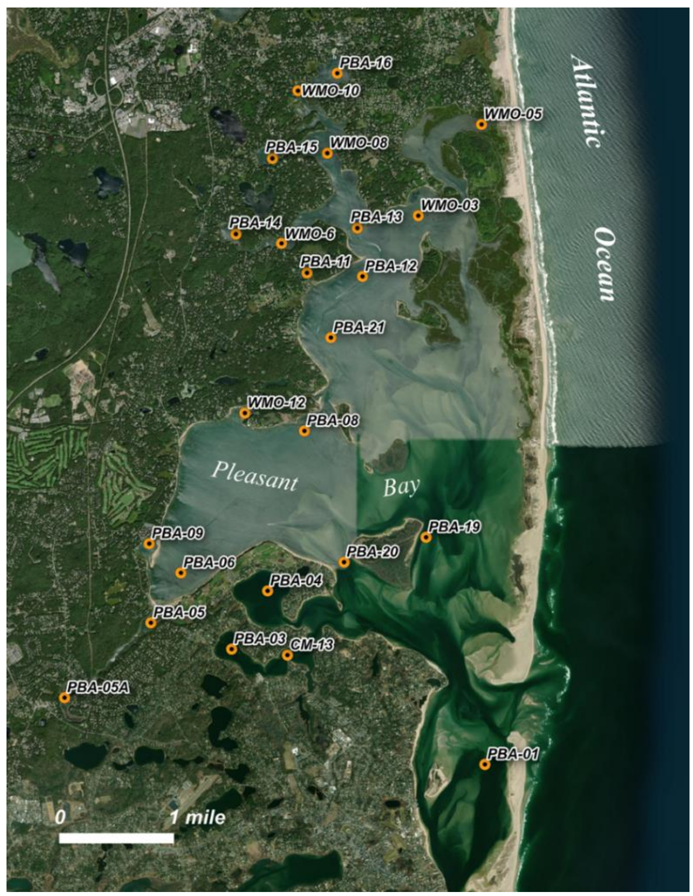
Massachusetts Estuaries Project

Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Pleasant Bay System, Orleans, Chatham and Harwich, Massachusetts

2020 Update



University of Massachusetts Dartmouth
School of Marine Science and Technology

FINAL REPORT – June 2021

Pleasant Bay MEP Update

Southeast New England Watershed Grants Program (SNEP)

Ecosystem Monitoring and Modeling for Implementation (Task 3)
of Regional Watershed Permit Implementation Project for
Nitrogen Management in Pleasant Bay, Cape Cod, MA

FINAL REPORT

June 2021

for the

Pleasant Bay Alliance

Prepared by:

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Pleasant Bay MEP 2020 Update

FINAL REPORT

June 2021

Prepared for

Pleasant Bay Alliance

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Executive Summary

Pleasant Bay MEP 2020 Update

FINAL REPORT
June 2021

The Pleasant Bay estuary is the largest embayment on Cape Cod, Massachusetts and is comprised of large open water areas and a number of smaller tributary sub-embayments, such as Meetinghouse Pond, Areys Pond, Lonnie's Pond, Round Cove, Muddy Creek and Bassing Harbor. The barrier beach that includes the Bay inlet and separates the Bay from the Atlantic Ocean is dynamic and the inlet structure and number changes often.

As part of the Massachusetts Estuaries Project (MEP), the MEP project team completed a 2006 ecological assessment of the Pleasant Bays system that included extensive data collection (*e.g.*, water column data, tidal elevations, bathymetry, sediment nutrient regeneration) and organization of the collected data into a series of linked models of the watershed nitrogen loading, tidal hydrodynamics, and measured water quality. These linked models were calibrated and validated using different sets of water quality parameters so they could be used to reliably predict the impacts of potential nitrogen management options and/or changes to the tidal regime. The MEP assessment concluded that large portions of the system, including all of the terminal ponds, were significantly impaired due to excessive nitrogen and that nitrogen had caused the estuary to lose more than 20% of its eelgrass since 1951.[1]

The Massachusetts Department of Environmental Protection (MassDEP) used the MEP assessment of Pleasant Bay to promulgate 16 nitrogen Total Maximum Daily Loads (TMDLs)[2] for various estuarine segments. TMDLs are required under the Clean Water Act for any state waters that are impaired. Following the 2007 adoption of the TMDLs, the watershed Towns began to work on developing and evaluating potential strategies to reduce nitrogen loads and concentrations to achieve acceptable water quality through Pleasant Bay.

As might be expected in such a highly dynamic system, the Pleasant Bay Estuary has changed since the completion of the MEP assessment. The most significant of these changes relates to the formation of new inlets with associated changes in hydrodynamics. A major shift occurred with the 2007 opening of a large new inlet opposite Allen Point in Chatham, which altered tides and water quality throughout most of the system. Various measurements have been collected to define how the initial post-breach conditions varied and how these conditions changed as the system continued to evolve. Towns in the watershed began to develop Comprehensive Wastewater Management Plans (CWMPs) and other strategies (*e.g.*, the new inlet to Muddy Creek) to address

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[1] 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 Pleasant Bay, Chatham, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 245 pp.

[2] MassDEP. 2007. FINAL Pleasant Bay System Total Maximum Daily Loads For Total Nitrogen (Report # 96-TMDL-12, Control #244.0). 53 pp.

the observed water quality impairments while remaining flexible to accommodate further changes in the Pleasant Bay system.

Through the existing cooperative agreements established through the Pleasant Bay Alliance (PBA), the towns applied to MassDEP for a first-of-its-kind Watershed Permit under the updated Cape Cod 208 project. The 208 Plan provided a structure for coordinated activities by Cape Cod towns to address TMDL provisions and compliance with the Clean Water Act. The 2018 Watershed Permit included a schedule for various Town activities, generally coordinated through CWMPs, to meet the TMDL nitrogen limits. The schedule and the nitrogen reduction activities were included in a 2018 Pleasant Bay Targeted Watershed Management Plan (TWMP). The TWMP schedule included provisions to incorporate new insights and the impact of changes in the system since the completion of the MEP assessment through regular adaptive management review.

In 2018, the PBA, Towns, and Coastal Systems Program at the School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST), technical lead of the MEP team, began discussing updating the MEP assessment of Pleasant Bay to better reflect current conditions in the Bay and using the updated linked models to review the water quality impacts of planned Town nitrogen management strategies. Using resources from the Southeast New England Coastal Watershed Restoration Program (SNEP) grant program and the Towns, CSP/SMAST and the rest of the MEP Technical Team updated key portions of the MEP linked models and provided updated tools for reliably predicting the impacts of potential nitrogen management options and/or changes to the tidal regime.

In the SNEP update completed for this project, the MEP Technical Team collected updated Pleasant Bay data and incorporated it into a new version of the Pleasant Bay linked models. The Team also reviewed more recent eelgrass distribution in the system which showed that eelgrass loss has continued and this showed that the Bay now has 55% less eelgrass than 1951. Updated information included in the SNEP updated assessment of Pleasant Bay:

- Review of 2015 to 2019 monthly summer water quality data
- Collection and incubation of 67 sediment cores to measure nitrogen regeneration
- 2018 bathymetry based on Lidar
- Tidal elevation data from 2017, 2018, and 2019
- Eelgrass areas in 2010 and 2019
- 2019 land use within the watershed with 2011 to 2015 water use for individual parcels, denitrifying septic systems, updated sewered parcels, building areas, agricultural uses, private treatment plant performance
- Natural N attenuation in Tar Kiln and Muddy Creek tributaries

Updated information was incorporated into updated linked models, including a watershed nitrogen loading model based on existing land use conditions, a hydrodynamic model of tidal exchanges and circulation, and a water quality model incorporating the results of the watershed nitrogen loading and the tidal hydrodynamics. Among the notable changes in the input data to the watershed nitrogen loading model from the MEP version were the following:

- 380 additional parcels in the Pleasant Bay watershed (4% increase from the MEP)
- 550 parcels with new municipal water accounts (9% increase from the MEP) and 272 fewer private wells

- 119 innovative and alternative denitrifying septic systems with results from three or more monitoring events (84 of which are in Chatham)
- 158 acres of additional building footprint (61% increase from MEP mainly due to better database records)
- 366 acres of road impervious surfaces (9% increase from MEP)

Among the notable changes in the input data to the tidal hydrodynamic model from the MEP version were the following:

- Meetinghouse Pond tide range has decreased about 17% since its post-breach maximum in 2007, and is now similar to the pre-breach range measured in 2004
- Chatham Fish Pier tide range is essentially the same as it was in 2007
- Muddy Creek residence time has decreased from 3.6 days in 2004 to 0.8 days in 2019 mainly due to the new inlet/bridge.
- Flood tide flow at the reconfigured 2007 breach inlet is divided among Pleasant Bay (85%) and Chatham Harbor (15%)
- Chatham Harbor is close to being functionally separate from the rest of Pleasant Bay with only 2% to 4% of the Bay tidal ebb flow exiting through Chatham Harbor
- Pleasant Bay system volume has decreased by 8% with increases in some subembayments (*e.g.*, Crows Pond, Ryders Cove) and decreases in others (*e.g.*, Muddy Creek, Lonnie's Pond)

The updated SNEP water quality model incorporates the results from the hydrodynamic model and the watershed nitrogen loading model. The model is calibrated with one set of water quality parameters (salinity) and validated with a separate set (bioactive nitrogen). The water quality model check of measured water column concentrations was based on watershed nitrogen loads from existing development and land uses. The overall difference between the measured bioactive nitrogen at the 27 monitoring stations in Pleasant Bay and the modeled results was 4% or 0.018 mg/L. This exceptionally good fit between measured and modeled results is slightly better than the 2006 MEP modeling results and supports the reliability of predictions based on the model.

Once the reliability of the model was ensured, the MEP Technical Team created a watershed nitrogen management scenario based on current nitrogen management plans within each of the four watershed towns. The current plans in the Towns are different than what was included in the 2018 TWMP. Team staff incorporated details from Town staff and their consultants regarding nitrogen management plans including the following for each town:

- Chatham: connect <u>all</u> of its wastewater discharges within the Pleasant Bay watershed (including one private treatment plant) to a sewer system and discharge the treated wastewater outside of the watershed
- Harwich: phased installation of sewers to connect most wastewater discharges within the Pleasant Bay watershed and discharge the treated wastewater outside of the watershed
- Brewster: a) reductions in golf course fertilizers at the town-owned Captains Golf Course and b) installation of innovative/alternative denitrifying septic systems with 12 mg/L TN discharge in two subwatersheds that directly discharge to Pleasant Bay (Freemans Way Well and Tar Kiln Stream)

- Orleans: a) a sewer system to collect wastewater mostly within the Meetinghouse Pond watershed and discharging the treated effluent outside of the Pleasant Bay watershed, b) installing 16 permeable reactive barriers (PRBs) to remove nitrogen from groundwater, and c) enhanced aquaculture in Lonnie's Pond to remove nitrogen within the pond (goal = 300 kg/yr removal)

The net result of the update of the linked MEP models and the town nitrogen management strategies showed that current CWMP activities will collectively attain the Pleasant Bay nitrogen TMDLs at its sentinel stations. The results of the nitrogen management scenario showed that the combined nitrogen management strategies within the four watershed towns generally result in bioactive nitrogen concentrations that meet or are less than the TMDL thresholds at both of the primary sentinel stations and 6 of the 8 secondary stations (Table E-1). The two secondary water monitoring stations where the TMDL thresholds were not attained were WMO-5, Pochet and WMO-6, Namequoit River.

An additional scenario was also completed using the 2020 watershed nitrogen loads in the SNEP model and combined with the watershed reductions in the TWMP. This scenario adjusted watershed loads by removing nitrogen loading reductions Towns have completed since the MEP to avoid "double counting" (*e.g.*, additional sewered properties in Chatham, golf course fertilizer reductions in Brewster, enhanced aquaculture in Orleans/Lonnie's Pond) and utilized the 2020 hydrodynamic model. The TWMP scenario results showed that the combined nitrogen reductions within the four watershed towns generally resulted in bioactive nitrogen concentrations that meet or are less than the TMDL thresholds at both of the primary sentinel stations and 7 of the 8 secondary stations (the TMDL threshold was not attained was WMO-5, Pochet).

The comparison between the results of the two nitrogen management scenarios show that different sets of nitrogen loads can generally attain the TMDL nitrogen thresholds. They also show that Towns may want to reconcile and update the balance of responsibilities among the towns around Pleasant Bay to meet the TMDLs as CWMPs and system hydrodynamics change. During these discussions, Towns should also consider the need to discuss the following factors:

- The impact of future development within the watershed (changes in development between MEP and the SNEP update increased attenuated watershed nitrogen loads by 3% over approximately 10 years).
- The impact of future changes in tidal hydrodynamics. The tidal inlet to Pleasant Bay is constantly readjusting. The current configuration has essentially isolated Chatham Harbor, but the MEP configuration had significant Pleasant Bay flow through this basin.
- The regulatory and planning implications of plans from certain towns to remove more nitrogen than originally planned in the TWMP. For example, Chatham plans to connect all watershed properties to the municipal sewer system, which discharges outside of the Pleasant Bay watershed. This level of nitrogen removal benefits the water quality in the overall Pleasant Bay system, but analysis has not been completed to evaluate how this benefits other towns.

Evaluation of these issues and other anticipated issues could be clarified with additional model runs (*i.e.*, scenarios) using the updated Pleasant Bay model. The updated SNEP version of the Pleasant Bay model was developed using the same procedures approved by EPA and MassDEP for the MEP, including calibration and validation to ensure that the model could be used for predictive analysis of scenarios. As additional changes occur in the Pleasant Bay system and in Town nitrogen management strategies, the linked models can be used to evaluate the responses in water quality throughout this large estuarine systems and changes in the ability to attain the nitrogen TMDLs for Pleasant Bay.

Table E-1. Comparison of model average bioactive N (DIN+PON) concentrations in Pleasant Bay for 2020 present conditions, 2020 Composite loading and the TWMP scenario. The primary sentinel threshold stations (0.16 mg/L target) are shaded orange, secondary threshold stations (0.21 mg/L target) are shaded blue. The Ryders Cove threshold is set as the average of the PBA-03 and CM-13. The Composite and TWMP nitrogen management scenarios attain the target concentration at both sentinel stations. The Composite scenario attains the threshold concentration at all but two of the secondary stations (*i.e.*, WMO-5, Pochet and WMO-6, Namequoit River; both shaded green), while the TWMP scenario attains the threshold at all secondary stations except WMO-5. Although the Composite watershed loads is significantly lower than the TWMP scenario load, the comparisons to the threshold loads are largely the same because of the updated 2020 tidal flushing in Chatham Harbor.

Sub-Embayment	monitoring station	2020 existing (mg/L)	2020 composite (mg/L)	2021 TWMP (mg/L)
Meetinghouse Pond	PBA-16	0.288	0.218	0.218
Meetinghouse @Rattles Dock	WMO-10	0.238	0.196	0.194
Meetinghouse @Off Lonnie's Inlet	WMO-08	0.192	0.171	0.170
Lonnie's Pond	PBA-15	0.246	0.205	0.210
Areys Pond	PBA-14	0.334	0.308	0.284
Namequoit River Upper	WMO-6	0.239	0.220	0.209
The River-Mouth	PBA-13	0.148	0.140	0.138
Pochet - Upper off Town Landing	WMO-05	0.279	0.256	0.230
Pochet - Basin@ Mouth	WMO-03	0.146	0.138	0.137
Little Pleasant Bay - Head	PBA-12	0.139	0.132	0.131
Little Pleasant Bay - Main Basin	PBA-21	0.132	0.126	0.126
Paw Wah Pond	PBA-11	0.207	0.187	0.158
Little Quanset Pond	WMO-12	0.185	0.173	0.159
Quanset Pond	WMO-01	0.153	0.143	0.137
Round Cove	PBA-09	0.254	0.150	0.180
Muddy Creek - Upper	PBA-05A	0.503	0.220	0.427
Muddy Creek - Lower	PBA-05	0.224	0.152	0.192
Pleasant Bay - Head	PBA-08	0.121	0.115	0.115
Pleasant Bay - Upper Strong Island	PBA-19	0.104	0.101	0.101
Pleasant Bay - off Muddy Creek	PBA-06	0.140	0.123	0.129
Pleasant Bay - lower Strong Island	PBA-20	0.103	0.100	0.100
Ryders Cove Upper	PBA-03	0.218	0.140	0.172
Ryders Cove Lower	CM-13	0.113	0.103	0.106
Crows Pond	PBA-04	0.116	0.106	0.112
Chatham Harbor - Upper	PBA-01	0.099	0.098	0.098

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I. Background

The Pleasant Bay estuary is the largest embayment on Cape Cod, Massachusetts and is comprised of large open water areas and a number of smaller tributary sub-embayments, such as Meetinghouse Pond, Areys Pond, Lonnie's Pond, Round Cove, Muddy Creek and Bassing Harbor (Figure I-1). The watershed to the Pleasant Bay estuary includes portions of four towns: Chatham, Harwich, Orleans, and Brewster. The Bay is separated from the Atlantic Ocean by a narrow barrier beach, Nauset Spit, that is located along its easternmost extent. The inlet connection between the Ocean and Bay has historically migrated north and south along the Spit, but has also had some more extreme configurations including multiple inlets and a connection of the Bay to Nantucket Sound.

As part of 10 year regional effort throughout southeastern Massachusetts to assess the ecological status of estuarine waters, the Massachusetts Estuaries Project (MEP) Technical Team completed a 2006 ecological assessment that found that large portions of the Pleasant Bay system were significantly impaired by excessive nitrogen.[3] This assessment included characterization of the ecosystem through a number of complementary measures, including:

- evaluation of six years of water column data,
- collection and incubation of sediment cores at 62 sites to directly measure nitrogen regeneration,
- measurement of benthic animals and characterization of habitat health at 41 locations throughout the system, and
- evaluation of historic and current eelgrass coverages.

This MEP assessment was accompanied by the development of a series of linked models of the watershed nitrogen loading, tidal hydrodynamics, and measured water quality. These linked models were calibrated and validated using different sets of water quality parameters so they could be used to reliably predict the impacts of potential nitrogen management options and/or changes to the tidal regime. The MEP assessment concluded that large portions of the system, including all of the terminal ponds, were significantly impaired due to excessive nitrogen.

The Massachusetts Department of Environmental Protection (MassDEP) used the MEP assessment of Pleasant Bay to promulgate 16 nitrogen Total Maximum Daily Loads (TMDLs)[4] for various estuarine segments (Table I-1). TMDLs are required under the Clean Water Act for any waters that are listed as impaired. Following the 2007 adoption of the TMDLs, the watershed Towns began to work on developing and evaluating potential strategies to reduce nitrogen loads and concentrations to achieve acceptable water quality through Pleasant Bay.

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

[4] MassDEP. 2007. FINAL Pleasant Bay System Total Maximum Daily Loads For Total Nitrogen (Report # 96-TMDL-12, Control #244.0). 53 pp.

Figure I-1. Pleasant Bay and various tributary sub-embayments/terminal ponds.

Table I-1. Massachusetts Department of Environmental Protection Nitrogen Total Maximum Daily Loads (TMDLs) for Pleasant Bay Embayment and Subembayments. In 2007, MassDEP promulgated 16 total nitrogen TMDLs for impaired segments of the Pleasant Bay system and 3 Pollution Prevention TMDLs for segments that were not impaired. TMDLs are the sum of watershed threshold loads, atmospheric deposition on the various segments of the estuary, and sediment inputs. It should also be noted that negative benthic fluxes (*i.e.*, nitrogen removal by the sediments) were set to zero by MassDEP in this table. This table is modified from the Table 5 in the MassDEP Pleasant Bay nitrogen TMDL document (MassDEP, 2007).

Subembayment	**MassDEP Segment ID**	**Impaired by N?**	**TMDL components (kg/d)**			**TMDL (kg/d)**
			Watershed Threshold	**Atmospheric Deposition**	**Benthic Load**	
Meetinghouse Pond		Yes	1.06	0.58	7.86	10
The River – Upper		Yes	1.74	0.29	4.10	6
The River – Lower		Yes	2.44	2.24	8.52	13
Lonnie's Pond		Yes	1.63	0.23	1.30	3
Areys Pond		Yes	0.92	0.18	4.93	6
Namequoit Pond		Yes	1.73	0.52	12.23	14
Paw Wah Pond		Yes	0.73	0.08	2.67	3
Pochet Neck		Yes	4.12	1.77	0	6
Little Pleasant Bay		Yes	5.88	24.09	35.22	65
Quanset Pond		Yes	1.08	0.17	4.79	6
Round Cove		Yes	2.96	0.17	6.74	10
Muddy Creek – Upper	MA96-51_2004	Yes	4.61	0.16	2.70	7
Muddy Creek – Lower	MA96-51_2004	Yes	2.14	0.21	0	2
Pleasant Bay		Yes	21.85	37.01	96.17	155
Ryder Cove – Bassing Harbor	MA96-50_2004	Yes	4.47	1.30	6.71	12
Frost Fish Creek – Bassing Harbor	MA96-49_2004	Yes	0.70	0.10	0	1
Crows Pond – Bassing Harbor	MA96-47_2004	No	4.22	1.39	0.61	6
Bassing Harbor	MA96-48_2004	No	1.67	1.07	0	3
Chatham Harbor	MA96-10_2004	No	17.10	14.15	0	31
System TOTAL			81.25	85.71	194.55	359

As the Towns began reviewing potential Pleasant Bay management options, various ecosystem components measured during the MEP were remeasured, often due to changes within the Bay. Among these events were:

- System hydrodynamics changed significantly in 2007 with the opening of a large new inlet opposite Allen Point in Chatham and measurements at two locations showed increased tidal ranges.[5]
- Between 2006 and 2009, more refined, site-specific measurements of eelgrass coverage in Little Pleasant Bay were collected annually.[6]
- In 2008, a more refined assessment of wetlands, sediment nitrogen regeneration, water quality, and tidal ranges in Muddy Creek was completed.[7]
- MassDEP completed two post-MEP updated eelgrass coverages of Pleasant Bay: 2006/2007 and 2010.
- In 2010, Harwich updated water use with its portion of the Pleasant Bay watershed and asked for an updated review of nitrogen attenuation in Muddy Creek incorporating the updated water use and the results from the refined 2008 targeted assessment.[8]
- Also in 2010, the Pleasant Bay Alliance asked the MEP team to utilize the Harwich update to evaluate the impact of an expanded inlet to Muddy Creek.[9]
- In 2014, benthic, fisheries, harbor seal, and habitat assessment data were collected.[10]
- Tidal elevations trends were evaluated twice: 2012[11] and 2015.[12]
- In 2016, the Muddy Creek inlet connection to the main Bay was expanded by the installation of a new Route 28 bridge.

Throughout all these changes, the Towns and the Pleasant Bay Alliance (PBA) continued to regularly collect water column data. After the 2007 breach, water quality improved in many locations in the Bay based on on-going monitoring, but 2015 statistical trend analysis of the data from 20 sampling stations throughout the Bay showed that none had definitive water quality

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[5] Applied Coastal Research and Engineering, Inc. August 29, 2008. Memorandum to U.S. Army Corps of Engineers, New England District. Hydrodynamic Model of Chatham Harbor/Pleasant Bay including 2007 North Breach. 23 pp.

[6] Neckles, H.A., B.S. Kopp, B.J. Peterson, P.S. Pooler. 2012. Integrating Scales of Seagrass Monitoring to Meet Conservation Needs. *Estuaries and Coasts*. 35:23–46. DOI 10.1007/s12237-011-9410-x.

[7] White, D., B. Howes, S. Kelley, J. Ramsey. 2008. Resource Assessment to Evaluate Ecological & Hydrodynamic Responses to Reinstalling a Water Control Structure in the Muddy Creek Dike. Report to the Pleasant Bay Alliance by the Coastal Systems Program-SMAST, University of Massachusetts-Dartmouth, New Bedford MA. 65 pp.

[8] CSP/SMAST MEP Technical Memorandum. June 25, 2010. Updated water use and Muddy Creek nitrogen attenuation and nitrogen loading to Pleasant Bay. From: E. Eichner, B. Howes, CSP/SMAST. S. Kelley, and J. Ramsey, ACRE. To: D. Young, CDM and F. Sampson, Chair, Harwich Water Quality Management Task Force.

[9] CSP/SMAST MEP Technical Memorandum. October 5, 2010. MEP Scenarios to evaluate water quality impacts of the addition of a 24 ft culvert in Muddy Creek inlet. From: E. Eichner, B. Howes, CSP/SMAST. S. Kelley, and J. Ramsey, ACRE. To: C. Ridley, PBA and B. Duncanson, Chair, Technical Resource Committee, PBA. 8 pp.

[10] Center for Coastal Studies. 2018. Interdisciplinary Multi-scale Marine Ecosystem Assessment: Pleasant Bay, Cape Cod, Massachusetts. 147 pp.

[11] Giese, G.S. 2012. Analysis of Tidal Data from Meetinghouse Pond, Chatham Fish Pier, and Boston: With Application to Management. Provincetown Center for Coastal Studies. 18 pp.

[12] Giese, G.S. and C.G. Kennedy. 2015. Analysis of Tidal Data from Meetinghouse Pond, Chatham Fish Pier, and Boston: January 2012 – June 2015. Provincetown Center for Coastal Studies. 12 pp.

improvements across all of the measured parameters.[13] This finding was consistent with the 2015 review of tidal elevation data that showed the mean tidal range at the two monitored Pleasant Bay locations (Meetinghouse Pond and Chatham Fish Pier) had been decreasing since the 2007 breach and by 2015, the range in Meetinghouse Pond was roughly equivalent to the range of the pre-breach MEP 2004 tidal range.[14]

As the Towns and PBA have worked on development, acceptance, and implementation of management strategies, the regulatory environment has also evolved. During the MEP assessment process and after the MEP report and TMDLs were finalized, Towns were working on Comprehensive Wastewater Management Plans (CWMPs), which included nitrogen management, financial, and implementation strategies to address the impaired waters of Pleasant Bay. While Town CWMPs were being developed, Barnstable County, through the Cape Cod Commission, began working on updated Cape Cod Area-wide Water Quality Management Plan ("208 Plan").[15] This Plan was approved by USEPA and MassDEP in 2015 and included regional updates to water quality policy and implementation. This Plan also included the formal designation of Cape Cod towns as Waste Treatment Management Agencies (WMAs) with requirements to meet the TMDLs through watershed permits and submit "bookend" nitrogen management strategies targeting the use of a) traditional and b) non-traditional technologies. These requirements led many Towns to revisit their CWMP strategies.

In 2018, the Pleasant Bay watershed Towns approved an inter-municipal agreement (IMA) to work through the Pleasant Bay Alliance (PBA) to collectively address the nitrogen TMDLs. The IMA specified that the Towns would work through a Targeted Watershed Management Plan (TWMP)[16] that would specify the nitrogen contributions and responsibilities of each of the watershed Towns. MassDEP approved a Watershed Permit for all four watershed Towns based on the TWMP and the IMA in August 2018.[17]

As the IMA was being developed, PBA and Town staff began having discussions with staff from the Coastal Systems Program at the School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST), technical lead of the MEP team, about updating the MEP assessment of Pleasant Bay and using the updated linked model to review the water quality impacts of planned TWMP strategies. In 2018, selected tasks for this update were incorporated into a Southeast New England Coastal Watershed Restoration Program (SNEP) proposal submitted by PBA. Selected tasks included updating key characteristics of the MEP assessment and linked watershed nitrogen loading, hydrodynamic, and water quality models. Once the models were recalibrated and revalidated, the updated model would be used to evaluate a scenario incorporating the planned Town nitrogen management strategies. Another scenario would also be completed to evaluate TMWP strategies using the MEP 2006 water quality model. Table I-2 shows the MEP system measurements collected and model input used and the information that was updated as part of the current SNEP project. The following chapters provide details on this SNEP effort and summarizes the findings from the two selected scenarios.

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[13] Cadmus Group, Inc. 2015. Pleasant Bay Alliance Water Quality Monitoring Program: Statistical Analysis of 2000-2014 Water Quality Monitoring Data. 97 pp.

[14] Giese, G.S. and C.G. Kennedy. 2015.

[15] Cape Cod Commission. 2015. Cape Cod Area Wide Water Quality Management Plan Update. 254 pp.

[16] Pleasant Bay Alliance. 2018. Pleasant Bay Targeted Watershed Management Plan. 97 pp.

[17] MassDEP. August 3, 2018. Pleasant Bay Watershed Permit. Permit No: 001-0. 16 pp.

Table I-2. Comparison of Pleasant Bay system assessment: MEP and SNEP update. MEP data collection was specified under a MassDEP and USEPA-approved MEP QAPP. An updated QAPP was approved for the SNEP data collection.

HYDRODYNAMIC AND WATER QUALITY MODEL/SYSTEM STATUS				
Task	**MEP Data Dates**	**MEP Details**	**SNEP Data Dates**	**SNEP Details**
Water column measurements	2000 to 2005	Monthly sampling between May and October at 35 stations following PBA QAPP procedures (1995 to 2005 available)	2015 to 2019	Monthly sampling between May and October at 27 stations following PBA QAPP procedures
Sediment nutrient regeneration	2000, 2003 to 2004	Collection and incubation of *in situ* sediment cores from 84 locations to directly measure nutrient regeneration	July/August 2019	Collection and incubation of *in situ* sediment cores from 67 locations to directly measure nutrient regeneration
Benthic infauna community assessment	Nov. 2003	benthic samples at 34 locations to assess infauna population (*i.e.*, species diversity, frequency, etc)	Not replicated	Adequate funding was not available
Continuous bottom waters measurement	2003 to 2004	*in situ* measurement of dissolved oxygen and chlorophyll, 1-2 months at 20 locations	Not replicated	Adequate funding was not available
Bathymetry	1997, 2000, 2004	Integration of three surveys of various portions; 2004 focused on inlet channel; supplemented with ADCP transects	2018	Lidar throughout system; supplemented with reading collected in Chatham Harbor and near inlet
Tidal elevation data	Oct to Nov 2004	7 stations within Pleasant Bay and 2 stations outside of the system for 43 days (sufficient to resolve major tidal constituents via harmonic analysis)	2017, 2018, 2019	7 stations: June 24 to July 24, 2019 Additional gauges: 2018 Muddy Creek gauges: 2017
Tidal current (ADCP) data	Nov 2004	cross-channel flow measurements at the system inlet channel and the mouth of The River through a complete tidal cycle on two dates (used to validate tidal model)		Not done, addressed through additional tidal data
Hydrodynamic modeling		RMA-2 (USACOE) with supplemental pre- and post-processing		Updated RMA-2 (USACOE) with supplemental pre- and post-processing
Streamflow and associated N inputs	2000 to 2005	streamflow and WQ samples from 5 freshwater discharges measured every other week through at least one complete hydrologic year	Not replicated	Relatively small component of overall Pleasant Bay load
Eelgrass Coverage	1951, 1995, 2001	Two surveys (1995 and 2001) MassDEP aerial interpretation with field verification plus 1951 aerial interpretation; CSP/SMAST conducted additional surveys in selected areas (*e.g.*, Bassing Harbor)	2010, 2019	Review of two MassDEP surveys since completion of MEP (2010 and 2019) and Neckles *et al* (2012) refined, targeted area survey

Table I-2 (continued). Comparison of Pleasant Bay system assessment: MEP and SNEP update. MEP data collection was specified under a MassDEP and USEPA-approved MEP QAPP. An updated QAPP was approved for the SNEP data collection.

