
| MTL | 0.1 | 2.2 | 0.3 | 1.1 |
| MLW | -4.5 | 1.4 | -4.4 | -2.8 |
| MLLW | -5.0 | 1.3 | -4.8 | -2.9 |
| Minimum Tide | -7.3 | 1.3 | -6.3 | -3.0 |
| Mean Range | 9.3 | 1.6 | 9.5 | 7.7 |

### V.2.2 ADCP currents and flows

In order to provide an independent confirmation of tidal hydrodynamics, tidal currents were measured on June 6, 2023 along two cross-channel transects (**Figure V-5**) over the course of a complete tide cycle. A boat-mounted ADCP (acoustic doppler current profiler) was configured to measure water velocities at discrete levels (0.8 feet or 0.25 meters) from the channel bottom to the sensor head of the ADCP near the water surface. As the boat moves along a survey transect, the ADCP is able to record the two-dimensional distribution of currents in the channel with high resolution. **Figures V-12 and V-13** show the cross-channel profile at maximum flood and ebb flows between the harbor jetties. With this detailed current data, the total discharge rate at the time of the transect can be calculated. When the transect is run multiple times during the flood and ebb of a tide cycle, the variation of tidal flows into and out of an estuary can be determined across the time span of the survey.

For Sesuit Harbor, the two transects were run hourly, over the course of a 12-hour survey. Total flows determined for each separate run at both transects are shown in **Figure V-14**. For the survey time period, the maximum flooding flows are 2,000 cfs at the inlet. After the peak in flood flows, the tide quickly turns, and measured peak ebb currents occur only 2 hours later, with a magnitude of about 1,700 cfs.
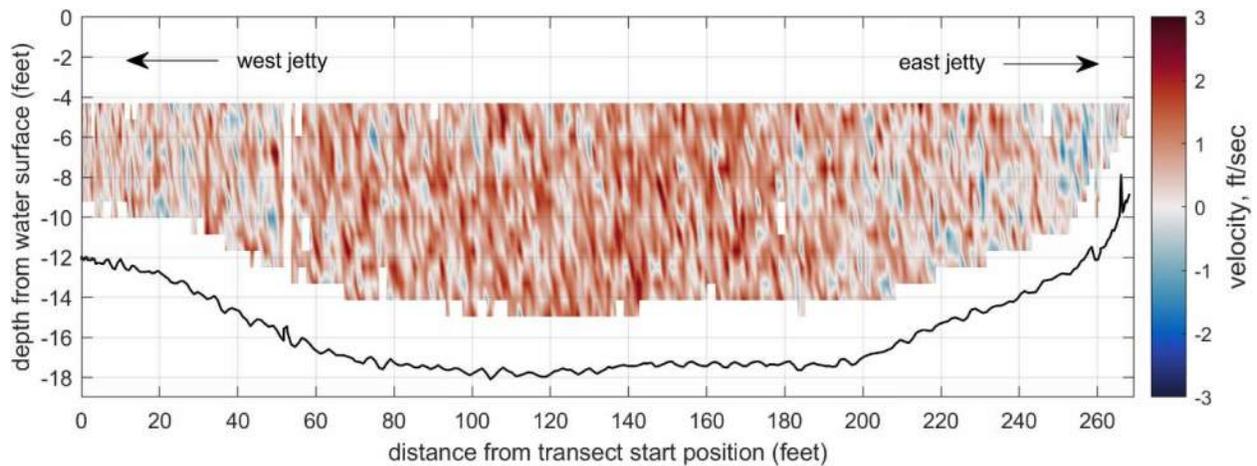
**Figure V-12. Along-channel velocity profile for maximum flood flows into Sesuit Harbor during the June 5, 2023 ADCP survey in the harbor inlet (outer transect, between jetties).** Positive velocities (red) indicate flows directed into the harbor. Measurements are shown for the vertical area between the ADCP acoustic head and the bottom blanking distance of the instrument. This transect was run at 13:06 EDT. The solid black line indicates the channel bottom, as measured by the ADCP.
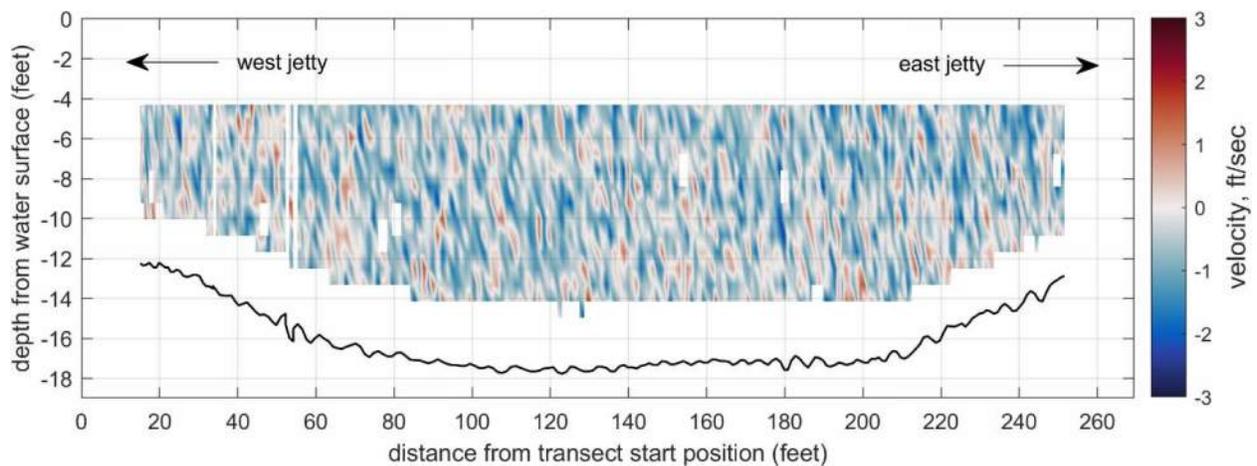


**Figure V-13. Along-channel velocity profile for maximum ebb flows out of Sesuit Harbor during the June 5, 2023 ADCP survey in the harbor inlet (outer transect, between jetties).** Negative velocities (blue) indicate flows directed out of the harbor. Measurements are shown for the vertical area between the ADCP acoustic head and the bottom blanking distance of the instrument. This transect was run at 14:55 EDT. The solid black line indicates the channel bottom, as measured by the ADCP.

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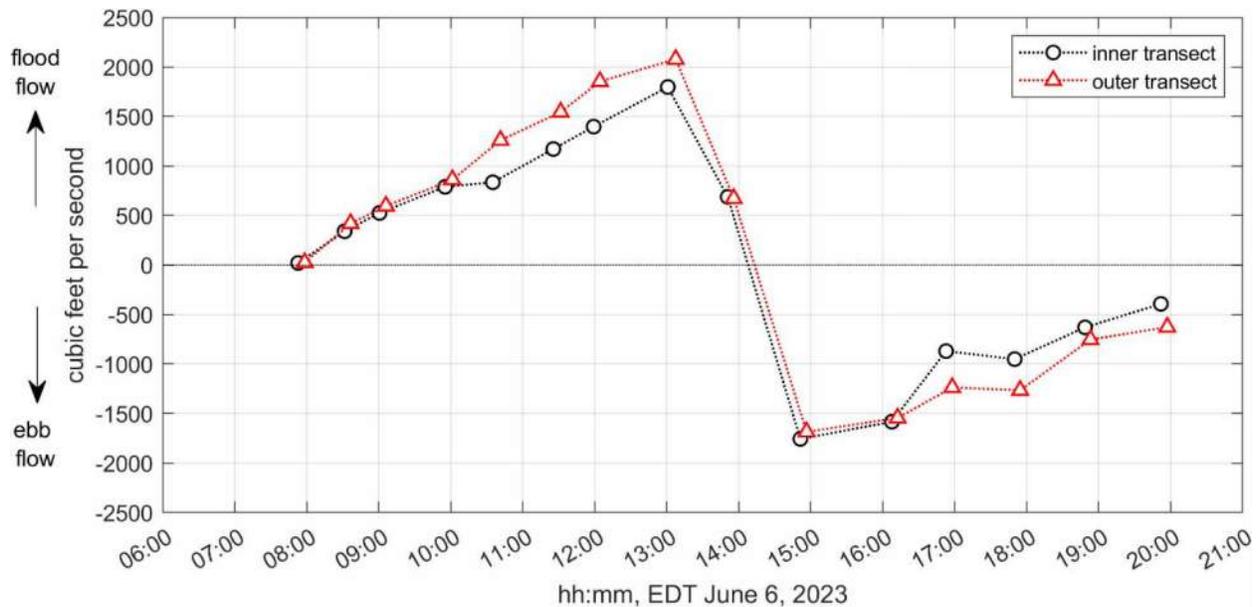
**Figure V-14. Total flow across the two ADCP transects followed at Sesuit Harbor, in June 2023**. Hourly total discharge measured into the Harbor (flood flow) and out of the Harbor (ebb flow) at the two transects in Figure V-6 are shown.

## V.3 HYDRODYNAMIC MODELING

For the modeling of the Sesuit Harbor system, Sustainable Coastal Solutions utilized a state-of-the-art computer model to evaluate tidal circulation and flushing in the system. 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 completed throughout the MEP study region, including Barnstable Harbor[71], Bass River[72], Wellfleet Harbor[73], and Pleasant Bay.[74]

### 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.[75] Further development included the introduction of the one-

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[71] Howes B., E. Eichner, S. Kelley, R. Samimy, J. S. Ramsey, D. Schlezinger, P. Detjens (2017). Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine the Critical Nitrogen Loading Threshold for the Barnstable Great Marshes - Bass Hole Estuarine System, Town of Barnstable and Dennis, Massachusetts, Massachusetts Department of Environmental Protection. Boston, MA. 213 pp.

[72] Howes B., S. Kelley, J.S. Ramsey, E. Eichner, R. Samimy, D. Schlezinger, P. Detjens (2011). Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine the Critical Nitrogen Loading Threshold for the Bass River Embayment System, Towns of Yarmouth and Dennis, Massachusetts, Massachusetts Department of Environmental Protection. Boston, MA. 222 pp.

[73] Howes B.L., S. Kelley, J. S. Ramsey, E. Eichner, R.I. Samimy, D.R. Schlezinger, P. Detjens (2017). Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Wellfleet Harbor Embayment System, Town of Wellfleet, Massachusetts, Massachusetts Department of Environmental Protection. Boston, MA. 189 pp.

[74] Howes B., S. Kelley, J. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2006).

[75] 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.

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.[76] 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

The extent of each finite element grid was generated using 2022 digital aerial photographs from the ESRI (MAXAR) online orthophoto world map. A time-varying water surface elevation boundary condition (measured tide) was specified at the Cape Cod Bay entrance of the Sesuit Harbor grid based on the tide gauge data collected in October 2022. 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. 2022 digital aerial imagery 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 computed grid consists of 18,938 nodes, which describe 8,517 total 2-dimensionsal (depth averaged) quadratic elements. The maximum nodal depth is -29.4 ft (NAVD88) along the open boundary of the grid in Cape Cod, and the typical modeled marsh plain elevation is 4.5 ft NAVD. The completed grid mesh of the Sesuit Harbor system is shown in **Figure V-15**.

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[76] Brigham Young University (1998). "User's Manual, Surfacewater Modeling System."
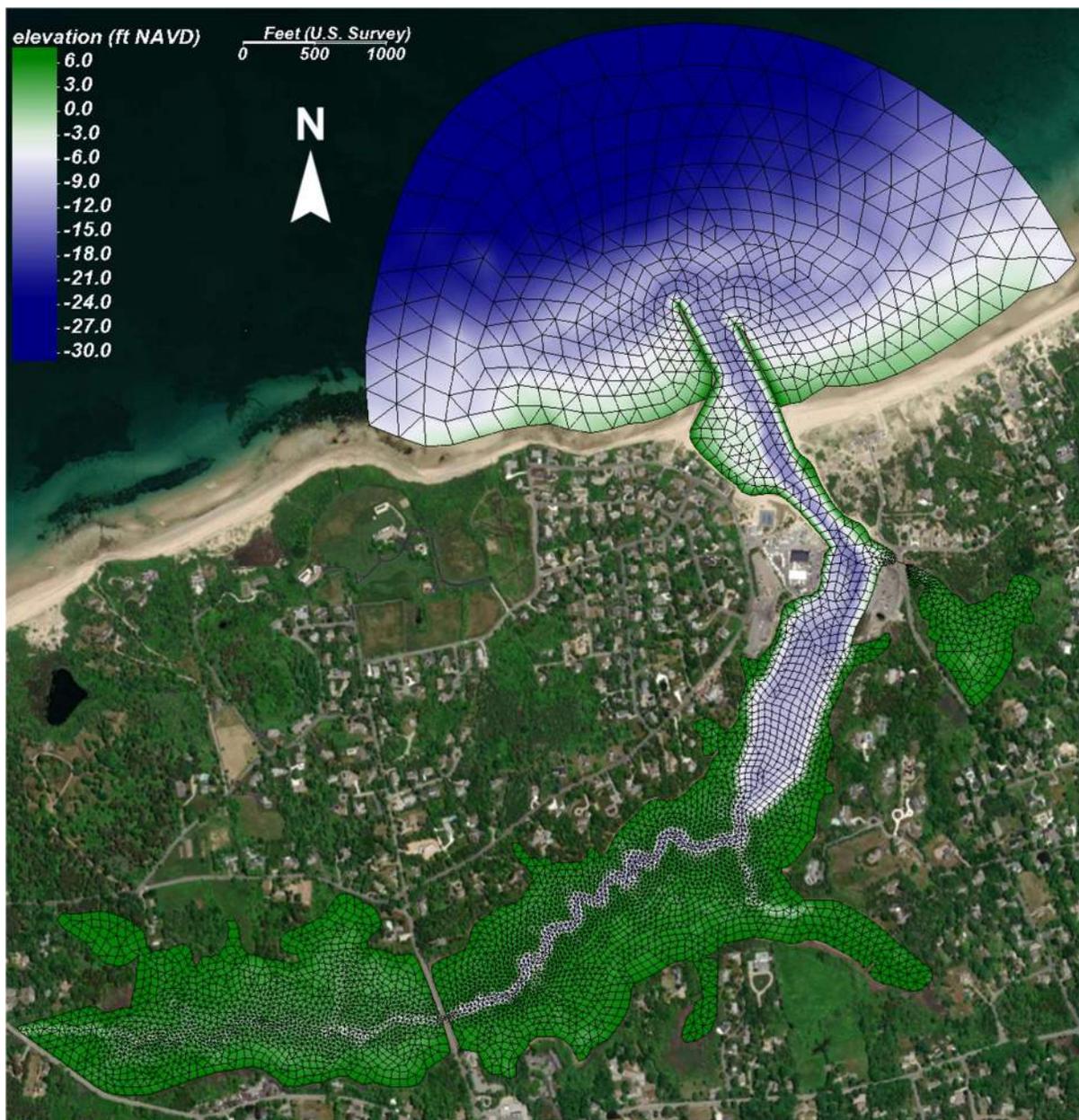
**Figure V-15. Hydrodynamic model grid mesh for Sesuit Harbor**. Colors are used to designate the different model material types used to vary model calibration parameters and compute flushing rates.

The finite element grid for the system provides the detail necessary to evaluate accurately the variation in hydrodynamic properties of Sesuit Harbor. 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 Sesuit Harbor 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 Cape Cod Bay, using data collected during the October 2022 gauge deployment. 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 Sesuit Harbor grid every model time step. The model runs of Sesuit Harbor used a 6-minute time step. 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 model grids, and specifying boundary conditions, the model for the Sesuit Harbor 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.

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 V-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 through a complete fortnightly spring/neap tide cycle. 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 October 9, 2022 at 23:40 EDT. 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 by comparing tidal flows at the inlet measured during the June 6, 2023 ADCP survey to flows computed using the hydrodynamic model.

The calibrated model was used to analyze existing detailed flow patterns and compute residence times.  The residence time analysis uses model results from the calibration time period.  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 14-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.[77]

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 Sesuit Creek and the Harbor basin, 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 the estuary.  Manning's values for different bottom types were initially selected based on ranges provided by the Civil Engineering Reference Manual,[78] 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-5**.

| Table V-5.  Manning's Roughness and eddy viscosity coefficients used in simulations of Sesuit Harbor. | | |
|---|---|---|
| System Sections | Bottom Friction | Eddy Viscosity N-sec/m$^2$ |
| Cape Cod Bay | 0.030 | 9,000 |
| Sesuit Harbor inlet and basin | 0.030 | 4,000 |
| Sesuit Creek channels | 0.030 | 2,000 |
| Sesuit Creek culvert | 0.020 | 2,000 |
| Marsh Plain | 0.070 | 2,000 |

### 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 element dimensions (numerical effects) and flow velocities (physics).  In most cases, the modeled systems were relatively insensitive to turbulent exchange coefficients because there

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

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

were no regions of strong turbulent flow. Typically, model turbulence coefficients were set between 2,000 and 4,000 N-sec/m$^2$ (see Table V-5) within the harbor and marsh 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 Sesuit Harbor 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 is 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-16 through V-20** illustrate sections of the 7-day simulation periods for the calibrated model. Modeled (blue line) and measured (black dot-dashed line) tides are compared at locations corresponding to each of the five tide gauge stations in the 2022 deployment.

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 between measured and modeled results: $K_1$, $M_2$, $M_4$, and $M_6$ (**Table V-6**). The constituent amplitudes shown in this table differ from those in Table V-2 because constituents were computed for only the separate 7-day sub-sections of the 30-days represented in Table V-2 results. In the lowest portion of Table V-6, differences between measured and modeled results are shown.