WATERSHED NITROGEN LOADING MODEL				
Task	**MEP Data Dates**	**MEP Details**	**SNEP Data Dates**	**SNEP Details**
Watershed delineations	2003	95 subwatersheds based on USGS groundwater modeling (Walter and Whealan, 2005)	2003	Same watersheds
Land use/Parcels	1999, 2004	From Town Assessors, varied by town	2019	From Town Assessors, varied by town
Parcel-by-parcel water use (wastewater proxy)	2002 to 2004	From Town water departments, varied by town from 3 year averages to 1 year	2011 to 2015	From Town water departments, years selected to reflect average flows (1)
Denitrifying septic system performance		Not available	2001 to 2018	From BCDHE (2); only systems with 3 or more sampling events/TN
Groundwater discharge permit performance		Only 1 existed; performance not included	2011 to 2017/18	From MassDEP (3); reported TN and flow
Properties connected to sewer	2001	From Town of Chatham (~ 4% in watershed)	2019	From Town of Chatham
Golf courses	2003	4 golf courses; turf-specific areas digitized from aerial photos; N application rates from GC superintendents except for Captains and Cape Cod National, which were being developed at the time	2011 to 2015; 2003	Update of Captains application rates based on 2011 to 2015 averages (4); all other remain same as MEP
Building areas		Not available, 1,500 sqft used for all developed lots based on available regional information	2011 to 2012	Footprints from 2019 MassGIS coverage; all buildings >150 sqft (5)
Road areas		Areas from *ca*. 2003 MassGIS coverage developed by MassDOT	2014 to 2018	Areas from 2019 MassGIS coverage developed by MassDOT (6)
Buildout assessment		Estimates of development on developable parcels based on input from each watershed town		Not completed for SNEP update

Notes:

(1) Water use update years selected based on review of recent average flows between 2008 and 2017 (SMAST Tech Memo, November 25, 2018)
(2) Location and effluent TN concentrations from Barnstable County Department of Health and Environment denitrifying septic system performance database (Emily Michele Olmsted and Brian Baumgaertel, BCDHE, personal communication, October, 2019)
(3) three private wastewater treatment facilities requiring MassDEP Groundwater Discharge Permits: Chatham Bars Inn, Pleasant Bay Health Center, and Wequassett Inn and Resort (Christos Dimisioris and Brian Dudley, personal communication, August, 2019)
(4) Captains GC application rates based on 2011 to 2015 data adjusted for turf area differences provided by HWG (M Nelson, personal communication, August, 2020)
(5) MassGIS (https://docs.digital.mass.gov/dataset/massgis-data-building-structures-2-d, accessed 10/1/19)
(6) MassGIS (https://docs.digital.mass.gov/dataset/massgis-data-massachusetts-department-transportation-massdot-roads, , accessed 10/1/19)

II. 2020 Watershed Nitrogen Loading

The Pleasant Bay MEP watershed nitrogen loading model was composed of individual subwatershed spreadsheets, one for each of the 95 subwatersheds within the system watershed (Figure II-1). These individual subwatershed spreadsheets were linked to a master spreadsheet that includes all of the nitrogen loading factors and calculations of nitrogen loads for each subwatershed and the overall system. The SNEP model update utilized this same construction strategy, while incorporating updated recent inputs, including land use, water use, road areas, wastewater treatment, golf course fertilizers, and building areas.

MEP subwatershed delineations were based on regional USGS groundwater modeling results and these same subwatershed delineations were used in the SNEP update.[18] The individual subwatershed components in both the MEP and SNEP watershed nitrogen loading models contain a listing of each of the parcels within the subwatershed, including those entirely within the subwatershed and those along the subwatershed boundary. Boundary parcels were generally assigned to a subwatershed if the portion of the parcel within the subwatershed was greater than 50% of the total parcel area or the portion within the subwatershed had an area of greater than 10,000 square feet. These split parcels were then re-reviewed to ensure that the sum of all subwatershed parcel areas (both whole and split parcels) was within 2% of the total area of the subwatershed. Select individual split parcels were also reviewed for the likely or actual location of their septic system leachfields. This process was completed again for the SNEP update because additional development and the accompanying division of parcels required a re-review of boundary parcels to match the 2% threshold match between along the subwatershed boundaries since many larger parcels had been subdivided since the MEP review.

<u>II.1. Model Inputs: Watersheds, Land Use, Water Use, Wastewater Treatment</u>

In all MEP assessments, water use was used as a proxy for wastewater generation along with correction factors to account for consumptive use, such as lawn irrigation. Consumptive use will vary, however, based on a number of factors, including how frequently precipitation occurs, whether precipitation is clustered on a few days or spread over many days, and how long and when high temperatures occur during the summer/plant growing season. MEP assessments generally used average water use from each property over a period of years in order to smooth out exceptionally high or low consumptive use years.

In order to avoid exceptionally high or low water use years in the SNEP update, project staff reviewed recent town-wide water uses for all four watershed towns. Project staff recommended that 2011 to 2015 averages best approximated recent average water use after reviewing data from 2008 to 2017.[19] After discussion with the Pleasant Bay SNEP Working Group, this recommendation was accepted and each of the Towns provided parcel-by-parcel water use from these years. These water uses were combined with 2019 Town Assessors' information (*e.g.*, addresses, map and parcel identifiers, etc.) and the parcel delineations through GIS techniques. These techniques were also used to link the Chatham parcels within the Pleasant Bay watershed that were identified as having connections to the municipal sewer system. Any parcels identified by Town Assessors land use classification as developed and did not have a water use assigned in

[18] As well as the 2010, Harwich water use update **(**CSP/SMAST Technical Memorandum. June 25, 2010.**)**

[19] CSP/SMAST Technical Memorandum. November 25, 2018. Selection of Appropriate Water Use Years in MEP Watershed Model Update. From: B. Howes and E. Eichner. To: Pleasant Bay SNEP Working Group. 8 pp.

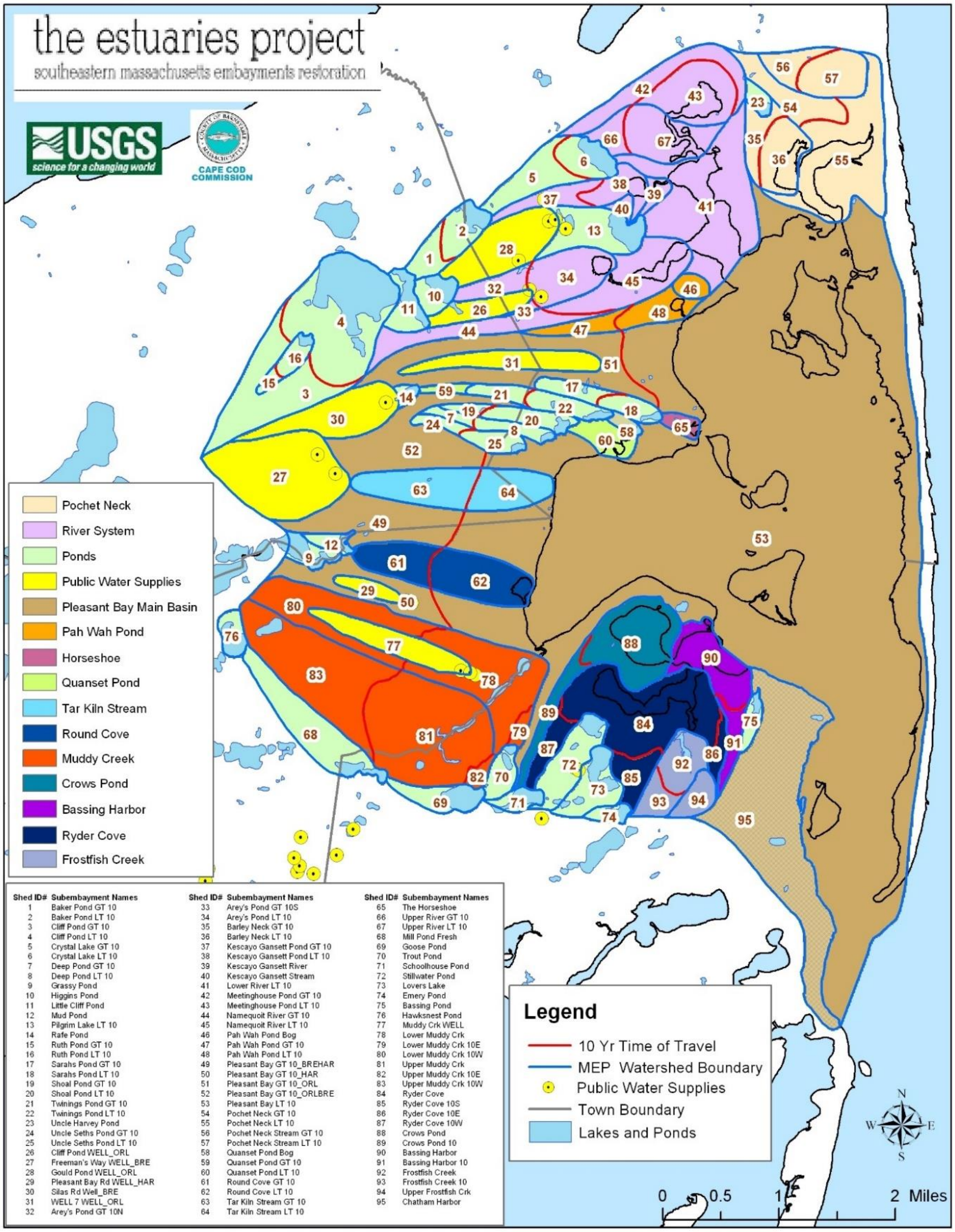

Figure II-1. Pleasant Bay Watershed and Subwatersheds. As part of the MEP, subwatersheds to streams, ponds and lake, subembayments, and 10 year time-of-travel lines were delineated through USGS groundwater modeling. These same watersheds were used in the SNEP update. Modified from Figure III-1 in the Pleasant Bay MEP report (Howes and others, 2006).

the Town water use database were assumed to have a private well on the lot for water supply.[20]

Based on this updated SNEP information, the average water use for all single-family residences within the Pleasant Bay watershed was 159 gallons per day, which was a 7% increase from the MEP average. Review of 2010 US Census information shows that all four towns had a decrease in year-round population and an increase in available housing stock listed as seasonal dwellings. Average 2000 US Census year-round occupancies among the four watershed towns reviewed at the time of the MEP ranged from 2.05 people per occupied housing unit (ppohu) to 2.45 ppohu. These occupancies had decreased to a range of 2.00 ppohu to 2.24 ppohu by the 2010 US Census, while at the same time each town had an increase in the total number of available housing units. Total housing units in the four watershed towns cumulatively increased by 2,314 units between the MEP and SNEP reviews or 231 units per year. Estimates of conservative summer population additions (*e.g.,* increasing by 30%) result in a reasonable match with the measured average residential water use within the watershed. These comparisons also show that land use changes are generally significantly different within the portions of the towns within the Pleasant Bay watershed compared to the town-wide changes.

The SNEP update showed that there were 9,453 parcels completely or partially within the watershed. This parcel count was an increase of 380 parcels (a 4% increase) from the MEP assessment. Of these parcels, 6,502 had municipal water accounts (*i.e.*, measured water use) and among these 5,952 (92%) were single-family residences (SFR). SFR were the predominant land use in the watershed, accounting for 68% of the parcels. The SFR count increased by 151 from the MEP assessment or an addition of approximately 10 per year within the watershed; this increase also means that more than half of the new parcels since the MEP were not SFR. The number of parcels with municipal water accounts increased by 550 (9% increase) since the MEP assessment. In the SNEP update, another 554 parcels had private wells and 70 parcels were connected to the Chatham municipal sewer system. For comparison, the MEP review had 47 sewered parcels in Chatham and 826 private wells in the Pleasant Bay watershed.

The comparison of MEP and SNEP land uses showed that increased development within the watershed changed very slowly; the number of parcels increased by approximately 25 additional parcels per year over the approximately 15 years since the MEP base data was developed. The comparison also showed that water supply infrastructure had also changed since the MEP review: in the SNEP update, private wells decreased by 272, while public water accounts increased by 550. Since this increase in public water connections was more than the increase in the number of parcels (+380), this comparison also shows that many of the properties with private wells at the time of the MEP were connected to public water supply systems by the time of the SNEP update.

As mentioned, water use is used as a proxy for wastewater generation in the MEP approach, but there are also other wastewater treatment options used within the watershed that needed to be incorporated in the watershed nitrogen loading model. Most of the parcels within the Pleasant Bay watershed rely on on-site septic systems for their wastewater treatment, but there are also a number of innovative/alternative (IA) denitrifying septic systems and three private wastewater treatment

[20] Town Assessors utilize a town-specific version of the Massachusetts Department of Revenue land use classification system for describing a property's land use. This classification system divides land uses into 10 categories and is described in MassDOR (2016).

facilities within the watershed. Standard on-site septic system nitrogen loads are based on MEP factors and the water use from each individual parcel, while IA effluent nitrogen monitoring data was used to determine nitrogen loads from properties with IAs installed. Barnstable County Department of Health and Environment (BCDHE) maintains nitrogen monitoring results for IA septic systems within the county and provided monitoring results for IA systems within the four watershed towns for the SNEP update.[21] Project staff determined which systems were located within the Pleasant Bay watershed and determined average total nitrogen concentrations for each IA system that had monitoring data from three or more samplings.[22] As a result, staff determined there were a total of 119 IA systems within the Pleasant Bay watershed that met the criteria established for the SNEP update: 84 in Chatham, 27 in Orleans, 3 in Brewster, and 5 in Harwich. The average TN concentration of the IAs within the watershed was 21.88 mg/L with a range of 4.63 to 172.52 mg/L for individual systems. This average was 83% of the 26.26 mg/L TN used for conventional Title 5 septic systems in the MEP nitrogen loading models.

Individual parcel wastewater nitrogen loads were also adjusted to account for the three private wastewater treatment facilities within the Pleasant Bay watershed. These facilities are required to have Groundwater Discharge Permits (GWDP) through MassDEP: Chatham Bars Inn, Pleasant Bay Health Center, and Wequassett Inn and Resort. MassDEP staff provided seven to eight years of GWDP reported flow and effluent total nitrogen concentrations for all three systems and this information was also incorporated into the SNEP update (Table II-1). Also included in the current conditions update was the identification of properties within the Pleasant Bay watershed that were currently connected to the Town of Chatham sewer system; wastewater nitrogen loads from these properties were removed from the watershed.

Table II-1. Private Wastewater Treatment Facilities within the Pleasant Bay Watershed. All facilities required MassDEP Groundwater Discharge Permits. MassDEP provided flow and effluent TN concentrations that was incorporated into the SNEP update of the Pleasant Bay nitrogen loading model (B. Dudley and C. Dimisioris, personal communications, 8/19).

Facility	MassDEP limits		Data Reviewed	N load in SNEP update
	Flow gpd	TN mg/L	years	kg/yr
Chatham Bars Inn	60,000	10	2011 to 2018	320
Pleasant Bay Health Center	26,500	10	2011 to 2018	102
Wequassett Resort & Golf Club	45,000	10	2011 to 2017	286

Another source of watershed nitrogen incorporated into the MEP watershed nitrogen loading model was fertilizer used at golf courses, cranberry bogs, and residences. Fertilized areas and turf nitrogen loading factors in the SNEP update remained the same as those in the MEP except for the turf application rates at the Captains Golf Course in Brewster. The MEP assessment determined golf course turf types based on review of aerial photos and/or plans, as well as their location within each of the subwatersheds. At the time of the MEP nitrogen loading model development, the Captains Golf Course was under regulatory review/just beginning construction and its nitrogen loads were based on fertilizer rates used for turf establishment. For the SNEP update, the town

[21] Emily Michele Olmsted and Brian Baumgaertel, BCDHE (personal communication 10/4/19).

[22] A minimum of 3 samplings was chosen as a criterion to ensure that outlier events would not to ensure that the N load from one site would be reasonably representative of that site.

consultant provided nitrogen application rates based on actual average 2011 to 2015 fertilizer usage[23] and these rates were incorporated into the updated nitrogen loading model. MEP residential parcel lawn areas, fertilizer application rates, and nitrogen leaching rates remained the same in the SNEP update. A recent updated review of lawn areas in the Town of Orleans found that the MEP factors for lawn area and application rate continue to be reasonable.[24] Nitrogen loads for fertilizers on cranberry bogs were based on bog areas determined by MassDEP for Water Management Act permitting,[25] staff review of whether bogs were flow through or pump on/pump off, and measured loads from other bogs in the ecoregion.[26]

Nitrogen loads from impervious surfaces were also included in both the SNEP update and the MEP watershed nitrogen loading models. In order to update the impervious surfaces nitrogen loads in the SNEP watershed nitrogen loading model, project staff incorporated updated MassGIS databases for building areas and road layouts from what was used in the MEP watershed nitrogen loading model. These databases were more refined than the base data available at the time of the development of the MEP models. At the time of the MEP assessment, available GIS information on building areas was limited throughout the region. In order to address this load in the Pleasant Bay nitrogen loading model, each developed lot was assigned a 1,500 sq-ft building. This building area seemed reasonable at the time based on the available information from other towns on Cape Cod. The building areas used in the SNEP update are much more refined and comprehensive. The MassGIS building area coverage used in the SNEP update is based on measurements made from aerial photos and LiDAR surveys.[27] This coverage includes all buildings greater than 150 sq-ft, including all sheds and garages. The resulting SNEP update has 6,895,583 sq-ft of additional building footprint (+61%) compared to the MEP model. By comparison, the road areas used in the SNEP update are based on an updated version of the same MassGIS/MassDOT coverage used during the MEP. This coverage includes road and right-of-way widths.[28] Total road area in the MEP model was 14,608,354 sq-ft, while it was 15,962,411 sq-ft (+9%) in the SNEP update.

II.2. Model Inputs: Nitrogen Loading Factors

In order to develop the Pleasant Bay watershed nitrogen loads, the MEP nitrogen loading model incorporated a number of nitrogen loading factors that were discussed with and approved by MassDEP. These factors were applied to the input values (*e.g.*, individual parcel water use) in order to develop nitrogen loads from each of the 95 subwatersheds. Table II-2 lists key factors. Most of these factors did not change for the SNEP update.

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[23] Mark Nelson, Horsley Witten Group (personal communication, 3/23/20)

[24] Howes, B., E. Eichner, and A. Unruh. 2016. Updated Watershed Nitrogen Loading from Lawn Fertilizer Applications within the Town of Orleans. Coastal Systems Group, School for Marine Science and Technology, University of Massachusetts Dartmouth. 27 pp.

[25] Jim McLaughlin, MassDEP SERO (personal communication, 8/19/19)

[26] *e.g.*, Howes, B.L. and J.M. Teal. 1995. Nitrogen balance in a Massachusetts cranberry bog and its relation to coastal eutrophication. *Environmental Science and Technology*. 29:960-974; DeMoranville, C., Howes, B., Schlezinger, D. and White, D. (2009). Cranberry Phosphorus Management: How Changes In Practice Can Reduce Output In Drainage Water. *Acta Hortic*. 810, 633-640. https://doi.org/10.17660/ActaHortic.2009.810.84

[27] https://docs.digital.mass.gov/dataset/massgis-data-building-structures-2-d, accessed 10/1/19

[28] SNEP: https://docs.digital.mass.gov/dataset/massgis-data-massachusetts-department-transportation-massdot-roads

Table II-2. Key Nitrogen Loading Factors used in the Pleasant Bay SNEP update. These factors are generally the same as those used in the MEP Pleasant Bay assessment (Howes, *et al.*, 2006) except as noted. Horse loading based on CCC review of nitrogen loading from horses.

Factor	value	units	notes
Nitrogen concentrations			
Road Run-off	1.5	mg N/L	same as MEP
Roof Run-off	0.75	mg N/L	same as MEP
Precipitation on surface waters	1.09	mg N/L	same as MEP
Natural Area Recharge	0.072	mg N/L	same as MEP
Septic system effluent	26.25	mg N/L	same as MEP
Recharge rates			
Impervious surfaces & surface waters	40	in/yr	same as MEP
Natural and lawn areas	27.25	in/yr	same as MEP
Water use: properties with private wells	159	gpd	based on SNEP updates
Fertilizers			
Average Residential Lawn Size	5,000	sqft	same as MEP
Residential N application rate	1.08	lbs N/1,000 sqft	same as MEP
N leaching rate: turf	20%		same as MEP
Cranberry bog: flow through	23.08	kg N/ha/yr	based on MEP updates
Cranberry bog: pump on-pump off	6.95	kg N/ha/yr	
Farm Animals			
Horses	12.96	kg N/animal/yr	added in 2010 Harwich update

II.3. Model Inputs: Nitrogen Attenuation Factors

The MEP watershed nitrogen loading model calculates both unattenuated and attenuated nitrogen loads. Unattenuated nitrogen loads are the subwatershed loads based on the input data and the nitrogen loading factors. The attenuated loads are the loads that arrive at the bay shoreline after natural removal of nitrogen that occurs along the flow paths to the bay.

In the MEP assessment, natural nitrogen removal or attenuation was incorporated for a) larger ponds and lakes and b) streams with direct discharge into Pleasant Bay or its tributary subembayments. As part of the MEP, water quality and flows were measured in five streams over at least one hydrologic year; this provided a direct measurement of nitrogen attenuation and a check on the watershed flows.[29] Since these measurements were not collected again in the SNEP update, the MEP stream attenuation rates were maintained in the SNEP watershed nitrogen loading update (Table II-3).

Ponds and lakes with delineated watersheds were generally assigned a standard 50% nitrogen attenuation rate in all MEP assessments completed in southeastern Massachusetts. Pond-specific attenuation rates were assigned to a small number of ponds where sufficient water quality monitoring was available. During the MEP assessment of Pleasant Bay, none of the ponds in the

[29] See Chapter 4 of the Pleasant Bay MEP report for details on the stream monitoring results.

Table II-3. Site-specific Nitrogen Attenuation Rates used in the Pleasant Bay SNEP update. These factors are generally the same as those used in the MEP Pleasant Bay assessment (Howes, *et al.*, 2006) except as noted.

System	Town	Nitrogen Attenuation Rate	Notes
Streams			
Into Lonnie's Pond	Orleans	70%	same as MEP
Into Paw Wah Pond	Orleans	60%	same as MEP
Tar Kiln Marsh	Orleans	60%	Change from MEP[1]
Into Ryder Cove	Chatham	7%	same as MEP
From Lovers Lake to Stillwater Pond	Chatham	52%	same as MEP
Ponds and Lakes[2]			
Uncle Harvey's Pond	Orleans	50%	same as MEP[3]
Pilgrim Lake	Orleans	50%	same as MEP[4]
Wetland/Estuary			
Upper Muddy Creek	Chatham/ Harwich	10%	Change from MEP and 2008/2010 update[5]
Lower Muddy Creek	Chatham/ Harwich	0%	

Notes
1. In the MEP, gauge readings and water quality samples within the Tar Kiln Marsh stream had a 69% nitrogen attenuation rate, but the stream was not assigned an attenuation rate in the modeling because of uncertainty in the stream data. A 2020 CSP/SMAST focused assessment of the system showed that a reasonable, but conservative, rate could be assigned (Howes and others, 2020).
2. All ponds and lakes within the Pleasant Bay watershed were assigned 50% nitrogen attenuation in the MEP. Uncle Harvey's Pond and Pilgrim Lake are highlighted because recent assessments reviewed nitrogen attenuation.
3. Uncle Harvey's Pond Management Plan review of water quality found that the pond had 58% attenuation (Eichner, E., B. Howes, and D. Schlezinger. 2018.). Attenuation was not changed from MEP standard 50%.
4. Pilgrim Lake Management Plan review of water quality found that the lake had 50% attenuation (Eichner, E., B. Howes, and D. Schlezinger. 2019.). Attenuation was not changed from MEP standard 50%.
5. Upper and Lower Muddy Creek attenuation rates in the MEP were 4% and 0%, respectively. The 2008 focused assessment of Muddy Creek (White and others, 2008) included more extensive water quality measurements of nitrogen entering and leaving the Creek and sediment interactions. In 2010, Harwich watershed loads were updated and attenuation rates were updated to 59% and 2%, respectively (CSP/SMAST Tech Memos). The current change is based on the review of water quality data included in the current project.

watershed, except for the Stillwater Pond/Lovers Lake system, had sufficient water quality monitoring data to assign pond-specific attenuation factor. Stillwater Pond and Lovers Lake had stream monitoring at the connection between the two ponds and at the stream discharge from Stillwater Pond to Ryders Cove.[30] The attenuation rates for this pond system were assigned based on the MEP stream monitoring results and these rates were maintained in the SNEP watershed nitrogen loading update. The other ponds or lakes in the Pleasant Bay watershed maintained the standard 50% nitrogen attenuation rate in the SNEP update. Two ponds in the Orleans portion of the Pleasant Bay watershed recently had sufficiently detailed water quality assessments and nitrogen budgets to provide pond-specific nitrogen attenuation factors. However, the attenuations

[30] See Figure IV-7 in Pleasant Bay MEP report

rates were not changed from 50% since the pond managements studies for Uncle Harveys Pond[31] and Pilgrim Lake[32] showed that 50% nitrogen attenuation continues to be a reasonable attenuation rate for these two ponds.

Tar Kiln Marsh stream is treated differently in the SNEP update than in the MEP or the 2010 update. During the data collection for the MEP, Tar Kiln Marsh stream was one of the streams discharging into Pleasant Bay that had a continuous gauge and regular water quality sampling. These results were synthesized and reported in the MEP report.[33] However, there were sufficient uncertainties in the data and the condition of the marsh system upstream of the gauge that led to a decision by the MEP Technical Team that no attenuation should be assigned to the stream based on MEP QAPP guidance to employ conservative assumptions when uncertainties are high. Recently, CSP/SMAST was asked to complete a more refined review of the Tar Kiln Marsh system by the Orleans Conservation Trust.[34] This review addressed some of the MEP tidal flow characteristics of the marsh and, as such, the SNEP project team has included a conservative 60% nitrogen attenuation within the Tar Kiln Marsh system.

Muddy Creek is part of the Pleasant Bay system that changed significantly between the MEP and the SNEP update. At the time of the MEP data collection, Muddy Creek had a somewhat restricted tidal connection to the main portion of Pleasant Bay; the local residence time for water in Muddy Creek was 3.6 days compared to the other tributary embayments, which were approximately 1 day or less.[35] Following review of water quality and tidal flushing data, the MEP assigned a 4% nitrogen attenuation to Upper Muddy Creek and no nitrogen attenuation to Lower Muddy Creek. In 2008, CSP/SMAST completed a refined assessment of Muddy Creek at the request of PBA to evaluate the potential restoration of a historic dike that used to separate the upper and lower portions.[36] This assessment included collection and incubation of 16 sediment cores to measure sediment nitrogen regeneration (compared to two in the MEP), two tidal flux water quality surveys including measurement of nitrogen portioning of total nitrogen, comprehensive mapping of wetland species and salinity zonation, and benthic community sampling. The new data was synthesized with refined and available historic water quality results and watershed N loading inputs, while also using the MEP model to evaluate the potential impact of reinstalling the dike. The MEP model was not updated or recalibrated with the new regeneration rates or water column nitrogen concentrations. Use of the MEP water quality model showed that reinstallation of the dike would decrease bioactive nitrogen concentration by 11.6%. Based on the two tidal flux water quality surveys and MEP watershed N loads, project staff also estimated that the nitrogen

31 Eichner, E., B. Howes, and D. Schlezinger. 2018. Uncle Harvey's 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.

32 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.

33 Table IV-7 in the Pleasant Bay MEP report

34 CSP/SMAST Technical Memorandum. August 29, 2020. Tar Kiln Salt Marsh: Plant Communities and Tidal Characteristics. From: B. Howes, M. Sundermeyer, P. Mancuso, A. Austin, CSP/SMAST and E. Eichner, TMDL Solutions. To: S. O'Grady, Director, Orleans Conservation Trust. 15 pp.

35 Table V-8 in the Pleasant Bay MEP report

36 White, D., B. Howes, S. Kelley, J. Ramsey. 2008.

attenuation in Upper Muddy Creek was 55% or 57% with minimal attenuation in Lower Muddy Creek.

In 2010, the watershed nitrogen loads to Muddy Creek and other Harwich portions were updated as part of wastewater planning in the Town of Harwich.[37] This update resulted in increased attenuation rates within Upper and Lower Muddy Creek. The MEP Technical Team updated three key components of the MEP Pleasant Bay linked models: 1) updated average Harwich water use from 2004 to 2007 data, 2) updated Harwich land use to 2006, and 3) updated the nitrogen attenuation in Muddy Creek based on the 2008 CSP/SMAST assessment of the system.[38] The loading update also included revised site-specific nitrogen loads for: a) Wequassett Inn, b) addition of farm animals, c) addition of a cranberry bog in the Lower Muddy Creek subwatershed, and d) inclusion of IA denitrifying septic systems in the Upper Muddy Creek subwatershed. No changes based on the 2007 breach or the inlet configuration for Muddy Creek were included in the MEP hydrodynamic model. The overall impact of the Harwich update resulted in: i) a reduced threshold load in Upper Muddy Creek and a decreased septic nitrogen removal to meet the threshold load (75% removal to 66% removal), ii) no change in Lower Muddy Creek (100% septic removal to meet threshold), and iii) an increased nitrogen load in Round Cove, no change in the threshold, and, therefore, a greater septic removal to meet the threshold load (40% removal to 64% removal).

Also in 2010, PBA asked the MEP Technical Team to use the updated MEP model developed for Harwich to evaluate the impact of a larger inlet to Muddy Creek.[39] This request required a modest recalibration and validation of the Pleasant Bay water quality model to ensure that its predictive ability was maintained. These revisions were mostly in the Muddy Creek area to accommodate the increased nitrogen attenuation rates as a result of the refined 2008 assessment. This effort found that the addition of a 24-foot culvert at the head of Muddy Creek would improve water quality in Muddy Creek and would not result in any significant changes in the rest of the Pleasant Bay system. The Team also looked at the potential impact the modeled increase in mean high water (MHW) in Upper Muddy Creek and decided that available data was insufficient to alter the attenuation rate based on uncertain upward movement of the salt marsh. As a result, the MEP Technical Team assigned nitrogen attenuation rates of 57% to Upper Muddy Creek and 2% for Lower Muddy Creek in this review.

<u>II.4. Existing Conditions Watershed Nitrogen Loads</u>

The existing conditions SNEP watershed nitrogen loading model includes all of the updated input data collected during this project and discussed above. Table II-4 shows the loads within each subwatershed divided among the primary watershed loading sources. Wastewater was the primary watershed nitrogen loading source in most subwatersheds. The nitrogen loading model

[37] CSP/SMAST MEP Technical Memorandum. June 25, 2010. Updated water use and Muddy Creek nitrogen attenuation and nitrogen loading to Pleasant Bay. From: E. Eichner, B. Howes, CSP/SMAST. S. Kelley, and J. Ramsey, ACRE. To: D. Young, CDM and F. Sampson, Chair, Harwich Water Quality Management Task Force. 7 pp.

[38] White, D., B. Howes, S. Kelley, J. Ramsey. 2008. .

[39] CSP/SMAST MEP Technical Memorandum. October 5, 2010. MEP Scenarios to evaluate water quality impacts of the addition of a 24 ft culvert in Muddy Creek inlet. From: E. Eichner, B. Howes, CSP/SMAST. S. Kelley, and J. Ramsey, ACRE. To: C. Ridley, PBA and B. Duncanson, Chair, Technical Resource Committee, PBA. 8 pp.

Table II-4. SNEP Update Existing Conditions Watershed Nitrogen Loads Sources. Unattenuated nitrogen loads from the primary watershed nitrogen loading sources are shown. Loads were based on data collected for the SNEP update and MEP nitrogen loading factors and other watershed-specific factors updated since the MEP. Loads do not include nitrogen deposition on estuary surfaces. Attenuated loads are based on natural attenuation in ponds, lakes, and stream as specified in the text. Wastewater was the primary source of watershed nitrogen loading (70%); this percentage is approximately the same as in the MEP (69%). Column values may not sum to totals due to rounding.

	Unattenuated Watershed Nitrogen Loads Components: SNEP Update Existing Conditions (kg/yr)						SNEP Existing Conditions Watershed Loads TOTAL (kg/yr)	
Watershed	Wastewater		Fertilizers	Impervious Surfaces	Water Body Surface Area	"Natural" Surfaces	Unattenuated TOTAL	Attenuated TOTAL
	Septic Systems	WWTF						
Meetinghouse Pond	2,127	0	145	210	0	53	2,535	2,535
The River – upper	759	0	74	94	155	65	1,146	934
The River – lower	1,107	0	107	152	147	99	1,613	1,381
Lonnie's Pond	680	0	69	106	318	96	1,270	801
Areys Pond	442	0	43	60	147	76	768	594
Namequoit River	786	0	73	114	93	89	1,154	1,002
Paw Wah Pond	541	0	47	60	0	32	679	679
Pochet Neck	2,425	0	229	297	32	154	3,138	3,074
Little Pleasant Bay	2,113	71	528	327	73	276	3,389	3,364
Quanset Pond	521	0	43	71	59	36	729	499
Tar Kiln Stream	718	0	701	64	0	43	1,525	610
Round Cove	1,673	0	162	207	14	49	2,105	2,097
The Horseshoe	272	0	26	35	23	24	379	208
Muddy Creek - upper	3,983	0	366	488	186	181	5,204	4,500
Muddy Creek - lower	3,189	0	318	405	85	139	4,137	3,931
Pleasant Bay	5,541	317	2,067	700	437	542	9,602	8,991
Bassing Harbor - Ryder Cove	3,498	0	323	418	439	129	4,807	4,377
Bassing Harbor - Frost Fish Creek	1,024	0	125	135	0	33	1,318	1,318
Bassing Harbor - Crows Pond	1,220	0	102	165	5	39	1,531	1,526
Bassing Harbor	696	0	57	104	5	26	889	875
Chatham Harbor	5,234	320	664	606	31	120	6,974	6,974
TOTAL - System	**38,549**	**708**	**6,269**	**4,818**	**2,249**	**2,301**	**54,894**	**50,271**

produced two sets of nitrogen loads: unattenuated and attenuated. The unattenuated loads are based on the nitrogen loads within each of the subwatersheds and were completed using the same procedures, but different inputs, as the MEP unattenuated loads to provide direct comparison. The attenuated loads incorporate all the nitrogen removed naturally through attenuation in ponds, lakes, and streams.

The existing condition attenuated nitrogen loads are the loads discharged into Pleasant Bay and its tributary embayments. These attenuated loads are the input loads to the linked water quality model and the watershed loading component of the water column nitrogen concentrations measured in the bay. In Table II-5, attenuated and unattenuated SNEP update subwatershed loads are compared to the comparable MEP loads, as well as the comparable 2010 loads based on the Harwich water use updates. The 2010 loads are the last version of the MEP model prior to the completion of the SNEP update that was revalidated for use in making water quality predictions.

Comparison of the SNEP existing conditions watershed nitrogen loads to the 2010 update loads shows only small changes in the overall unattenuated load, but a more significant increase in the attenuated load and within individual subwatersheds (see Table II-5). The unattenuated whole watershed nitrogen load in the 2010 update was 54,826 kg/yr, while the comparable SNEP update load was 54,894 kg/yr (+68 kg/yr or 0.1%). However, changes in unattenuated subwatersheds ranged between -32% (Tar Kiln Stream) and +40% (Bassing Harbor). Similarly, the SNEP attenuated whole watershed load was 2,106 kg/yr greater than the 2010 update (50,771 kg/yr vs. 48,755 kg/yr), but this was only a 4% increase. Among the subwatersheds, changes in attenuated nitrogen loads ranged between -73% (Tar Kiln Stream) and +132% (Muddy Creek – Upper). Obviously changes in nitrogen attenuation created the biggest percent changes in subwatershed loads, but changes in water use rates (*e.g.*, Meetinghouse Pond, +12% in both attenuated and unattenuated loads with a slight decrease in parcels with water use) and distribution of loads (e.g., Chatham Harbor had a 11% increase in attenuated load, while Ryder Cove had a 19% increase) will also have an impact on the water column nitrogen concentrations and ability to meet the TMDLs . Comparison of unattenuated and attenuated whole watershed loads showed that natural nitrogen attenuation within the watershed removed 4,123 kg/yr (8% of the unattenuated system load). This removal rate is approximately the same as the comparison of the MEP attenuated and unattenuated loads (*i.e.*, 7% removal)

II.5. Wastewater Plan Composite Future Nitrogen Loads

In order to address the TMDLs and the terms of the inter-town IMA in coordination with the PBA, the Pleasant Bay watershed towns have been developing nitrogen management strategies through their individual town Comprehensive Wastewater Management Plans (CWMPs). Once all the SNEP existing conditions updates (*e.g.*, sediment regeneration, existing watershed nitrogen loads, tidal movements), were incorporated into the respective Pleasant Bay linked models, the models were recalibrated and revalidated using the same procedures as during the MEP. Once the model was revalidated, it could be used to produce reliable predictions of the impact of various nitrogen management strategies on water quality in the Bay and its various tributary subembayments, as well as meeting the TMDL nitrogen loading thresholds. Project staff reviewed current nitrogen management plans with each of the watershed towns and their respective CWMP consultants in order to incorporate the details of each plan into a nitrogen management scenario using the linked models. The resulting watershed nitrogen loads for this scenario are included in Table II-5.

Table II-5. Comparison of SNEP Watershed Nitrogen Loads (unattenuated and attenuated) to MEP and 2010 watershed N loads. Nitrogen loads are only watershed loads and do not include N loads on the estuary surfaces. Existing SNEP N loads were only slightly greater than the 2010 Update, though the distribution of the loads throughout the watershed was different. Future nitrogen management loads include all current town CWMP nitrogen management strategies based on the 2020 existing conditions update. Watershed groupings are from MEP; various groupings occurred in some of the loading sets (*e.g.*, TWMP loads for Pleasant Bay subwatershed include Little Pleasant Bay, Tar Kiln Stream, and the Horseshoe). Future N management loads attain the target watershed load portions of the assigned TMDLs in 10 of the 19 subwatersheds without consideration of hydrodynamic update, as well as the overall system load (indicated by gold fill). TMDL for Pleasant Bay Main includes Tar Kiln Stream and The Horseshoe.

	MEP				TMDL	SMAST 2010 Update		2018 PBA TWMP	2020 SNEP Update			
	Existing N load (kg/yr)		Threshold N load (kg/y)	reduction to attain threshold	Watershed Threshold Loads	Existing Watershed (kg/yr)		Existing atten (kg/y)	Existing N Load (kg/yr)		Future N Mgmt (kg/yr)	
Watershed	unatten	atten	atten	%	kg/yr	unatten	atten	atten	unatten	atten	unatten	atten
Meetinghouse Pond	2,256	2,256	386	-82.9%	387	2,266	2,266	2,256	2,535	2,535	522	522
The River – upper	1,234	1,012	634	-37.4%	635	1,244	1,023	1,005	1,146	934	915	705
The River – lower	1,655	1,416	892	-37.0%	891	1,678	1,439	1,406	1,613	1,381	1,450	1,226
Lonnie's Pond	1,376	896	593	-33.8%	595	1,385	902	878	1,270	801	1,116	360
Areys Pond	650	475	334	-29.7%	336	655	481	462	768	594	768	594
Namequoit River	1,155	1,001	632	-36.8%	631	1,167	1,010	986	1,154	1,002	945	799
Paw Wah Pond	679	679	266	-60.9%	266	687	687	679	679	679	543	543
Pochet Neck	3,135	3,073	1,505	-51.0%	1,504	3,153	3,091	3,073	3,138	3,074	2,519	2,460
Little Pleasant Bay	2,760	2,736	1,913	-30.1%	2,146	3,466	3,442		3,389	3,364	2,896	2,810
Quanset Pond	865	651	394	-39.5%	394	867	652	641	729	499	704	473
Tar Kiln Stream	2,235	2,235	1,907	-14.7%	-	2,242	2,242		1,525	610	1,196	478
Round Cove	1,554	1,545	1,080	-30.1%	1,080	2,288	2,279	2,278	2,105	2,097	970	962
The Horseshoe	431	233	233	0.0%	-	435	236		379	208	365	201
Muddy Creek - upper	3,955	3,643	1,684	-53.8%	1,683	5,217	2,153	2,168	5,204	4,500	1,610	1,298
Muddy Creek - lower	3,306	3,092	780	-74.8%	781	4,191	3,892	3,920	4,137	3,931	1,448	1,337
Pleasant Bay Main	9,127	8,453	6,067	-28.2%	7,975	10,226	9,770	15,694	9,603	8,991	6,723	5,978
Bassing Harbor - Ryder Cove	4,054	3,609	1,630	-54.8%	1,632	4,123	3,673	3,613	4,807	4,377	1,309	1,048
Bassing Harbor - Frost Fish Creek	1,059	1,059	257	-75.7%	256	1,063	1,063	1,059	1,318	1,318	294	294
Bassing Harbor - Crows Pond	1,542	1,540	1,540	0.0%	1,540	1,568	1,563	1,537	1,531	1,526	312	309
Bassing Harbor	621	609	609	0.0%	610	636	623	607	889	875	192	187
Chatham Harbor	6,241	6,241	6,241	0.0%	6,242	6,269	6,269	6,241	6,974	6,974	1,740	1,740
TOTAL - System	**49,890**	**46,454**	**29,577**	**-36.3%**	**29,583**	**54,826**	**48,755**	**48,503**	**54,894**	**50,271**	**28,537**	**24,324**

It should be noted that these strategies may be further refined as towns evaluate costs and other factors, but the strategies were current at the time of discussion between project and town/consultant staffs. It should also be noted that future additional development/land uses were not included in this nitrogen management scenario (*e.g.*, buildout within the watershed was not assessed); the strategies only apply to the updated current land uses within the watershed. The overview of each of the town strategies in this cumulative Pleasant Bay scenario are briefly summarized here:

Chatham

Based on discussions with Town staff, the current Town of Chatham nitrogen management plan is to connect all of its wastewater discharges within the Pleasant Bay watershed to a sewer system and to_discharge the treated wastewater outside of the watershed.[40] For the purposes of the SNEP nitrogen management scenario, both private wastewater treatment plants within the watershed were also assumed to be connected to the planned sewer system. No other nitrogen management changes to the updated current conditions nitrogen loads within Chatham were included in the SNEP nitrogen management scenario.

Harwich

The Town of Harwich is planning a phased installation of sewers to connect all wastewater discharges within the Pleasant Bay watershed. All collected wastewater would be discharged outside of the watershed **(**Figure II-2**)**.[41] For the purposes of the SNEP scenario, all planned sewering phases occur at the same time. No other changes in updated current nitrogen loads were included in the SNEP scenario.

Brewster

Current Town of Brewster nitrogen management plans focus on two components: a) reductions in golf course fertilizers at the town-owned Captains Golf Course and b) installation of innovative/alternative (IA) denitrifying septic systems in two subwatersheds that directly discharge to Pleasant Bay without passing through freshwater ponds.[42] The proposed fertilizer reductions are in addition to the fertilizer reductions from MEP watershed nitrogen loads and N recapture system (*i.e.*, fertigation) at the golf course that were included in the current conditions SNEP update loads. In addition to the golf course fertilizer changes, the current Town plan also includes IA systems with 12 mg/L TN discharge for all developed properties within the Freemans Way Well (#27) and the Tar Kiln Stream LT 10 (#69) subwatersheds. It was acknowledged that the 12 mg/L TN is lower than any IA systems currently permitted by MassDEP. No other changes in updated current nitrogen loads within Brewster were included in the SNEP nitrogen management scenario.

Orleans

The Town of Orleans is currently planning three steps to address nitrogen management within the town's portion of the Pleasant Bay watershed: 1) a sewer system to collect wastewater mostly within the Meetinghouse Pond watershed and discharging the treated effluent outside of the Pleasant Bay watershed, 2) installing 16 permeable reactive barriers (PRBs) to remove nitrogen from groundwater, and 3) enhanced aquaculture in Lonnie's Pond to remove nitrogen within the pond (Figure II-3). The current target for nitrogen removal by enhanced aquaculture in Lonnie's

[40] Bob Duncanson, Town of Chatham (personal communication, 10/18/19)

[41] David Young, CDM Smith (personal communication, 9/27/19)

[42] Mark Nelson, Horsley Witten Group (personal communication, 8/12/20)

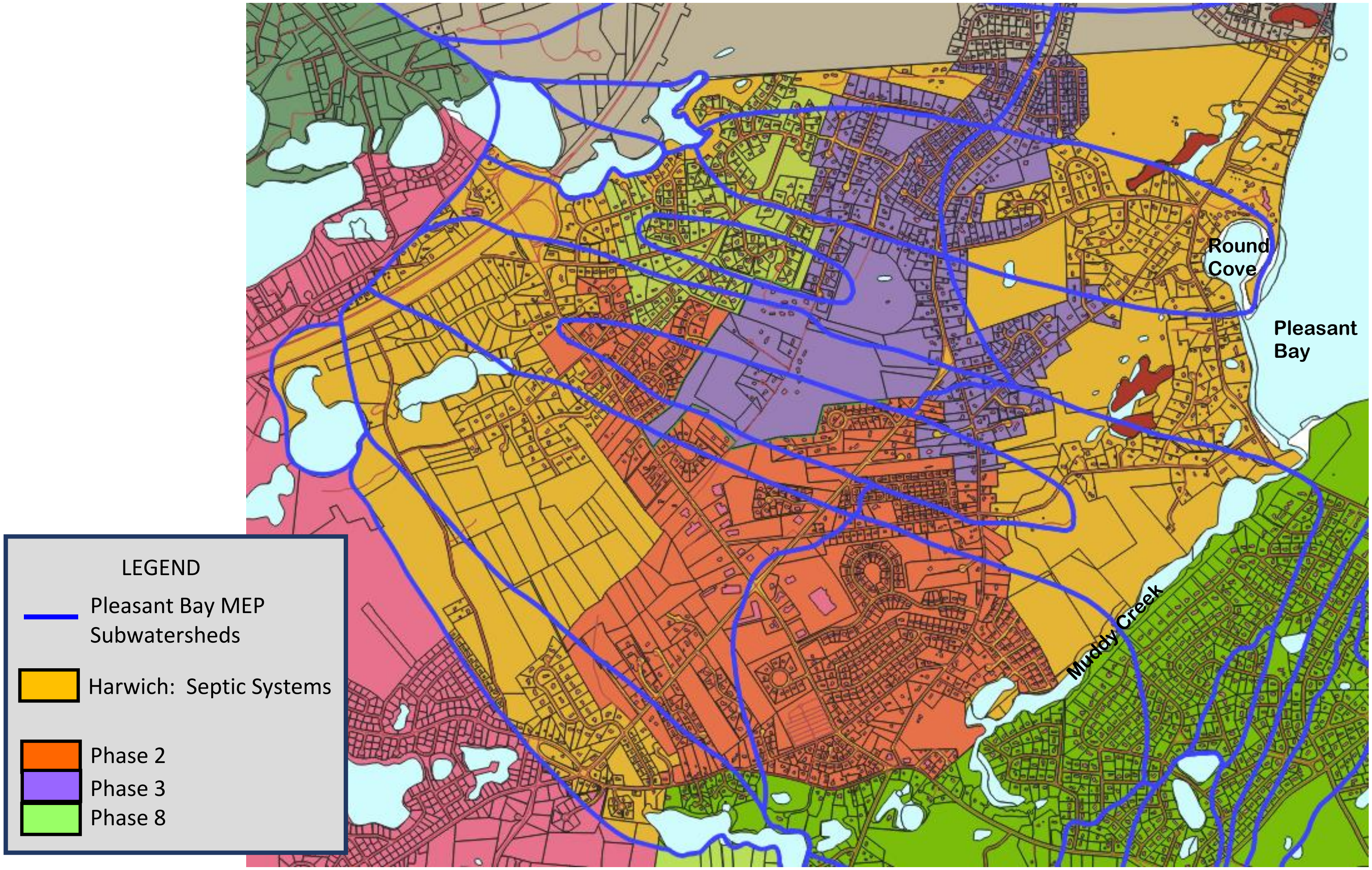

Figure II-2. Town of Harwich Parcels within the Pleasant Bay Watershed and Planned Sewer Phases for Nitrogen Management. The Town of Harwich is currently planning to install sewers over three phases to collect wastewater within the Pleasant Bay watershed and discharge the treated effluent outside of the Pleasant Bay watershed. In the Town nitrogen management scenario completed for the current SNEP project, all three sewering phases were assumed to be implemented. Map is interpretation of sewering plan as of April 2018 (David Young, CDM Smith, personal communication, 9/27/19).

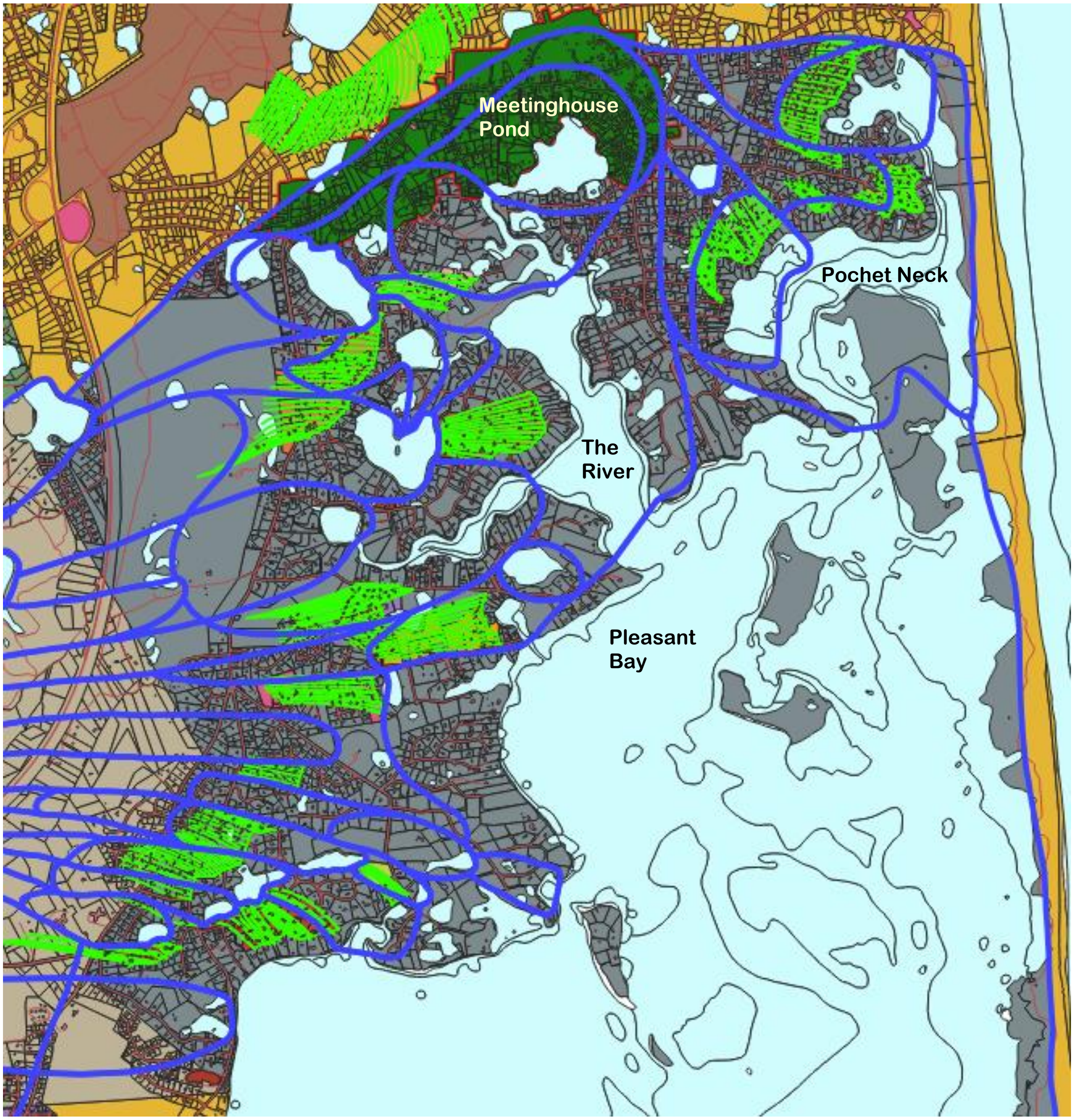

Figure II-3. Town of Orleans Parcels within the Pleasant Bay Watershed and Planned Nitrogen Management Strategies: Meetinghouse Pond Sewer Area and PRB Impact Areas. The Town of Orleans is currently planning to install sewers to collect wastewater within the indicated area mostly upgradient of Meetinghouse Pond (dark green) and discharge the treated effluent outside of the Pleasant Bay watershed. In addition, the current plan calls for the installation of 16 permeable reactive barriers (PRBs) to remove nitrogen within groundwater; the areas impacted by the PRBs are shown by the bright green groundwater flow paths. The Town also intends to continue the Lonnie's Pond enhanced aquaculture program to remove nitrogen from the pond's water column. Map is interpretation of sewering and PRB plan as of February 2020 (Tom Parece, AECOM, personal communication, 2/27/20).

Pond is 75 kg/yr,[43] but the long-term goal for enhanced aquaculture in the CWMP is 300 kg/yr N removal. This higher amount of removal was incorporated into the SNEP nitrogen management scenario and is the entire projected MEP nitrogen removal necessary to meet the threshold N/TMDL.[44]

Nitrogen removal by the planned PRBs required the identification of all properties impacted by the PRBs and determination of an appropriate nitrogen removal rate for the PRBs. After much discussion among project staff and town consultants, a nitrogen removal rate of 80% was assumed for the planned PRBs. This rate was based largely on the performance of the PRB the town installed as a demonstration project near the Nauset Middle School wastewater discharge. This nitrogen removal rate was applied to the existing conditions SNEP loads of wastewater, lawn fertilizers, impervious surfaces (*e.g.*, roofs, roads), and natural areas on properties identified by project staff within estimated groundwater flow paths for each PRB. These flow paths were developed by the Town wastewater consultants using a town-specific groundwater model.[45] Aside from the PRBs, Meetinghouse Pond sewer collection area, and Lonnie's Pond enhanced aquaculture, no other changes in updated current nitrogen loads for Orleans were included in the SNEP nitrogen management scenario.

The overall impact of the town strategies reviewed in the nitrogen management scenario was that 10 subwatershed nitrogen loads were less than the 19 TMDL subwatershed threshold loads and the overall watershed load was less than the system watershed TMDL threshold load (see Table II-5). Orleans had one of the estuary segments that met the TMDL subwatershed loads (Lonnie's Pond), one was in Harwich (Round Cove), four were in Chatham (Ryder Cove, Crows Pond, Bassing Harbor main, and Chatham Harbor), one was shared between Harwich and Chatham (Muddy Creek – upper), and one was shared among all four watershed towns (Pleasant Bay main). Collectively, the planned nitrogen management strategies would reduce updated existing SNEP unattenuated watershed loads by 26,301 kg/yr (-52%).

II.6. Town by Town Nitrogen Loads

A regular part of the IMA and town CWMP discussions has been determining the responsibilities of each watershed town to meet the TMDL individual subwatershed thresholds as well the overall system threshold. During the initial MEP report presentations, the Towns and PBA asked for a town-by-town breakdown of MEP watershed loads.[46] In this review, 31% of MEP attenuated loads were from Orleans, 14% were from Brewster, 18% were from Harwich, and 37% were from Chatham. In the TWMP breakdown, which was based on the 2010 MEP update, attenuated watershed loads from Orleans, Brewster, Harwich, and Chatham were 30%, 13%, 23%, and 34%, respectively.[47]

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[43] Howes, B. and E. Eichner. 2018. Lonnie's Pond Aquaculture and Nitrogen Management Plan. Prepared for the Town of Orleans. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 128 pp.

[44] Table VIII-4 in the Pleasant Bay MEP report

[45] AECOM Technical Memorandum. February 26, 2020. Task 12.1.B.2 - Technical Memorandum: Permeable Reactive Barriers (PRB) Full-Scale Watershed Planning Town of Orleans, Massachusetts – DRAFT. To: G. Meservey, Town of Orleans. From: T. Parece. 38 pp.

[46] Cape Cod Commission Memorandum. November 28, 2007. Individual town nitrogen loads by TMDL watershed/segments to Pleasant Bay. From: E. Eichner. To: PBA Watershed Working Group, Carole Ridley, CCC members. 3 pp.

[47] Pleasant Bay Alliance. 2018. Pleasant Bay Targeted Watershed Management Plan. 97 pp.

In the SNEP update of existing conditions, the town-by-town percentages shift mostly in the relationship between Brewster and Chatham. The percentage of the overall attenuated watershed loads from Orleans, Brewster, Harwich, and Chatham in the SNEP update were 29%, 9%, 24%, and 38%, respectively (Table II-6). The attenuated load from Orleans was divided among 13 subwatersheds with the most loads in Pochet Neck (21% of Orleans total), Meetinghouse Pond (17%), Pleasant Bay Main (12%), Little Pleasant Bay (11%) and less than 10% in portions of 9 other subwatersheds. The attenuated load from Brewster was divided among 10 subwatersheds with 61% of the load added to Pleasant Bay Main, 18% to Little Pleasant Bay, 12% to Tar Kiln Stream and 2% or less of the load added to 7 other subwatersheds. Attenuated load from Chatham was divided among 9 subwatersheds with 39% of the load added to Chatham Harbor, 23% to Ryder Cove, and 10% or less of the load added to 7 other subwatersheds. Attenuated nitrogen load from Harwich was divided among 5 subwatersheds with 31% added to Upper Muddy Creek, 26% to Pleasant Bay Main, 22% to Lower Muddy Creek, 17% to Round Cove, and 4% to Little Pleasant Bay.

The planned implementation of watershed nitrogen management strategies shifted the balance of system nitrogen load among the towns and occasionally altered which subwatersheds were the main contributors to each town's nitrogen loading share of the overall Pleasant Bay watershed load. Implementation of planned strategies in Orleans maintained Pochet Neck subwatershed as the predominant nitrogen source (23%) within the town, but the planned sewering in the Meetinghouse Pond subwatershed reduced its load to approximately 5% of the town's load (see Table II-6). In Brewster, Pleasant Bay Main subwatershed continued to be the predominant source (55%) with Little Pleasant Bay (21%) and Tar Kiln Stream (12%) as the next largest sources. In Harwich, the rank order of subwatershed loads adjusted slightly with the planned sewering within the Muddy Creek subwatershed reducing its load enough to cause Pleasant Bay Main subwatershed to be the largest source of attenuate load (33%) after management strategies are implemented. In Chatham, loads from the Chatham Harbor (34%) and Ryder Cove (20%) subwatersheds remained the largest portions of the overall town attenuated load after implementation of nitrogen management strategies.

Among the Towns, Chatham removed the most nitrogen (13,979 kg/y) through the implementation of nitrogen management strategies. Harwich had the second most nitrogen removed (7,155 kg/yr) followed by Orleans (4,175 kg/yr) and then Brewster (992 kg/yr). Comparison among the town loads to individual subwatersheds showed that Chatham had the most nitrogen removed within a single watershed (5,234 kg/yr removed from the Chatham Harbor subwatershed). The remaining top five subwatershed nitrogen removals by individual towns were: 2) Ryder Cove (Chatham, 3,329 kg/yr removed), 3) Upper Muddy Creek (Harwich, 2,758 kg/yr removed), 4) Meetinghouse Pond (Orleans, 2,013 kg/yr removed), and 5) Lower Muddy Creek (Harwich, 1,632 kg/yr removed). The percentage of the overall Pleasant Bay attenuated watershed loads from Orleans, Brewster, Harwich, and Chatham in the SNEP update after application of the planned nitrogen management strategies were 44%, 14%, 21%, and 21%, respectively (see Table II-6).

Table II-6. Town-by-Town Attenuated Watershed Nitrogen Loads: SNEP Update Existing Conditions and Town Nitrogen Management Strategies. Attenuated loads under both existing conditions and after implementation of Town nitrogen management strategies are shown. Under existing conditions SNEP update, only Crows Pond in Chatham has a watershed load less than the TMDL threshold load. After the implementation of current planned Town nitrogen management strategies *without incorporating tidal hydrodynamic changes* all Chatham-only subwatersheds, except Frostfish Creek, attain their TMDL threshold loads, plus Lonnie's Pond, Round Cove, and Upper Muddy Creek (indicated by bright green). *The Pleasant Bay Main as defined for the TMDL also attains its TMDL; the TMDL for Pleasant Bay Main includes loads from The Horseshoe and Tar Kiln Stream. Planned nitrogen reductions were large enough to reduce the system load below its TMDL threshold load. Town shares of the overall system load are shown; planned nitrogen management strategies redistribute the percentage of the overall system share for each of the towns. The division of the watershed loads among the towns created some small differences in the watershed total (<1%) and some totals may not match due to rounding.