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 generally less than 0.1 ft and within the same order magnitude of the accuracy of the tide gauges (0.03 ft). Time lag errors for the marsh system were within two timesteps of the time increment resolved by the 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 ($R^2$) between measured and modeled results and the low mean absolute error (MAE) values for all stations (**Table V-7**).
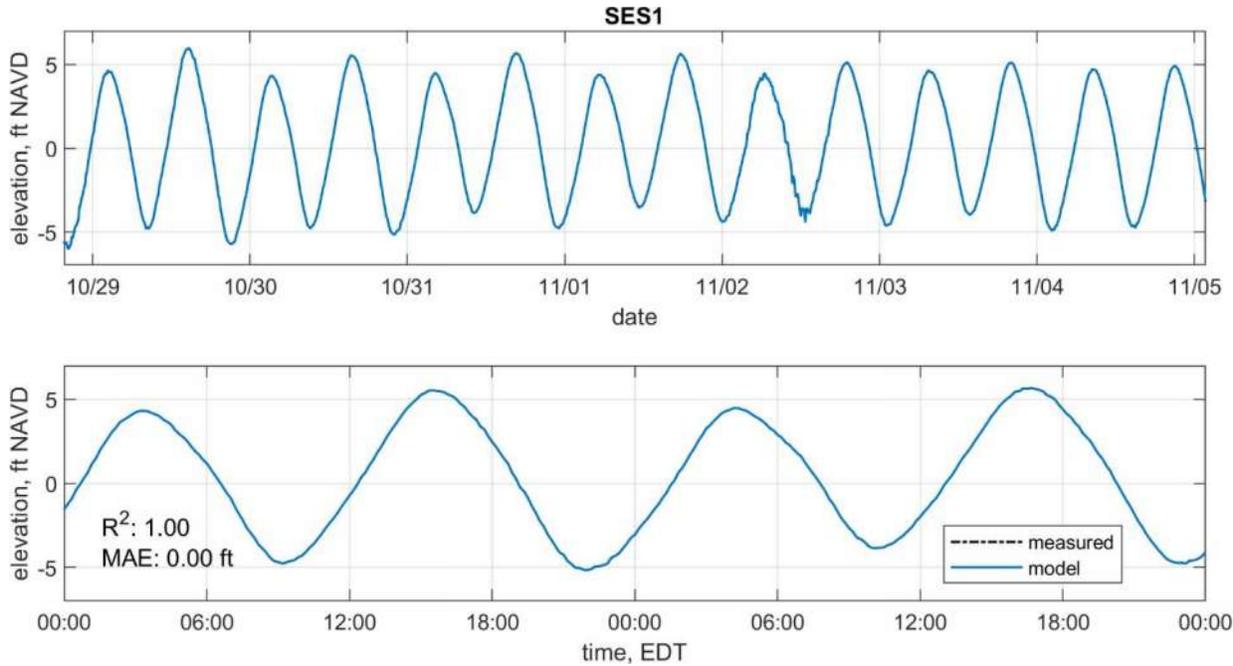
**Figure V-16. Comparison of model output and measured tides at SES1 station.** SES1 was located offshore in Cape Cod Bay and the comparison is for the final calibration model run (starting October 28, 2022 at 13:40 EDT). The bottom plot is a 48-hour detail shown in the top plot (starting at October 30, 2022 at 00:00).
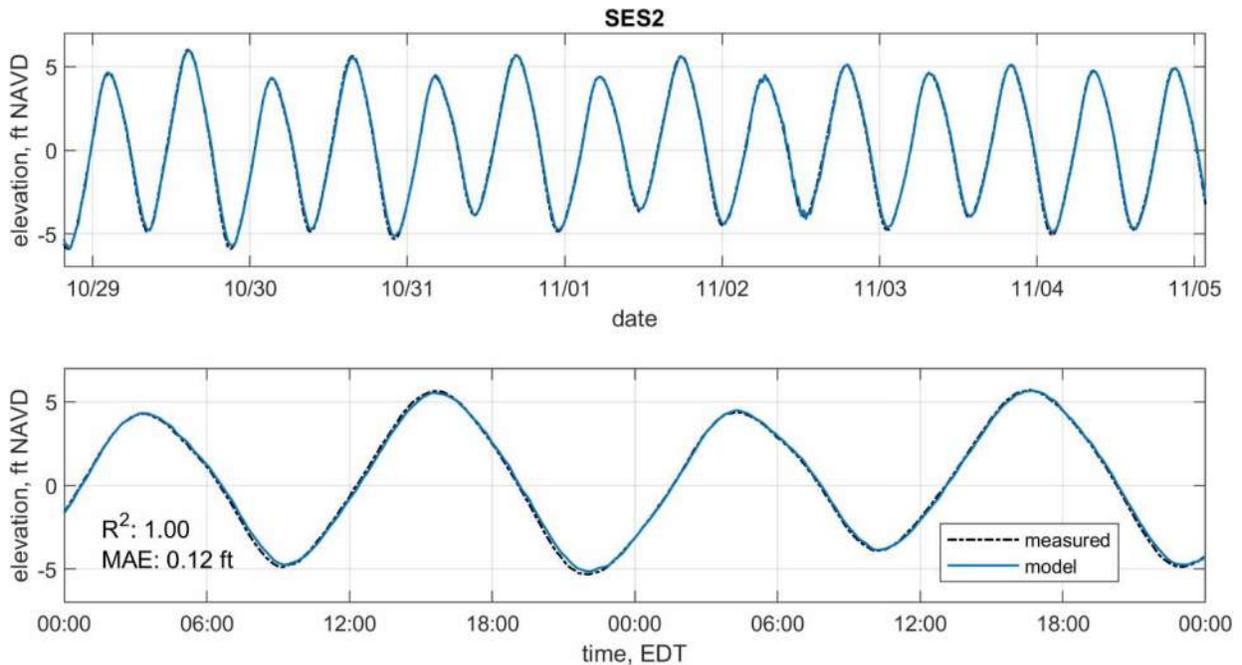


**Figure V-17. Comparison of model output and measured tides at SES2 station.** SES2 was located at the harbor boat ramp and the comparison is for the final calibration model run (starting October 28, 2022 at 13:40 EDT). The bottom plot is a 48-hour detail shown in the top plot (starting at October 30, 2022 at 00:00).
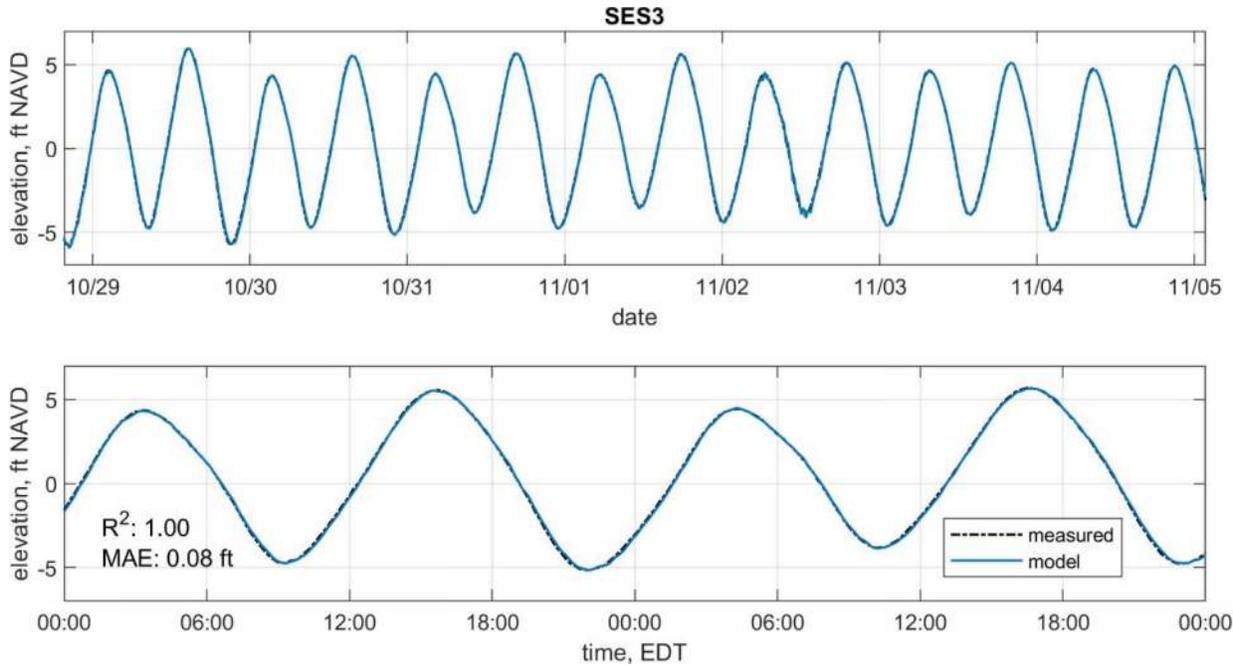
**Figure V-18.  Comparison of model output and measured tides at SES3 station.**  SES3 was located in the main harbor basin and the comparison is for the final calibration model run (starting October 28, 2022 at 13:40 EDT).  The bottom plot is a 48-hour detail shown in the top plot (starting at October 30, 2022 at 00:00).
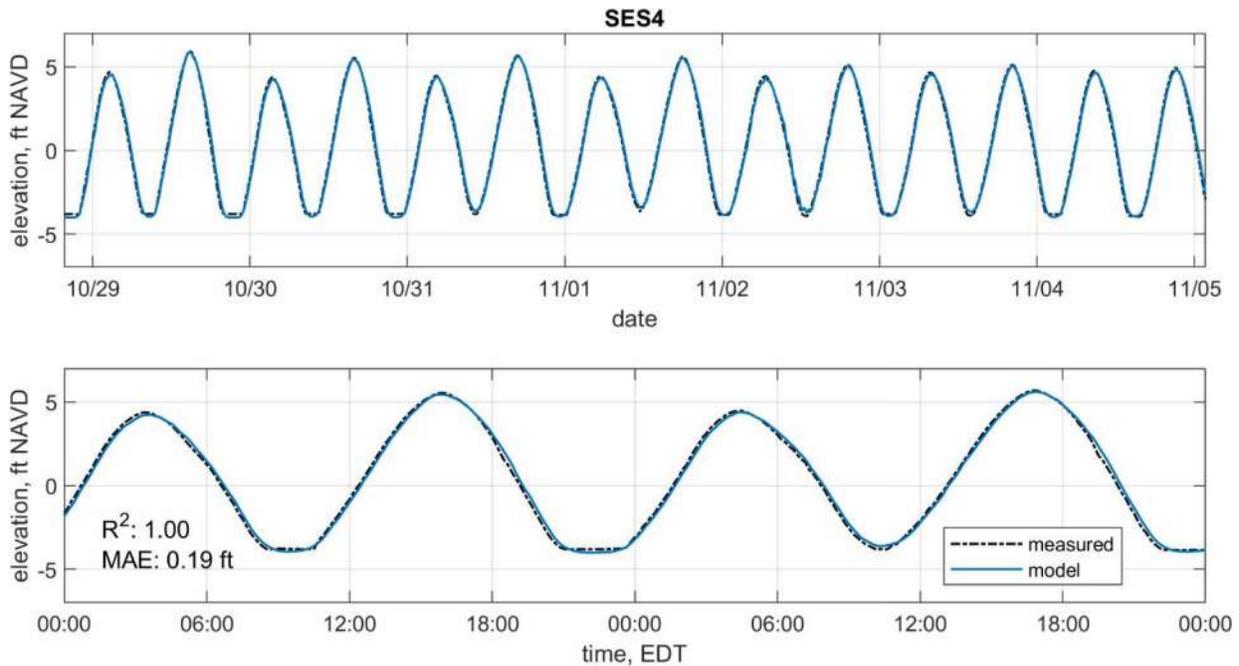


**Figure V-19.  Comparison of model output and measured tides at SES4 station.**  SES4 was located east of the Bridge Street culvert and the comparison is for the final calibration model run (starting October 28, 2022 at 13:40 EDT).  The bottom plot is a 48-hour detail shown in the top plot (starting at October 30, 2022 at 00:00).
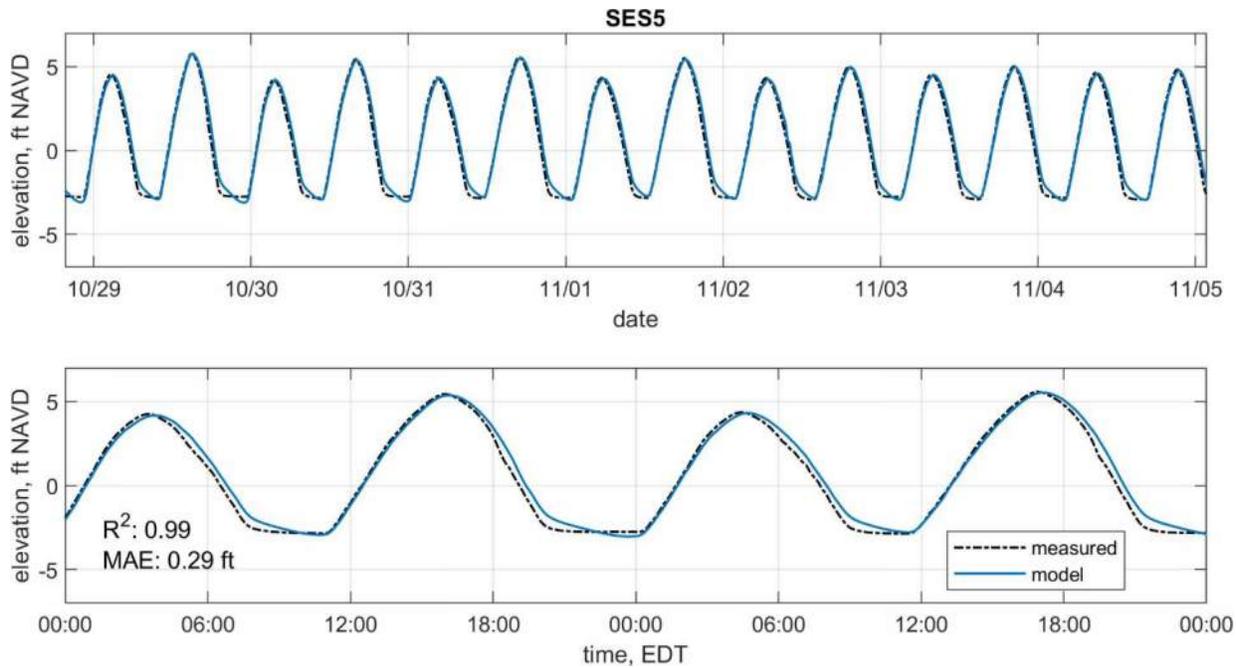
**Figure V-20. Comparison of model output and measured tides at SES5 station.** SES5 was located west of the Bridge Street culvert and the comparison is for the final calibration model run (starting October 28, 2022 at 13:40 EDT). The bottom plot is a 48-hour detail shown in the top plot (starting at October 30, 2022 at 00:00).

**Table V-6.    Tidal constituents for measured water level data and calibrated model output for the Sesuit Harbor system, during the modeled calibration time period.** Differences between measured and model readings are shown in the bottom section.

| | | Measured tide during calibration period | | | | | |
|---|---|---|---|---|---|---|---|
| Location | Constituent Amplitude (ft) | | | | Phase (deg) | | |
| | $K_1$ | $M_2$ | $M_4$ | $M_6$ | $\varphi K_1$ | $\varphi M_2$ | $\varphi M_4$ |
| SES1 - Offshore | 0.55 | 4.48 | 0.08 | 0.20 | 207.3 | 41.6 | 106.5 |
| SES2 - Boat Ramp | 0.60 | 4.53 | 0.09 | 0.20 | 205.5 | 41.0 | 113.1 |
| SES3 – Harbor Basin | 0.55 | 4.49 | 0.08 | 0.20 | 206.9 | 41.8 | 108.7 |
| SES4 – downstream Bridge St | 0.49 | 4.33 | 0.08 | 0.07 | 216.7 | 43.6 | 100.5 |
| SES5 – upstream Bridge St | 0.43 | 3.91 | 0.38 | 0.12 | 225.0 | 44.8 | 92.5 |

| | | Modeled calibration run | | | | | |
|---|---|---|---|---|---|---|---|
| Location | Constituent Amplitude (ft) | | | | Phase (deg) | | |
| | $K_1$ | $M_2$ | $M_4$ | $M_6$ | $\varphi K_1$ | $\varphi M_2$ | $\varphi M_4$ |
| SES1 - Offshore | 0.55 | 4.48 | 0.08 | 0.20 | 207.3 | 41.6 | 106.5 |
| SES2 - Boat Ramp | 0.56 | 4.47 | 0.08 | 0.19 | 208.5 | 43.1 | 92.8 |
| SES3 – Harbor Basin | 0.56 | 4.47 | 0.08 | 0.19 | 208.6 | 43.2 | 92.6 |
| SES4 – downstream Bridge St | 0.51 | 4.28 | 0.05 | 0.08 | 218.3 | 47.1 | 106.8 |
| SES5 – upstream Bridge St | 0.47 | 3.90 | 0.25 | 0.11 | 226.1 | 50.6 | 93.2 |

| | | Error (measured - modeled) | | | | | |
|---|---|---|---|---|---|---|---|
| Location | Constituent Amplitude (ft) | | | | Phase (minutes) | | |
| | $K_1$ | $M_2$ | $M_4$ | $M_6$ | $\varphi K_1$ | $\varphi M_2$ | $\varphi M_4$ |
| SES1 - Offshore | 0.00 | 0.00 | 0.00 | 0.00 | 0.0 | 0.0 | 0.0 |
| SES2 - Boat Ramp | 0.04 | 0.06 | 0.01 | 0.01 | -12.0 | -4.3 | 21.0 |
| SES3 – Harbor Basin | -0.01 | 0.02 | 0.00 | 0.01 | -6.8 | -2.8 | 16.6 |
| SES4 – downstream Bridge St | -0.02 | 0.05 | 0.03 | -0.01 | -6.6 | -7.2 | -6.5 |
| SES5 – upstream Bridge St | -0.04 | 0.01 | 0.13 | 0.01 | -4.4 | -12.0 | -0.8 |

**Table V-7.    Selected calibration statistics for the Sesuit Harbor hydrodynamic model.** $R^2$ is correlation between measured and modeled (1.00 = 100% match).  MAE = mean absolute error

| Station | $R^2$ | MAE (feet) |
|---|---|---|
| SES1 - Offshore | 1.00 | 0.00 |
| SES2 - Boat Ramp | 1.00 | 0.12 |
| SES3 – Harbor Basin | 1.00 | 0.08 |
| SES4 – downstream Bridge St | 1.00 | 0.19 |
| SES5 – upstream Bridge St | 0.99 | 0.29 |

### V.3.4 ADCP Verification

The performance of the hydrodynamic model was further corroborated by comparing tidal flows measured by an ADCP at two inlet transects (see Figure V-6), and flow rates computed in the model at the same locations (**Figures V-20 and V-21**). Flow rates measured by the ADCP are available from 15 discrete runs of the transects during the course of the ADCP survey, through one complete tide cycle. The model run began on June 5, 2023 at noon, to allow ample time for model spin up before the time of the first runs of the ADCP transects, starting just before 8:00 on June 6. The model shows very good agreement with measured ADCP flowrates at both transects, with $R^2$ values of 0.93 and 0.97, and mean absolute error (MAE) values of 210 and 158 cfs for the inner and outer transects, respectively.
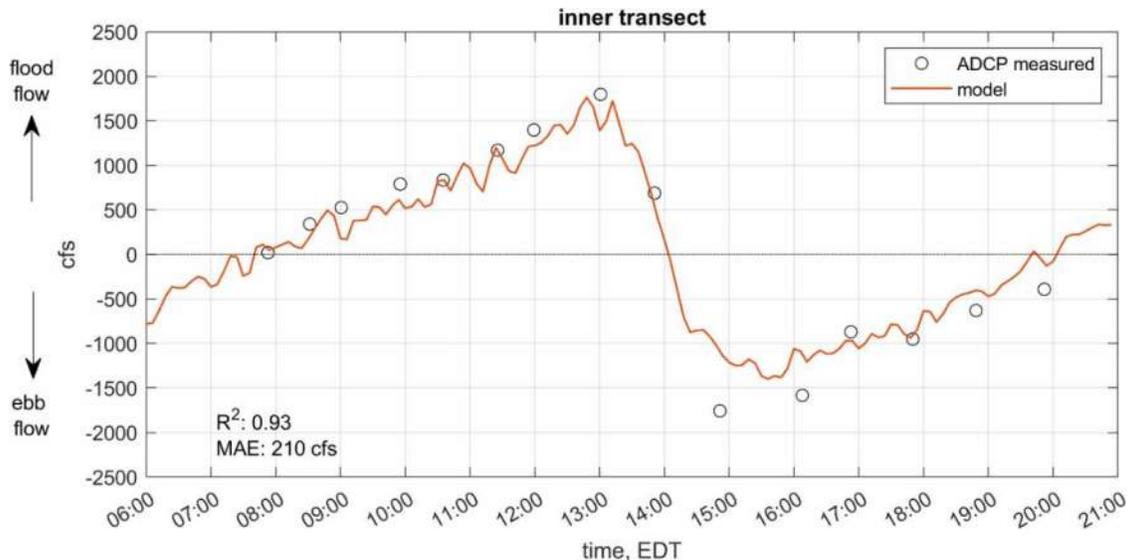


**Figure V-21. Comparison of measured and modeled ADCP flow rates for the inner ADCP transect.** Measured flow (black circles) and hydrodynamic model output (orange line) are shown.
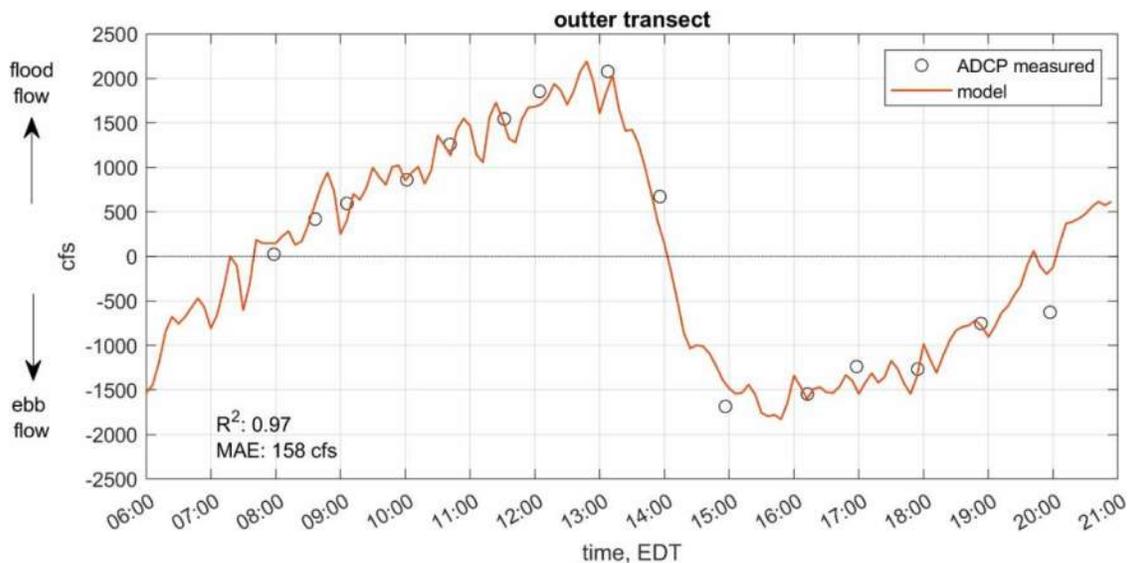


**Figure V-22. Comparison of measured and modeled ADCP flow rates for the outer ADCP transect.** Measured flow (black circles) and hydrodynamic model output (orange line) are shown.

### V.3.4  Model Circulation Characteristics

The final calibrated model serves as a useful tool in investigating the circulation characteristics of the Sesuit Harbor 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-23** shows the distribution of current velocities at maximum flood and ebb flows.
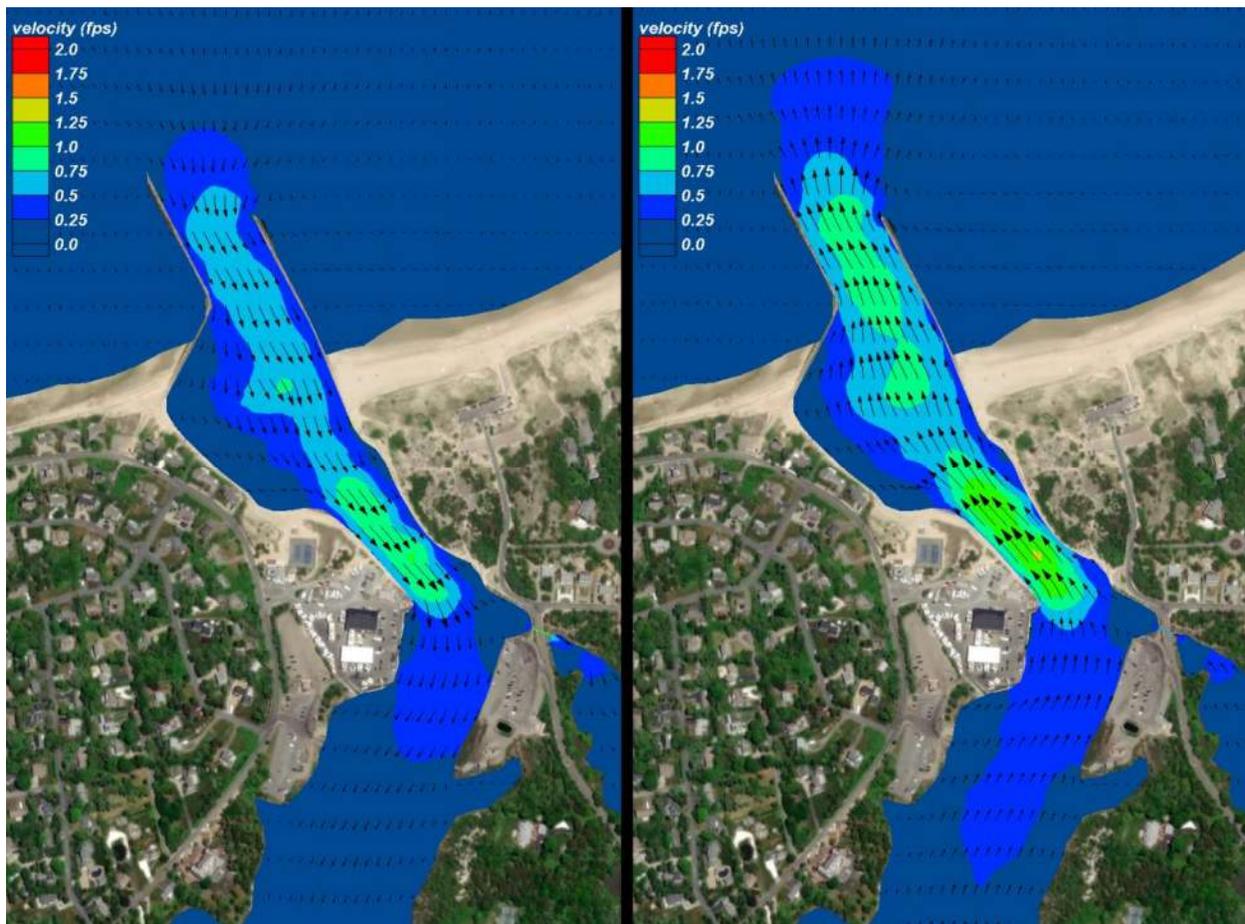


**Figure V-23.  Example of Sesuit Harbor hydrodynamic model output for model time steps.** Model time steps represent maximum flood (left panel) and maximum ebb (right panel) flows at the inlet. Color contours indicate velocity magnitude, and vectors indicate the direction of flow.

The total flow rate of water flowing through channels at different areas of the harbor and creek can be computed with the hydrodynamic model. The variation of flow as the tide floods and ebbs at the Harbor inlet and at the Bridge Street culvert can be modeled (**Figure V-24**). During spring tides, the maximum flow rates reach 2,000 ft$^3$/sec at the inlet, while at Bridge Street maximum flows reach 725 ft$^3$/sec.

A velocity time series taken from the model, inside the Bridge Street culvert, is shown in **Figure V-25**. This plot shows that maximum velocities during springs tides are near or exceed 3 ft/sec.

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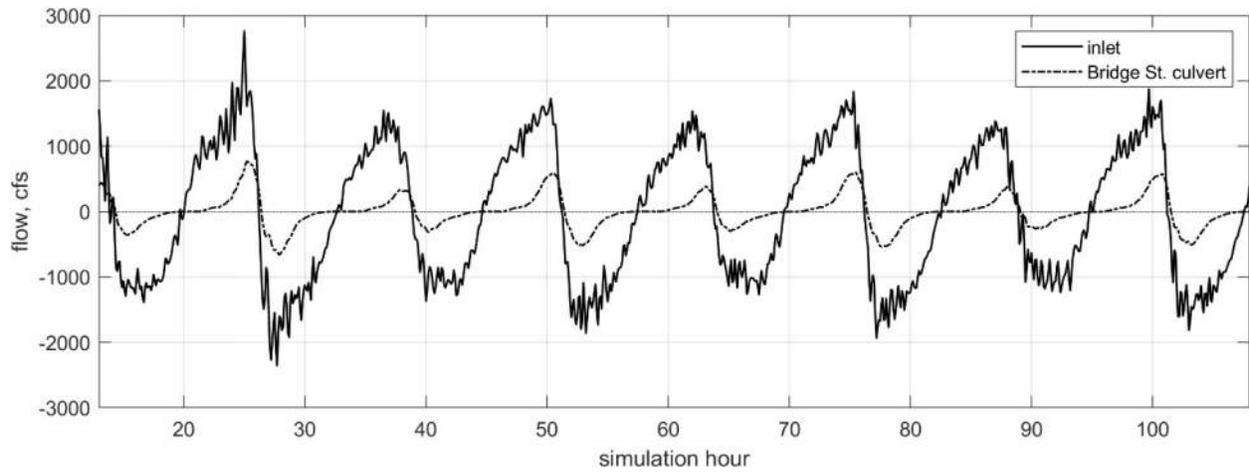
**Figure V-24. Computed flow rates at Sesuit Harbor inlet and at the Bridge Street culvert.**
The model period shown corresponds to spring tide conditions, where the tide range is largest, and resulting flow rates are correspondingly large compared to neap tide conditions. Positive flows indicate flooding tide flows, while negative flows indicate ebbing tide flows.
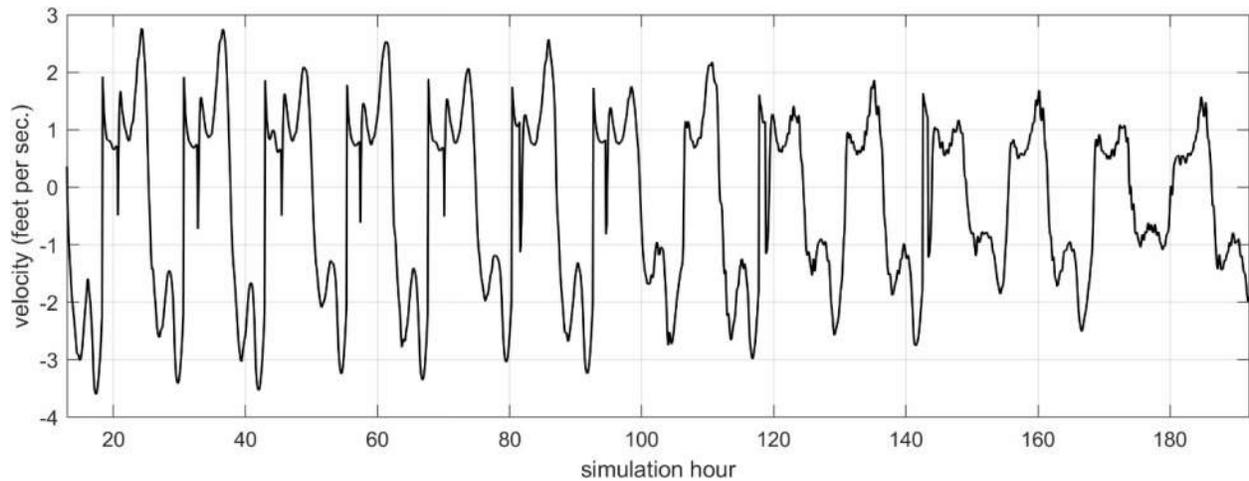


**Figure V-25. Computed tidal velocities in the Bridge culvert, during the model calibration time period.** Positive flows indicate flooding tide flows, while negative flows indicate ebbing tide flows.

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## V.3.5 Flushing Characteristics

Since the magnitude of freshwater inflow is much smaller in comparison to the tidal exchange through the inlet (about 1% of the mean tide prism of the system), the primary hydrological/hydrodynamic mechanism controlling estuarine water quality within Sesuit Harbor is tidal exchange with Cape Cod Bay. The exchange of water between the system and Cape Cod Bay 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:

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

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

In addition to system residence times, a second residence time, 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 western segment of Sesuit Creek as an example, the system residence time is the average time required for water to migrate from the western half of the creek, through the Bridge Street culvert and the eastern half of the creek, and finally through the harbor Basin and out the inlet and into Cape Cod Bay. Alternatively, the local residence time is the average time required for water to exit the western half of Sesuit Creek through the Bridge Street Culvert (not exiting Cape Cod 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 mean low tide volume is large compared to the mean tide prism. **Local residence times** are more applicable for systems like Sesuit Harbor with an extensive

marsh plain that tend to have a mean low tide volume that is small compared to the mean tide prism of the system.

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 Cape Cod Bay over a flood tide cycle (tidal prism) for system residence times (**Tables V-8 and V-9**).

| Table V-8. Mean volume and average tidal prism during simulation period, for three segments of the Sesuit Harbor system. | | |
|---|---|---|
| Embayment | Mean Volume $(ft^3)$ | Tidal Prism Volume $(ft^3)$ |
| Sesuit Harbor – whole system | 16,365,770 | 20,071,370 |
| Sesuit Creek (east and west) | 5,235,360 | 7,781,690 |
| Sesuit Creek above Bridge St. | 1,749,030 | 3,148,830 |

| Table V-9. Computed System and Local water residence times for the Sesuit Harbor system. | | |
|---|---|---|
| Embayment | Local Residence Time (days) | System Residence Time (days) |
| Sesuit Harbor – whole system | 0.4 | 0.4 |
| Sesuit Creek (east and west) | 0.3 | 1.1 |
| Sesuit Creek above Bridge St. | 0.3 | 2.7 |

Residence times were averaged for tidal cycles comprising a representative 14-day period (27 tide cycles), and are listed in Table V-9. The modeled time period used to compute the flushing rates started October 9, 2022, 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.

The computed flushing rates for the entire system show that as a whole, the system flushes very well.  A flushing time of 0.4 days for the entire estuary shows that on average, water is resident in the system for less than one half of a day.  The low local residence times for the whole Sesuit Harbor 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.

For the two subdivisions of Sesuit Harbor listed in Table V-9 (the whole of Sesuit Creek upstream of the Harbor Basin and the eastern reach of Sesuit Creek west of Bridge Street) computed system residence times are multiples longer than their corresponding local residence time, but still are small enough that they indicate that these areas benefit from effective tidal flushing.

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 Sesuit Harbor 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 Cape Cod Bay typically is strong because of the effects of the local winds and tidal induced mixing, the "strong littoral drift" assumption will only 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,[79] was employed to study the effects of nitrogen loading in the Sesuit Harbor 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 Sesuit Harbor.  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 the Town of Dennis.

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.

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 Sesuit Harbor 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 Sesuit Harbor system, consisting of the background concentrations of total nitrogen in the waters entering from Cape Cod 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 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 Sesuit Harbor.  The governing equation of the RMA-4 constituent model can be most simply expressed as a form of the transport equation, in two dimensions:

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

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

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 $\sigma$ 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 Sesuit Harbor also were used for the water quality constituent modeling portion of this study. Based on 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 defined by data from a long-term monitoring station in Cape Cod Bay. This boundary condition data was applied to the entire model domain: 0.433 mg/L TN and 31.08 ppt, respectively.