	Existing Conditions Attenuated: SNEP Update (kg/yr)					Town Nitrogen Management Strategies Attenuated: SNEP Update (kg/yr)					Reduction from existing conditions due to planned mgmt		TMDL watershed threshold
Watershed	ORL	BRE	HAR	CHA	TOTAL	ORL	BRE	HAR	CHA	TOTAL	kg/yr	%	kg/yr
Meetinghouse Pond	2,535	-	-	-	2,535	522	-	-	-	522	2,013	79%	387
The River - Upper	919	15	-	-	934	690	15	-	-	705	229	25%	635
The River - Lower	1,351	30	-	-	1,381	1,196	30	-	-	1,226	155	11%	891
Lonnie's Pond	730	71	-	-	801	290	71	-	-	360	440	55%	595
Areys Pond	488	106	-	-	594	488	106	-	-	594	-	0%	336
Namequoit River	933	69	-	-	1,002	730	69	-	-	799	203	20%	631
Pah Wah Pond	679	-	-	-	679	543	-	-	-	543	136	20%	266
Pochet Neck	3,074	-	-	-	3,074	2,460	-	-	-	2,460	614	20%	1,504
Little Pleasant Bay	1,706	802	464	392	3,364	1,497	725	366	222	2,810	554	16%	2,146
Quanset Pond	412	87	-	-	499	386	87	-	-	473	26	5%	394
Round Cove	-	3	2,094	-	2,097	-	3	959	-	962	1,135	54%	1,080
The Horseshoe	208	-	-	-	208	201	-	-	-	201	7	3%	-
Muddy Creek – Upper	-	-	3,499	1,001	4,500	-	-	1,016	282	1,298	3,202	71%	1,683
Muddy Creek – Lower	-	-	2,662	1,269	3,931	-	-	1,030	307	1,337	2,594	66%	781
Tar Kiln Stream	65	545	-	-	610	65	413	-	-	478	132	22%	-
Pleasant Bay Main	1,820	2,673	3,250	1,248	8,991	1,677	1,890	1,718	693	5,978	3,013	34%	7,975*
Ryder Cove	-	-	-	4,377	4,377	-	-	-	1,048	1,048	3,329	76%	1,632
Frostfish Creek	-	-	-	1,318	1,318	-	-	-	294	294	1,024	78%	256
Crows Pond	-	-	-	1,526	1,526	-	-	-	309	309	1,217	80%	1,540
Bassing Harbor	-	-	-	875	875	-	-	-	187	187	688	79%	610
Chatham Harbor	-	-	-	6,974	6,974	-	-	-	1,740	1,740	5,234	75%	6,242
OVERALL	14,921	4,401	11,969	18,980	50,271	10,744	3,410	5,089	5,082	24,324	25,945	52%	29,656
TOWN SHARE	30%	9%	24%	38%		44%	14%	21%	21%				

II.7 Benthic Regeneration of Nitrogen from Bottom Sediments

The overall objective of the benthic nutrient flux surveys was to quantify the summertime exchange of nitrogen, between the sediments and overlying waters within each major basin area comprising the Pleasant Bay embayment system. The mass exchange of nitrogen between water column and sediments is a fundamental factor in controlling nitrogen levels within coastal waters. These fluxes and their associated biogeochemical pools relate directly to carbon, nutrient and oxygen dynamics and the nutrient related ecological health of these shallow marine ecosystems. In addition, these data are required for the proper modeling of nitrogen in shallow aquatic systems, both fresh and salt water.

II.7.A. Sediment-Water column Exchange of Nitrogen

As has been well documented for the Pleasant Bay System, nitrogen loading and resulting nitrogen levels within estuaries are the critical factors controlling their nutrient related ecological health and habitat quality. Nitrogen enters the Pleasant Bay embayment system predominantly in highly bioavailable forms from the surrounding upland watershed and more refractory forms in the inflowing tidal waters. If all of this nitrogen remained within the water column (once it entered), then predicting water column nitrogen levels would be simply a matter of determining the watershed loads, dispersion, and hydrodynamic flushing. However, as nitrogen enters the embayment from the surrounding watersheds, it is predominantly in the bioavailable form nitrate. This nitrate and other bioavailable forms are rapidly taken up by phytoplankton for growth, *i.e.*, it is converted from dissolved forms into phytoplankton "particles". Most of these "particles" remain in the water column for sufficient time to be flushed out to a downstream larger water body (like the Atlantic Ocean). However, some of these phytoplankton particles are deposited on the bottom after being grazed by zooplankton or filtered from the water by shellfish and other benthic animals. In addition, these nitrogen rich particles may die and settle to the bottom in longer residence time systems (greater than 8 days). In both cases (grazing or senescence settling), a fraction of the phytoplankton with their associated nitrogen "load" become incorporated into the surficial sediments of the bays.

In shallow embayments, the fraction of the phytoplankton population which becomes surficial sediments generally: (1) increases with decreased hydrodynamic flushing, (2) increases in low velocity settings, (3) increases within enclosed tributary basins, particularly if they are deeper than the adjacent embayment (*e.g.,* Paw Wah Pond, Lonnie's/Kescayo Gansett Pond, Meetinghouse Pond, Areys Pond). To some extent, the settling characteristics can be evaluated by observation of the grain-size and organic content of sediments within an estuary.

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

II.7.B. Method for determining sediment-water column nitrogen exchange

As part of the Pleasant Bay SNEP update and in order to determine the contribution of sediment regeneration to nutrient levels, sediment samples were collected during the most sensitive summer interval (July-August) and incubated under *in situ* conditions. Sediment core samples were collected from 67 sites in Upper Pleasant Bay, Pleasant Bay and their tributary sub-basins (Bassing Harbor sub-embayment, Muddy Creek, Round Cove, Paw Wah Pond Quanset Pond, Pochet, The River (including Areys, Lonnie's and Meetinghouse Ponds and associated inlet channels) and Chatham Harbor (Figure II-4).

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 in July/August 2019 by SCUBA divers and cores transported by small boat to a shore side field lab. Cores were maintained from collection through incubation at *in situ* temperatures. Bottom water was collected and filtered from each core site to replace the headspace water of the flux cores prior to incubation. The locations were selected based upon the observed gradients in the MEP sediment studies of Pleasant Bay, changes in the bays sediments since the MEP assessment and to cover the major component basins of the Pleasant Bay System. Sampling was distributed throughout the embayment system and the results for each site combined for calculating the net nitrogen regeneration rates for the water quality modeling effort.

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

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

Figure II-4. Pleasant Bay embayment system 2019 sediment sampling sites. At total of 67 sites (yellow dots), sediment cores were collected and incubated to determine nitrogen regeneration rates using MEP methods. Numbers are for reference in Table IV-10.

II.7.C. Rates of Summer Nitrogen Regeneration from Sediments

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

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

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

In order to model the nitrogen distribution within an embayment it is important to be able to account for the net nitrogen flux from the sediments within each part of each system. This requires that an estimate of the particulate input and nitrate uptake be obtained for comparison to the rate of nitrogen release. Only sediments with a net release of nitrogen contribute a true additional nitrogen load in summer to the overlying waters, while those with a net input to the sediments serve as an attenuation mechanism for nitrogen within the embayment. Particulate organic nitrogen that is deposited to the sediments, remineralized and oxidized to nitrate and then denitrified contributes to the difference between particle settling and sediment nitrogen release in the water quality models.

Overall, coastal sediments are not generally overlain by nitrate-rich waters and the major nitrogen input is via phytoplankton grazing or direct settling. In these systems, on an annual basis, the amount of nitrogen input to sediments is generally higher than the amount of nitrogen release. This net sink results from the burial of reworked refractory organic compounds, sorption of inorganic nitrogen and some denitrification of produced inorganic nitrogen before it can "escape" to the overlying waters. However, this net sink evaluation of coastal sediments is based upon annual fluxes. If seasonality is considered, it is clear that sediments undergo periods of net input and net output. The net output is generally during warmer periods and the net input is during colder periods. The result can be an accumulation of nitrogen within late fall, winter, and early spring and a net release during summer. The conceptual model of this seasonality has the sediments acting as a battery with the flux balance controlled by temperature (Figure II-5).

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

In order to determine the net nitrogen flux between water column and sediments, all of the above factors were considered. The net input or release of nitrogen within a specific embayment was determined based upon the measured ammonium release, measured nitrate uptake or release, and estimate of particulate nitrogen input. Dissolved organic nitrogen fluxes were not used in this analysis, since they were highly variable and generally showed a net balance within the bounds of the method (*e.g.*, no net release).

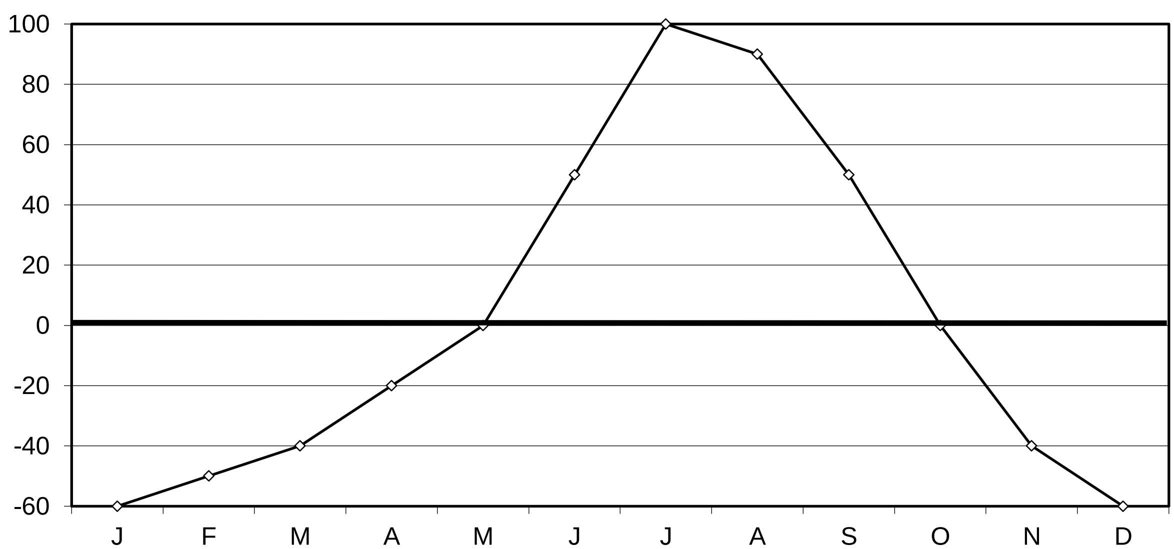

Figure II-5. Conceptual diagram showing the seasonal variation in sediment N flux. Maximum positive flux (sediment output) occurs in the summer months and maximum negative flux (sediment up-take) occurs during the winter months.

Sediment sampling was conducted within each of the sub-embayments of the Pleasant Bay System in order to obtain the nitrogen regeneration rates required for parameterization of the water quality model (see Figure IV-4**)**. The distribution of cores was established to cover gradients in sediment type, flow field and phytoplankton density. For each core, the nitrogen flux rates were evaluated relative to measured sediment organic carbon and nitrogen content and bulk density and an analysis of each site's tidal flow velocities. The maximum bottom water flow velocity at each coring site was determined from the hydrodynamic model. These data were then used to determine the nitrogen balance within each sub-embayment.

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

Changing hydrodynamics and areas of deposition have resulted in shifts in sediment nitrogen regeneration since the MEP assessment, but no significant system difference. Net nitrogen release or uptake from the sediments within the Pleasant Bay System Embayment for use in the water quality modeling effort (Section IV) are presented in Table II-7. Net nitrogen release shows significant spatial variation, but is typical of other embayments within the MEP region. Most notable changes from the MEP are in Chatham Harbor and Muddy Creek. Chatham Harbor previously had high water velocities due to its conducting all tidal flows from the southern inlet to/from Pleasant Bay. At present, it has flows from both north and south and has become depositional, with a consequent increase in its sediment release. This release has little effect on water quality since Chatham Harbor remains well flushed and little water entering Pleasant Bay passes through it. Muddy Creek also has seen a significant lowering of its sediment nitrogen release, particularly in its upper basin, due to the increased flushing resulting from the new tidal inlet (bridge) and improved water quality. However, comparing the overall nitrogen release from the sediments of the other basins of the Pleasant Bay System in 2019 to release rates from the MEP, it is clear that there is not a significant difference overall, with no change in the total flux from the main basins and only a modest decline in the overall enclosed ponds or their tidal channels. Individual basins did show some changes (as noted above). Overall, although there are a large number of sub-embayments to the Pleasant Bay System, the rates of sediment nitrogen regeneration generally fell into three groups within a 10 fold range:

(A) small enclosed terminal basins with their associated tidal rivers generally show high nitrogen release rates (Meetinghouse Pond - Channel, Lonnie's Pond, Areys Pond - Namequoit River, Quanset Pond, Round Cove).
(B) moderate sized tributary tidal sub-embayments with more moderate nitrogen release rates (The River, Pochet, Muddy Creek[48]),
(C) large lagoonal estuarine basins with uptake to moderate nitrogen release (Little Pleasant Bay, Pleasant Bay, Chatham Harbor).

The general pattern is for higher release from either the terminal basins or associated rivers (or both) in the small enclosed basins (group A) which tend to have higher nitrogen levels due to their circulation and tend to focus watershed nitrogen loads. In contrast the larger tributary sub-embayments (group B) tend to have better circulation relative to the watershed inputs and only moderate nitrogen regeneration rates. In contrast, the large main basins of the lagoonal estuarine component (group C) showed uptake to moderate regeneration rates consistent with their deep waters and depositional nature (Little Pleasant Bay, Pleasant Bay, and eastern channel form Chatham Harbor to Little Pleasant Bay, channel between Strong Island and Bassing Harbor) or their shift to moderate net nitrogen flux under the new hydrodynamics that has resulted in sediment deposition in (Chatham Harbor). The net nitrogen uptake by the predominantly salt marsh basin of Pochet is consistent with many observations of salt marsh nitrogen cycling (*e.g.*, West Falmouth Harbor). The overall pattern generally reflects the particle distribution within Pleasant Bay, due to phytoplankton production and deposition. This pattern, on a smaller scale, was also observed within upper Cape embayments of Popponesset Bay and Three Bays, which have similar patterns of loading and multiple large sub-embayments. Lowering the nitrogen inputs to the inner basins will result in lower net nitrogen release rates over relatively short time scales.

Higher nitrogen net fluxes from sediments of the more nitrogen enriched basins also may result from differences in sediment nitrogen cycling. There is an indication that the very reducing (anoxic) nature of the deep ponds (*e.g.*, Lonnie's Pond, Areys Pond) may be increasing the percentage of nitrogen which is released from the sediments versus the amount of nitrogen being lost to denitrification via the pathway of mineralization→ nitrification → denitrification. The coupled nitrification-denitrification step in the pathway is significantly influenced by the availability of oxygen within the surficial sediments for nitrifying bacteria. The anoxic/sulfidic nature of the sediment of the deep regions of these basins may be affecting enhancement of nitrogen release and is supported by comparisons of measured release with estimates of total nitrogen regeneration (*i.e.*, maximum potentially releasable). Using this rough approximation, a greater proportion of the potential release rates of nitrogen is achieved in the upper basins than from the other sites. Note that this approach yields general patterns and cannot be used to determine accurate nitrogen removal rates. Lowering nitrogen loading to these upper systems should improve sediment oxidation and improve nitrogen removal rates by these sediments, although quantifying this enhancement is highly site specific. However, based upon this information a linear model for the lowering of nitrogen release with lowered watershed nitrogen loading is conservative. The summer net sediment nitrogen release rates (Table II-7) were used in the update to the water quality model (Section IV).

[48] Muddy Creek's sediment N release dropped significantly after the tidal flushing was improved by the new inlet

Table II-7. Rates of net nitrogen return from sediments to the overlying waters of the Pleasant Bay embayment system. These values are combined with the basin areas to determine total nitrogen mass in the water quality model (see Chapter VI). Measurements represent July - August rates.

Sub-embayment	Site ID	Sediment N Regeneration mg N/m2/d		
		Mean	s.d.	N
Meetinghouse Pond				
Pond Basin	47,49	1.7	22.5	2
Lonnie's Pond (Includes summer cores from oyster monitoring)				
Pond Basin	53,54	93.7	18.2	9
Areys Pond				
Pond Basin	22,23	-18.5	1.6	2
Namequoit River	24,25,26	24.7	35.1	3
The River				
Meetinghouse Channel	50,51	64.0	31.0	2
Upper River	52,29	5.8	8.6	2
Mid River	28	8.7	1.9	1
Lower River	27,45	33.1	24.1	2
Mouth River	44	14.4	1.8	1
Paw Wah Pond				
Pond Basin	46	5.0	5.7	1
Quanset Pond				
Pond Basin	—	99.1	6.2	2
Round Cove				
Cove Basin	Rnd 1,2	-19.7	5.1	2
Muddy Creek				
Upper	Mud 1,2	-2.7	8.3	2
Lower	Mud 3,4	14.0	10.4	2
Bassing Harbor Sub-System				
Ryders Cove	RC-1,2,3,4,5,pbx	3.0	21.4	6
Crows Pond	CP-1,2,3	4.2	29.4	3
Bassing Harbor Basin	PB-17, BH-1,2	4.2	4.1	3
Pochet				
Upper-Mid	38,39,40	30.3	20.2	3
Lower Basin	41,42	16.2	26.5	2
Little Pleasant Bay				
Upper	43,60,61,62	57.2	40.7	4
Mid	56,59	1.2	13.0	2
Broad Creek	41,35	12.8	14.9	1
Lower	31,32,33,34,35,55	-12.4	6.0	6
Pleasant Bay				
Main Basin	5A,5	-17.1	0.1	2
Little PB-Chatham Hbr Channel	32,33,14,15,16	3.4	8.0	5
Strong Island-Bassing Hbr	17,18	3.4	8.4	2
Chatham Harbor				
Basin	2,9,10,11,PB-X	53.5	22.7	4

III. Pleasant Bay 2020 Hydrodynamic Model Update

A new hydrodynamic model was developed for the Pleasant Bay system, which includes the present configuration of the Pleasant Bay/Chatham Harbor inlet complex. This new model is based on tides collected in 2019 (stations shown in Figure III-1, left panel) and recent bathymetry. The barrier beach system of Nauset Beach, North Beach Island and Monomoy has evolved to form a tidal connection (called Fool's Cut, Figure III-1, right panel) between Chatham Harbor and Nantucket Sound. Continued expansion of the north inlet since its formation in 2007 has made it the primary channel of tidal exchange between the open ocean and Pleasant Bay. Flow patterns from the model show that similar volumes of water are exchanged through both north and south inlets. As was found in a 2018 study of the existing and future morphology of the Pleasant Bay inlet complex, the majority of the prism that flows through the south inlet is directed through Fool's cut, and is exchanged with Nantucket Sound.

III.1. Data Collection and Review

Numerical models rely on many different sources of data to create an accurate representation of the physical system that they are used to simulate. Data used in the development of the Pleasant Bay hydrodynamic model include recent bathymetry/topography, aerial photography and tide data.

Figure III-1. March 2020 aerial map of the Pleasant Bay system with 2019 tide gauge stations. Tide gauges were located at location shown in left aerial. Right aerial shows March 2020 inlet configuration, including the Fool's Cut connection to Nantucket Sound.

III.1.A. Bathymetry Input Data

Due to bathymetric changes since the 2007 MEP analysis, updated bathymetry was developed for use in the 2020 update to the model of Pleasant Bay. This included wide-coverage LiDAR from a 2018 flight by the US Army Corps of Engineers (USACE) and sidescan sonar bathymetry collected by the Center for Coastal Studies in October 2018 and 2014. Supplemental bathymetry in the northern reaches of Pleasant Bay were available from sources developed for the original MEP model of Pleasant Bay. All bathymetry data were tide corrected, and referenced to the North American Vertical Datum of 1988 (NAVD 88).

III.1.B. Updated Tide Data

Tide data were collected in June/July 2019 by SMAST at six-gauge stations located in Pleasant Bay (Figure III-1) and one located offshore of Nauset Beach, near the north inlet. A concurrent tide data record collected in Stage Harbor by the Center for Coastal Studies were also made available for this analysis. Plots of tides elevations for the full duration of the 2019 gauge deployment are shown in Figure III-2. A two-day segment of the gauge record is shown in Figure III-3, with data from all stations plotted together. This plot shows that the tide range in the main basin of Pleasant Bay is a little more than half of the offshore tide, with most of the attenuation occurring on the lower portion of the tide. The propagation of the tidal wave across the length of the Bay can also be seen, by a discernable delay of the tide signal at the Pochet station compared to the stations closer to the inlet complex (for example, at the fish pier). The tide in Stage Harbor is nearly in sync with the tide offshore of Nauset beach, but with a reduced range.

III.1.C. Tide Datums

Standard tide datums were calculated for the eight gauge records (Table III-1). These results show that the elevation of the mean tide level (MTL) increases 0.9 feet between offshore and Meetinghouse Pond. The tide range for station in Pleasant bay and its attached sub-embayments is about 52% of the offshore range. The range in Chatham Harbor is 76% of the offshore station. MTL at Stage Harbor is the same as for offshore Nauset Beach, and it has a range that is half of that open ocean gauge.

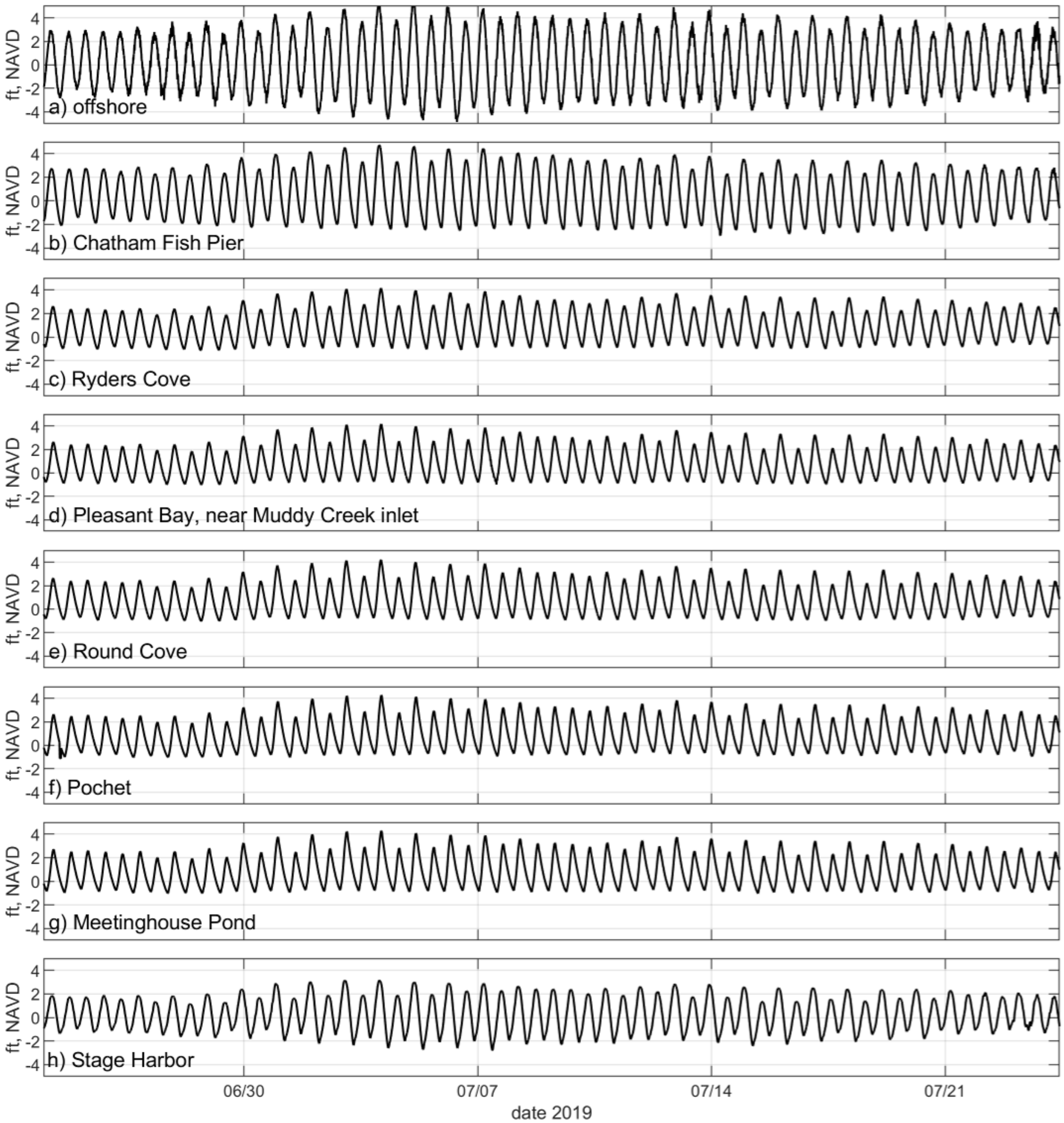

Figure III-2. Tidal Records at Pleasant Bay Stations. Complete tides records collected at stations (Figure III-1) in Pleasant Bay, offshore Nauset Beach, and Stage Harbor, between June 24 and July 24, 2019.

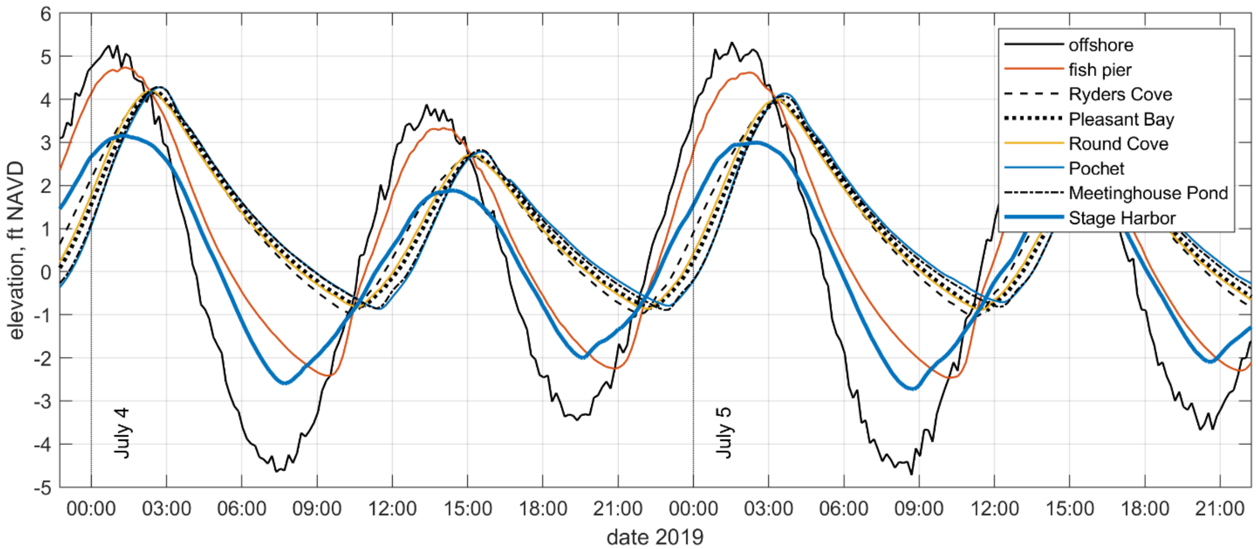

Figure III-3. Detail of tidal records. Two-day segment of tide records from the 2019 Pleasant Bay deployment, plotted together.

Table III-1. Tide datums for stations in Pleasant Bay, offshore (PLB1) and Stage Harbor (STHB). Readings are based on 28-day period (lunar month) between June 24 and July 22, 2019. Station location are indicated in Figure III-1. Mean range is in feet, and tide datum elevations are in feet, NAVD.

station	PLB1	PLB2	PLB3	PLB4	PLB5	PLB6	PLB7	STHB
Mean range	7.2	5.5	3.8	3.7	3.8	3.8	3.9	3.9
Maximum	5.3	4.7	4.2	4.2	4.2	4.3	4.3	3.2
MHHW	4.3	3.7	3.4	3.3	3.4	3.5	3.4	2.5
MHW	3.8	3.2	2.9	2.9	2.9	3.0	3.0	2.1
MTL	0.2	0.5	1.0	1.0	1.0	1.1	1.1	0.2
MLW	-3.4	-2.2	-0.9	-0.9	-0.9	-0.8	-0.9	-1.8
MLLW	-3.7	-2.4	-1.0	-0.9	-0.9	-0.9	-0.9	-2.0
Minimum	-4.9	-3.0	-1.1	-1.0	-1.0	-1.1	-1.1	-2.8

III.1.D. Harmonic analysis

A tidal harmonic analysis was performed using the 2019 tide data. The observed ocean tide is the superposition of several tidal components. Each component is related to phenomena such as the earth-moon system's rotation around its common center of mass, and the gravitational pull on the earth's oceans by the sun. Standard tidal harmonics are designated using alpha-numeric identifiers, including the K1 principal solar-diurnal constituent, and the M2 principal lunar semi-diurnal constituent. Tide predictions published by NOAA and similar agencies are developed using tidal harmonics determined from a harmonic analysis of measured tides.

Tidal harmonic amplitudes and phases calculated for the 2019 gauge data used in this study are presented in Tables III-1 and III-2. Generally, the constituent amplitudes will decrease between the open ocean and the inner areas of a non-resonant estuary. Constituent phase lag will increase across an estuary due to the time it takes for the tidal wave to propagate through the system. The amplitude of the M2 in Meetinghouse Pond is half of its amplitude offshore, indicating a large degree of tidal attenuation (similar to the decrease in tide range report in Table III-1). The M4 and M6 have larger amplitudes larger at stations inside Pleasant Bay compared to offshore. These two constituents are harmonically-related overtides of the M2, with frequencies that are two and three times greater, respectively. The growth of the M4 and M6 is due to the transferring of energy from the M2 due to frictional losses as the tide propagates through an estuary.

The harmonic analysis of this study used 21 separate constituents, and results for the largest 12 constituents are reported in Tables III-2 and III-3. A comparison of the original tide record from the offshore station and the astronomical tide computed using the 21 tide constituents of the analysis is presented in Figure III-4, along with the tide residual that results when the astronomical tide is subtracted from the original time series. This residual represents the non-tidal component of the measured tide, caused primarily by atmospheric forcing and wave action. The energy content of the residual signal (calculated as the variance of the signal) at the offshore station is only 0.7% of the total measured tide signal, which indicates that less than one percent of the recorded offshore tide is due to non-tidal forces. At Meetinghouse Pond, the residual is slightly larger, but still only 3.0% of the measured tide.

Table III-2. Tidal Amplitudes. Amplitudes of the 12 largest tide harmonic constituents, including the principal lunar semidiurnal (M2) and the principal solar diurnal (K1) constituents, for stations in Pleasant Bay, offshore Nauset Beach (PLB1) and Stage Harbor (STHB). Constituents are ordered from largest to smallest value at the offshore gauge. Constituent periods are in hours. Station location are shown in Figure III-1.