Freshwater groundwater inputs to Sesuit Harbor and average direct rainfall to the estuary's surface were applied to the model using values developed specifically for this analysis. Stream inputs of freshwater are based on measurements at Scargo Stream, summarized in Section IV. Groundwater inputs of freshwater to the upper and lower portion of Sesuit Harbor are based on 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 0.995 and RMS errors of 0.76 ppt compared to measured salinities at each of the Sesuit Harbor monitoring stations (**Figures VI-2 and VI-3**).  Modeled salinity concentrations throughout Sesuit Harbor 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 0.90 and RMS error of 0.076 mg/L (**Figures VI-5 and VI-6**) compared to the measured TN data at the Sesuit Harbor monitoring stations (**Table VI-3**).  Modeled Total Nitrogen concentrations throughout Sesuit Harbor 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.
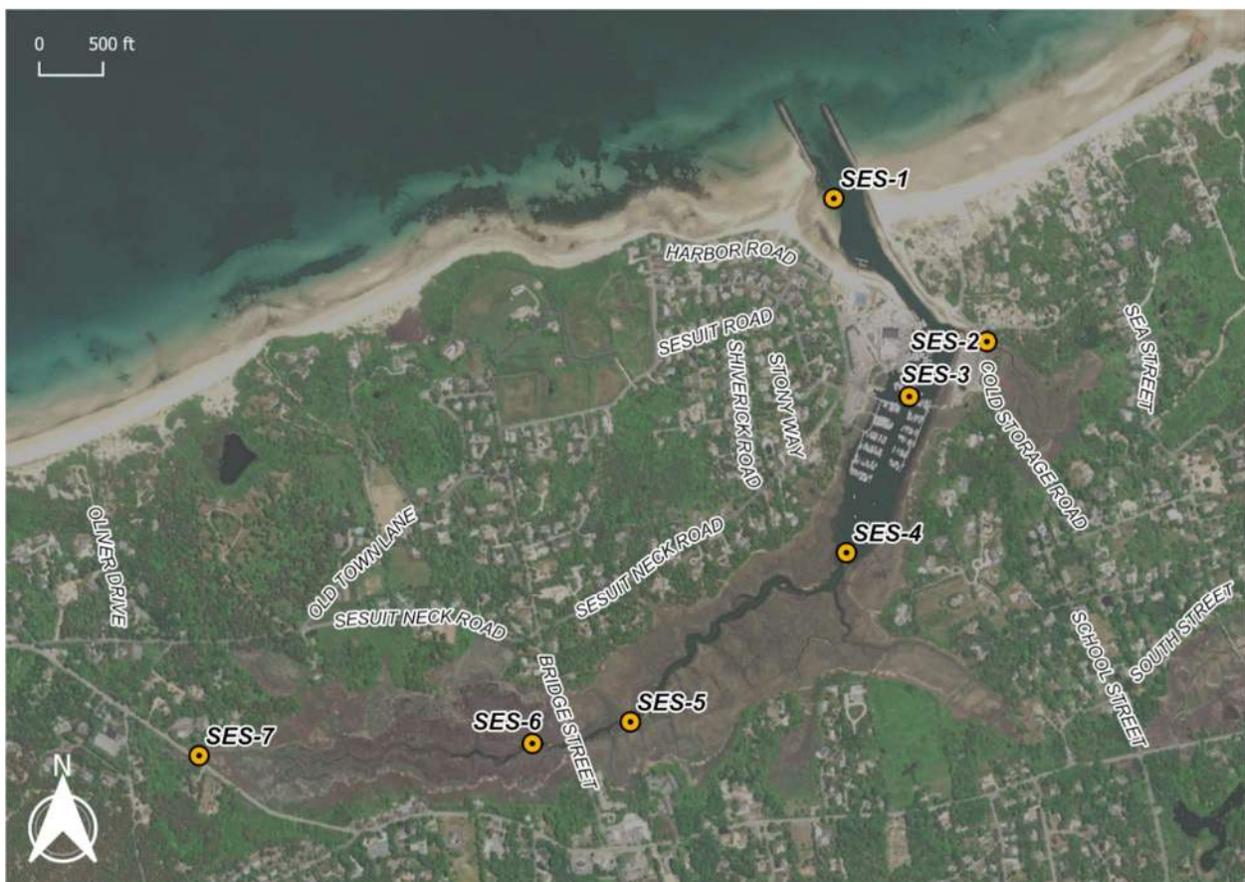


**Figure VI-1.  Estuarine water quality monitoring station locations in the Sesuit Harbor estuary system.**  Station labels correspond to those provided in Table VI-1.

**Table VI-1.** **Diffusion coefficient values specified for the material type subdivisions of the Sesuit Harbor hydrodynamic model.**

| mesh material type | Diffusion coefficient (D) $m^2$/sec |
|---|---|
| Cape Cod Bay | 7.0 |
| Sesuit Harbor inlet and basin | 7.0 |
| Sesuit Creek east, marsh and channels | 5.0 |
| Sesuit Creek culvert | 1.0 |
| Sesuit Creek west, marsh and channels | 0.1 |
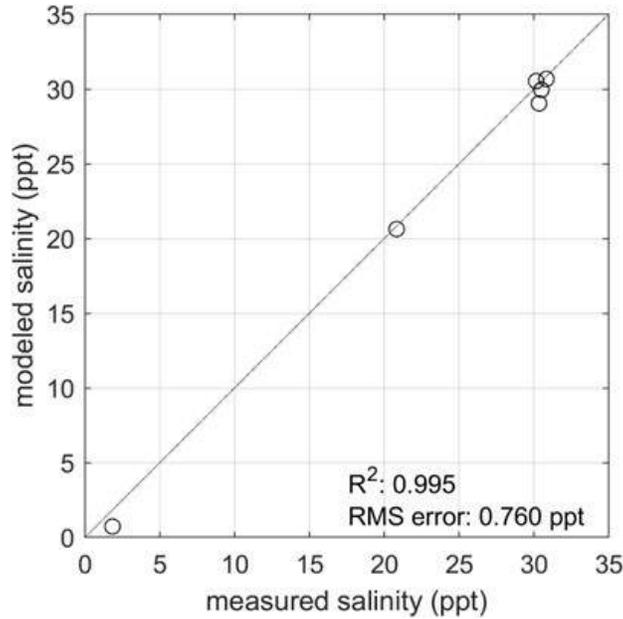


**Figure VI-2. Sesuit Harbor water quality model comparison of modeled and measured salinity concentrations.** Modeled salinity values at Sesuit Harbor monitoring stations are plotted against measured concentrations, together with the unity line. Computed correlation ($R^2$) is 0.995 and RMS error for this model verification run is 0.760 ppt.
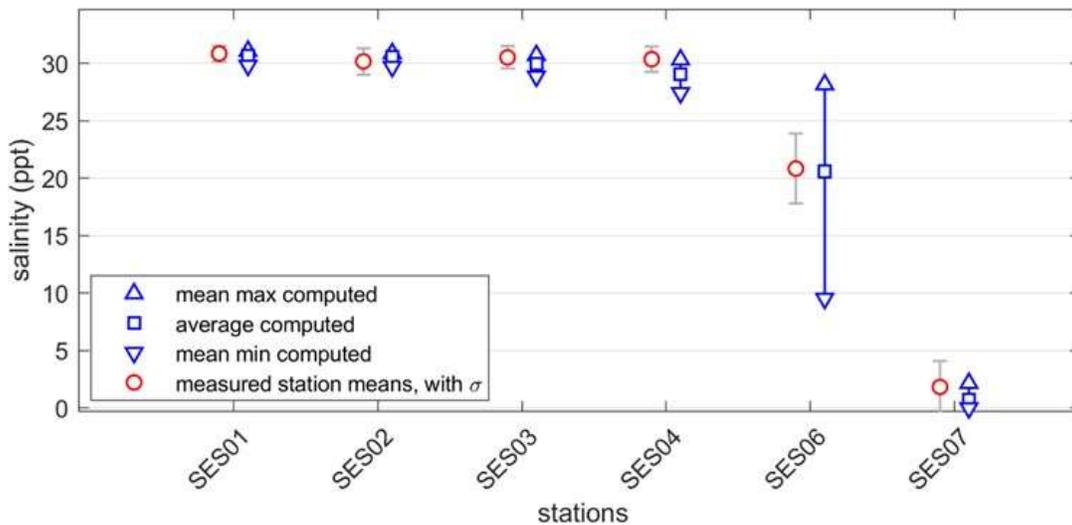


**Figure VI-3. Comparison of measured mid-ebb salinity (with standard deviation) and tidally-averaged model output in Sesuit Harbor.** Also plotted are means of modeled tide cycle maximum and minimum concentrations.

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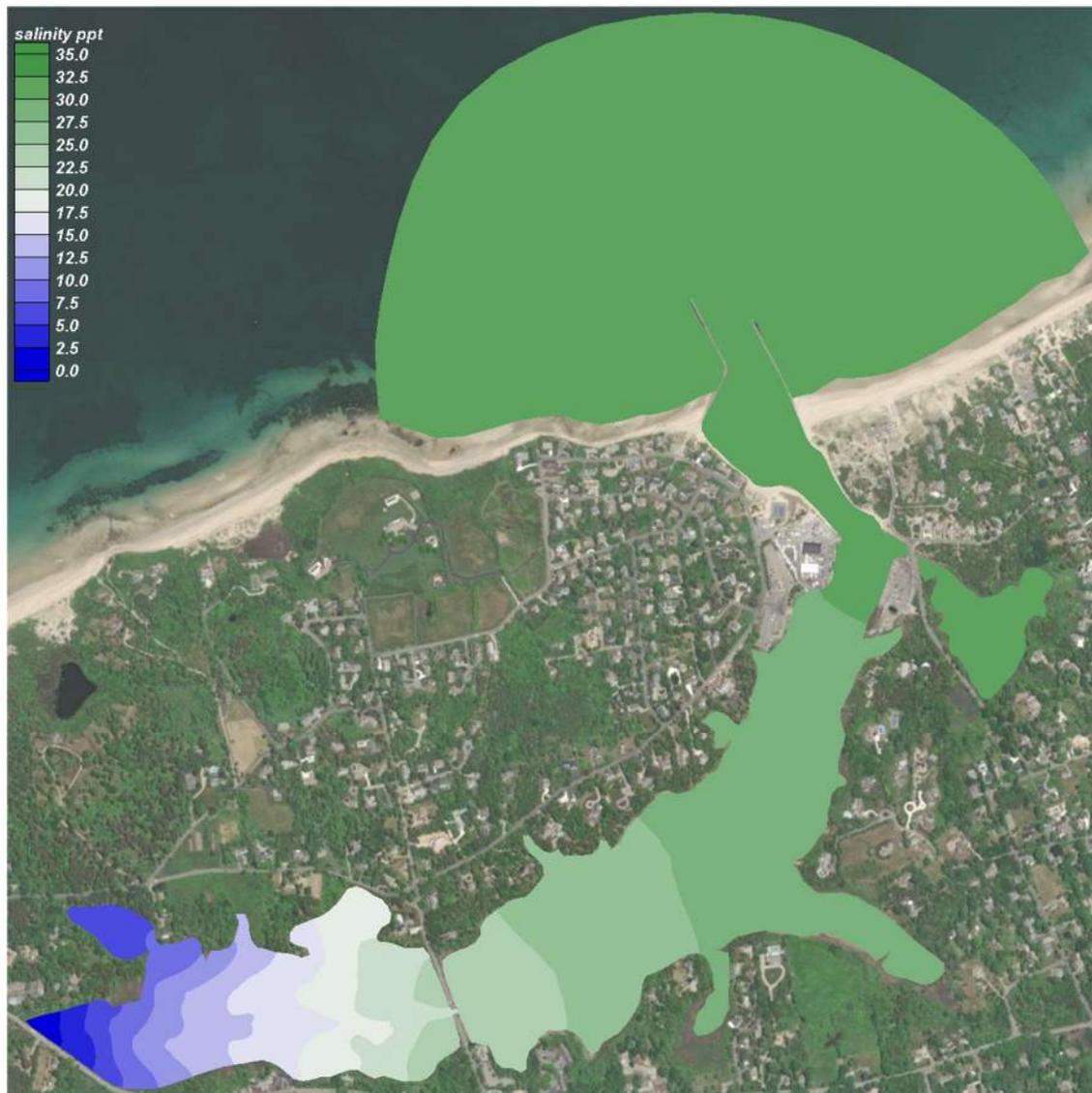
**Figure VI-4. Modeled color contours of tidally-averaged salinity from the calibration run of the Sesuit Harbor RMA4 water quality model.**

| sub-embayment / surface water discharge | watershed load (kg/day) | direct atmospheric deposition (kg/day) | benthic flux net (kg/day) |
|---|---|---|---|
| Sesuit Harbor | 5.232 | 0.362 | 6.634 |
| Sesuit Creek east | 9.875 | 0.084 | -0.565 |
| Sesuit Creek west | 12.150 | 0.013 | 0.306 |
| **System Total** | 27.257 | 0.459 | 6.375 |

Table VI-2. *Present* sub-embayment loads used for total nitrogen modeling of the Sesuit Harbor system, with total watershed N loads, atmospheric N loads, and benthic flux. Watershed loads are summary of attenuated N loads, while benthic flux loads are based on sediment core incubations, respectively (all summarized in Section IV).
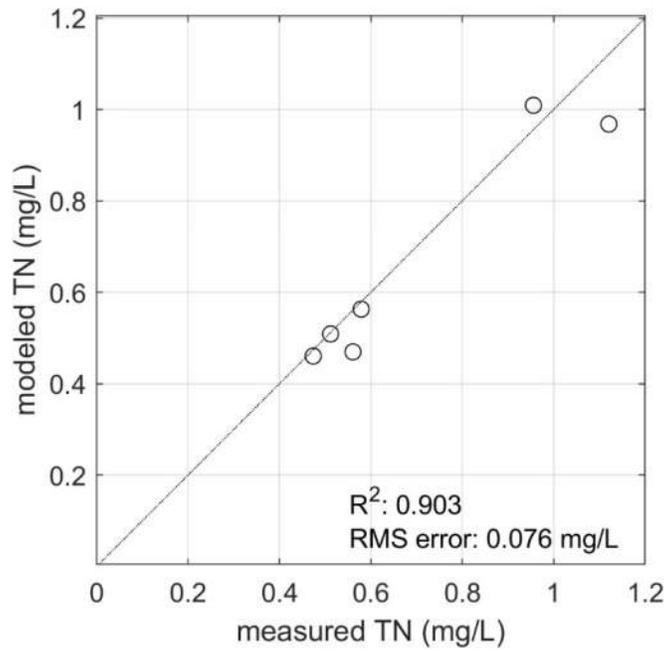
**Figure VI-5. Sesuit Harbor water quality model comparison of modeled and measured total nitrogen concentrations.** Modeled TN values at Sesuit Harbor monitoring stations are plotted against measured concentrations, together with the unity line. Computed correlation ($R^2$) is 0.90 and RMS error for this model verification run is 0.076 mg/L.
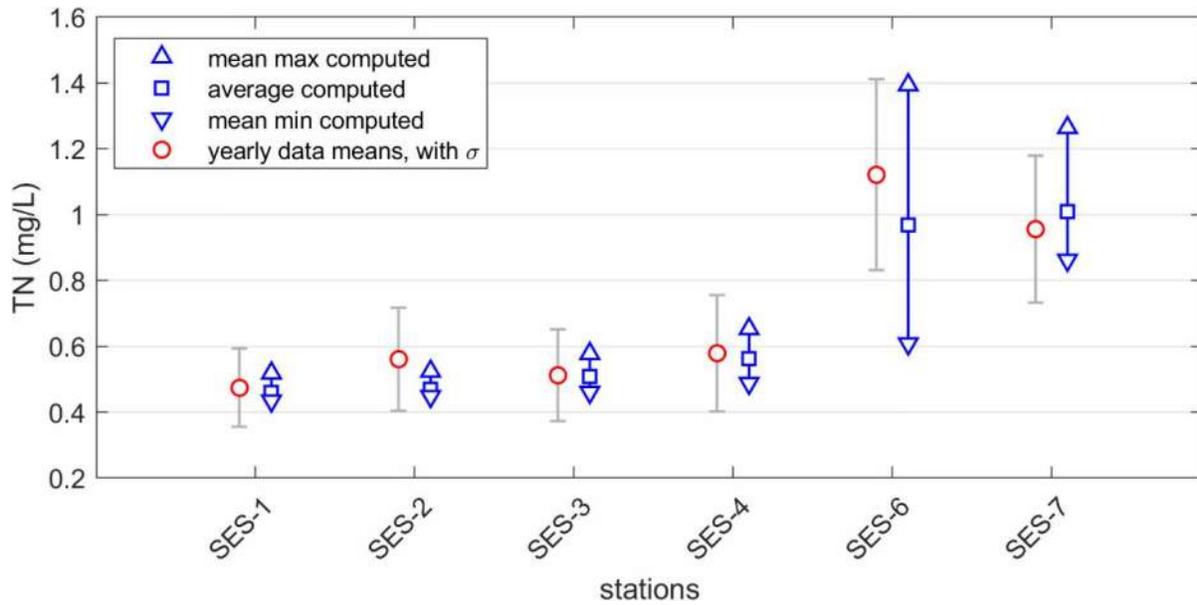


**Figure VI-6. Comparison of mean measured mid-ebb TN concentrations (with standard deviation) and tidally averaged model output.** Also plotted are modeled means of tide cycle maximum and minimum concentrations.

**Table VI-3.    Measured data and modeled nitrogen concentrations for the Sesuit Harbor 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 2017 through 2022.

| monitoring station | Location | data mean | s.d. all data | N | model min | model max | model average |
|---|---|---|---|---|---|---|---|
| SES out | Outside System | 0.433 | 0.154 | 35 | | | |
| SES-1 | Inlet | 0.474 | 0.119 | 41 | 0.434 | 0.519 | 0.460 |
| SES-2 | Cold Storage Road | 0.561 | 0.157 | 23 | 0.448 | 0.524 | 0.470 |
| SES-3 | Main Basin | 0.512 | 0.139 | 23 | 0.461 | 0.578 | 0.509 |
| SES-4 | Main Basin S | 0.579 | 0.177 | 23 | 0.488 | 0.653 | 0.563 |
| SES-6 | Mid Marsh E | 1.121 | 0.290 | 12 | 0.608 | 1.394 | 0.968 |
| SES-7 | Mid Marsh W | 0.956 | 0.223 | 22 | 0.862 | 1.264 | 1.009 |
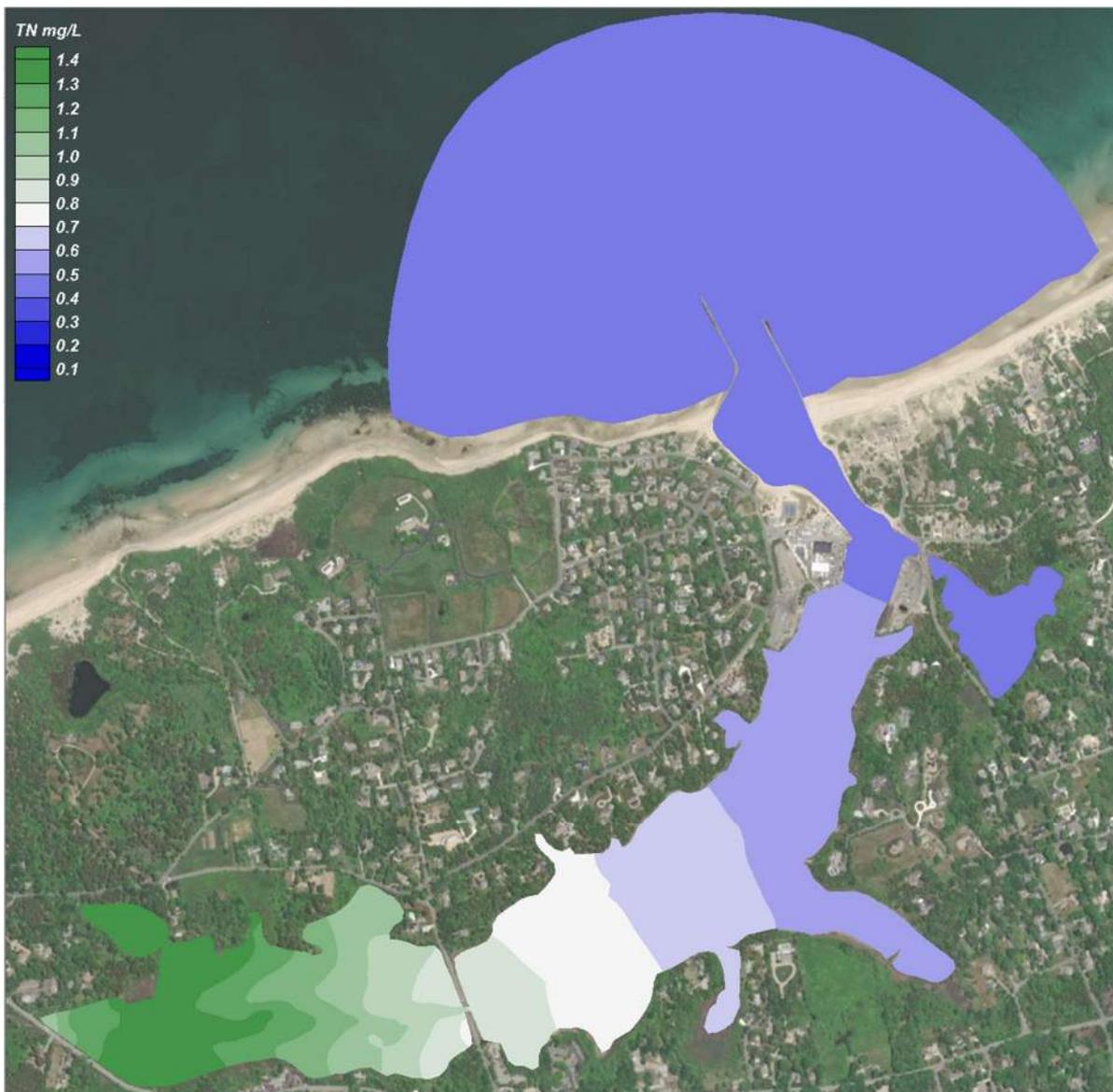


**Figure VI-7.   Modeled color contours of tidally-averaged TN concentration (mg/L) in Sesuit Harbor for present/current conditions N loading.**

## VI.2.1. CALIBRATED RESIDENCE TIME CALCULATION

The calibrated water quality model of Sesuit Harbor can be used to compute a flushing rate that better reflects how nitrogen moves within the system.  This modeling takes into account the advection of tidal flows, mixing and diffusion of water quality constituents due to turbulence, and dilution due to groundwater flows.  This provides a more accurate representation of tidal flushing of the system compared to the simpler method based on tidal prism exchange that was presented in Chapter V.