Const.	period	PLB1	PLB2	PLB3	PLB4	PLB5	PLB6	PLB7	STHB
M2	12.42	3.29	2.59	1.69	1.63	1.64	1.64	1.64	1.85
N2	12.66	0.76	0.50	0.33	0.31	0.32	0.31	0.31	0.45
K1	23.93	0.55	0.45	0.36	0.34	0.35	0.35	0.35	0.42
O1	25.82	0.37	0.32	0.28	0.28	0.28	0.27	0.28	0.29
S2	12.00	0.31	0.22	0.11	0.10	0.11	0.11	0.11	0.14
L2	12.19	0.17	0.14	0.15	0.14	0.14	0.14	0.14	0.08
2N2	12.90	0.10	0.11	0.06	0.06	0.06	0.07	0.07	0.08
M1	24.83	0.06	0.03	0.03	0.03	0.03	0.04	0.04	0.05
Q1	26.87	0.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04
OO1	22.31	0.03	0.03	0.02	0.02	0.02	0.02	0.02	0.02
M4	6.21	0.02	0.23	0.19	0.27	0.28	0.38	0.37	0.09
M6	4.14	0.02	0.08	0.05	0.04	0.04	0.05	0.05	0.05

Table III-3. Tidal Phases: Harmonic Constituents. Phases in degrees of the 12 largest tide harmonic constituents, ordered by amplitude at the offshore gauge. Phases are all relative to 0002h, June 24, 2019.									
Const.	**period**	**PLB1**	**PLB2**	**PLB3**	**PLB4**	**PLB5**	**PLB6**	**PLB7**	**STHB**
M2	12.42	157.47	173.74	210.08	220.54	215.87	229.26	228.03	174.12
N2	12.66	326.43	347.69	25.38	34.99	30.12	43.71	41.80	340.37
K1	23.93	340.82	3.71	33.57	38.91	36.49	40.54	41.13	350.91
O1	25.82	95.88	128.30	160.51	164.48	162.21	168.29	167.46	118.15
S2	12.00	29.48	33.80	76.70	86.24	81.69	99.02	95.05	51.96
L2	12.19	185.60	181.16	223.98	235.43	230.79	244.67	243.48	201.65
2N2	12.90	148.33	148.79	168.23	180.95	176.23	184.41	185.42	161.68
M1	24.83	146.79	179.53	194.73	195.76	193.50	205.30	200.46	167.50
Q1	26.87	266.72	314.55	349.94	0.03	357.74	4.87	11.00	289.55
OO1	22.31	45.03	63.97	54.71	74.50	70.96	91.68	98.67	42.96
M4	6.21	29.55	265.08	350.84	20.09	10.78	35.67	33.13	77.84
M6	4.14	308.81	267.00	300.98	272.03	258.59	226.42	242.40	72.96

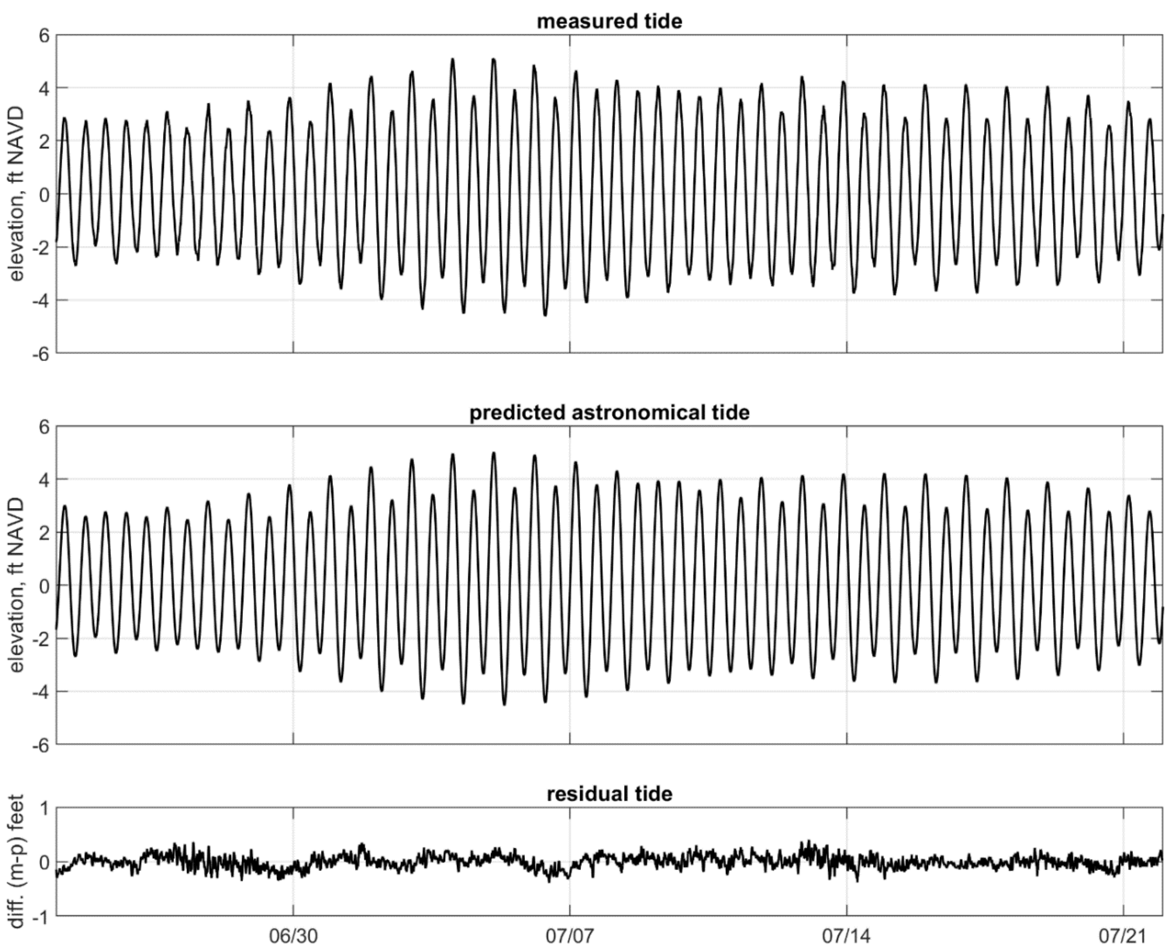

Figure III-4. Tidal Residuals Analysis. Measured offshore tide compared to the predicted astronomical tide that results from the tide harmonic analysis, and the residual tide that is the difference between the measured and astronomical tides.

The constituent phases in Table III-3 can be used to determine the time delay of the tide at different areas of Pleasant Bay, relative to the offshore tide. Phase lags of the M2 tide (the principal component of the observed tide) are shown in Table III-4, compared to offshore. These results show that the innermost area of Pleasant Bay have an arrival time of the tide that is up to two and a half hours later that the tide offshore. Also, the tide in Stage harbor lags the tide offshore Nauset Beach by about a half hour.

Table III-4. Tide lags at Pleasant Bay stations. Comparison of tide lag (M2 tide) at 2019 stations in Pleasant Bay, compared to offshore, in hours and minutes.

Chatham Fish Pier (PLB2)	34 min
Stage Harbor	35 min
Ryder Cove (PLB3)	1 hour 49 min
Pleasant Bay (PLB4)	2 hours 11 min
Round Cove (PLB5)	2 hours 1 min
Pochet (PLB6)	2 hours 29 min
Meetinghouse Pond (PLB7)	2 hours 26 min

III.1.E. Comparison of tides measured in past studies.

Tide records from month-long deployments from 2004 (pre-north breach), 2007 post breach, and 2019 are available to compare present tidal conditions with those that existed prior to and immediately following the 2007 north inlet breach. These datasets provide what are essentially snapshots of tidal conditions from these periods. A more temporally detailed analysis of tide conditions in Pleasant Bay is available using a long-term and ongoing Meetinghouse Pond gauge record maintained by the Center for Coastal Studies (Giese and Legare, 2019).

Table III-5 shows a comparison of MHW elevations and mean tide range at gauge stations located offshore Nauset Beach, at the Chatham Harbor Fish Pier and Meetinghouse Pond, at three different month-long periods. The results show that the tide range in Meetinghouse Pond has decreased about 17% since its maximum in 2007, and is now similar to the range measured in 2004, pre-breach. At the fish pier, the range is essentially the same as it was in 2007.

Table III-5. Comparison of Historic Tide Ranges. Comparison of Mean High Water (MHW) tide datum (feet, NAVD) and mean tide range (feet), at station offshore Nauset Beach, Chatham Fish Pier and Meetinghouse Pond, for four different month-long periods in 2004, 2007 and 2019.

Gauge Station	2004	2007	2019
Offshore PLB1 MHW	3.6	3.8	3.8
Offshore PLB1 range	6.7	7.3	7.2
Fish Pier PLB2 MHW	2.8	3.3	3.2
Fish Pier PLB2 range	4.3	5.6	5.5
Meetinghouse PLB7 MHW	2.9	3.4	3.0
Meetinghouse PLB7 range	4.0	4.7	3.9

III.2. Hydrodynamic Model

Available data were used to develop a numerical hydrodynamic model of the Pleasant Bay system. The final configured hydrodynamic model is then used as a component of the water quality model developed for this project. The RMA suit of models, developed in cooperation with the USACE is a finite element numerical code that includes hydrodynamic (RMA-2), water quality (RMA-4), particle tracking (RMA-TRK) and sediment transport modules (SED2D).

A new model mesh was created for this study. It includes the three inlets of the Chatham Harbor inlet complex. The mesh is made up of 8,580 triangular quadratic elements, described by a network of 19,710 nodes (Figure III-5). A composite bathymetry/topography data set made up of available land elevation data was interpolated to the mesh (Figure III-6). Depths in the model range between -64 feet NAVD, in the included offshore region of the grid, to +3 feet NAVD on the marsh plain area included in the interior area of the Bay. Model parameters that represent bottom friction, eddy viscosity, and marsh porosity were varied across the model domain by grouping grid elements into subregions called "material types" that are specified in the model (Figure III-5).

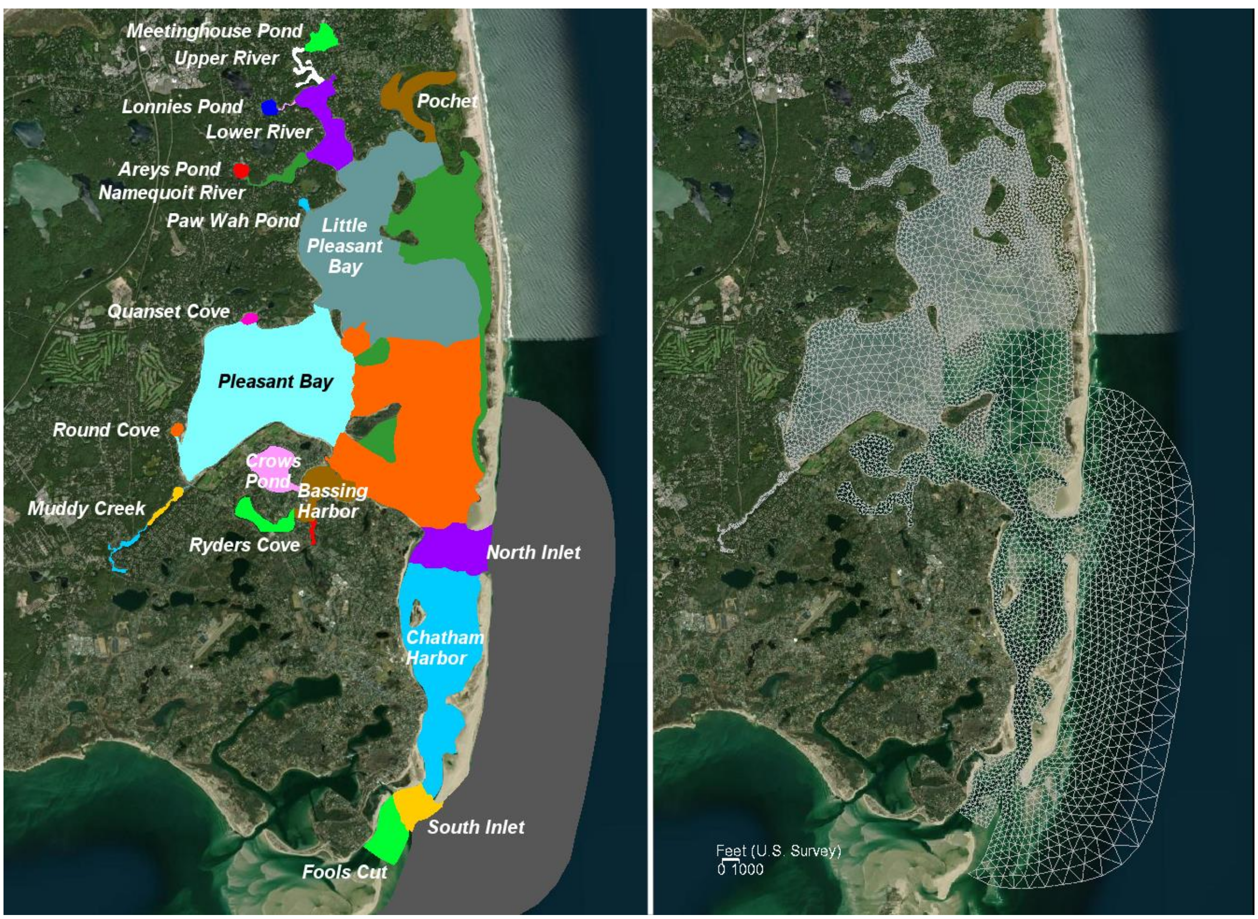

Figure III-5. 2020 Hydrodynamic Model Domain. Grid mesh (right) of the 2020 Pleasant Bay hydrodynamic/water quality model, and material type boundaries (left) used to vary model parameters.

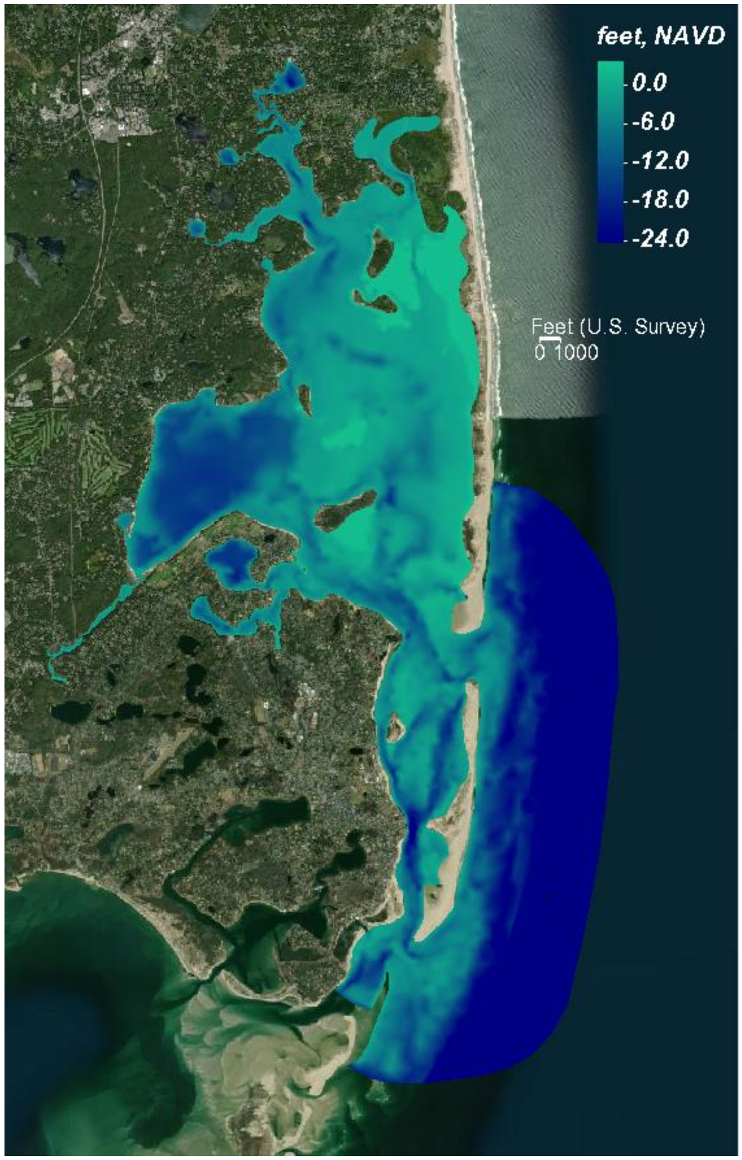

Figure III-6. Bathymetry of the 2020 Pleasant Bay hydrodynamic model.

III.2.A. Hydrodynamic Model Calibration

After completing the creation of the model mesh, the process of calibrating the model to 2019 tidal conditions was undertaken. A 14-tide-cycle period starting June 25, 2019 at 1700h was used as the model calibration time period. This period covers the transition from neap to spring tide conditions. Model parameters (primarily friction coefficients specified for each separate grid material type) were varied over the course of several mode runs in order to minimize error and maximize model agreement with measured tides at the six gauge stations located in Pleasant Bay. Error is measured using the comparison of the amplitude and phase of four tide constituents calculated for measured and modeled tides at the gauge stations (Table III-6). The constituents used in this comparison are the K1 principal solar diurnal and M2 principal lunar semi-diurnal constituents that are indicators of tide attenuation though the inlets and channel of the system, and the M4 and M6 harmonics of the M2, which indicate the degree of energy transference from the M2 to its overtides due to frictional effects across the estuary.

Table III-6. Modeled tidal calibration: tidal constituents for measured water level data and calibrated model output, with model error amplitudes					
Measured tide during calibration period					
Location	Constituent Amplitude (ft)				Phase (deg)
	K_1	M_2	M_4	M_6	ΦM_2
Offshore (PBL1)	0.54	3.00	0.01	0.02	44.7
Chatham Fish Pier	0.49	2.40	0.18	0.06	61.2
Ryders Cove (PBL3)	0.40	1.61	0.15	0.06	95.6
Pleasant Bay (PBL4)	0.38	1.55	0.24	0.04	106.4
Round Cove (PBL5)	0.39	1.56	0.24	0.04	101.5
Pochet (PBL6)	0.40	1.55	0.35	0.03	116.1
Meetinghouse Pond	0.40	1.56	0.33	0.04	114.7
Modeled tide from calibration run					
Location	Constituent Amplitude (ft)				Phase (deg)
	K_1	M_2	M_4	M_6	ΦM_2
Offshore	0.54	3.00	0.01	0.02	44.7
Chatham Fish Pier	0.48	2.25	0.21	0.04	57.3
Ryders Cove	0.42	1.63	0.22	0.04	89.8
Pleasant Bay	0.41	1.56	0.27	0.03	104.5
Round Cove	0.41	1.56	0.27	0.03	104.7
Pochet	0.41	1.57	0.33	0.05	111.9
Meetinghouse Pond	0.41	1.58	0.32	0.04	109.9
Error					
Location	Error Amplitude (ft)				Phase error (min)
	K_1	M_2	M_4	M_6	ΦM_2
Offshore	0.00	0.00	0.00	0.00	0.0
Chatham Fish Pier	-0.01	-0.15	0.03	-0.03	-15.9
Ryders Cove	0.02	0.02	0.07	-0.02	-23.7
Pleasant Bay	0.03	0.01	0.03	-0.01	-7.8
Round Cove	0.02	-0.01	0.03	-0.01	13.4
Pochet	0.00	0.02	-0.02	0.02	-17.1
Meetinghouse Pond	0.01	0.02	-0.01	0.01	-19.7

A station-by-station comparison of modeled and measured tides is provided in Figures III-7 through III-13. The RMS error between measured and modeled tides is less than 5% of the range at each station, and is of the order of accuracy of the tide gauges. Phase error of the M2 tide is also of the order of the 10-minute time step used in the gauge deployment. The final values of the model parameters specified for the calibrated model are provided in Table III-7. Though a gauge was not deployed in Muddy Creek for this study, tide data collected in 2016 were available. This record was collected after the double-barrel culvert under Route 28 was replaced with the present bridge and open channel. Model tides in Muddy Creek were calibrated by comparing the amplitude of the M2 tide constituent determined for the 2016 record and the model.

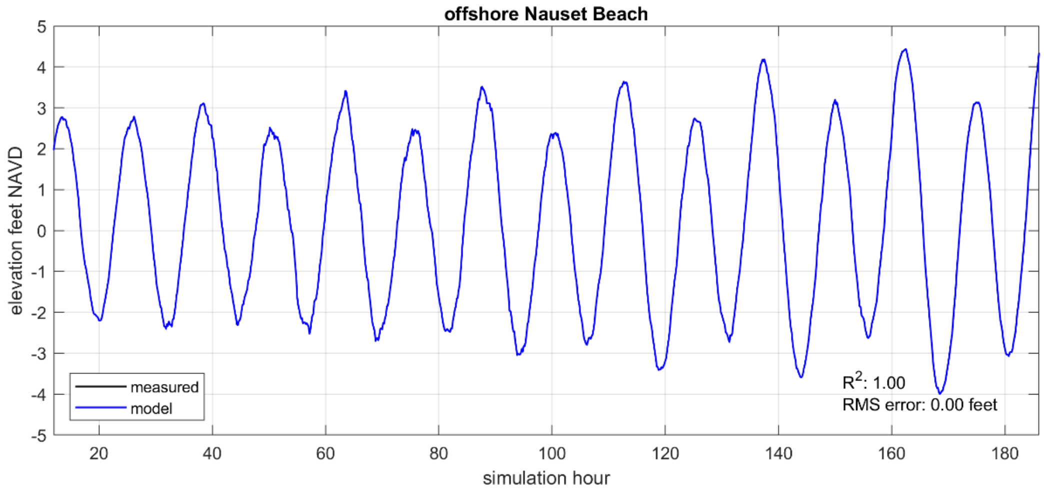

Figure III-7. Comparison of measured and modeled tides offshore Nauset Beach (PLB1).

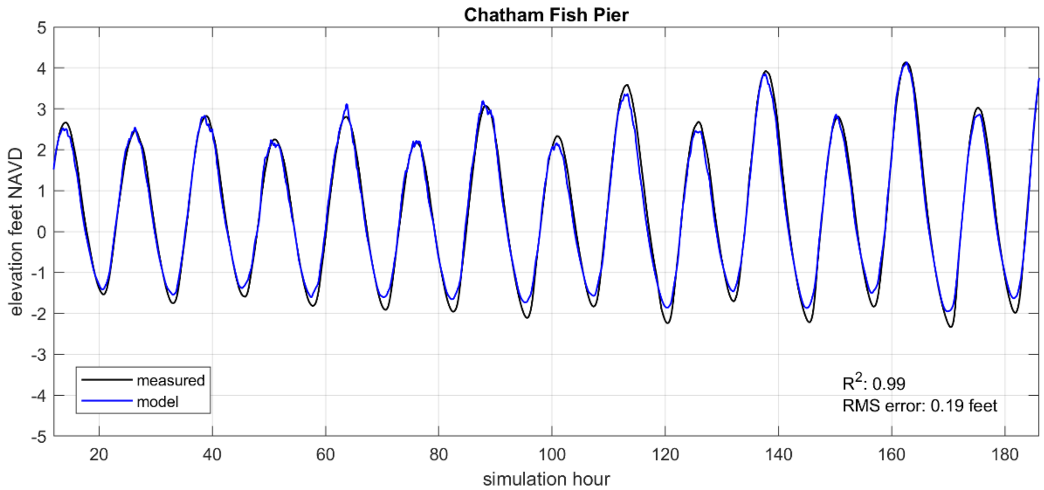

Figure III-8. Comparison of measured and modeled tides at Chatham Fish Pier (PLB2).

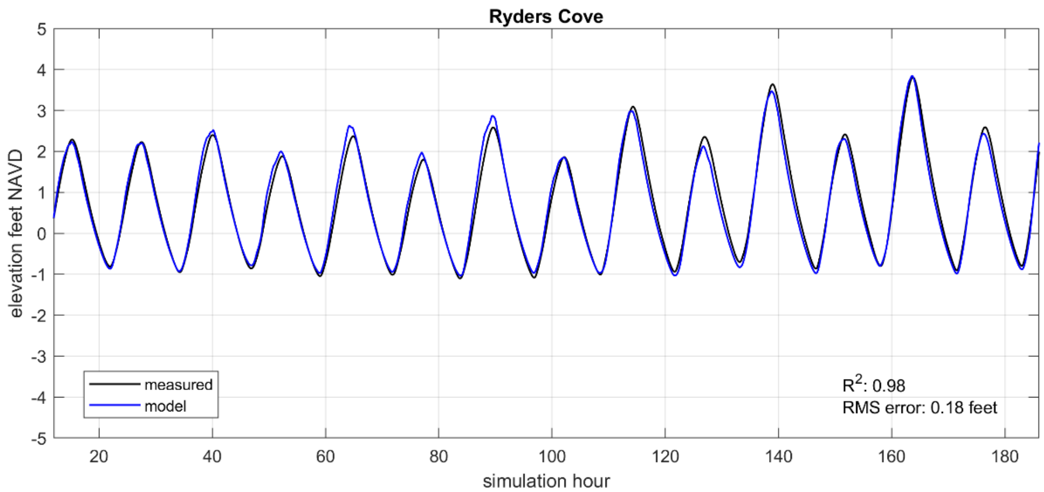

Figure III-9. Comparison of measured and modeled tides at Ryders Cove (PLB3).

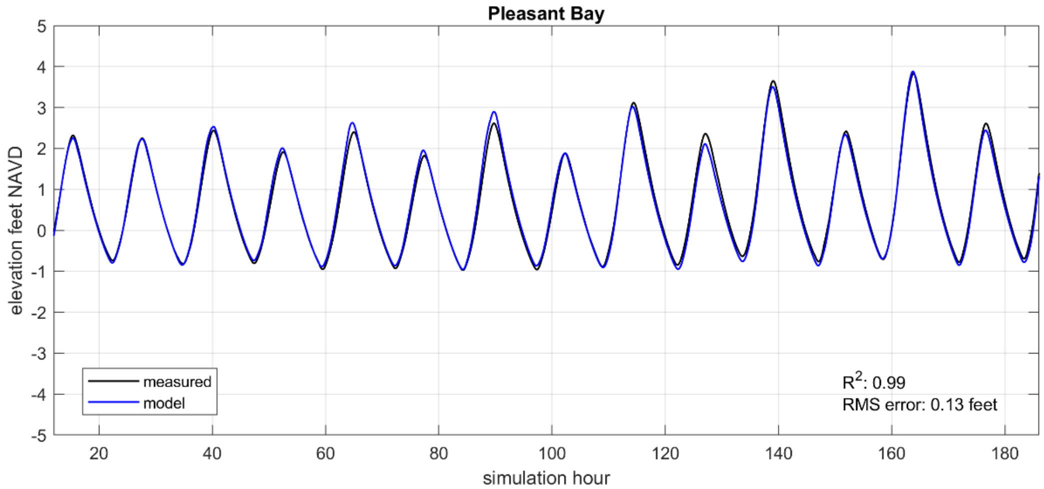

Figure III-10. Comparison of measured and modeled tides at Pleasant Bay, near Muddy Creek (PLB4).

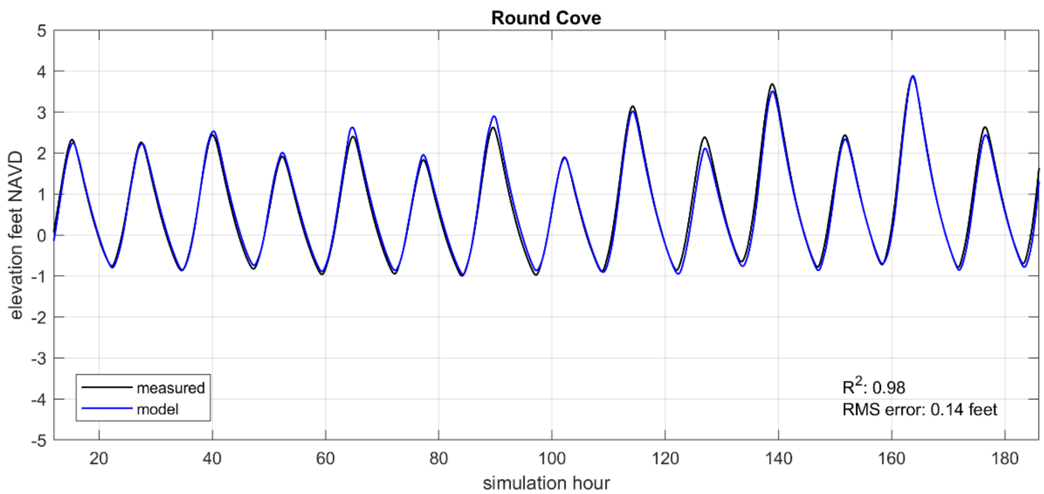

Figure III-11. Comparison of measured and modeled tides in Round Cove (PLB5).

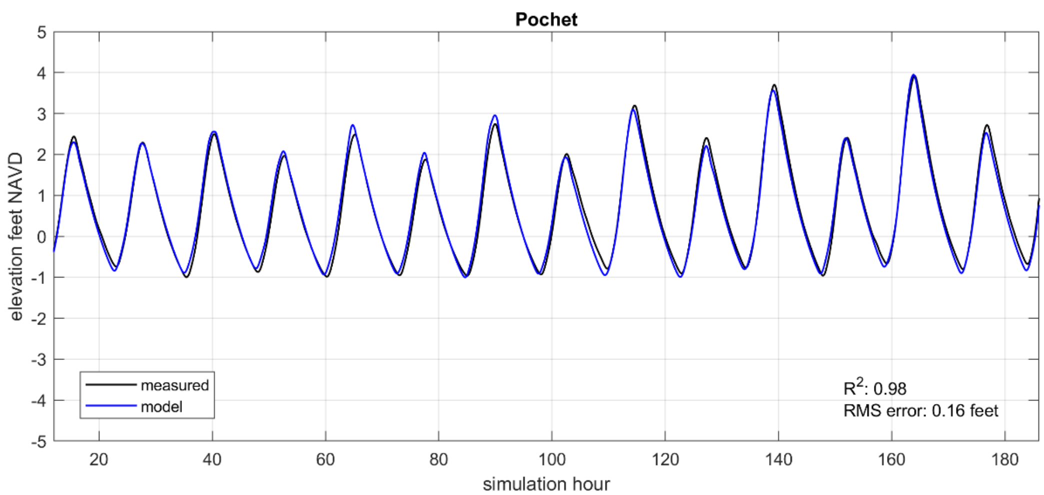

Figure III-12. Comparison of measured and modeled tides at Pochet (PLB6).

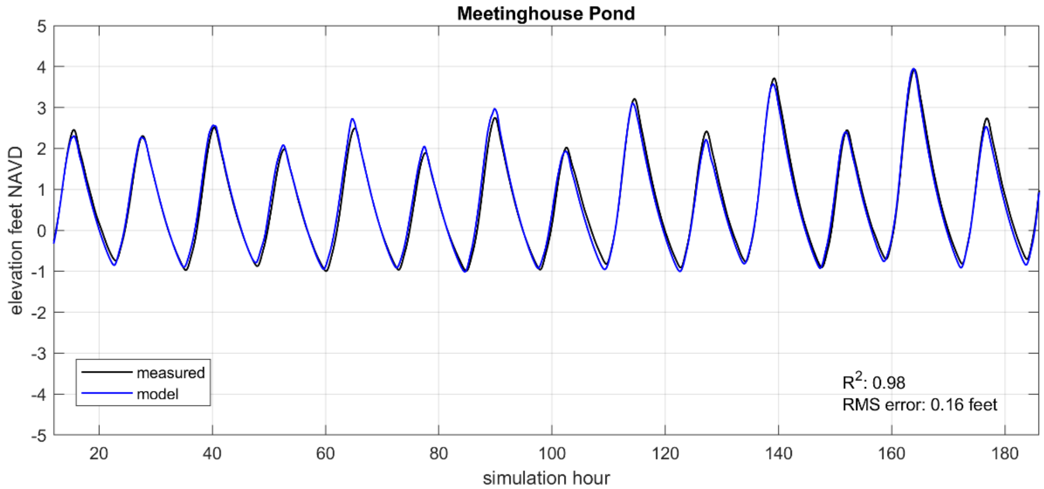

Figure III-13. Comparison of measured and modeled tides in Meetinghouse Pond (PLB7).