The alternate water quality model-based flushing rate calculation is based on the concept of a continuous stirred tank reactor (CSTR).[80]  A conservative tracer is initially equally distributed throughout an embayment, and is then allowed to dissipate with the action of the tide.  As a result, the concentration of the tracer will decrease unevenly in different areas of the embayment.  The residence time at a particular location is determined as the time it takes for the concentration of the tracer to drop below 37% of the original starting concentration, which is defined as the residence time.

For this calculation, the conservative tracer is modeled using an initial concentration of 1.0 set for all areas of Sesuit Harbor, and the open boundary concentration was also set to 0.  In this way, the residence time for the selected points in the harbor was determined as the period between the time of the first low tide of the model run and the time when the modeled concentration first falls below 0.37 at each location.

The Sesuit Harbor model was run for a simulated period of one week.  Time series of concentrations of the modeled conservative constituent were output at locations indicated in **Figure VI-8**.  The first model time step where the concentration dropped below 0.37 was recorded for each location, and are mapped in Figure VI-10.  Values of residence times determined by this method range from less than a half tide cycle at stations nearest the inlet and also at the head of Sesuit Creek where Scargo Stream enters, to as high as 1 day in the middle section of Sesuit Creek and in Cold Storage Road Marsh.  This modeling reinforces how the boat basin is a significant transition zone between the marsh and the inlet.

These results show that Sesuit Harbor flushes efficiently, which corroborates the residence time calculations based on hydrodynamics alone from Chapter V.  The results also indicate that the true residence times of the system are within the range between the system and local residence times listed in Table V-9.

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[80] Monsen, N.E., J.E. Cloern, L.V. Lucas, and S.G. Monismith.  2002.  A comment on the use of flushing time, residence time, and age as transport timescales. *Limnol. Oceanogr*.,47(5), 2002, 1545–1553.
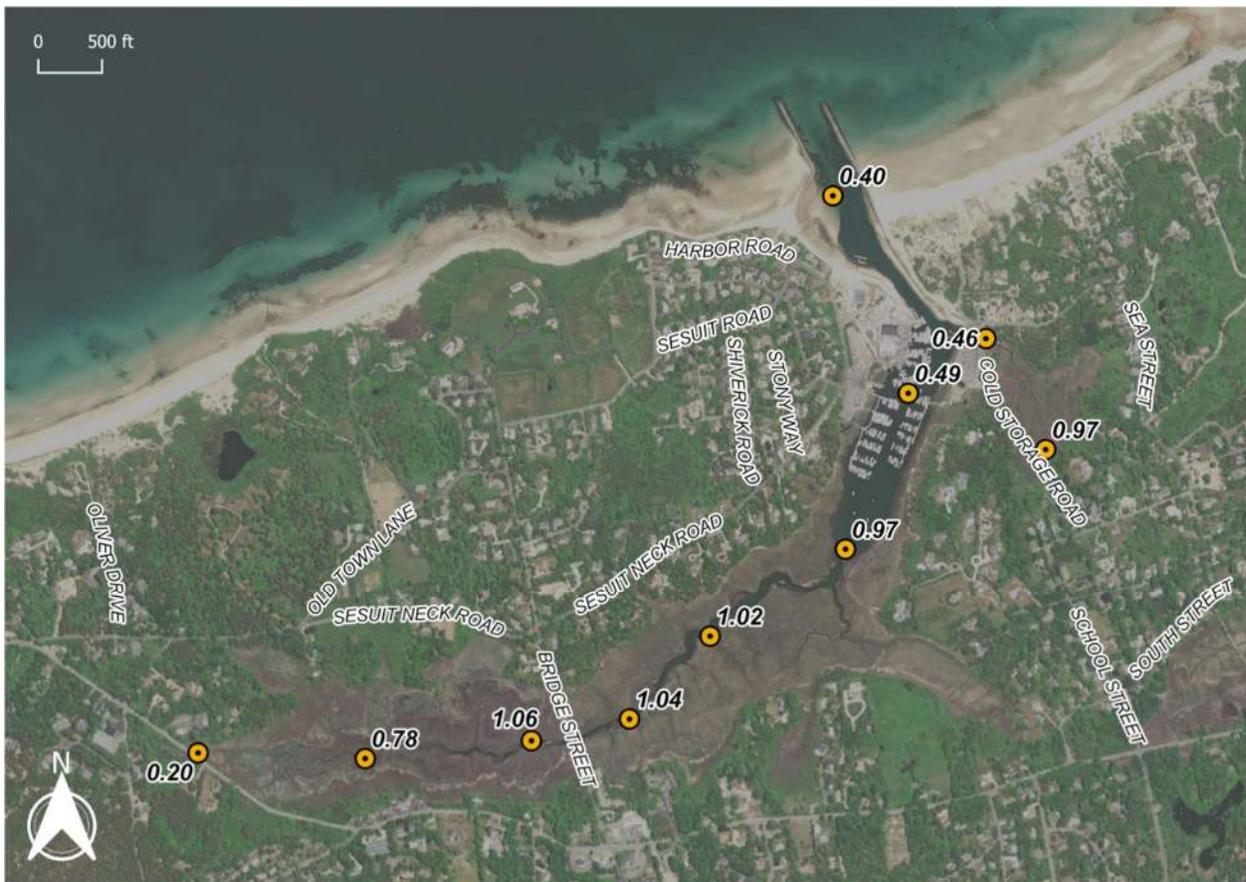
**Figure VI-8.  Map of residence times in days determined using the water quality model of Sesuit Harbor.**

# 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 Sesuit Harbor estuarine system in the Town of Dennis, 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 both 2005-2006 and 2021-2022. 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. Within even the healthiest of systems, DO conditions can naturally vary significantly and the same conditions can represent healthy or impaired conditions. For example, in healthy marshes DO can become anoxic, because of the natural abundance of organic compounds, while in embayment basins persistent anoxia can represent unhealthy, impaired conditions. 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 usually is not present in harbors dug within historical marshes. In systems without historical eelgrass, 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

80

Buzzards Bay and Nantucket Harbor (Woods Hole Oceanographic Institution) and New Bedford (SMAST).

## VII.2 BOTTOM WATER DISSOLVED OXYGEN AND CHLOROPHYLL

DO levels near atmospheric equilibration are important for maintaining healthy animal and plant communities, while chlorophyll readings reflect the response of the phytoplankton population to nutrient inputs. These two readings are related as phytoplankton photosynthesis can inflate DO levels and excessive phytoplankton growth can create greater sediment accretion and DO demand. Short-duration oxygen depletions can significantly affect communities even if they are relatively rare on an annual basis. Given the importance of DO as an 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[81] 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. Sesuit Harbor is not listed in the current MassDEP surface water regulations, so it is classified as a SA water[82] under the baseline classification for surface waters not listed in the regulations.[83] SA waters are "designated as excellent habitat."[84]

DO levels will vary depending on the characteristics of estuaries, as 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 due to higher temperatures. 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 and chlorophyll levels can change rapidly, traditional grab sampling programs typically underestimate the frequency and duration of low oxygen or high chlorophyll conditions within shallow embayments.[85] In order to address this, a part of regular MEP procedures was the deployment of autonomous recording oxygen and chlorophyll sensors. Sensor moorings were deployed at two locations in Sesuit Harbor during the summers of 2005 and 2006 in anticipation of a MEP assessment; updated sensor data collection was not included as a task in the 2021-2022 Sesuit Harbor data collection. It should be noted that both sensor deployments were before the 2008 installation of a larger culvert under Bridge Street. Both sensor deployments were moored

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[81] 314 CMR 4
[82] 314 CMR 4.05(4)
[83] 314 CMR 4.06(5)
[84] 314 CMR 4.05(4)(a)
[85] 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.

30 cm above the bottom at north (2005) and south (2006) ends of the main boat basin (**Figure VII-1**).  Sensors were deployed for 26 days and 36 days from the end of June through July in 2005 and 2006, respectively.   The DO and chlorophyll sensors on a YSI 6600 platform were first calibrated in the laboratory and then checked with standard mixtures at the time of initial instrument mooring deployment.  In addition, periodic calibration samples were collected at the sensor depth and, for DO, 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.

DO concentrations during both deployments showed regular variation mostly due to diurnal and tidal influences, but generally showed no impairment.  Similar to other estuaries assessed during the MEP, the Sesuit Harbor marsh sensor deployment showed high frequency DO variation, but generally acceptable concentrations (**Figures VII-2 and VII-3**).   The frequency of DO concentrations less than the MassDEP minimum for SA waters (*i.e.*, 6 mg/L[86]) was very low at both locations (**Table VII-1**).  Frequencies of DO concentrations less than 6 mg/L were lower than other MEP systems along Cape Cod Bay (*i.e.*, Rock Harbor in Orleans,[87] various embayment portions of Wellfleet Harbor[88]).  Neither station had any anoxic measurements (*i.e.*, <1 mg/L) during their deployment.

Chlorophyll-*a* concentrations during both deployments were generally low to moderate (~4-8 µg/L at the lower location in 2005 and 2-8 µg/L at the upper location in 2006; **Figures VII-4 and VII-5**).  Average chlorophyll-*a* concentrations were 5.2 µg/L and 3.9 µg/L in 2005 and 2006, respectively (**Table VII-2**).  Concentrations greater than 10 µg/L only occurred in 2% and 35 of the readings during 2005 and 2006, respectively.  Review of the duration of concentrations greater than 10 µg/L showed that they averaged 4 hours or less, which indicates that regular tidal movements were usually exchanging a large portion of the water column and available water column nitrogen was not producing excessive phytoplankton growth.  Percentage of readings >5 µg/L closely approximated percentages measured in Rock Harbor in Orleans and the healthy habitat portions of Wellfleet Harbor.

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[86] 314 CMR 4.05(4)(a)1.

[87] Howes B., S. Kelley, J. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner.  2007.  Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Threshold for the Rock Harbor Embayment System, Orleans, MA.  SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection.  Boston, MA.  132 pp.

[88] Howes B., S. Kelley, J. S. Ramsey, E. Eichner, R. Samimy, D. Schlezinger, P. Detjens.  2017.  Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Wellfleet Harbor Embayment System, Town of Wellfleet, Massachusetts, Massachusetts Department of Environmental Protection.  Boston, MA.  189 pp.

**Figure VII-1. Locations of Continuous Water Quality Sensors Deployed in Sesuit Harbor.** A sonde sensor mooring was deployed in Sesuit Harbor at two different locations during the summers of 2005 and 2006 in anticipation of a MEP assessment; updated sensor data collection was not included as a task in the 2021-2022 Sesuit Harbor data collection. Both sensor deployments were moored 30 cm above the bottom at locations within the main boat basin: the north/lower location in 2005 and south/upper location in 2006. Sensors were deployed for 26 days and 36 days from the end of June through July in 2005 and 2006, respectively. It should be noted that both sensor deployments were before the 2008 installation of a larger culvert under Bridge Street. The sonde included sensors for chlorophyll-*a* and dissolved oxygen and readings were recorded every 15 minutes. Periodic water quality samples were collected at the sensor depth for QA/QC purposes.
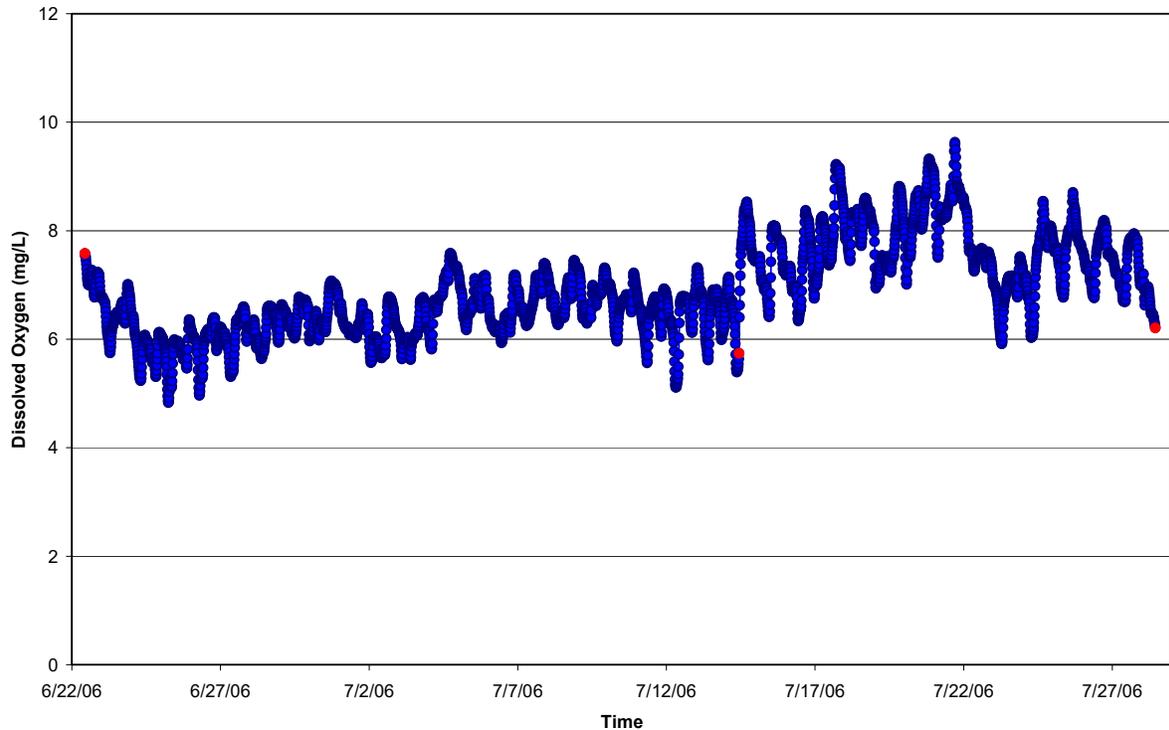
**Figure VII-2. Continuous bottom water record of summer 2006 dissolved oxygen at the Sesuit Harbor Upper station.** Sensor was deployed from June 22 through July 28, 2006 within 30 cm of the bottom with measurements every 15 minutes. Calibration samples are shown as red dots.
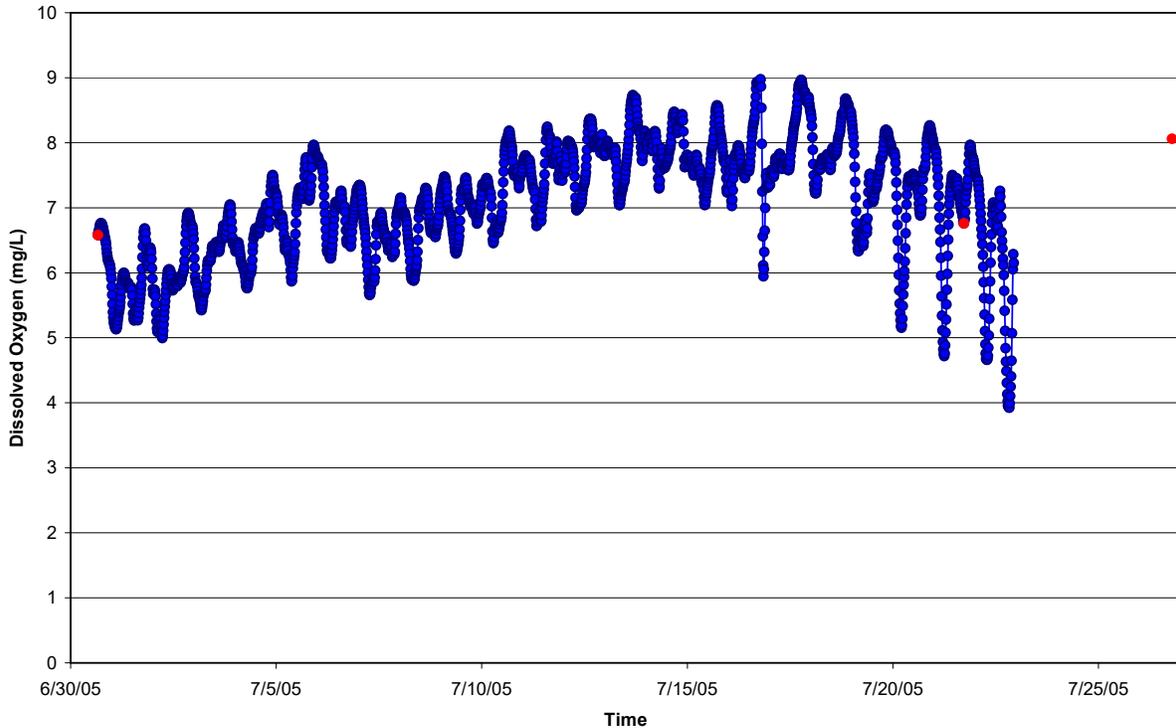


**Figure VII-3. Continuous bottom water record of summer 2005 dissolved oxygen at the Sesuit Harbor Lower station.** A sensor was deployed from June 30 through July 26, 2005 within 30 cm of the bottom with measurements every 15 minutes. Calibration samples are shown as red dots.

**Table VII-1. Continuous dissolved oxygen readings in Sesuit Harbor: percent of time bottom water levels were less than various benchmark dissolved oxygen levels.** MassDEP regulations establish 6 mg/L as a minimum concentration for SA waters, but allow lower concentrations if they are natural conditions. Duration (percent of deployment time) that bottom water dissolved oxygen levels were less than various benchmark levels in Sesuit Harbor during the 2005 and 2006 deployments. Average durations of events less than the benchmark level (in hours) are also shown. All data collected by the Coastal Systems Program, SMAST.

| System | Dissolved Oxygen: Continuous Record | | | | |
|---|---|---|---|---|---|
| | Deployment Days | < 6 mg/L (% of days) | < 5 mg/L (% of days) | < 4 mg/L (% of days) | < 3 mg/L (% of days) |
| Sesuit Harbor Lower 2005 (6/30 - 7/26) | 26.1 | 13% | 1% | 0.2% | 0.0% |
| Duration | average (hrs) | 5.3 | 1.9 | 1.2 | n/a |
| Sesuit Harbor Upper 2006 (6/22 - 7/28) | 36.0 | 12% | 0.2% | 0.0% | 0.0% |
| Duration | average (hrs) | 3.8 | 1.0 | n/a | n/a |

**Table VII-2. Continuous chlorophyll-*a* readings in Sesuit Harbor: percent of time bottom water levels were greater than various benchmark chlorophyll-*a* levels.** Duration (percent of deployment time) that bottom water chlorophyll-*a* levels were greater than various benchmark levels in Sesuit Harbor during the 2005 and 2006 deployments. Average duration of events greater than the benchmark levels (in hours) are also shown. Average chlorophyll-a concentration during the entire 2005 deployment was 5.2 µg/L and 3.9 µg/L during the 2006 deployment. All data collected by the Coastal Systems Program, SMAST.

| System | Chlorophyll-*a* : Continuous Record | | | | |
|---|---|---|---|---|---|
| | Deployment Days | > 5 µg/L (% of days) | > 10 µg/L (% of days) | > 15 µg/L (% of days) | > 20 µg/L (% of days) |
| Sesuit Harbor Lower 2005 (6/30 - 7/26) | 26.1 | 48% | 2% | 0.0% | 0.0% |
| Duration | average (hrs) | 6.5 | 1.9 | n/a | n/a |
| Sesuit Harbor Upper 2006 (6/22 - 7/28) | 36.0 | 29% | 3% | 0.1% | 0.0% |
| Duration | average (hrs) | 7.2 | 4.1 | 1.0 | n/a |

**Figure VII-4. Continuous bottom water record of summer 2006 chlorophyll-a concentrations at the Sesuit Harbor Upper station.** The sensor was deployed from June 22 through July 28, 2006 within 30 cm of the bottom with measurements every 15 minutes. Calibration samples are shown as red dots.
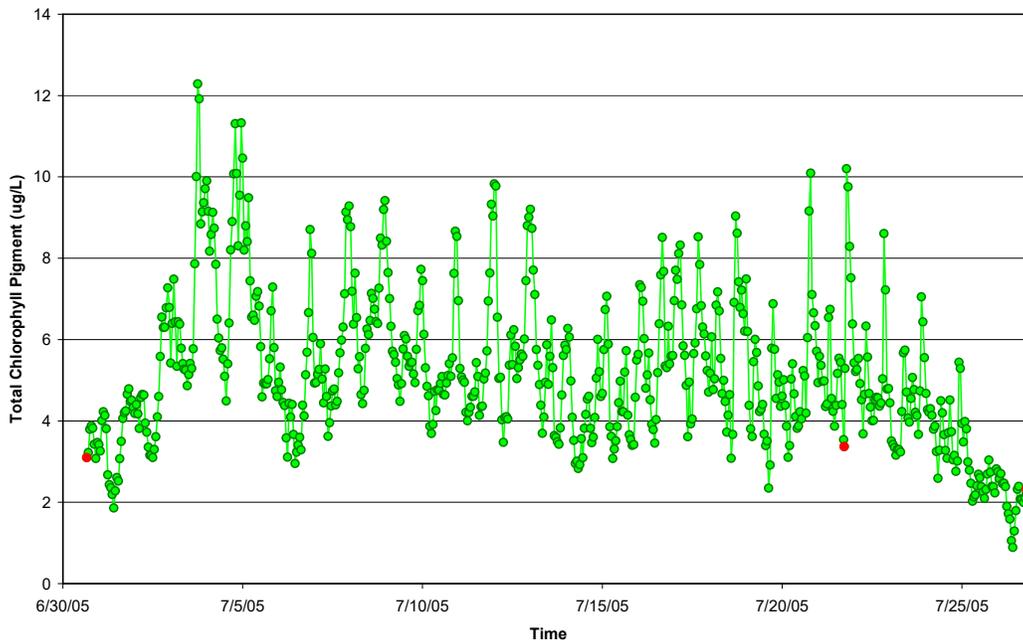


**Figure VII-5. Continuous bottom water record of summer 2005 chlorophyll-a concentrations at the Sesuit Harbor Lower station.** The sensor was deployed from June 30 through July 26, 2005 within 30 cm of the bottom with measurements every 15 minutes. Calibration samples are shown as red dots.
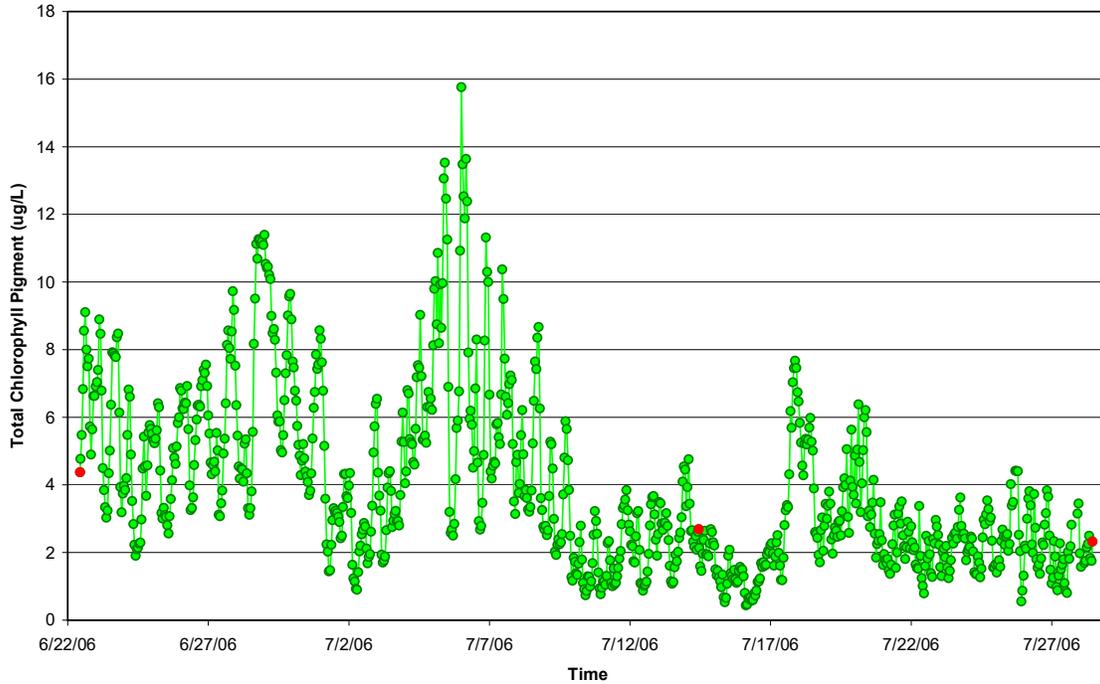
## VII.3  EELGRASS DISTRIBUTION - TEMPORAL ANALYSIS

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.  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.

The history of eelgrass distribution in Sesuit Harbor is complex because of the significant changes that have occurred in the system.  The earliest eelgrass coverage estimates were developed by MassDEP Eelgrass Mapping Program[89] from 1951 Massachusetts Department of Transportation (MassDOT) aerial photos (**Figure VII-6**).  This MassDEP interpretation shows 1.3 acres of eelgrass beds along the edges of the main channel downstream of a more extensive salt marsh system than exists today (see 1943 map in **Figure I-2**).  In 1958, the main boating basin was dredged out of a portion of the upstream salt marsh and by 1961, there were two jetties armoring the inlet and notable changes to the shoreline leading to the basin (see 1961 map in **Figure I-2**).  Four eelgrass surveys have been conducted in the vicinity of the Sesuit Harbor marsh system by MassDEP since 1995, but none of these surveys have indicated eelgrass near the Harbor inlet or within any portion of the Harbor system.  The closest historical eelgrass beds from these surveys are 2.5 km to the west near Corporation Beach (**Figure VII-7**).  CSP/SMAST field activities in 2022 (*i.e.*, collection of sediment cores and benthic infauna samples) noted very sparse eelgrass in the inlet channel (~21 sq ft of bottom), but none was noted in 2005.  Given that the main boating basin of Sesuit Harbor was created in 1958 and the main channel was dredged in 2022, any eelgrass in this portion of the Harbor system is predominantly due to anthropogenic creation of habitat.

During the July 2022 collection of sediment cores, CSP/SMAST divers did note some sparse macroalgae and algal mats at the edges of the main boating channel, but none outside of the area of the Northside Marina slips or in the salt marsh portions of Sesuit Creek.  These areas would have been impacted by the January 2022 dredging of the main channel,[90] so the presence of algal mats may have been due to redistribution and resettling of sediments associated with the dredging.  Typically, the presence of algal mats is indicative of some level of ecosystem impairment.

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[89] https://www.mass.gov/guides/eelgrass-mapping-project
[90] https://www.capecod.gov/2022/02/26/project-summary-sesuit-harbor-dennis-dredging-project/ (accessed 11/28/23)

**Department of Environmental Protection Eelgrass Mapping Program**

**Sesuit Harbor**

**1951 Eelgrass plus field verification points**

**Legend**

- 1951 Historic Eelgrass Resource
- 1995 field verification points
- 2001 field verification points

0  145  290     580     870     1,160
Meters
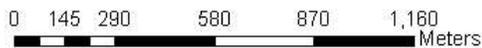
**Figure VII-6. 1951 MassDEP Eelgrass Beds within the Sesuit Harbor Embayment System.** MassDEP interpreted 1951 MassDOT aerial photographs to delineate eelgrass beds.  This interpretation showed 1.3 acres of eelgrass near the Sesuit Harbor inlet (gold cross-hatched area). In 1951, the boat basin area was a salt marsh with a downstream extension of the creek that exists today (shown on the base map for this figure).  In 1958, the boat basin was dredged within the salt marsh area and the jetties at the inlet were completed by 1961.  Subsequent MassDEP eelgrass mapping from 1995 through 2015/2017 showed no eelgrass in the area (confirmed by the indicated yellow and blue dots in the figure).  All data was provided by the DEP Eelgrass Mapping Program.
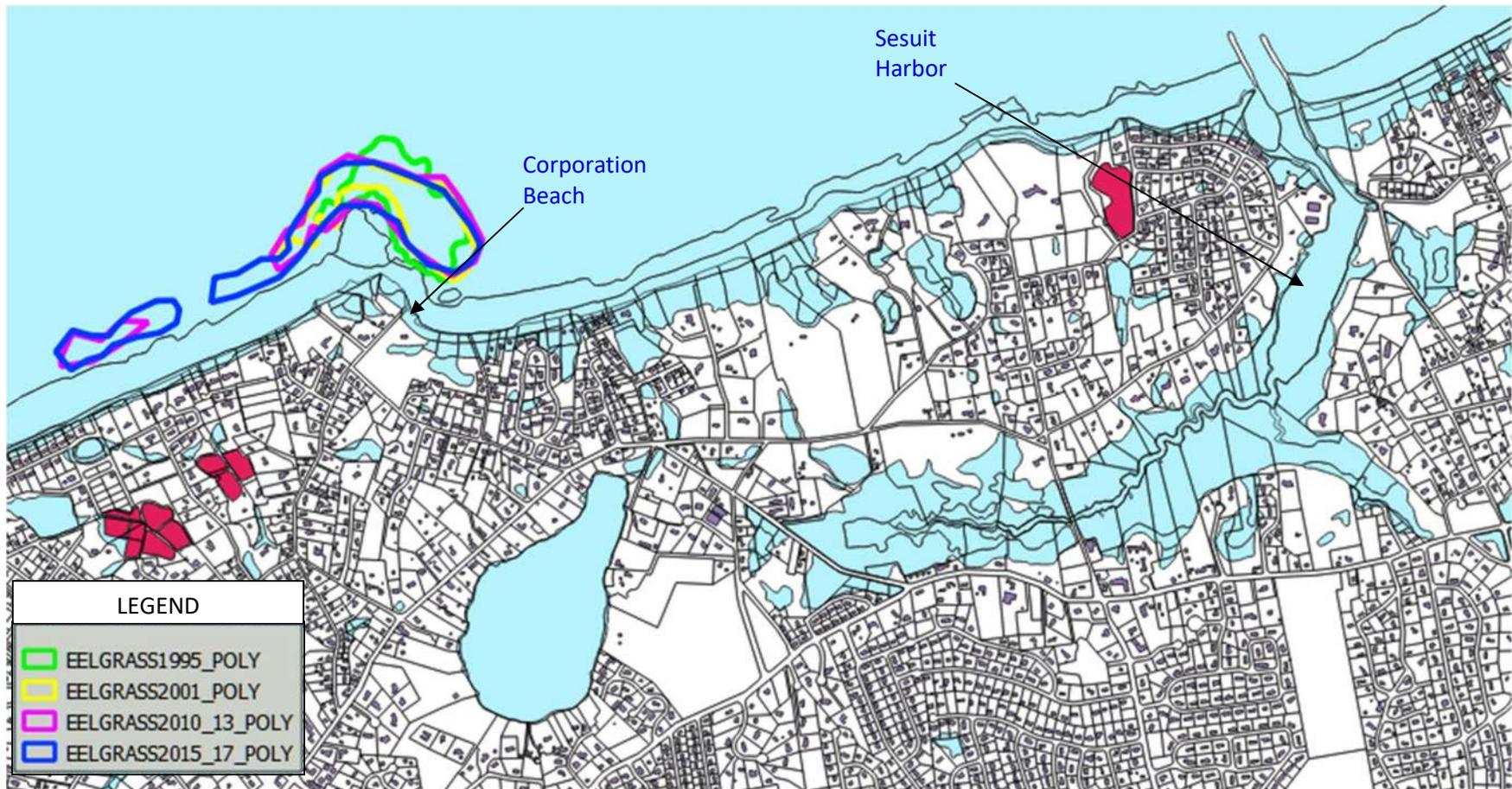
**Figure VII-7. 1995-2017 MassDEP Eelgrass Beds near Sesuit Harbor system.** Delineation of eelgrass beds mapped by MassDEP in 1995, 2001, 2010/2013, and 2015/2017 based on aerial interpretation show the same general area of coverage 2.5 km west of Sesuit Harbor. None of these reviews showed any eelgrass within Sesuit Harbor. Sesuit Harbor has supported only sparse eelgrass habitat since the 1958 dredging of the boat basin.

## 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 known life-history information and animal-sediment relationships.[91] 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 Sesuit Harbor system, this is due more to the structure of the system and its history than its health. As such, to the extent that Sesuit Harbor 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).

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 the diversity index is <1 and evenness statistic 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.

As part of the current Sesuit Harbor assessment, quantitative sediment infauna sampling was conducted at seven (7) locations with replicate assays at all sampling sites. Infauna samples were collected on November 22, 2022 using standard MEP procedures. Sampling was 10 months after the January/February 2022 dredging was completed, which is sufficient time for the reestablishment of benthic communities representative of current conditions, especially given that the dominant species present tend to have short lifespans and high reproductive rates. Infauna samples were also previously collected December 15, 2005 in preparation for a Sesuit Harbor MEP assessment that was not completed. Both 2022 and 2005 infauna sampling sites in the Sesuit Harbor system are shown in **Figure VII-8**.

The 2022 infauna survey indicated variations in different portions of the Sesuit Harbor estuary, reflecting the salt marsh, inlet, and boat basin. Species adapted to high organic matter loading and sulfidic sediments would be expected in the salt marsh sections, but not in the boat basin or inlet. In the salt marsh portions of the system (2022 sampling stations C8, C11, C13, and C16),

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

oligochaete and polychaete worms are dominant species (69% to 93% of identified species). These types of species often thrive in anoxic sediments, often producing high numbers of individuals. Dominant species were *Tubificoides* spp. ("sludge worms") at both C11 and C16 on opposite sides of Bridge Street and *Paranais littoralis*, which tends to live in brackish conditions, at C13. In the slightly deeper portion of the main salt marsh channel at station C8, the species count was similar to the upstream stations and a polychaete (*Polydora* spp.) was the dominant species, but the second most common species was an amphipod (*Corophium bonelli*). Amphipods are often found in high organic settings, but only in settings with slightly lower organic/nitrogen loads than where oligochaetes and polychaetes are dominant. In the boat basin (station C5), infauna had the highest number of species, highest diversity (3.65) and evenness (0.79) indices of any of the 2022 infauna sites (**Table VII-3**). Dominant species at C5, however, were high organic loading species with polychaetes as 82% of the counted individuals and 79% of the identified species. The two inlet station (stations C1 and C3) had differences with the infauna population at C3, which is closest to the boat basin, dominated by *Capitella capitata,* which is a high organic loading polychaete species and C1, which is closest to the inlet, dominated by an amphipod (*Photis spp.*), which would be consistent with greater tidal flushing near the inlet creating slightly lower organic loads. Overall, these conditions show moderately impaired conditions in the marsh and boat basin and significantly impaired conditions at the inlet.