Table III-7. 2020 Model Input Values: Eddy viscosity (E, pascal-sec) and Manning friction coefficient (n). These inputs were specified for the material type subdivisions of the Pleasant Bay hydrodynamic model (as shown in Figure III-5).

mesh material type	E	n	mesh material type	E	n
Offshore	9000	0.020	Muddy Creek Inlet	4000	0.045
North Inlet	4000	0.022	Round Cove	4000	0.030
Chatham Harbor	4500	0.020	Quanset Pond	4000	0.030
South Inlet	4000	0.035	Paw Wah Pond	4000	0.030
Fools Cut	4000	0.035	Pochet	4000	0.030
Pleasant Bay	4000	0.030	The River	1000	0.025
Pleasant Bay Marsh	9000	0.070	Namequoit River	1000	0.025
Ryders Cove	1000	0.025	Areys Pond	1000	0.025
Crows Pond	1000	0.025	Lonnie's Pond	1000	0.025
Bassing Harbor	1000	0.025	Upper River	1000	0.025
Muddy Creek	1000	0.025	Meetinghouse Pond	1000	0.025

III.3. Flushing Characteristics of Pleasant Bay

The calibrated model can be used to investigate the flushing characteristics of the estuary and inlet complex. Local flushing times were computed for 2019 tidal conditions. The local flushing time T in hours is computed as T=12.42V/P, where V is the mean embayment volume, P is the mean embayment prism volume and 12.42 is the period of the M2 tide constituent in hours. T in days is determined by dividing T in hours by 24. The local flushing time provides an estimate of the tidal flushing capacity of an embayment, where higher numbers indicate poorer tidal flushing conditions, and more sensitivity to watershed nutrient loading. Mean embayment volumes, prisms and flushing times for Pleasant Bay embayments based on 2019 tidal conditions are presented in Table III-8. For comparison, values determined for 2004 pre-north-inlet-breach tidal conditions are presented in Table III-9. The flushing time values in Table III-8 indicate that all areas of the Pleasant Bay system have decent tidal flushing, and that water quality issues would be more controlled by watershed nutrient loading and inlet configuration. In the comparison between 2004 and 2019 conditions, it is seen that most areas of the system have flushing times that are equivalent for both time periods. This is an expected result, since the tide ranges observed in 2004 and 2019 (see Table III-5) are also similar. One area of the system that has experienced a substantial improvement in flushing between 2004 and 2019 is Muddy Creek, where the inlet culvert of the creek was replaced with an open span bridge in 2016. For the Creek, flushing time has decreased from 3.6 to 0.8 days, indicating a large improvement in tidal flushing conditions for this sub-embayment.

Table III-8. 2019 embayment mean volumes, average tidal prism and local flushing times.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)	Flushing time (days)
Pleasant Bay + Chatham Harbor	1,920,851,000	1,017,647,000	1.0
Bassing Harbor	107,383,000	50,516,000	1.1
Crows Pond	59,692,000	19,066,000	1.6
Ryder Cove	19,736,000	10,680,000	1.0
Muddy Creek	5,130,000	3,363,000	0.8
The River	93,142,000	52,441,000	0.9
Areys Pond	20,432,000	7,329,000	1.4
Lonnie's Pond	4,788,000	2,357,000	1.1
Meetinghouse Pond	6,112,000	2,577,000	1.2

Table III-9. 2004 embayment mean volumes, average tidal prism and local flushing times.

Embayment	Mean Volume (ft^3)	Tide Prism Volume (ft^3)	Flushing time (days)
Pleasant Bay + Chatham Harbor	2,076,848,000	1,190,817,000	0.9
Bassing Harbor	109,139,000	66,133,000	0.9
Crows Pond	50,208,000	21,898,000	1.2
Ryder Cove	18,070,000	12,534,000	0.7
Muddy Creek	5,541,000	806,000	3.6
The River	96,032,000	60,199,000	0.8
Areys Pond	19,406,000	8,167,000	1.2
Lonnie's Pond	5,474,000	2,623,000	1.1
Meetinghouse Pond	6,330,000	2,864,000	1.1

Tide prism distribution to the different channels of the Chatham Harbor inlet complex can be computed using the model. Bank-to-bank observation transects across each channel opening (that is, north and south inlets, Fool's Cut, the north and south ends of Chatham Harbor and the entrance to Pleasant Bay proper) are specified in the model. Time varying hydrodynamic flux is computed in the model at these transects. Average flood and ebb tide prisms are then calculated for each of the transects using the model output. In Figure III-14, the flow across each inlet transect is shown as a percentage of the combined volume exchanged through the north and south inlets together. The results of this analysis of tide flows at the inlet complex indicate that:

- there is slightly more volume exchanged through the north inlet than the south,
- most of the prism exchanged through the south inlet passes through Fools Cut,
- Chatham Harbor floods from both ends, but ebbs to the south, and
- Pleasant Bay receives its flood tide prism via the north inlet only.

These results are similar to a recent coastal processes analysis of the 2018 conditions of the inlet complex (Applied Coastal and Center for Coastal Studies, 2019). Because Pleasant Bay proper is exchanging tide prism with the open ocean directly though the north inlet, it is experiencing optimum flushing conditions. Though the tide range in Pleasant Bay and its sub-embayments is about the same as it was prior to the 2007 north inlet breach, tidal flushing of the system is much more efficient now, since the tide prism of Pleasant Bay no longer has to flow through Chatham Harbor. Therefore, water quality improvements observed in Pleasant Bay today compared to pre-north-breach conditions of the inlet complex are because of the more direct flow path for tides through the north inlet, rather than a larger tide range in Pleasant Bay.

Figure III-14. Pleasant Bay 2019 Flood and Ebb tide distribution. Percent of total prism of combined north and south inlets, average flood tide (left) and ebb (right).

IV. Pleasant Bay 2020 Water Quality Model Update

A new RMA-4 water quality model of the Pleasant Bay estuary system was developed, based on the RMA-2 hydrodynamic model of 2019 conditions of the Chatham Harbor inlet complex (Kelley, 2021). This water quality model is parameterized using updated water quality data, benthic flux measurements and watershed N loading. The calibration of the water quality model is based on two separate constituents, salinity and bioactive N concentrations measured at 27 stations located in Pleasant Bay, offshore of Nauset Beach and in Stage Harbor.

IV.1. Model Input data

IV.1.A. Water Quality Measurements

Bioactive N (DIN+PON) concentrations for stations (Figure IV-1) in the Pleasant Bay system are provided in Table IV-1. The values in this table represent means and standard deviations calculated using data measured in the summer seasons of 2015 through 2019.

IV.1.B. N Loading to Pleasant Bay

2020 existing condition N loading to Pleasant Bay and its sub-embayments are provided in Table IV-2. Sub-embayment N loads are broken down into watershed, atmospheric deposition, and net benthic flux components. Benthic flux loads are based on rates derived using 2019 measured benthic core data, applied to the surface area of each sub-embayment.

IV.1.C. Freshwater Inputs

Groundwater inputs to Pleasant Bay sub-embayments and average direct rainfall to the estuary's surface were applied to the model using values developed for the 2004 MEP model of Pleasant Bay (Table IV-3).

IV.2. Model Development, Calibration, and Results

The water quality model of Pleasant Bay was developed by calibrating the model by comparing model output to measured salinity and bioactive N data. In each model run, salinity and N concentrations were specified at the model open boundaries offshore Nauset Beach and at Fool's Cut using measured data from monitoring stations PBA-17a and CM-7, respectively. Freshwater recharge and watershed N loads were applied to the model at grid cells near the landward edge of the model mesh. Atmospheric deposition, benthic flux N loads and direct rainfall were applied to the remainder of the elements in each model sub-division.

For model calibration, 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 and bioactive N output from the model was compared to the measured averaged at each of the water quality monitoring stations. The objective of the model calibration is to minimize RMS error and maximize the R^2 correlation between the measured data and model output at the monitoring stations by adjusting the diffusion coefficients set for the model.

The final calibrated salinity model has an R^2 of 0.92 and RMS errors of 0.5 ppt, while the bioactive N model has an R^2 of 0.96 and RMS error or 0.018 mg/L. Plots of the comparison between measured data and model output are provided in Figures IV-2 and IV-3 for the salinity model and Figures IV-4 and IV-5 for the bioactive N model. The final values of the model diffusion coefficients applied to the model are provided in Table IV-4. Maps of tidally averaged salinity and bioactive N, for existing conditions, are presented in Figures IV-6 and IV-7.

Table IV-1. Average Measured and modeled bioactive N concentrations. Measured bioactive nitrogen (DIN+PON) data and modeled bioactive nitrogen concentrations for the Pleasant Bay estuarine system used in the model calibration plots of Figures IV-2 and IV-3. All concentrations are given in mg/L N. "Data mean" values are calculated as the average of the separate yearly means. Data represented in this table were collected in the summers of 2015 through 2019.

Bioactive Nitrogen	monitoring station	Bioactive Nitrogen			model min (mg/L)	model max (mg/L)	model average (mg/L)
		data mean (mg/L)	s.d. all data (mg/L)	N			
Meetinghouse Pond	PBA-16	0.289	0.078	56	0.276	0.299	0.288
Meetinghouse Pond	WMO-10	0.225	0.036	56	0.198	0.271	0.238
The River – mid	WMO-08	0.224	0.076	28	0.160	0.219	0.192
Lonnie's Pond (Kescayo Ganset Pond)	PBA-15	0.249	0.059	55	0.228	0.264	0.246
Areys Pond	PBA-14	0.324	0.084	54	0.302	0.364	0.334
Namequoit River - upper	WMO-6	0.277	0.062	28	0.168	0.317	0.239
The River - lower	PBA-13	0.161	0.036	52	0.127	0.168	0.148
Pochet – upper	WMO-05	0.267	0.066	25	0.245	0.318	0.279
Pochet – mouth	WMO-03	0.152	0.030	27	0.128	0.166	0.146
Little Pleasant Bay - head	PBA-12	0.131	0.026	50	0.120	0.155	0.139
Little Pleasant Bay - main basin	PBA-21	0.104	0.021	47	0.114	0.148	0.132
Paw Wah Pond	PBA-11	0.242	0.182	55	0.168	0.239	0.207
Little Quanset Pond	WMO-12	0.203	0.040	25	0.164	0.206	0.185
Quanset Pond	WMO-01	0.183	0.049	53	0.132	0.172	0.153
Round Cove	PBA-09	0.278	0.083	57	0.236	0.273	0.254
Muddy Creek - upper	PBA-05a	0.490	0.085	27	0.361	0.591	0.503
Muddy Creek - lower	PBA-05	0.224	0.048	29	0.171	0.283	0.224
Pleasant Bay - head	PBA-08	0.133	0.034	47	0.103	0.134	0.121
Pleasant Bay- upper Strong Island	PBA-19	0.096	0.020	27	0.086	0.125	0.104
Pleasant Bay - off Muddy Creek	PBA-06	0.130	0.033	53	0.132	0.147	0.140
Pleasant Bay - Strong Island channel	PBA-20	0.114	0.024	46	0.087	0.122	0.103
Ryders Cove - upper	PBA-03	0.216	0.057	45	0.204	0.230	0.218
Ryders Cove - lower	CM-13	0.123	0.027	46	0.091	0.137	0.113
Crows Pond	PBA-04	0.144	0.051	51	0.111	0.119	0.116
Chatham Harbor - upper	PBA-01	0.105	0.015	39	0.090	0.113	0.099
Chatham Harbor – lower (Flood Tide)	PBA-17a	0.084	0.012	23	-	-	-
South Boundary off Stage Harbor	CM-7	0.107	0.023	110	-	-	-

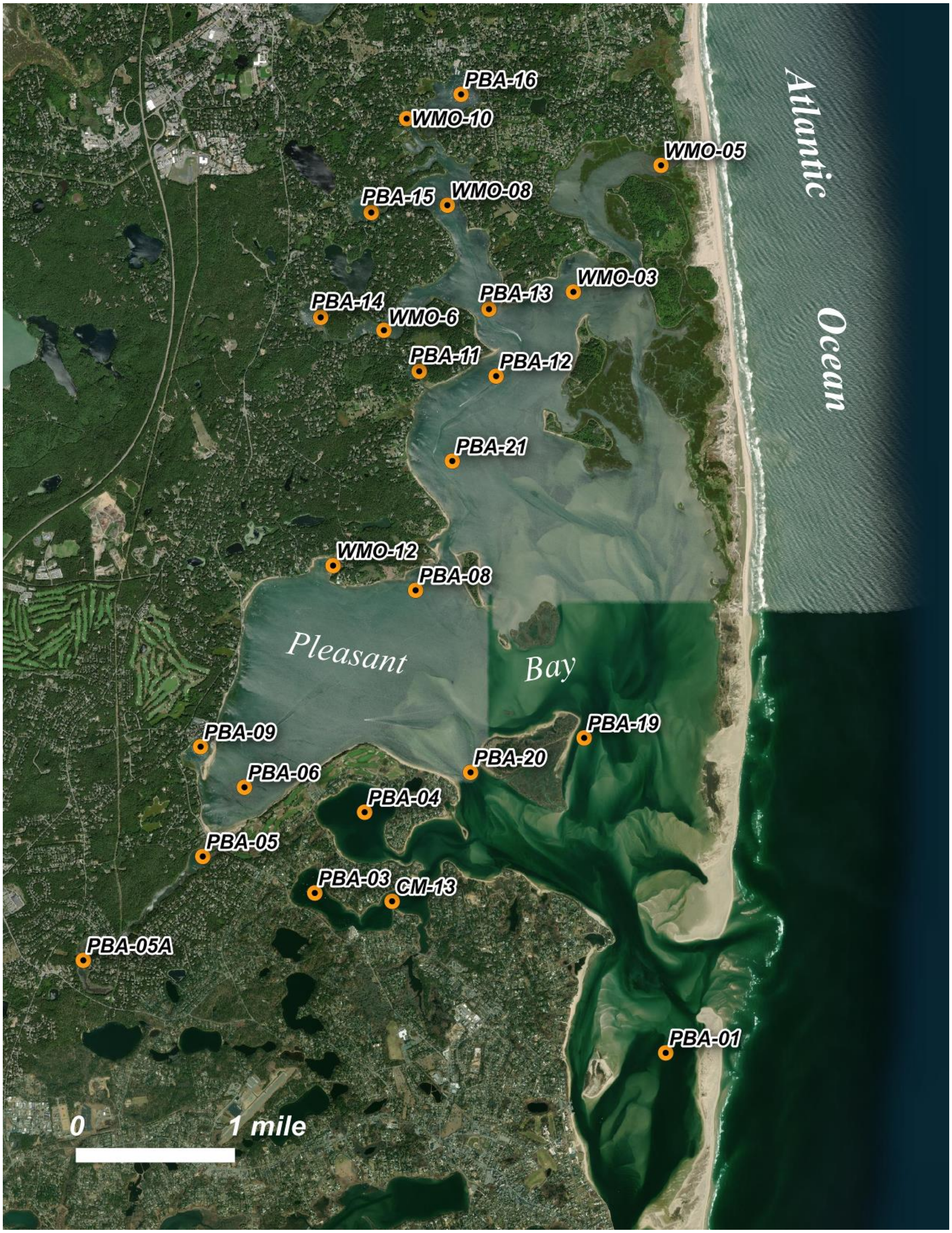

Figure IV-1. Water quality monitoring station locations in the Pleasant Bay estuary system. Station labels correspond to those provided in Table 1.

Table IV-2. Nitrogen loads used in 2020 N modeling. Sub-embayment and surface water loads used for total nitrogen modeling of the Pleasant Bay system, with total watershed N loads, atmospheric N loads, and benthic flux. These loads represent present loading conditions for the listed sub-embayments.			
sub-embayment	**watershed load (kg/day)**	**direct atmospheric deposition (kg/day)**	**benthic flux net (kg/day)**
Meetinghouse Pond	6.945	0.510	5.936
The River – upper	2.559	0.288	2.861
The River – lower	3.784	2.241	27.975
Lonnie's Pond	2.195	0.225	6.568
Areys Pond	1.627	0.181	5.259
Namequoit River	2.745	0.523	3.930
Paw Wah Pond	1.860	0.082	0.169
Pochet Neck	8.422	1.784	13.139
Little Pleasant Bay	9.216	23.492	112.064
Quanset Pond	1.367	0.170	6.052
Tar Kiln Stream	1.671	0.000	-
Round Cove	5.745	0.170	0.206
The Horseshoe	0.570	0.063	-
Muddy Creek - upper	12.329	0.170	1.255
Muddy Creek - lower	10.770	0.247	1.817
Pleasant Bay	24.633	18.730	21.023
Pleasant Bay/Chatham Harbor Channel	-	17.393	19.350
Bassing Harbor - Ryder Cove	11.992	1.299	1.439
Bassing Harbor - Frost Fish Creek	3.611	0.096	0.127
Bassing Harbor - Crows Pond	4.181	1.389	0.210
Bassing Harbor	2.397	1.071	2.354
Chatham Harbor	19.107	13.840	244.628
TOTAL - Pleasant Bay System	137.726	83.962	476.364

Table IV-3. Freshwater Input for 2020 Water Quality Model. Total input of groundwater recharge and average estuary surface precipitation, in ft^3/day, for Pleasant Bay model subdivisions.			
sub-embayment	**input**	**sub-embayment**	**input**
Meetinghouse Pond	88,641	Round Cove	88,394
The upper River	105,224	Lower Muddy Creek	233,980
The River	155,718	Upper Muddy Creek	305,416
Lonnie's Pond	151,888	Crows Pond	94,660
Lonnie's Pond River	43,782	Ryders Cove	263,613
Areys Pond	115,563	Frost Fish	62,342
Namequoit River	134,113	Bassing Harbor	65,638
Pah Wah Pond	48,808	Pleasant Bay	1,321,160
Quanset Pond	54,076	Chatham Harbor	229,343

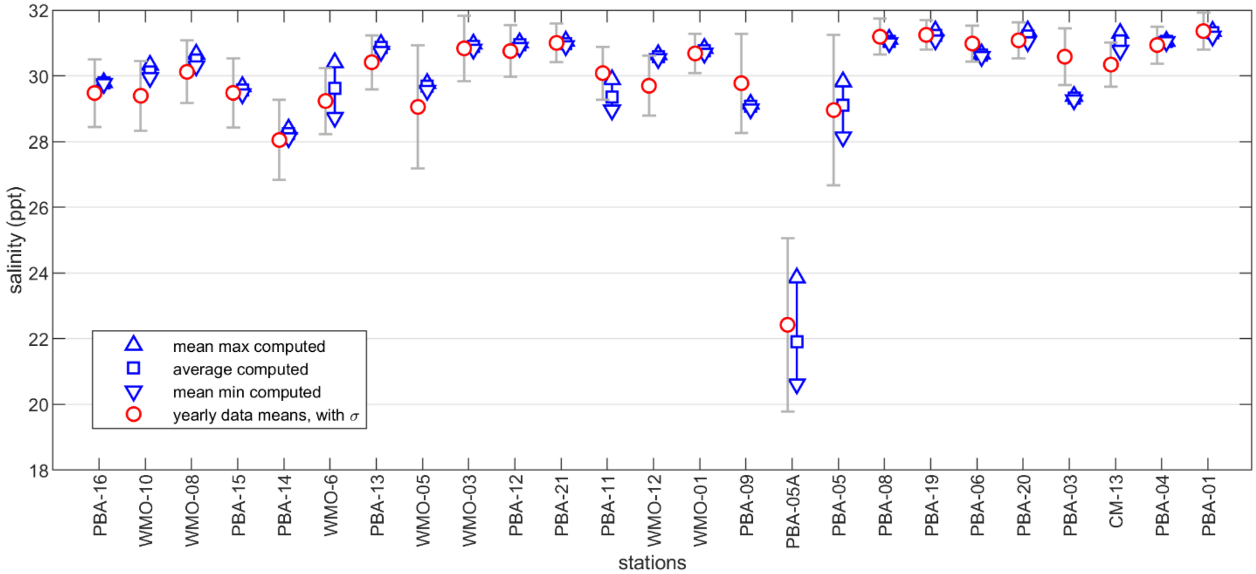

Figure IV-2. Comparison of Measured and Modeled Salinity (2020). Comparison of measured mid-tide 2015-2019 mean mid-ebb salinity concentrations (with standard deviation) and tidally averaged model output, using the 2020 updated model. Also plotted are modeled means of tide cycle maximum and minimum concentrations.

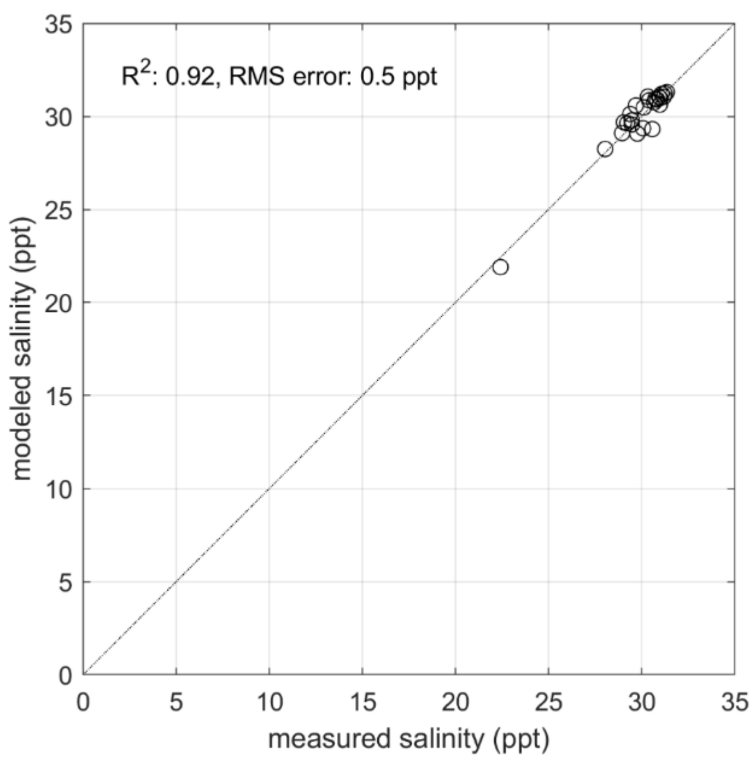

Figure IV-3. Modeled vs Measured Salinity 2020 RMS Review. Updated 2020 model salinity values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) is 0.92 and RMS error for this model verification run is 0.5 ppt.

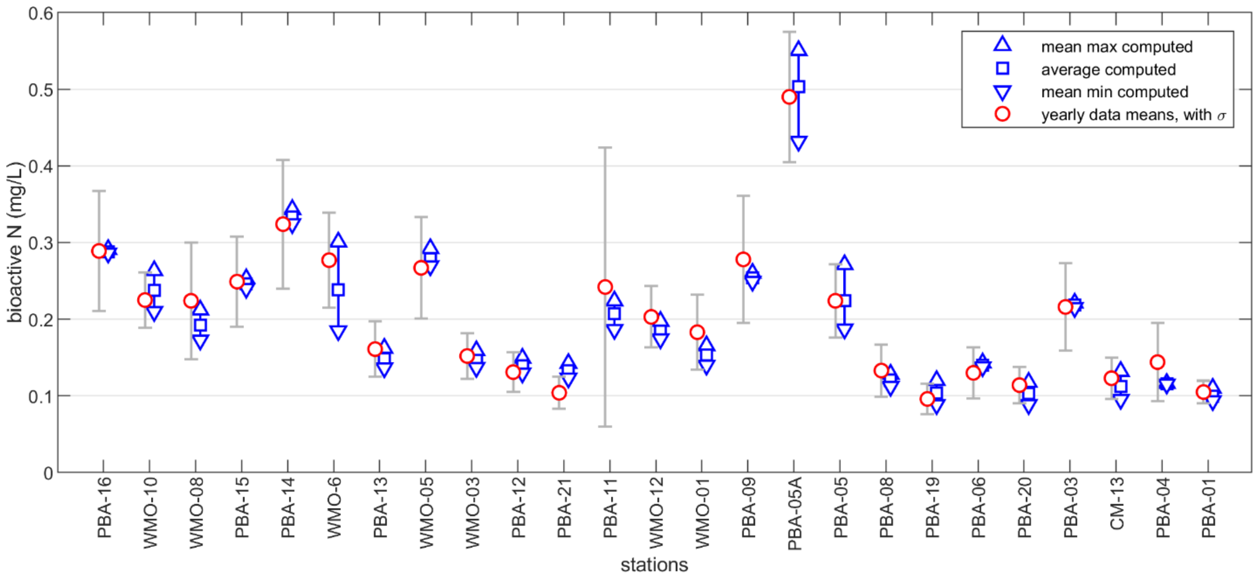

Figure IV-4. Comparison of Measured and Modeled Bioactive N (2020). Comparison of measured mid-tide 2015-2019 mean bioactive N concentrations (with standard deviation) and tidally averaged model output, using the updated 2020 model. Also plotted are modeled means of tide cycle maximum and minimum concentrations.

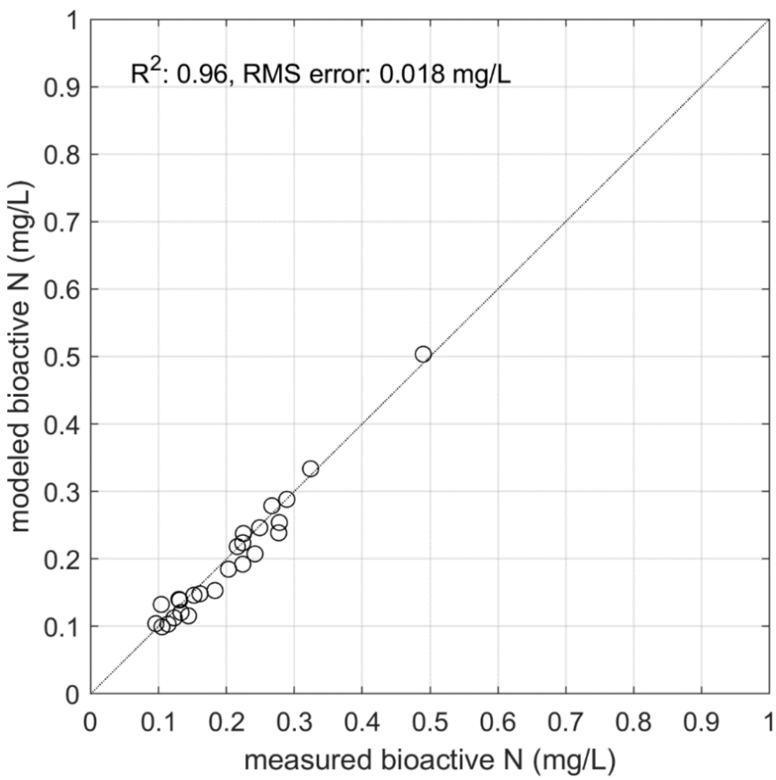

Figure IV-5. Modeled vs Measured Bioactive N 2020 RMS Review. Model Bioactive N target values are plotted against measured concentrations, together with the unity line. Computed correlation (R^2) is 0.96 and RMS error for this model verification run is 0.018 mg/L.

Table IV-4. 2020 Model Diffusion Coefficients. Diffusion coefficient values (D, m^2/sec) specified for the material type subdivisions of the Pleasant Bay hydrodynamic model (as shown in Figure 5 of the Pleasant Bay hydrodynamic model report.

mesh material type	D	mesh material type	D
Offshore	100	Muddy Creek Inlet	300
North Inlet	100	Round Cove	0.2
Chatham Harbor	100	Quanset Pond	0.2
South Inlet	100	Paw Wah Pond	0.1
Fools Cut	100	Pochet	2
Pleasant Bay	10	The River	20
Pleasant Bay Marsh	10	Namequoit River	5
Ryders Cove	1.5	Areys Pond	5
Crows Pond	5	Lonnie’s Pond	12
Bassing Harbor	100	Upper River	25
Muddy Creek	3	Meetinghouse Pond	1

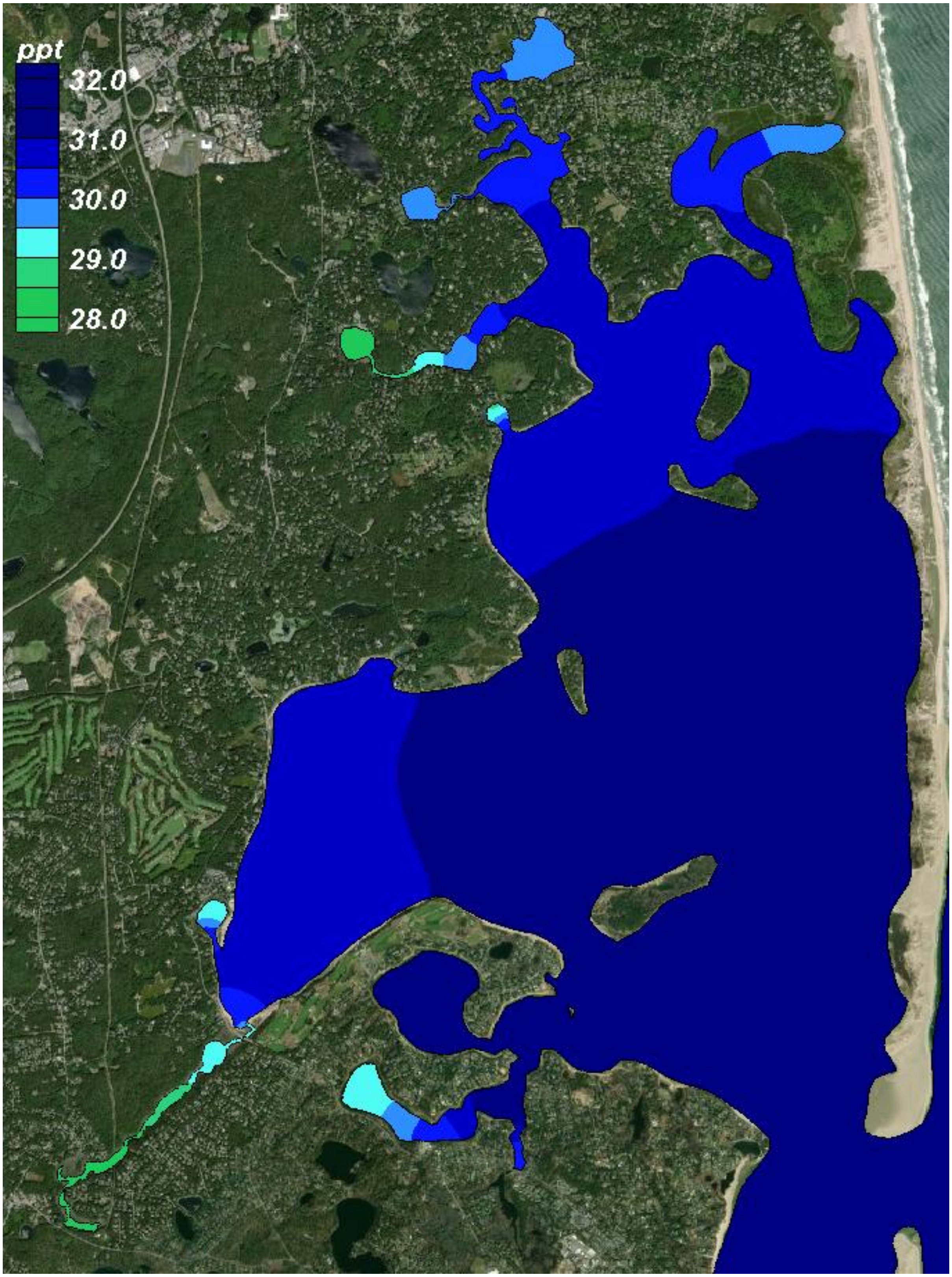

Figure IV-6. 2020 Water Quality Modeled Salinity Contours. Contours of tidally averaged salinity (ppt) in Pleasant Bay from the updated 2020 Water Quality Model.

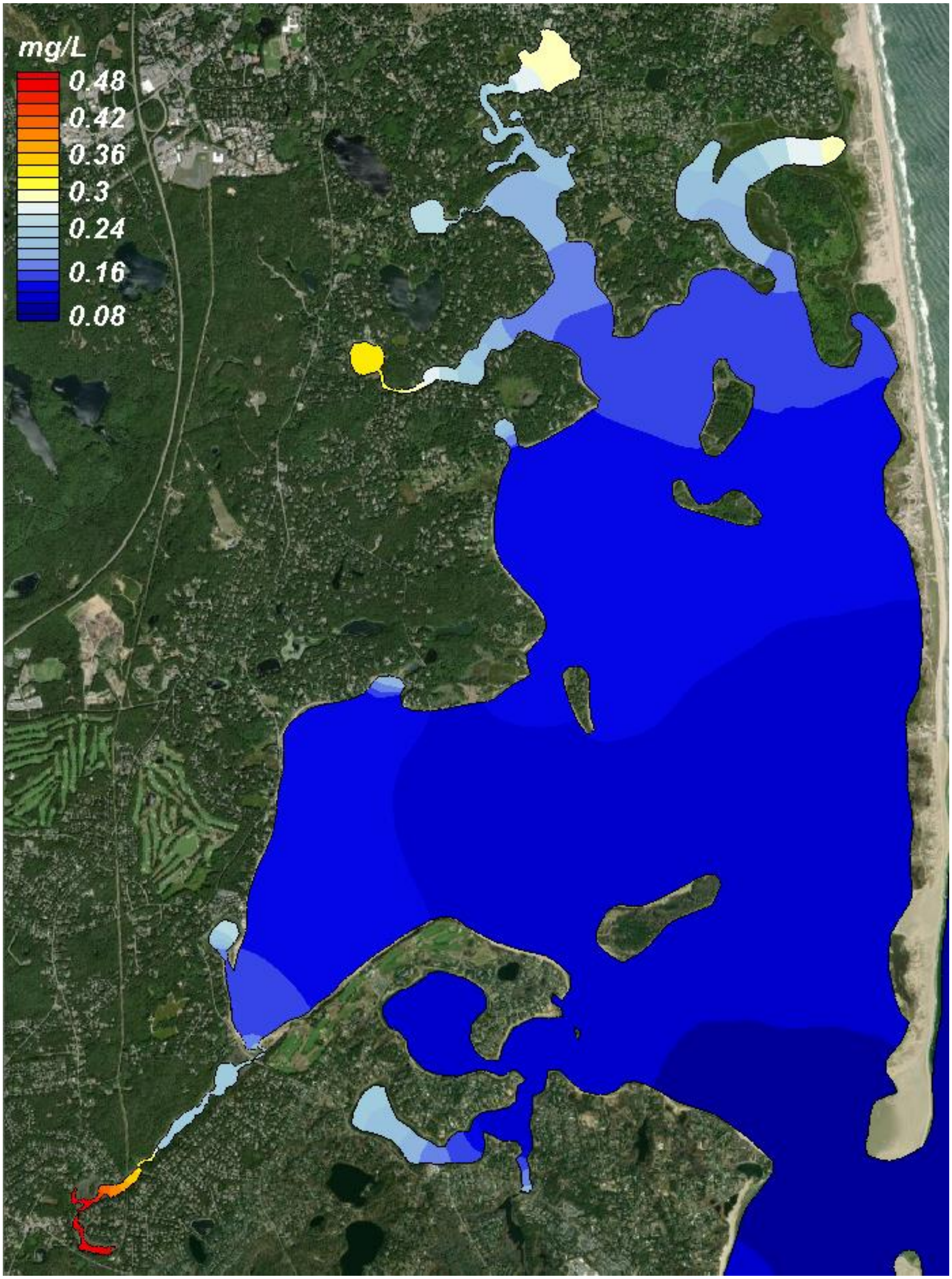

Figure IV-7. 2020 Water Quality Modeled Existing Conditions Bioactive N Contours. Contours of tidally averaged bioactive N (mg/L) in Pleasant Bay based on existing conditions from the updated 2020 Water Quality Model.

IV.3. Pleasant Bay Basins Residence Time

The calibrated water quality model of Pleasant Bay can be used to compute a flushing rate that accounts for the advection of tidal flows, mixing and diffusion of water quality constituents due to turbulence, and dilution due to groundwater flows to the sub-embayments of the system. This provides a more accurate representation of tidal flushing of the system and its attached sub-embayments compared to the simpler method based on tidal prism exchange that was presented in the hydrodynamic report.

The alternate water quality model-based flushing rate calculation is based on the concept of a continuous stirred tank reactor (CSTR, Monsen, *et al.*, 2002). 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 Pleasant Bay and Chatham Harbor, and a concentration of 0 set for all remaining areas of the model domain. The open boundary concentration was also set to 0. In this way, the residence time for the selected points in Pleasant Bay 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.

The Pleasant Bay model was run for a simulated period of one month. Time series of concentrations of the modeled conservative constituent were output at the water quality monitoring stations designated in Figure IV-1. The first model time step where the concentration dropped below 0.37 was recorded for each monitoring station. Residence times (in days) for each station are mapped in Figure IV-8. Values of residence times determined by this method range from less than a half tide cycle for stations nearest the north inlet, to as high as 10 days in Meetinghouse Pond.

These residence time results provide more detail concerning the efficiency of tidal exchange between the open ocean and different areas of the estuary, compared to the simpler tide prism method. In Figure IV-8 it is seen that the residence time at the head of Little Pleasant Bay is 3.8 days, compared to 2.8 days off Sampson Island, 5.8 days in Pleasant Bay near the inlet to Muddy Creek, and 0.2 days near Strong Island. These results show that residence times in the main basin of Pleasant Bay can vary by more than an order of magnitude, which is much more resolution than can be provided by the simpler tide prism method.

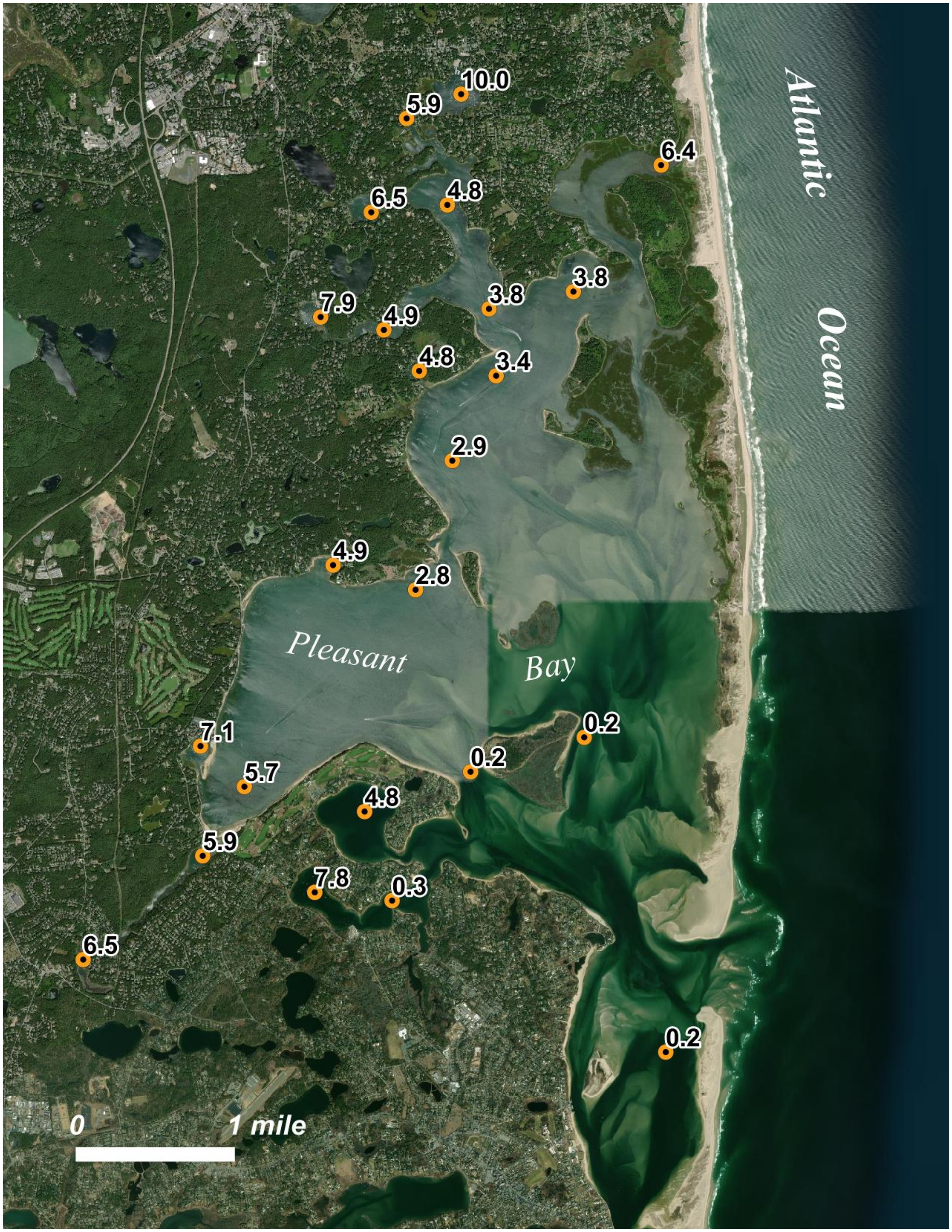

Figure IV-8. 2020 Residence Times in Pleasant Bay. Map of residence times in days determined using the 2020 water quality model of Pleasant Bay, for locations that correspond to the water quality stations mapped in Figure IV-1.

V. Pleasant Bay Wastewater Planning Scenarios

In order to address the TMDLs and the terms of the inter-town IMA in coordination with the PBA, the Pleasant Bay watershed towns have been developing nitrogen management strategies through their individual town Comprehensive Wastewater Management Plans (CWMPs). Once all the SNEP existing conditions updates (*e.g.*, sediment regeneration, existing watershed nitrogen loads, tidal movements), were incorporated into the respective Pleasant Bay linked models, the water quality model was recalibrated and revalidated using the same procedures as during the MEP. Once the model was revalidated, it could be used to produce reliable predictions of *in-situ* nutrient related water quality resulting from nitrogen management strategies. Under the SNEP scope, the PBA requested a scenario to evaluate the collective impact of all of the Town's various nitrogen management strategies on water quality in the Bay and its various tributary subembayments. The project team was also asked to review whether the collective impact of these strategies would attain the Pleasant Bay TMDL nitrogen loading thresholds. Project staff reviewed current nitrogen management plans with each of the watershed towns and their respective CWMP consultants in order to incorporate the details of each plan into a nitrogen management scenario using the linked models.

It should be noted that these strategies may be further refined as towns evaluate costs and other factors, but the strategies were current at the time of discussion between project and town/consultant staffs. It should also be noted that future additional development/land uses were not included in this nitrogen management scenario (*e.g.*, buildout within the watershed was not assessed); the strategies only apply to the updated current land uses within the watershed. The overview of each of the town strategies in this cumulative Pleasant Bay scenario are briefly summarized here:

<u>Chatham</u>

Based on discussions with Town staff, the current Town of Chatham nitrogen management plan is to connect <u>all</u> of its wastewater discharges within the Pleasant Bay watershed to a sewer system and to discharge the treated wastewater outside of the watershed.[49] For the purposes of the SNEP nitrogen management scenario, both private wastewater treatment plants within the watershed were also assumed to be connected to the planned sewer system. No other nitrogen management changes to the updated current conditions nitrogen loads within Chatham were included in the SNEP nitrogen management scenario.

<u>Harwich</u>

The Town of Harwich is planning a phased installation of sewers to connect all wastewater discharges within the Pleasant Bay watershed. All collected wastewater would be discharged outside of the watershed **(**see Figure II-2**)**.[50] For the purposes of the SNEP scenario, all planned sewering phases occur at the same time. No other changes in updated current nitrogen loads were included in the SNEP scenario.

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[49] Bob Duncanson, Town of Chatham (personal communication, 10/18/19)

[50] David Young, CDM Smith (personal communication, 9/27/19)

Brewster

Current Town of Brewster nitrogen management plans focus on two components: a) reductions in golf course fertilizers at the town-owned Captains Golf Course and b) installation of innovative/alternative (IA) denitrifying septic systems in two subwatersheds that directly discharge to Pleasant Bay without passing through freshwater ponds.[51] The proposed fertilizer reductions are in addition to the fertilizer reductions from MEP watershed nitrogen loads and N recapture system (*i.e.*, fertigation) at the golf course that were included in the current conditions SNEP update loads. In addition to the golf course fertilizer changes, the current Town plan also includes IA systems with 12 mg/L TN discharge for all developed properties within the Freemans Way Well (#27) and the Tar Kiln Stream LT 10 (#69) subwatersheds. It was acknowledged that the 12 mg/L TN is lower than any IA systems currently permitted by MassDEP. No other changes in updated current nitrogen loads within Brewster were included in the SNEP nitrogen management scenario.

Orleans

The Town of Orleans is currently planning three steps to address nitrogen management within the town's portion of the Pleasant Bay watershed: 1) a sewer system to collect wastewater mostly within the Meetinghouse Pond watershed and discharging the treated effluent outside of the Pleasant Bay watershed, 2) installing 16 permeable reactive barriers (PRBs) to remove nitrogen from groundwater, and 3) enhanced aquaculture in Lonnie's Pond to remove nitrogen within the pond (see Figure II-3). The current target for nitrogen removal by enhanced aquaculture in Lonnie's Pond is 75 kg/yr,[52] but the long-term goal for enhanced aquaculture in the CWMP is 300 kg/yr N removal. This higher amount of removal was incorporated into the SNEP nitrogen management scenario and is the entire projected MEP nitrogen removal necessary to meet the threshold N/TMDL.[53]

Nitrogen removal by the planned PRBs required the identification of all properties impacted by the PRBs and determination of an appropriate nitrogen removal rate for the PRBs. After much discussion among project staff and town consultants, a nitrogen removal rate of 80% was assumed for the planned PRBs. This rate was based largely on the performance of the PRB the town installed as a demonstration project near the Nauset Middle School wastewater discharge. This nitrogen removal rate was applied to the existing conditions SNEP loads of wastewater, lawn fertilizers, impervious surfaces (*e.g.*, roofs, roads), and natural areas on properties identified by project staff within estimated groundwater flow paths for each PRB. These flow paths were developed by the Town wastewater consultants using a town-specific groundwater model.[54] Aside from the PRBs, Meetinghouse Pond sewer collection area, and Lonnie's Pond enhanced aquaculture, no other changes in updated current nitrogen loads for Orleans were included in the SNEP nitrogen management scenario.

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51 Mark Nelson, Horsley Witten Group (personal communication, 8/12/20)

52 Howes, B. and E. Eichner. 2018. Lonnie's Pond Aquaculture and Nitrogen Management Plan. Prepared for the Town of Orleans. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 128 pp.

53 Table VIII-4 in the Pleasant Bay MEP report

54 AECOM Technical Memorandum. February 26, 2020. Task 12.1.B.2 - Technical Memorandum: Permeable Reactive Barriers (PRB) Full-Scale Watershed Planning Town of Orleans, Massachusetts – DRAFT. To: G. Meservey, Town of Orleans. From: T. Parece. 38 pp.

The overall impact of the town strategies reviewed in the nitrogen management/composite scenario was that 10 subwatershed nitrogen loads were less than the 19 TMDL subwatershed threshold loads and the overall watershed load was less than the system watershed TMDL threshold load (Table V-1). This comparison to TMDLs does not incorporate the updated hydrodynamics included in the SNEP project; whether these loads attain the TMDL threshold concentrations and MEP benthic community check station concentrations is determined when these loads are incorporated into the updated water quality model. Just on the basis of the watershed nitrogen loads, Orleans had one of the estuary segments that met the TMDL subwatershed loads (Lonnie's Pond), one was in Harwich (Round Cove), four were in Chatham (Ryder Cove, Crows Pond, Bassing Harbor main, and Chatham Harbor), one was shared between Harwich and Chatham (Muddy Creek – upper), and one was shared among all four watershed towns (Pleasant Bay main). Collectively, the planned nitrogen management strategies would reduce updated existing SNEP unattenuated watershed loads by 26,301 kg/yr (-52%).

The composite watershed loads in Table V-1 were combined with direct atmospheric loads and adjusted benthic flux loads and then incorporated into the 2020 Pleasant Bay water quality model (Table V-2). Benthic loads for this scenario were developed using the existing conditions 2020 flux values adjusted by estimating the PON change over background (the existing PON offshore Nauset Beach) that would result for the scenario watershed load change. The benthic flux of the scenario is then calculated by multiplying the existing flux by the ratio of estimated future PON to existing PON at the sub-embayment. Direct atmospheric deposition remains unchanged from present 2020 conditions.

The comparison of tidally averaged bioactive N concentrations for 2020 present and 2020 composite loading scenario loading was developed for all water quality monitoring stations (Table V-3). In Table V-3, secondary threshold stations are shaded light blue, while primary threshold stations are shaded light orange. A contour map of tidally average bioactive N for the 2020 Composite scenario run is presented in Figure V-1.

The modeling results in Table V-3 indicate that the 2020 Composite scenario loads achieve the target concentration of 0.16 mg/L at both primary threshold stations. The secondary threshold concentration of 0.21 mg/L is met at all stations except Pochet (WMO-05) and the upper Namequoit River (WMO-06).

PBA also asked to have a scenario completed using the 2020 Composite nitrogen loads with the original MEP water quality model in order to compare and contrast results. In this scenario, the Table V-2 nitrogen loads were utilized and the original MEP water quality model was utilized after a number of QA/QC reviews on new equipment confirmed that it was providing the same results. Using the original MEP water quality model, the composite nitrogen management scenario attains the target concentration at both sentinel stations, but attains the secondary target at only three of the 8 stations (i.e., PBA-15, Lonnie's Pond; WMO-12, Little Quanset Pond; and PBA-09, Round Cove).

Table V-1. SNEP Watershed Nitrogen Loads (unattenuated and attenuated) for future composite Town Watershed Nitrogen Management. Future nitrogen management loads include all current town CWMP nitrogen management strategies based on the 2020 existing conditions update plus the implementation of all . Watershed groupings are from MEP; various groupings occurred in some of the loading sets (*e.g.*, TWMP loads for Pleasant Bay subwatershed include Little Pleasant Bay, Tar Kiln Stream, and the Horseshoe). Future N management loads attain the target watershed load portions of the assigned TMDLs in 10 of the 19 subwatersheds without consideration of hydrodynamic update, as well as the overall system load (indicated by gold fill). TMDL for Pleasant Bay Main includes Tar Kiln Stream and The Horseshoe. Nitrogen loads are only watershed loads and do not include N loads on the estuary surfaces. Updated existing SNEP N loads were only slightly greater than the 2010 Update, though the distribution of the loads throughout the watershed was different.

	TMDL	2020 SNEP Update			
	Watershed Threshold Loads	Existing N Load (kg/yr)		Future N Mgmt (kg/yr)	
Watershed	kg/yr	unatten	atten	unatten	atten
Meetinghouse Pond	387	2,535	2,535	522	522
The River – upper	635	1,146	934	915	705
The River – lower	891	1,613	1,381	1,450	1,226
Lonnie's Pond	595	1,270	801	1,116	360
Areys Pond	336	768	594	768	594
Namequoit River	631	1,154	1,002	945	799
Paw Wah Pond	266	679	679	543	543
Pochet Neck	1,504	3,138	3,074	2,519	2,460
Little Pleasant Bay	2,146	3,389	3,364	2,896	2,810
Quanset Pond	394	729	499	704	473
Tar Kiln Stream	-	1,525	610	1,196	478
Round Cove	1,080	2,105	2,097	970	962
The Horseshoe	-	379	208	365	201
Muddy Creek - upper	1,683	5,204	4,500	1,610	1,298
Muddy Creek - lower	781	4,137	3,931	1,448	1,337
Pleasant Bay Main	7,975	9,603	8,991	6,723	5,978
Bassing Harbor - Ryder Cove	1,632	4,807	4,377	1,309	1,048
Bassing Harbor - Frost Fish Creek	256	1,318	1,318	294	294
Bassing Harbor - Crows Pond	1,540	1,531	1,526	312	309
Bassing Harbor	610	889	875	192	187
Chatham Harbor	6,242	6,974	6,974	1,740	1,740
TOTAL - System	**29,583**	**54,894**	**50,271**	**28,537**	**24,324**

Table V-2. 2020 Composite Scenario Nitrogen Loads. Sub-embayment and surface water loads used for total nitrogen modeling of the Pleasant Bay system, with total watershed N loads, atmospheric N loads, and benthic flux. The watershed loads are based on changes to existing conditions based on planned town nitrogen management strategies.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Meetinghouse Pond	1.430	0.510	4.009
The River – upper	1.932	0.288	1.941
The River – lower	3.359	2.241	25.507
Lonnie’s Pond	0.838	0.225	4.667
Areys Pond	1.627	0.181	4.889
Namequoit River	1.942	0.523	3.670
Paw Wah Pond	1.488	0.082	0.149
Pochet Neck	6.740	1.784	12.246
Little Pleasant Bay	7.866	23.492	111.076
Quanset Pond	1.296	0.170	5.603
Tar Kiln Stream	1.310	0.000	-
Round Cove	2.636	0.170	-1.194
The Horseshoe	0.551	0.063	-
Muddy Creek - upper	3.564	0.170	0.578
Muddy Creek - lower	3.677	0.247	1.172
Pleasant Bay	16.871	18.730	20.837
Pleasant Bay/Chatham Harbor Channel	-	17.393	19.350
Bassing Harbor - Ryder Cove	2.871	1.299	1.007
Bassing Harbor - Frost Fish Creek	0.805	0.096	0.116
Bassing Harbor - Crows Pond	0.847	1.389	0.163
Bassing Harbor	0.512	1.071	2.147
Chatham Harbor	4.767	13.840	244.628
TOTAL - Pleasant Bay System	**66.929**	**83.962**	**462.560**

Table V-3. Comparison of model average bioactive N (DIN+PON) concentrations in Pleasant Bay for 2020 present conditions and 2020 Composite loading. The primary sentinel threshold stations (0.16 mg/L target) are shaded orange, secondary threshold stations (0.21 mg/L target) are shaded blue. The Ryders Cove threshold is set as the average of the PBA-03 and CM-13. The Composite nitrogen management scenario attains the target concentration at both sentinel stations and at all but two of the secondary stations (*i.e.*, WMO-5, Pochet and WMO-6, Namequoit River).

Sub-Embayment	monitoring station	2020 existing (mg/L)	2020 composite (mg/L)	% change
Meetinghouse Pond	PBA-16	0.288	0.218	-34.3%
Meetinghouse @Rattles Dock	WMO-10	0.238	0.196	-27.3%
Meetinghouse @Off Lonnie's Inlet	WMO-08	0.192	0.171	-19.4%
Lonnie's Pond	PBA-15	0.246	0.205	-25.3%
Areys Pond	PBA-14	0.334	0.308	-10.4%
Namequoit River Upper	WMO-6	0.239	0.220	-12.3%
The River-Mouth	PBA-13	0.148	0.140	-12.5%
Pochet - Upper off Town Landing	WMO-05	0.279	0.256	-11.8%
Pochet - Basin@ Mouth	WMO-03	0.146	0.138	-12.9%
Little Pleasant Bay - Head	PBA-12	0.139	0.132	-12.7%
Little Pleasant Bay - Main Basin	PBA-21	0.132	0.126	-12.5%
Paw Wah Pond	PBA-11	0.207	0.187	-16.3%
Little Quanset Pond	WMO-12	0.185	0.173	-11.9%
Quanset Pond	WMO-01	0.153	0.143	-14.5%
Round Cove	PBA-09	0.254	0.150	-61.2%
Muddy Creek - Upper	PBA-05A	0.503	0.220	-67.5%
Muddy Creek - Lower	PBA-05	0.224	0.152	-51.4%
Pleasant Bay - Head	PBA-08	0.121	0.115	-16.2%
Pleasant Bay - Upper Strong Island	PBA-19	0.104	0.101	-15.0%
Pleasant Bay - off Muddy Creek	PBA-06	0.140	0.123	-30.4%
Pleasant Bay - lower Strong Island	PBA-20	0.103	0.100	-15.8%
Ryders Cove Upper	PBA-03	0.218	0.140	-58.2%
Ryders Cove Lower	CM-13	0.113	0.103	-34.5%
Crows Pond	PBA-04	0.116	0.106	-31.3%
Chatham Harbor - Upper	PBA-01	0.099	0.098	-6.7%

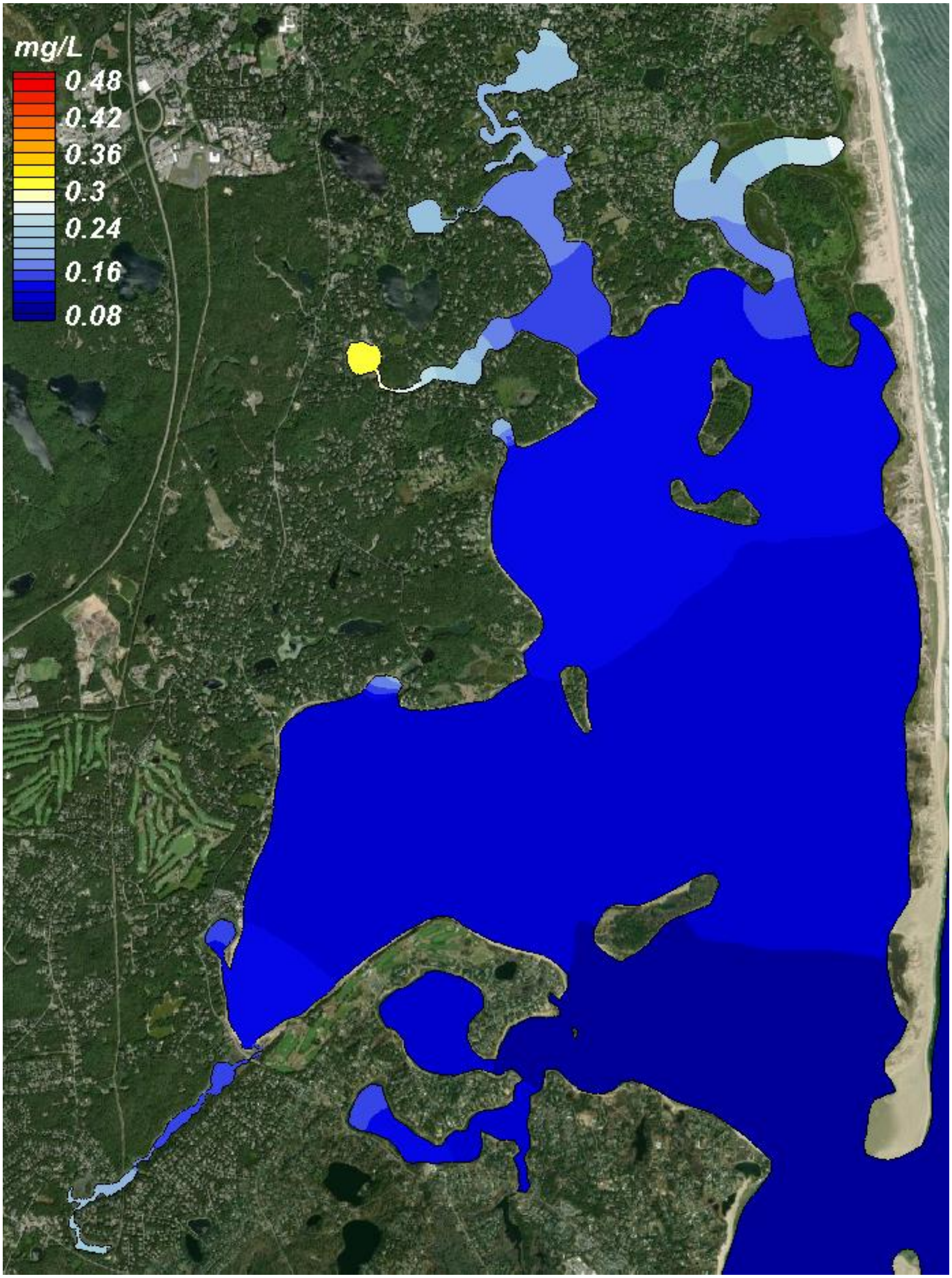

Figure V-1. 2020 Water Quality Modeled Composite Scenario Bioactive N. Contours of tidally averaged bioactive N (mg/L) in Pleasant Bay based on 2020 composite nitrogen management strategies.

Table V-4. Comparison of model average bioactive N (DIN+PON) concentrations in Pleasant Bay for 2020 Composite loading and MEP utilizing the MEP water quality model. The primary sentinel threshold stations (0.16 mg/L target) are shaded orange, secondary threshold stations (0.21 mg/L target) are shaded blue. The Composite nitrogen management scenario attains the target concentration at both sentinel stations, but attains the secondary target at only three of the 8 stations (*i.e.*, PBA-15, Lonnie's Pond; WMO-12, Little Quanset Pond; and PBA-09, Round Cove).

Sub-Embayment	monitoring station	MEP (mg/L)	2020 composite (mg/L)	% change
Meetinghouse Pond	PBA-16	0.389	0.284	-27.0%
Meetinghouse Pond	WMO-10	0.264	0.220	-16.7%
The River - upper	WMO-09	0.241	0.207	-14.0%
The River – mid	WMO-08	0.212	0.190	-10.5%
Lonnie's Pond (Kescayo Ganset Pond)	PBA-15	0.251	0.212	-15.5%
Areys Pond	PBA-14	0.298	0.282	-5.2%
Namequoit River - upper	WMO-6	0.240	0.221	-7.9%
Namequoit River - lower	WMO-7	0.217	0.198	-8.5%
The River - lower	PBA-13	0.195	0.179	-8.6%
Pochet – upper	WMO-05	0.270	0.240	-11.0%
Pochet - lower	WMO-04	0.210	0.192	-8.6%
Pochet – mouth	WMO-03	0.184	0.170	-7.5%
Little Pleasant Bay – head SENTINEL	PBA-12	0.178	0.165	-7.6%
Little Pleasant Bay - main basin	PBA-21	0.162	0.151	-6.8%
Paw Wah Pond	PBA-11	0.258	0.247	-4.3%
Little Quanset Pond	WMO-12	0.233	0.204	-12.4%
Quanset Pond	WMO-01	0.194	0.175	-9.7%
Round Cove	PBA-09	0.255	0.204	-20.0%
Muddy Creek - upper	PBA-05a	0.728	0.518	-28.8%
Muddy Creek - lower	PBA-05	0.298	0.230 *	-22.8%
Pleasant Bay - head	PBA-08	0.151	0.141	-6.7%
Pleasant Bay - off Quanset Pond	WMO-02	0.163	0.150	-8.1%
Pleasant Bay- upper Strong Island	PBA-19	0.118	0.114	-3.6%
Pleasant Bay - mid west basin	PBA-07	0.172	0.157	-9.2%
Pleasant Bay - off Muddy Creek	PBA-06	0.198	0.174	-12.1%
Pleasant Bay - Strong Island channel	PBA-20	0.125	0.119	-4.8%
Ryders Cove – upper SENTINEL Average	PBA-03	0.252	0.175	-30.5%
Ryders Cove – lower SENTINEL Average	CM-13	0.160	0.135	-15.4%
Frost Fish - lower	CM-14	0.245	0.168	-31.5%
Crows Pond	PBA-04	0.164	0.139	-15.2%
Bassing Harbor	PBA-02	0.128	0.119	-7.3%
Pleasant Bay - lower	PBA-18	0.117	0.112	-4.0%
Chatham Harbor - upper	PBA-01	0.104	0.102	-1.9%
Chatham Harbor - lower	PBA-17	0.099	0.098	-1.1%

VI. Habitat Quality within the Pleasant Bay System – Eelgrass Distribution

Eelgrass surveys and analysis of historical data for the Pleasant Bay System by the DEP Eelgrass Mapping Program and USGS were reviewed and synthesized by the SNEP/MEP Technical Team. During the MEP, the Technical Team reviewed eelgrass coverage in 1951, 1995, and 2001 as part of the habitat assessment of Pleasant Bay and to understand coverage losses due to nitrogen additions. Since the completion of the MEP assessment, MassDEP has completed two additional eelgrass surveys of Pleasant Bay in 2010 and 2019. As part of the SNEP effort, the project team compared eelgrass coverages across all available surveys.