Comparison of 2022 infauna survey results to 2005 results shows that the system infauna population has generally become more impacted except in the boat basin. In 2005, the infauna survey generally found more diverse and balanced communities than in 2022. Diversity and evenness indices at all sites except near the boat basin decreased in 2022: 18% to 42% decrease in diversity and 20% to 34% decrease in evenness (see **Table VII-3**). The improvements at the boat basin may be due to the pumpout facility that was installed in 2009.[92] Species review in 2005 showed that mostly the same 2022 polychaete species were dominant (>70%) throughout the system, except for at the inlet and near the boat slip where amphipods were the predominant species (49% at C1_05 and 79% at C5_05). Oligochaete worms were only noted within the salt marsh upstream of Bridge Street. The greater presence of amphipods and higher diversity/evenness in 2005 would be consistent with the lower TN concentrations (and resulting lower organic load) measured throughout the system compared to current 2022 conditions.[93] The similar change in salt marsh species on both sides of Bridge Street suggest changes in TN loads rather than changes resulting from the larger culvert under Bridge Street. The decreases in diversity and evenness at the inlet stations, while reduced changes in the interior system, suggest that some of the changes in infauna near the inlet may be due to the relatively recent dredging rather than watershed N load changes.

Overall, the infauna survey indicated that Sesuit Harbor system is supporting impacted infauna habitat with dominance of species that thrive in high organic/nitrogen load environments (*i.e.*, polychaetes). These survey results show moderately impaired conditions in the marsh and basin and significantly impaired conditions at the inlet. The survey results were generally consistent

[92] https://www.mass.gov/doc/2008-cpr-grant-awards/download (accessed 12/1/23).

[93] CSP/SMAST Technical Memorandum. January 11, 2022. Integrated Estuarine Water Quality Database and Review: Swan Pond, Bass River, and Sesuit Harbor. From: B. Howes and E. Eichner. To: D. Young, CDM Smith and T. Andrade, Town Engineer, Town of Dennis. 20 pp.

with the presence of algal mats near the inlet; systems with algal mats tend to have insufficient tidal flushing given current levels of watershed nitrogen loading. In addition, benthic conditions have worsened since 2005 when high organic/nitrogen load species were still dominant, but had higher mixtures of amphipods, which tend to be present in slightly lower organic/nitrogen loading settings. This change in the infauna population is consistent with the increase noted in average TN concentrations since 2005. Based upon all lines of evidence it appears that the Sesuit Harbor Estuary has moderately impaired conditions in the marsh and boat basin and significantly impaired conditions at the inlet.
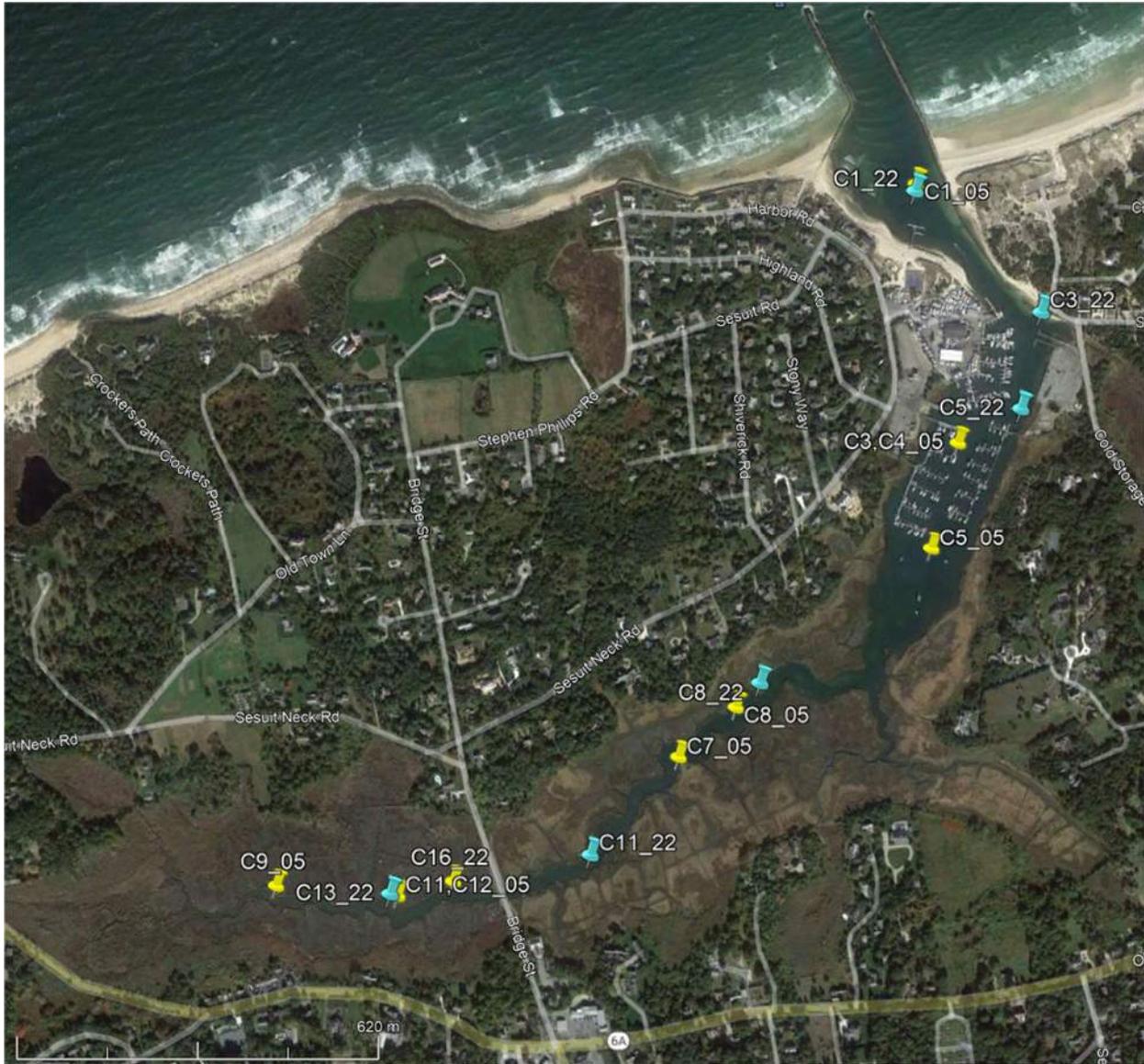


**Figure VII-8. Sesuit Harbor 2022 and 2005 benthic infaunal sampling stations.** Samples were collected on November 22, 2022 at the stations indicated by the yellow pushpin symbols, while samples collected on December 15, 2005 were collected at stations indicated by the blue pushpin symbols. Base map is 10/2021 aerial photograph from Google Earth.

**Table VII-3. Benthic infaunal community data of Sesuit Harbor, Town of Dennis, MA (2022 and 2005).** 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 and two time periods: 2005 and 2022. Samples are grouped by the various sections of the Harbor ecosystem: inlet, boat basin, eastern marsh, and western marsh. Bridge Street is the dividing line between the two sections of marsh. Samples represent a surface area of $0.018 \ m^2$. Stations refer to map in Figure VII-8. Note station numbers in 2022 are not always in the same places as station numbers in 2005. Duplicates were collected at each site. 2022 samples were collected on November 22, while 2005 samples were collected on December 15. Comparison of 2022 and 2005 survey results show that the system generally has community characteristics and species consistent with more impaired conditions in 2022 than in 2005, although there is some improvement near the boat basin.

| Year | System Section | Stations | Average Species | Average Individuals | Average Weiner Diversity (H') | Average Evenness (E) | Diversity index change: 2022-2005 | Evenness index change: 2022-2005 |
|------|----------------|----------|-----------------|----------------------|-------------------------------|----------------------|------------------------------------|-----------------------------------|
| 2022 | INLET | C1, C3 | 7 | 92 | 0.80 | 0.33 | -0.57 | -0.17 |
| 2022 | BASIN | C5 | 25 | 248 | 3.65 | 0.79 | 2.43 | 0.19 |
| 2022 | E MARSH | C8, C11 | 17 | 395 | 2.37 | 0.59 | -0.52 | -0.15 |
| 2022 | W MARSH | C13, C16 | 11 | 315 | 1.76 | 0.60 | -0.51 | -0.21 |
|  |  |  |  |  |  |  |  |  |
| 2005 | INLET | C1 | 7 | 781 | 1.37 | 0.51 |  |  |
| 2005 | BASIN | C3/C4, C5 | 4 | 498 | 1.22 | 0.60 |  |  |
| 2005 | E MARSH | C7, C8 | 16 | 245 | 2.89 | 0.73 |  |  |
| 2005 | W MARSH | C9, C11/C12 | 7 | 512 | 2.27 | 0.81 |  |  |

***Other Benthic Resource Characteristics:***

In addition to benthic infaunal community characterization, MEP-type assessments also review other biological resources assessments for insights into habitat assessments and the development of nutrient thresholds. The Massachusetts Division of Marine Fisheries (MassDMF) has an extensive library of shellfish resources maps which indicate the current status of shellfish growing areas based on the results of sanitary surveys (**Figure VII-9**). As is the case with some systems on Cape Cod, all of the enclosed waters of Sesuit Harbor are classified as conditionally approved for shellfishing. Conditionally approved areas are "closed some of the time due to rainfall or seasonally poor water quality or other predictable events. When open, it is treated as an Approved area."[94] Approved areas are "open to shellfish harvesting for direct human consumption subject to local rules and regulations. Closed only during major coast-wide events (*e.g.*, hurricane, oil spill, red tide event)."

MassDMF has also classified various portions of Sesuit Harbor as supportive of specific shellfish communities (**Figure VII-10**). The major shellfish species with potential habitat within the Sesuit Harbor Estuary are quahogs, soft shell clams, American oyster, and blue mussels. Quahogs have the largest habitat area including the boat basin and a small area of the inlet. Blue mussel habitat includes fringing areas of the harbor and eastern portions of Sesuit Creek within the salt marsh. The benthic infauna survey identified a number of various mollusca species (1-2 individuals per sample), including *Mercenaria mercenaria* (quahog), *Cumingia tellinoides, Gemma gemma* (amethyst gem clam), and *Tellina agillus* (northern dwarf tellin).

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[94] https://www.mass.gov/info-details/shellfish-classification-areas (accessed 12/5/23)

**Figure VII-9. Sesuit Harbor MassDMF Shellfish Growing Sanitary Classification.** All portions of Sesuit Harbor are classified as conditionally approved. https://www.mass.gov/info-details/shellfish-classification-areas (accessed 12/5/23).
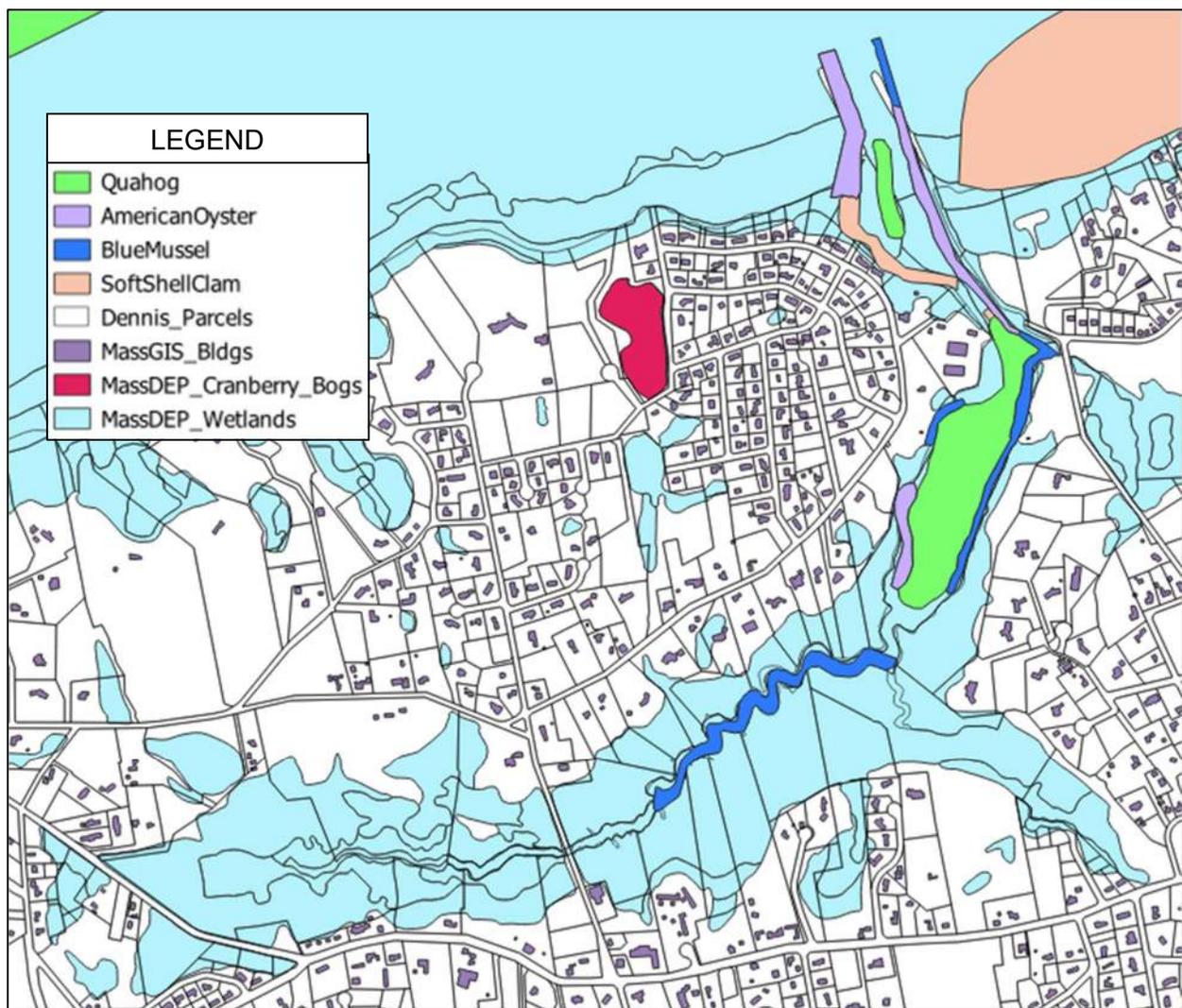
**Figure VII-10. Sesuit Harbor: MassDMF Shellfish Suitability Areas.** MassDMF classified portions of Sesuit Harbor as suitable habitats of species of shellfish in 2011. Habitats for four species were identified in Sesuit Harbor: Quahog, American Oyster, Blue Mussel, and Soft Shell Clams. https://www.mass.gov/info-details/massgis-data-shellfish-suitability-areas#production- (accessed 12/5/23).

# 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 Sesuit Harbor 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 Sesuit Harbor estuary shows a mixed set of habitat health with healthy indicators and significantly impaired indicators in various portions. The boat basin segment of the system generally has healthy habitat indicators, while other segments (*i.e.*, salt marsh and inlet) generally show moderately to significantly impaired indicators, including poor infauna species mixes, high chlorophyll levels, and macroalgae mats. However, historical eelgrass, which has a been a primary indicator for most of the Cape Cod estuaries assessed through the MEP, has only been sparsely and occasionally noted in the system since the 1958 dredging of the salt marsh to create the Harbor boat basin. The system also benefits from the large tidal range in Cape Cod Bay (~10 ft), which exchanges a large portion of the system volume on a daily basis. Assessment of habitat quality must necessarily consider the natural function and tolerances of the various components of the estuarine ecosystem being evaluated (**Table VIII-1**), specifically:

*Eelgrass:* Eelgrass is not present within the estuarine reach of this system. Based upon all available information, it appears that the Sesuit Harbor Estuary is not structured to support significant eelgrass habitat. This structure is similar to other salt marsh dominant systems throughout southeastern Massachusetts and among the system assessed during the MEP that are along Cape Cod Bay, including Sandwich Harbor,[95] Scorton Creek,[96] Namskaket Creek,[97] and Little Namskaket Creek.[98] Rock Harbor in Orleans, which is similar to Sesuit Harbor in that it also has a dredged harbor basin, also did not have historical eelgrass within the system.[99] Because eelgrass is not a primary management focus, threshold development for protection/restoration of this system will focus on infaunal habitat quality.

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[95] Howes B., T. Ruthven, E. Eichner, R. Samimy, J. Ramsey, D. Schlezinger, P. Detjens (2015). Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Sandwich Harbor Estuary, Sandwich, Massachusetts. Massachusetts Department of Environmental Protection. Boston, MA. 173 pp.

[96] 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.

[97] 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.

[98] 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.

[99] 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 Rock Harbor Embayment System, Orleans, MA. SMAST/DEP Massachusetts Estuaries Project, MassDEP. Boston, MA. 132 pp.

***Water Quality:***   Dissolved oxygen concentrations are generally indicative of healthy habitats throughout the Sesuit Harbor estuary, but TN concentrations have notably increased since 2005-2010.  Continuous dissolved oxygen and chlorophyll readings were recorded from near-sediment depths in 2005 and 2006 when TN concentrations were generally lower throughout the Sesuit Harbor system than they are currently.  Similar readings were not collected in 2022.  Continuous DO readings in 2005 and 2006 were less than MassDEP regulatory minimum 13% and 12% of all readings, respectively, which is indicative of generally healthy habitat conditions (Section VII).  Chlorophyll readings, similarly, showed generally healthy habitat conditions.  Regular summer water column sampling in 2017-2022 had DO averages of 5.7 to 6.1 mg/L within the boat basin and inlet and 4.0 to 4.7 mg/L in the salt marsh with minimum readings of 4.3 mg/L and 1.9 mg/L, respectively.  These readings are relatively consistent:  higher concentrations would be expected in the inlet and boat basin, while salt marshes, which are organic and nutrient-rich, typically have periodic oxygen depletion to <2 mg/L.

TN concentrations also had a similar pattern with higher concentrations in the salt marsh and lower concentrations in the inlet and boat basin, but 2017-2022 TN concentrations at all stations had notably higher average TN concentrations than in 2005-2010.  Average TN concentrations in the inlet and boat basin in 2005-2010 were between 0.39 and 0.51 mg/L, while salt marsh stations averaged 0.70 to 0.89 mg/L.  By 2017-2022, these TN ranges had increased to 0.47 to 0.58 mg/L and 0.96 to 1.12 mg/L, respectively (Section VI).

***Infaunal Animal Communities:***  Infauna communities within most sections of the Sesuit Harbor estuary were dominated by species and species assemblages associated with excessive organic/nitrogen loads in 2022 and species had shifted to greater dominance of these species since similar infauna samples collected in 2005 (Section VII).  In 2005, most infauna samples were dominated by assemblages of organic enriched tolerant species (*e.g.*, polychaetes and amphipods), which are typically found in high nutrient settings.  Polychaete dominance would be expected in the salt marsh portion of the estuary, but their dominance throughout the system suggests excessive organic/nitrogen loads.  By 2022, the only station with significant amphipods, which are generally found in settings where organic loads are lower than where polychaetes dominate, was near the inlet.  Review of infauna community diversity and evenness indices similarly indicate decreases at all stations between 2005 and 2022 except for the boat basin.  These changes in the infauna population are consistent with the increases measured in water column TN concentrations.  Based upon all lines of evidence it appears that the Sesuit Harbor Estuary has exceeded its threshold nitrogen level for assimilating additional nitrogen without impairment.