Project staff reviewed eelgrass coverage surveys conducted between 1951 and 2019 by MassDEP and a detailed selected coverage by the USGS conducted with regard to the 2007 breach.[55] The primary use of the data is to indicate (a) if eelgrass once or currently colonizes a basin and (b) if large-scale system-wide shifts have occurred. Integration of these data sets with more recent surveys provides a view of temporal trends in eelgrass distribution from 1951 to 1995 to 2001 and 2007, 2010, and 2019 (Figures VI-1 through VI-4); the period in which watershed nitrogen loading significantly increased to its present level. More extensive discussion of the 1951, 1995, and 2001 coverages is included in the Pleasant Bay MEP report.[56] This review of coverages during multiple time periods can be used to determine the stability of the eelgrass community.

Pleasant Bay Eelgrass Presence

Currently, eelgrass is present within large portions of the Pleasant Bay System, indicative of a system with high habitat quality areas. These eelgrass beds are generally restricted to the larger lagoonal basins, Little Pleasant Bay, Pleasant Bay and Chatham Harbor. There are also smaller eelgrass areas in Pochet and fringing shallow areas in The River and Meetinghouse Pond. The only tributary embayment to Pleasant Bay with significant eelgrass habitat is Bassing Harbor (see below). The basins presently supporting eelgrass habitat also supported habitat in the 1951 historical analysis. However, it is clear from the 1951, 1995, 2001, 2010 and 2019 temporal sequence that the eelgrass areas in each basin, are declining in coverage. In The River and Pochet, the eelgrass areas were always patchy and resided in the shallows. By the 2019 survey this pattern continues: the eelgrass beds are persisting, but they appear to be declining.

Virtually all of the small enclosed basins did not appear to support eelgrass historically and do not support it today, with the exception of the small patch in the shallows of Meetinghouse Pond. The general pattern is consistent with the deeper waters of these basins and their location and structure which tends to result in nitrogen enrichment.

The overall pattern of eelgrass distribution and temporal decline in coverage is fully consistent with the spatial pattern of nitrogen enrichment (Section IV) and oxygen and chlorophyll levels in the various basins. The pattern of decline is typical of environmental changes brought on by nutrient enrichment. Nutrient enrichment tends to result in loss of eelgrass habitat in the more

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[55] Neckles, H.A., B.S. Kopp, B.J. Peterson, P.S. Pooler. 2012. Integrating Scales of Seagrass Monitoring to Meet Conservation Needs. *Estuaries and Coasts*. 35:23–46. DOI 10.1007/s12237-011-9410-x.

[56] 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 Pleasant Bay, Chatham, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 245 pp.

tidally restricted basins which also tend to be the focus areas for watershed nitrogen inputs. Loss is first in the deeper waters (like in kettle basins) where increases in turbidity from increased phytoplankton production cause shading of the bottom. The pattern of loss from the tidal reaches furthest from the inlet can also be seen in the Pleasant Bay System, however, recent losses within the region of the Chatham Harbor basin do not fit the pattern.

Other factors influence eelgrass bed loss in embayments. Such non-nitrogen related factors vary from boat mooring density, pier construction, boating pressure and shell fishing, all of which can add stress the eelgrass community and result in loss of coverage. While these factors may add stress in nutrient enriched areas, these do not seem to be the overarching factor within Pleasant Bay basins. Instead, it appears that in selected areas in Pleasant Bay, observed eelgrass losses are related mainly to sediment movement and changing hydrodynamics (*e.g.,* Lower Little Pleasant Bay and Chatham Harbor). In the region of the 2007 breach (Lower Little Pleasant Bay), the sandy sediments are unstable in places due to the high water velocities. These conditions have been noted in several studies, including the Pleasant Bay MEP assessment as being unsuitable for eelgrass coverage. In Chatham Harbor, where beds were relatively stable pre-breach, the new flow system where Chatham Harbor receives tidal water from both the north and south inlets has resulted in a depositional environment with elevated sediment oxygen demand and reduced eelgrass coverage (Figure VI-4). At present, it is not possible to determine the relative roles of sediment movement, sediment deposition and organic deposition in this decline, but it appears to be the result of a changing flow system rather than increased watershed nitrogen loading. This latter observation is consistent with the timing of the onset of loss and the tracking of hydrodynamic changes.

It is possible to determine a general idea of short- and long-term rates of change in eelgrass coverage from the mapping data, from the five available surveys. Over the nearly 70 years (1951-2019), the Pleasant Bay System has lost almost 1,300 acres of eelgrass habitat or 55% of its 1951 coverage. This loss has occurred as watershed nitrogen loading rates (1951 to 2001) increased several fold due to land use changes, although some of the recent losses appear to be related to changes in hydrodynamics and sediment deposition (watershed N loading which has only increased ~4% over the past 20 years).

Potential recovery of eelgrass coverage in Pleasant Bay proper can be gauged based upon the response of eelgrass coverage and bed density pre- and post-breach. The 2007 breach resulted in a rapid increase in tidal flushing of the upper basins as seen in the increase in tidal prism (tide range) with increased water quality. In the proximity of the 2007 breach, the USGS conducted eelgrass surveys (2006, 2007, 2008), which showed a rapid increase in eelgrass health, coverage and plant density. While these results have continued to be altered by changes in flow and sediment transport, the observed improvements following increased tidal flushing are similar to what can be expected with a lowering of watershed N loading to in the estuary.

Based upon the 1951 coverage it appears that nitrogen management to restore eelgrass habitat has the potential to recover a significant resource within Pleasant Bay (Table VI-1). However, for the reasons discussed above, creation of eelgrass habitat within the enclosed tributary basins is unlikely and is not supported by the historical analysis, which does not show eelgrass within these portions of the system. Most of the eelgrass habitat has been lost in the larger basins. These smaller tributary basins are where most of the nitrogen entering from the watershed enters first before being flushed to Little Pleasant Bay and Pleasant Bay. Improved habitat quality in these systems will provide improved habitat downstream and provide restored eelgrass habitat in areas such as Little Pleasant Bay, The River, and the Bassing Harbor sub-system.

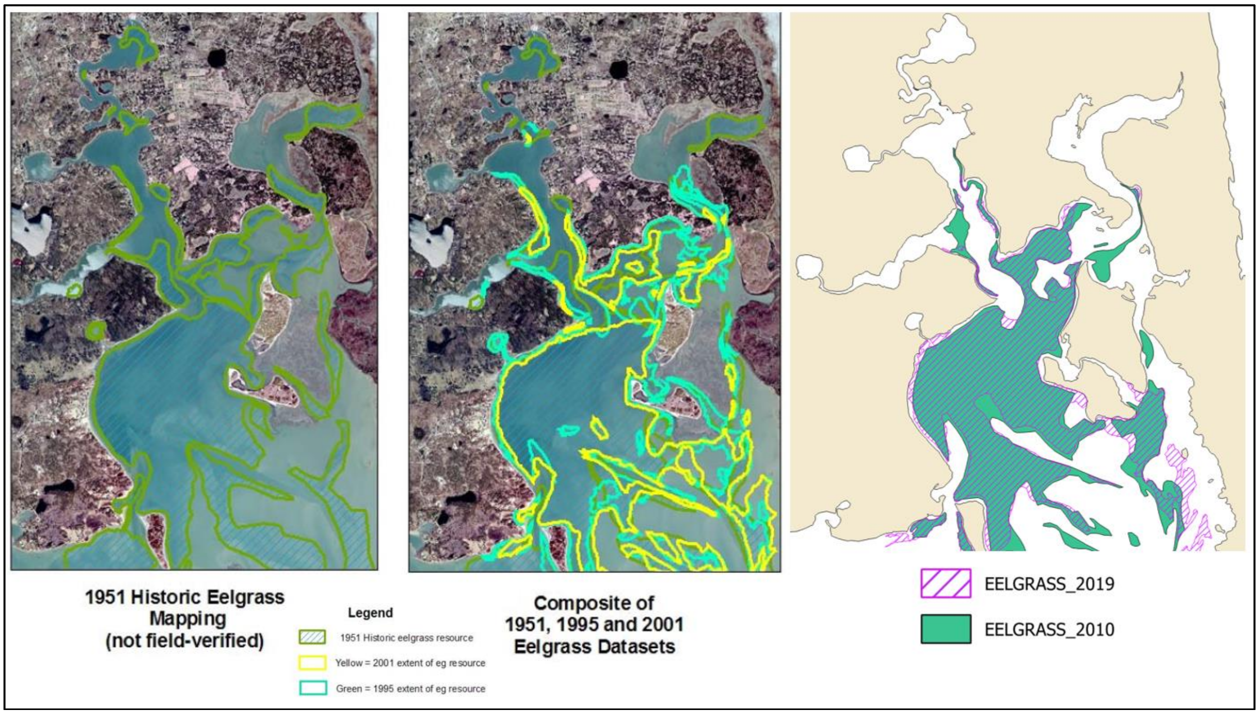

Figure VI-1. Eelgrass bed distribution within The River and Upper Little Pleasant Bay portion of the Pleasant Bay System. The 1951 coverage is shown in the left figure; areas inside the green outlines were eelgrass beds. The 1995 areas are depicted by the green outline inside of which circumscribes the eelgrass beds, while the yellow lines outline the 2001 coverage (middle figure). The right figure shows the 2010 coverage (green), while the 2019 coverage is indicated by the pink stripe fill. All data was provided by the Mass DEP Eelgrass Mapping Program.

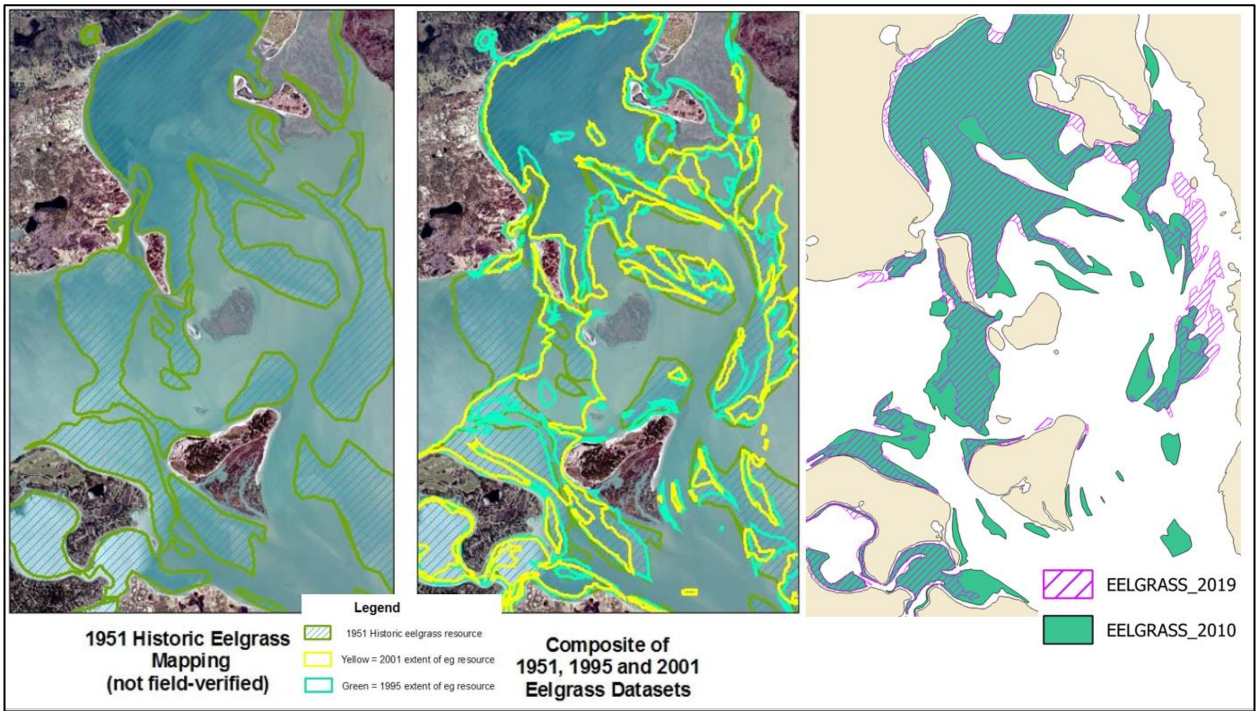

Figure VI-2. Eelgrass bed distribution within Little Pleasant Bay and eastern Pleasant Bay. The 1951 coverage is shown in the left figure; areas inside the green outlines were eelgrass beds. The 1995 areas are depicted by the green outline inside of which circumscribes the eelgrass beds, while the yellow lines outline the 2001 coverage (middle figure). The right figure shows the 2010 coverage (green), while the 2019 coverage is indicated by the pink stripe fill. All data was provided by the Mass DEP Eelgrass Mapping Program.

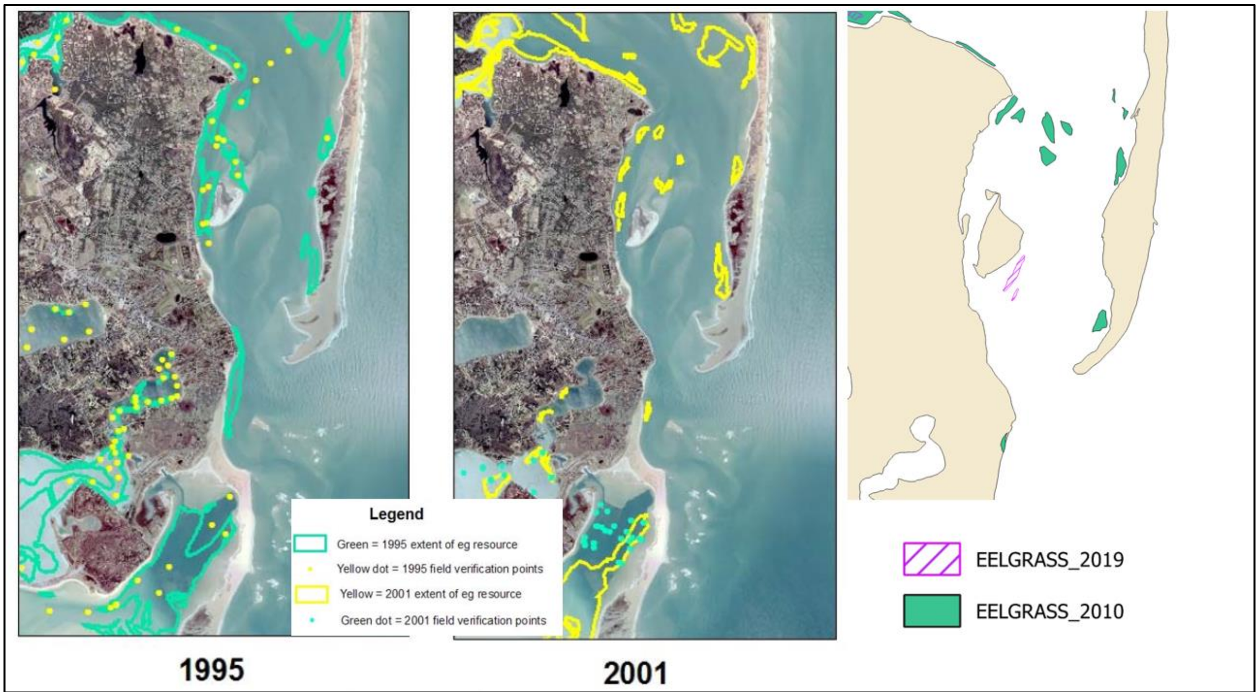

Figure VI-3. Eelgrass bed distribution within Chatham Harbor. The 1995 areas are depicted by the green outline inside of which circumscribes the eelgrass beds, while the yellow lines outline the 2001 coverage (middle figure). The right figure shows the 2010 coverage (green), while the 2019 coverage is indicated by the pink stripe fill. All data was provided by the Mass DEP Eelgrass Mapping Program.

Table VI-1. Changes in eelgrass coverage in the Pleasant Bay Estuarine System within the Towns of Chatham, Harwich, Brewster and Orleans over ~70 years. Based upon eelgrass surveys by the MassDEP Eelgrass Mapping Program. Eelgrass loss from 2001 to 2019 appears to result from both increased N inputs (+4%) and coastal processes/sand transport.

Pleasant Bay Estuarine System					
Eelgrass Coverage (acres)					% Change from 1951
1951	1995	2001	2010	2019	
2,390	1,899	1,807	1,342	1,070	55%
Coverages by MassDEP Eelgrass Mapping Program					

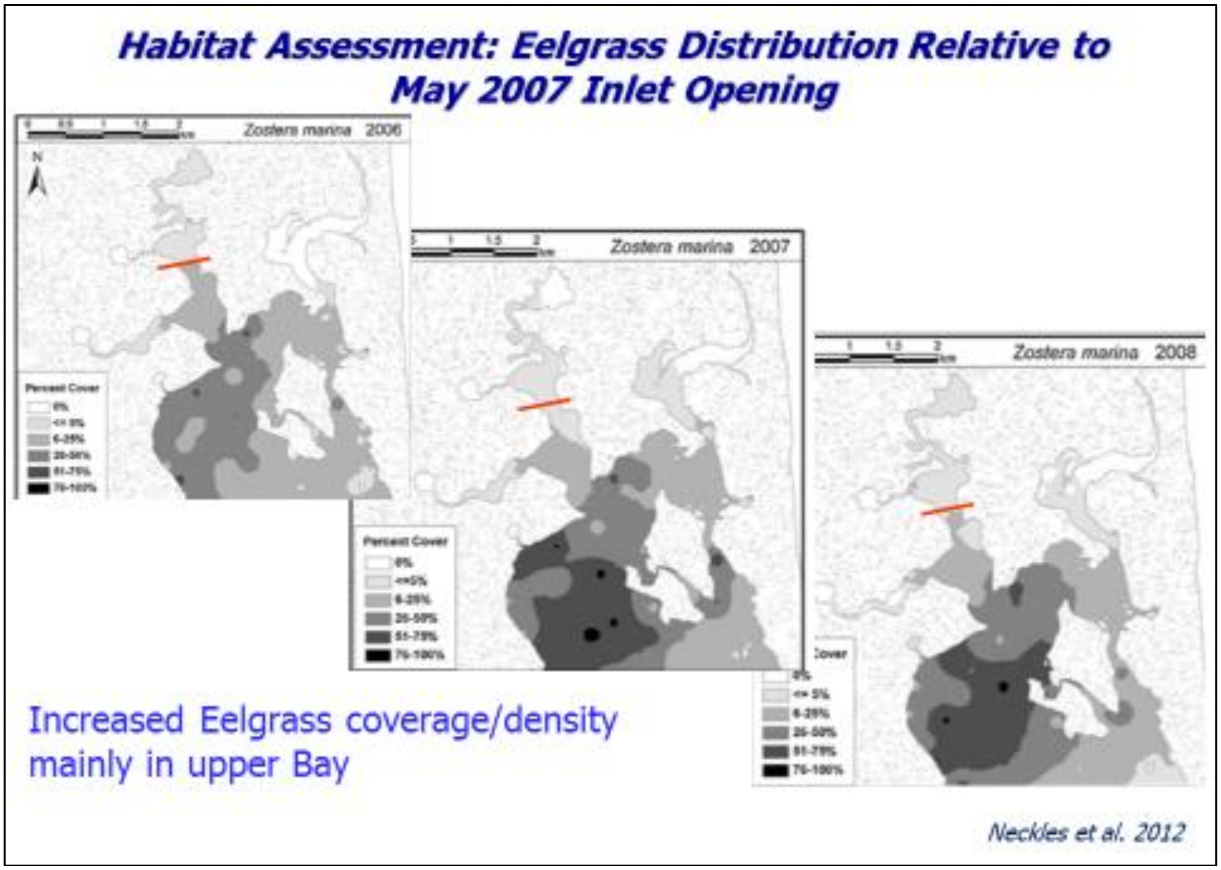

Figure VI-4. Annual eelgrass mapping of upper Pleasant Bay 2006, 2007, 2008 to gauge effects of increased tidal flow and associated localized improvements in nitrogen related water quality due to the 2007 breach. During the growing seasons in 2007 and 2008 (post-breach) eelgrass coverage and density increased (Neckles, *et al.*, 2012).

VII. TWMP Scenario

After the completion of the draft SNEP18 report, the PBA Working group asked the MEP Technical Team to complete one additional scenario within the SNEP18 project window and include the results in the final report: evaluate the water quality impact of the previously agreed to reductions in watershed nitrogen loads included in the 2018 Pleasant Bay Targeted Watershed Management Plan (TWMP). The 2018 Pleasant Bay TWMP included subwatershed nitrogen reductions based on MEP reductions provided in a scenario that demonstrated one possible option for attaining the Pleasant Bay nitrogen thresholds/TMDLs.[57]

The details of the SNEP TWMP scenario included the use of the updated 2020 SNEP present watershed nitrogen loads and hydrodynamics with the incorporation of the watershed nitrogen loading reductions specified in Table 2 of the 2018 TWMP report.[58] In the scenario, benthic loads were adjusted to reflect the watershed nitrogen loads, just as they are in all MEP water quality modeling. In addition, since a number of nitrogen loading reductions had occurred in the watershed since the MEP (*e.g.*, additional sewered properties in Chatham, golf course fertilizer reductions in Brewster, enhanced aquaculture in Orleans/Lonnie's Pond), project staff returned these loads to conditions that existed in 2004/2005 (*i.e.*, the watershed nitrogen loading inputs for the MEP). This step ensured no "double counting" of watershed nitrogen removals for comparison to the impact of 2020 town nitrogen management strategies reviewed as part of the current SNEP project (see Chapter V above). Watershed nitrogen loads for the TWMP scenario are shown in Table VII-1.

Tidally averaged bioactive N concentrations for TWMP scenario was developed for all water quality monitoring stations and compared to concentrations based on 2020 present and 2020 composite loading scenario loading (Table VII-2). In Table VII-2, secondary threshold stations are shaded light blue, while primary threshold stations are shaded light orange. A contour map of tidally average bioactive N for the TWMP scenario is presented in Figure VI-1.

The modeling results in Table VII-2 indicate that the TWMP nitrogen reduction applied to the 2020 present conditions loads achieve the target concentration of 0.16 mg/L at both primary threshold stations. The secondary threshold concentration of 0.21 mg/L is met at all stations except Pochet (WMO-05).

[57] Chapter 8 in Howes B., S.W. Kelley, J.S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner. 2006. Pleasant Bay MEP Report.

[58] p. 14 of 40 in Pleasant Bay Alliance. May 2018. Pleasant Bay Targeted Watershed Management Plan.

Table VII-1. TWMP Scenario Nitrogen Loads. Watershed loads reflect updated land use and water use organized during the SNEP project with the load reductions specified in the TWMP. Direct atmospheric loads are the same as utilized in all SNEP modeling, while net benthic loads were adjusted based on the watershed loads.

sub-embayment	watershed load (kg/day)	direct atmospheric deposition (kg/day)	benthic flux net (kg/day)
Meetinghouse Pond	1.805	0.510	4.004
The River – upper	1.523	0.288	1.937
The River – lower	2.348	2.241	25.067
Lonnie's Pond	1.378	0.225	5.281
Areys Pond	1.238	0.181	4.338
Namequoit River	1.740	0.523	3.215
Paw Wah Pond	0.729	0.082	0.105
Pochet Neck	4.123	1.784	10.472
Little Pleasant Bay	5.121	23.492	110.145
Quanset Pond	0.663	0.170	4.425
Tar Kiln Stream	1.608	0.000	-
Round Cove	2.430	0.170	0.198
The Horseshoe	0.570	0.063	-
Muddy Creek - upper	10.200	0.170	1.255
Muddy Creek - lower	6.468	0.247	1.564
Pleasant Bay	15.745	18.730	21.765
Pleasant Bay/Chatham Harbor Channel	-	17.393	20.211
Bassing Harbor - Ryder Cove	6.638	1.299	1.183
Bassing Harbor - Frost Fish Creek	1.559	0.096	0.127
Bassing Harbor - Crows Pond	4.181	1.389	0.172
Bassing Harbor	2.397	1.071	2.354
Chatham Harbor	19.501	13.840	250.431
TOTAL - Pleasant Bay System	91.967	83.962	468.249

Table VII-2. Comparison of model average bioactive N (DIN+PON) concentrations in Pleasant Bay for 2020 present conditions, 2020 Composite Wastewater Plans loading, and TWMP Scenario Loads. Concentration percent change over background is given between 2020 existing and May 2021 loading scenarios. The primary sentinel threshold stations (0.16 mg/L target) are shaded orange, secondary threshold stations (0.21 mg/L target) are shaded blue. The Ryders Cove threshold is set as the average of the PBA-03 and CM-13. The TWMP reductions attain the target concentration at both sentinel stations and at all but one of the secondary stations (*i.e.*, WMO-5, Pochet).

Sub-Embayment	monitoring station	2020 existing (mg/L)	2020 composite (mg/L)	2021 TWMP (mg/L)	% change
Meetinghouse Pond	PBA-16	0.288	0.218	0.218	-34.3%
Meetinghouse @Rattles Dock	WMO-10	0.238	0.196	0.194	-28.6%
Meetinghouse @Off Lonnie's Inlet	WMO-08	0.192	0.171	0.170	-20.4%
Lonnie's Pond	PBA-15	0.246	0.205	0.210	-22.2%
Areys Pond	PBA-14	0.334	0.308	0.284	-20.0%
Namequoit River Upper	WMO-6	0.239	0.220	0.209	-19.4%
The River-Mouth	PBA-13	0.148	0.140	0.138	-15.6%
Pochet - Upper off Town Landing	WMO-05	0.279	0.256	0.230	-25.1%
Pochet - Basin@ Mouth	WMO-03	0.146	0.138	0.137	-14.5%
Little Pleasant Bay - Head	PBA-12	0.139	0.132	0.131	-14.5%
Little Pleasant Bay - Main Basin	PBA-21	0.132	0.126	0.126	-12.5%
Paw Wah Pond	PBA-11	0.207	0.187	0.158	-39.8%
Little Quanset Pond	WMO-12	0.185	0.173	0.159	-25.7%
Quanset Pond	WMO-01	0.153	0.143	0.137	-23.2%
Round Cove	PBA-09	0.254	0.150	0.180	-43.5%
Muddy Creek - Upper	PBA-05A	0.503	0.220	0.427	-18.1%
Muddy Creek - Lower	PBA-05	0.224	0.152	0.192	-22.9%
Pleasant Bay - Head	PBA-08	0.121	0.115	0.115	-16.2%
Pleasant Bay - Upper Strong Island	PBA-19	0.104	0.101	0.101	-15.0%
Pleasant Bay - off Muddy Creek	PBA-06	0.140	0.123	0.129	-19.6%
Pleasant Bay - lower Strong Island	PBA-20	0.103	0.100	0.100	-15.8%
Ryders Cove Upper	PBA-03	0.218	0.140	0.172	-34.3%
Ryders Cove Lower	CM-13	0.113	0.103	0.106	-24.1%
Crows Pond	PBA-04	0.116	0.106	0.112	-12.5%
Chatham Harbor - Upper	PBA-01	0.099	0.098	0.098	-6.7%

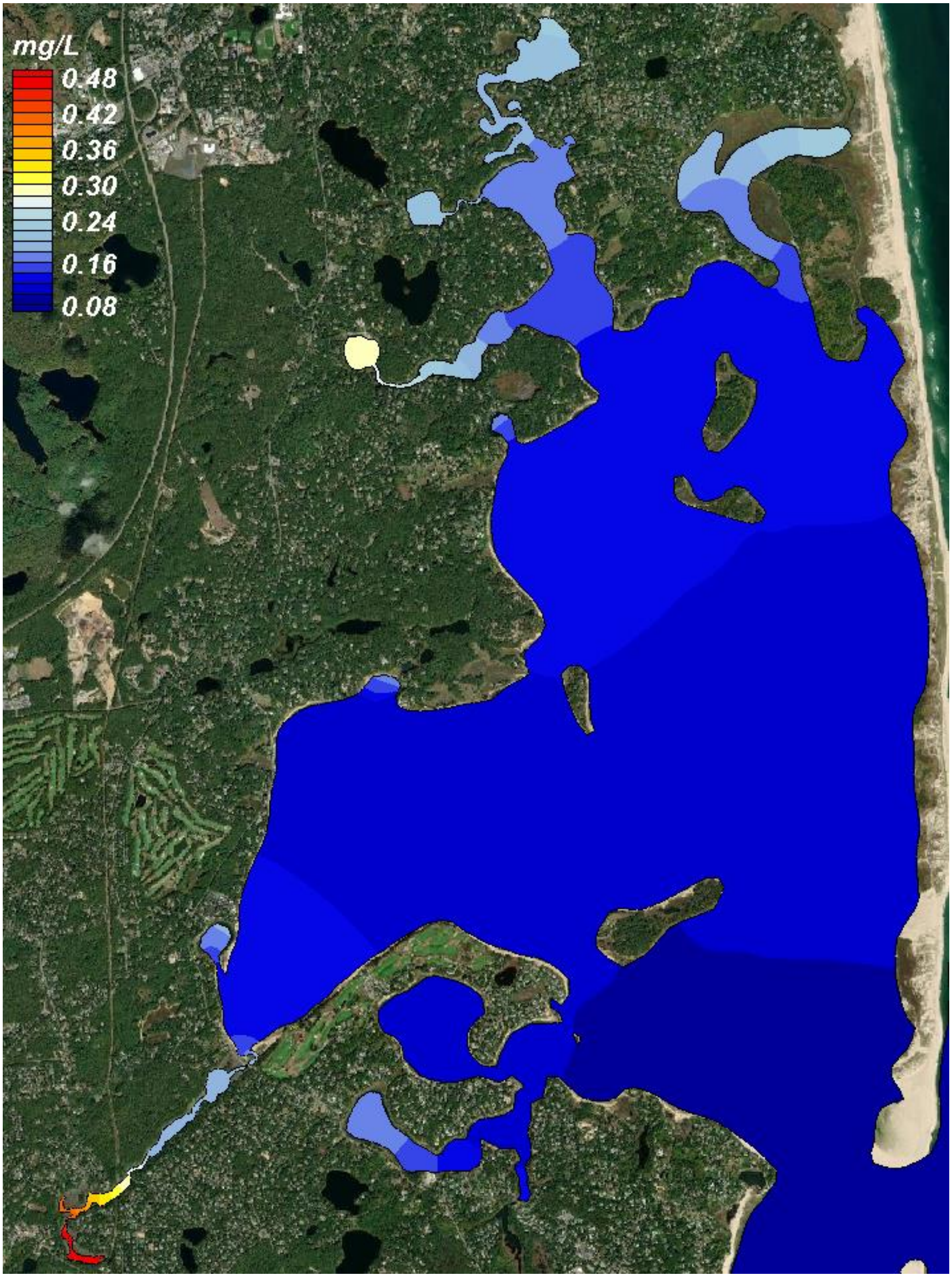

Figure VII-1. Water Quality Modeled TWMP Scenario Bioactive N. Contours of modeled tidally averaged bioactive N concentration (mg/L) in Pleasant Bay based on TWMP reductions applied to 2020 watershed nitrogen loads.

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