**Table VIII-1. Summary of Nutrient Related Habitat Health within the Sesuit Harbor Estuary.** The tidal reach of this estuary includes salt marsh, dredged boat basin, and armored inlet with historical manipulation. Assessment data presented in Chapter VII is the basis for characterizations in this table.

| Health Indicator | Sesuit Harbor Marsh Estuary | | | |
|---|---|---|---|---|
| | West Salt Marsh | East Salt Marsh | Boat Basin | Inlet |
| Dissolved Oxygen | H[1] | H[1] | H[1] | H[1] |
| Chlorophyll | SI[3] | H[2] | H[2] | H[2] |
| Macroalgae | H[4] | H[4] | H[4] | SI[4] |
| Eelgrass | --[5] | --[5] | --[5] | --[5] |
| Infaunal Animals | MI[6] | H-MI[7] | H[8] | SI[9] |
| **Overall:** | **H-MI[10]** | **H-MI[11]** | **H[12]** | **SI[13]** |

Notes:

1 – field measurements on mid-ebb from 2017-2022 throughout system noted minimum >4 mg/L in inlet and boat basin stations, lower concentrations, but no anoxia, in marsh stations. 2005/2006 July moorings 30 cm off bottom at north and south ends of boat basin recorded DO concentrations >6 mg/L (MassDEP minimum) in 87-88% of readings and no concentrations <3 mg/L.

2 - field measurements on mid-ebb from 2017-2022 throughout system noted mostly low chlorophyll levels (<3 µg/L) except for west salt marsh station. 2005/2006 July moorings 30 cm off bottom at north and south ends of boat basin recorded low average chlorophyll concentrations (3.9 -5.2 µg/L) with minimal readings (0.1%) greater than 15 µg/L.

3 – West salt marsh station averaged high concentration (16 µg/L) in 2017-2022 mid-ebb samples perhaps due to expansion of mud flats after replacement of Bridge Street culvert in 2008.

4 - algal mats and drift algae (*Gracillaria*) present at inlet stations with decreasing density from inlet to boat basin.

5 - no evidence that this estuary is supportive of eelgrass; 1951 survey prior to boat basin dredging noted eelgrass in inlet, but subsequent MassDEP surveys and field confirmation since 1995 have not noted eelgrass in system and very sparse stems were noted in CSP/SMAST 2022 field work.

6 - high numbers of individuals, moderate species numbers, diversity and evenness, stress species (*e.g., Tubificoides*) dominant, notable loss of diversity and evenness since 2005.

7 – high numbers of individuals and species numbers, high-moderate diversity, moderate evenness, stress species are most frequent species, notable loss of diversity and evenness since 2005

8 – high numbers of individuals and species numbers, high diversity and evenness, but stress species are most frequent species, notable increase in diversity and evenness since 2005

9 – low numbers of individuals, species numbers, diversity and evenness, stress species (*e.g., Capitella capitata*), notable loss of diversity and evenness since 2005.

10 – marsh with high DO, high chlorophyll, macroalgae absent, degradation of benthic community since 2005

11 - marsh with high DO, low chlorophyll, macroalgae absent, degradation of benthic community since 2005

12 – basin dredged from salt marsh in 1958, high DO, low chlorophyll, macroalgae absent, no historical eelgrass, improved metrics for benthic community since 2005 (perhaps benefiting from 2009 installation of Harbor pumpout facility)

13 – high DO, low chlorophyll, extensive algal mats and macroalgae, 1951 eelgrass (pre-boat basin dredging), no eelgrass since 1995, benthic stress species, low diversity and evenness, notable loss of benthic individuals, diversity and evenness since 2005.

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 and throughout the system.  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 Sesuit Harbor estuarine system is based primarily upon: 1) the system's structure and functions within the various segments (salt marsh, boat basin, inlet), 2) macroalgal distribution, 3) current benthic community indicators and 4) nitrogen levels.  As a salt marsh dominated estuary, Sesuit Harbor Marsh does not and has not supported notable 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 dominated estuaries of this type is through stimulation of macroalgal production and accumulation.  Given the system-specific assessment data, it is possible to develop a site-specific threshold.

As a result of the present significant impairment of the infaunal habitat and its greater impairment since 2005, the threshold development necessarily focuses on the embayment reach.  The threshold for restoring and maintaining high quality infaunal habitat is 0.50 mg/L TN at a sentinel station at the edge of the boat basin and the eastern edge of the salt march creek (current Town monitoring station SES-4).  This determination is discussed below and the watershed nitrogen loads that will achieve this nitrogen threshold are developed in Section VIII.3.

The recent average TN concentration at SES-4 was elevated and increased since 2005-2010: 0.58 mg/L average in 2017-2022 compared to 0.51 mg/L average in 2005-2010.  The station is between infaunal areas with improved and degraded conditions in 2022 compared to 2005 (*i.e.*, improved in the boat basin and degraded in the eastern salt marsh).  The 0.50 mg/L TN threshold compares well with past MEP assessments, including:

- 0.5 mg/L TN threshold selected for Rock Harbor in Orleans at a station at the upper region of the boat basin with elevated TN levels (0.686 mg/L TN average), stressful levels of summer oxygen depletion (to 2 mg/L DO), sulfidic sediments, and depleted infaunal communities dominated by stress indicator species (*Capitella, Streblospio*) [100]
- 0.5 mg/L TN threshold selected for Saquatucket Harbor in Harwich at a mid-basin station with elevated TN levels (0.658 mg/L TN average), DO levels generally >4 mg/L, moderate to high chlorophyll-*a* concentrations (6-20 µg/L; frequently >20 µg/L); moderate infauna species count, very high individual count, low diversity & evenness, dominated by moderate organic enrichment indicator species (gammrid amphipods) [101]
- 0.5 mg/L TN threshold selected for Wychmere Harbor in Harwich at a mid-basin station with elevated TN levels (0.812 mg/L TN average), DO levels generally >4 mg/L, but sediment signs of recent anoxia, high chlorophyll-*a* concentrations (10-25 µg/L;

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

[101] Howes B., H. Ruthven, J. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner.  2010.

frequently >25 µg/L); drift algae present (Ulva, Gracillaria, Codium), moderate infauna species count, very high individual count, low diversity & evenness, dominated by moderate organic enrichment indicator species (gammrid amphipods)[102]

Based on the observations of the system, the project team concluded that an upper limit of 0.50 mg/L TN at SES-4 would support healthy infaunal habitat throughout the Sesuit Harbor system. Attaining this concentration as SES-4 would lower concentrations and improve infaunal communities in the salt marsh and inlet, while maintaining acceptable conditions in the boat basin segment. This threshold for Sesuit Harbor applies as long as the system maintains its present hydrodynamic characteristics (flushing and velocity). The nitrogen threshold for Sesuit Harbor is intentionally conservative based upon all available data from comparable systems. The nitrogen loads associated with this threshold concentration are discussed below.

## VIII.3  DEVELOPMENT OF TARGET NITROGEN LOADS

Using the recommended 0.50 mg/L TN threshold, project staff used the linked validated water quality model to develop a Sesuit Harbor watershed nitrogen reduction scenario to attain the threshold. Watershed nitrogen loads were sequentially lowered, using reductions in septic effluent discharges only, until the nitrogen levels reached the threshold level at SES-4, the sentinel station chosen for Sesuit Harbor. It is important to note that load reductions can be produced by reduction of any or all sources or by increasing the natural attenuation of nitrogen within the freshwater systems to the embayment. The load reductions presented below represent only one of a number of potential reduction approaches that could be evaluated by the community. The scenario presented here in this section is meant to provide an example that achieves the restoration goals set for the harbor, and demonstrate the general degree and spatial pattern of reduction that will be required for restoration of this nitrogen impaired embayment. A comparison between present septic and total watershed loading and the loadings for the modeled threshold scenario is provided in **Tables VIII-2 and VIII-3**, respectively.

As shown in Table VIII-2, attaining the threshold for the selected scenario would require a 57% overall reduction in nitrogen loads from watershed septic systems with variations in subwatershed reductions varying from 50% to 60%. The overall watershed reduction in nitrogen loads when combined with other sources, *i.e.*, impervious surface and turf loads, is a 48% reduction (see Table VIII-3). **Table VIII-4** shows the nitrogen loads associated with the threshold scenario: reduced watershed loads, current conditions atmospheric deposition loads, and benthic loads adjusted to reflect the changes in the scenario. The distribution of tidally-averaged nitrogen concentrations associated with the threshold scenario is shown in **Figure VIII-1 and Table VIII-5**.

Although the above modeling results provide one manner of achieving the selected threshold level for the system, the specific example does not represent the only method for achieving this goal. However, this example provides a general sense of what could be possible when considering future N loading reductions to the Harbor.

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[102] Howes B., H. Ruthven, J. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner.  2010.

**Table VIII-2. Reductions in Watershed Septic Loads to Attain Threshold Concentration.**  Comparison of sub-embayment watershed *septic loads* (attenuated) used for modeling of present and threshold loading scenarios of the Sesuit Harbor system.  These loads do not include direct atmospheric deposition (onto the sub-embayment surface), benthic flux, runoff, or fertilizer loading terms.

| sub-embayment | present septic load (kg/day) | septic portion of threshold load (kg/day) | threshold % change |
|---|---|---|---|
| Sesuit Harbor | 4.542 | 1.817 | -60.0% |
| Sesuit Creek east | 7.876 | 3.938 | -50.0% |
| Sesuit Creek west | 10.635 | 4.254 | -60.0% |
| **System Total** | **23.052** | **10.008** | **-56.6%** |

**Table VIII-3. Reductions in Overall Watershed Loads to Attain Threshold Concentration.**  Comparison of sub-embayment *total watershed loads* (including septic, runoff, and fertilizer) used for modeling of present and threshold loading scenarios of the Sesuit Harbor system.  These loads do not include direct atmospheric deposition (onto the sub-embayment surface) or benthic flux loading terms.

| sub-embayment | present load (kg/day) | threshold load (kg/day) | threshold % change |
|---|---|---|---|
| Sesuit Harbor | 5.232 | 2.507 | -52.1% |
| Sesuit Creek east | 9.875 | 5.938 | -39.9% |
| Sesuit Creek west | 12.150 | 5.769 | -52.5% |
| System Total | 27.257 | 14.213 | -47.9% |

**Table VIII-4.  Threshold sub-embayment loads used to Attain Threshold Concentration.**  Adjusted total watershed N loads, current conditions atmospheric deposition loads, and benthic loads adjusted to reflect the changes in the scenario are shown.

| sub-embayment | watershed load (kg/day) | direct atmospheric deposition (kg/day) | benthic flux net (kg/day) |
|---|---|---|---|
| Sesuit Harbor | 2.507 | 0.362 | 6.181 |
| Sesuit Creek east | 5.938 | 0.084 | -0.424 |
| Sesuit Creek west | 5.769 | 0.013 | 0.194 |
| System Total | 14.213 | 0.459 | 5.950 |

**Table VIII-5. Comparison present total nitrogen concentration and threshold scenario concentrations.** Modeled average total N concentrations from present loading and the threshold loading scenario. The N threshold station (SES-4) used to determine threshold watershed loading is shown in bold print.

| Location | monitoring station | present (mg/L) | threshold (mg/L) | % change |
|---|---|---|---|---|
| Inlet | SES-1 | 0.460 | 0.447 | -48.1% |
| Lower Harbor basin | SES-2 | 0.470 | 0.451 | -51.4% |
| Cold Storage Rd. Marsh | SES-3 | 0.509 | 0.471 | -50.0% |
| **Upper Harbor Basin** | **SES-4** | **0.563** | **0.496** | **-51.5%** |
| West Sesuit Creek | SES-6 | 0.968 | 0.651 | -59.3% |
| Head of Sesuit Creek | SES-7 | 1.009 | 0.888 | -21.0% |



**Figure VIII-1. Threshold Scenario: contour plot of tidally averaged modeled total nitrogen concentrations (mg/L) in the Sesuit Harbor system.** The location of the threshold sentinel station (SES-4) is indicated.

## IX. WATER QUALITY SCENARIOS: BUILDOUT AND NO ANTHROPOGENIC

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 additional 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)]. Through the current project, buildout and no anthropogenic loading scenarios were requested.

### 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. For the Sesuit Harbor buildout, an additional step was added to review wetland areas based on a MassDEP coverage[103] and reduce buildout potential for lots that include wetland areas.

Other provisions of standard MEP buildout assessments 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 Dennis 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

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[103] MassGIS 2017 coverage, https://www.mass.gov/info-details/massgis-data-massdep-wetlands-2005

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 even though it is in a zoning district with a 40,000 sqft minimum lot size will be assigned an additional residential dwelling in the MEP buildout scenario. 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 the zoning 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 Sesuit Harbor subwatersheds. There is a total of 72 projected new future residential parcels and three parcels classified by the Town Assessor as developable for commercial uses (*i.e.*, land use code 390). In this scenario, each additional residential or commercial 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 Sesuit Harbor watersheds will increase the attenuated system-wide nitrogen loading rate by 5%.

Under buildout conditions, the TN concentration at the sentinel station (SES04) increases to 0.571 mg/L or 6.2% greater than under existing conditions (**Table IX-3**). Overall TN concentrations at the water quality monitoring stations throughout the system increase by 5 to 7% in this scenario compared to current conditions. 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 system nitrogen loads based on no anthropogenic watershed nitrogen loads inputs. 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 (SES04) is 0.426 mg/L (**Table IX-5**). This concentration is 105% lower than current conditions concentration and slightly lower than the Cape Cod Bay background concentration because of the freshwater inputs from the watershed. The Cape Cod Bay background concentration extends from the inlet through the boat basin in this scenario. In this scenario, overall TN concentrations throughout the system decrease by 100% to 170% at the various water quality monitoring stations compared to existing conditions.

**Table IX-1. Buildout Scenario: Developable Parcels in Sesuit Harbor Watershed.** Buildout is based on standard MEP procedures, including reviewing Town Assessor land use classifications and current town zoning, plus a correction for wetland areas. 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. Seventy-two (72) additional residential parcels are projected in the Sesuit Harbor watershed distributed among the indicated subwatersheds. Future commercial development is based on three parcels classified by the Town Assessor as developable for commercial uses.

| Watershed | Shed ID# | Total New residential units | Developable Commercial Properties |
|---|---|---|---|
| | | | sqft |
| Scargo Lake LT10 | 1 | 6 | - |
| Scargo Lake GT10 | 2 | 3 | - |
| Scargo Stream/Sesuit Crk West GT10N | 3 | 6 | - |
| Sesuit Creek West LT10 | 4 | 24 | - |
| Sesuit Creek West GT10 | 5 | 3 | 65,755 |
| Sesuit Creek East LT10 | 6 | 9 | 42,113 |
| Sesuit Creek East GT10 | 7 | 8 | - |
| Sesuit Harbor LT10 | 8 | 12 | - |
| Sesuit Harbor GT10 | 9 | 1 | - |
| Cedar Pond | 10 | 0 | - |
| TOTAL | | 72 | 107,867 |

**Table IX-2. *Buildout* scenario sub-embayment N loads used for total nitrogen modeling of the Sesuit Harbor system**. Total watershed N loads, atmospheric N loads, and benthic flux are shown. System total buildout watershed load is 5.2% higher than existing conditions. 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) |
|---|---|---|---|---|---|
| Sesuit Harbor | 5.499 | 5.232 | 0.362 | 6.736 | 12.730 |
| Sesuit Creek east | 10.288 | 9.875 | 0.084 | -0.580 | -0.565 |
| Sesuit Creek west | 12.880 | 12.150 | 0.013 | 0.317 | 0.306 |
| **System Total** | **28.667** | **27.257** | **0.459** | **6.472** | **12.471** |

**Table IX-3.** **Sesuit Harbor 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 Cape Cod Bay is 0.433 mg/L. Buildout scenario TN concentration at the threshold station (SES04, **bold print**) is *greater than the 0.50 mg/L TN threshold for Sesuit Harbor*.

| Location | Inlet | Lower Harbor basin | Cold Storage Rd. Marsh | **Upper Harbor Basin** | West Sesuit Creek | Head of Sesuit Creek |
|---|---|---|---|---|---|---|
| monitoring station | SES01 | SES02 | SES03 | **SES04** | SES06 | SES07 |
| Present | 0.460 | 0.470 | 0.509 | **0.563** | 0.968 | 1.009 |
| Buildout | 0.462 | 0.472 | 0.513 | **0.571** | 1.005 | 1.042 |
| % change from present | +7.4% | +5.4% | +5.3% | +6.2% | +6.9% | +5.7% |



**Figure IX-1.** **Color contours of tidally-averaged TN concentrations (mg/L) in Sesuit Harbor 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 Sesuit Harbor system**. Total watershed N loads, atmospheric N loads, and benthic flux are shown. System total no-anthropogenic watershed load is 97% lower than existing conditions. 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) |
|---|---|---|---|---|---|
| Sesuit Harbor | 0.123 | 5.232 | 0.362 | 5.712 | 12.730 |
| Sesuit Creek east | 0.300 | 9.875 | 0.084 | -0.272 | -0.565 |
| Sesuit Creek west | 0.286 | 12.150 | 0.013 | 0.097 | 0.306 |
| **System Total** | **0.710** | **27.257** | **0.459** | **5.537** | **12.471** |

**Table IX-5.** **Sesuit Harbor 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 Cape Cod Bay is 0.433 mg/L. No-anthropogenic scenario TN concentration at the threshold station (SES04, **bold print**) is *less than the 0.50 mg/L TN threshold for Sesuit Harbor*.

| Location | Inlet | Lower Harbor basin | Cold Storage Rd. Marsh | **Upper Harbor Basin** | West Sesuit Creek | Head of Sesuit Creek |
|---|---|---|---|---|---|---|
| monitoring station | SES01 | SES02 | SES03 | **SES04** | SES06 | SES07 |
| Present | 0.460 | 0.470 | 0.509 | **0.563** | 0.968 | 1.009 |
| No-anthropogenic loading | 0.433 | 0.433 | 0.433 | **0.426** | 0.322 | 0.03 |
| % change from present | -100.0% | -100.0% | -100.0% | **-105.4%** | -120.7% | -170.0% |

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

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