# PLEASANT BAY ALLIANCE

## 2024 Annual Report
**pursuant to**
## MassDEP Watershed Permit dated August 3, 2018

## APPENDICES

### Appendix A—Disaggregation of Pleasant Bay Sub-Watershed

Wright-Pierce Memorandum: Potential Modifications related to Dis-Aggregation of Pleasant Bay Sub-watershed, June 14, 2023 (revised October 16, 2023).

### Appendix B—Growth in Watershed Loads

Wright-Pierce Memorandum: Summary of Town Estimates of Watershed Growth, July 11, 2024 (revised September 4, 2024).

### Appendix C—Attenuation of Nitrogen Loads

HydroAnalysis Report, Review of Attenuated Nitrogen Loads to Pleasant Bay Sub-Embayments, March 2022.

SMAST Technical Memorandum, Pochet Neck and Muddy Creek Nitrogen Mass Exchange, March 23, 2023 (finalized August 9, 2023*)*.

SMAST Technical Memorandum, Impact of Changes in Tar Kiln and Upper Muddy Creek Nitrogen Attenuation Scenarios, June 5, 2023 (finalized August 9, 2023).

HydroAnalysis Report, Review of Estimated Nitrogen Attenuation in Pleasant Bay Sub-Embayments, February 2024.

### Appendix D—Nitrogen Removal Requirements

Wright-Pierce Memorandum: Revised Nitrogen Removal Requirements, September 12, 2024.

# Appendix A

**WRIGHT-PIERCE**
Engineering a Better Environment

# Memorandum

| | |
|---|---|
| Date: | **14 June 2023 (revised 16 October 2023)** |
| Project No.: | **13351F** |
| To: | **Carole Ridley, Pleasant Bay Alliance** |
| From: | **Mike Giggey** |
| Subject: | **Pleasant Bay Watershed Permit**<br>**Potential Modifications related to Dis-aggregation of Pleasant Bay Sub-watershed** |

There have been several discussions at recent Watershed Work Group meetings about the need to reevaluate the nitrogen loads and nitrogen removal requirements associated with the "Pleasant Bay" sub-watershed. In the Targeted Watershed Management Plan, this sub-watershed was treated as a single sub-watershed, because then-available data required the aggregation of loads and thresholds for four sub-watersheds from the 2006 MEP report. The TMWP refers to the "Pleasant Bay" sub-watershed as the aggregate of Pleasant Bay Main, Little Pleasant Bay, Tar Kiln Stream, and The Horseshoe. This memo lays out a methodology for disaggregating the data and presents the resulting changes that will be needed in the TMWP.

Attached to this memo are two tables. Table 1 presents calculations to support the disaggregation using the same attenuation rates as the TWMP. Table 2 presents the same data, but with a change in the attenuation percentage for Tar Kiln Stream, from no attenuation to 60% attenuation. (The change in Tar Kiln Stream attenuation could not be easily made if the four sub-watersheds are taken as a whole. The change in Tar Kiln Stream attenuation was the primary motivation for the disaggregation.)

Both Tables 1 and 2 have two parts. Part A presents the nitrogen loads, thresholds and removal needs as shown in the TWMP. Part B presents the data when "Pleasant Bay" is broken into its four pieces. The format of these tables matches the layout of TWMP Tables A-2 and A-3, as well as the important TWMP Table 2.

## Dis-aggregation of "Pleasant Bay" Subwatershed

In compiling data for this analysis, SMAST was able to provide the attenuated loads for the four separate sub-watersheds, data that were previously unavailable to the Alliance. The analysis of those data revealed the need to refine the load estimates used in the TWMP. That refinement relates to how the data from the 2006 MEP report were combined with the data from the 2010 SMAST technical memoranda related to changes in the Harwich loads. As shown in Table 1, this refinement results in an unattenuated nitrogen load for the four sub-watersheds that is 332 kg/yr less than used in the TWMP. Table 1 shows how that change affects the four towns. Harwich's attenuated loads decreases by 442 kg/yr, and the other towns all see small increases. With respect to nitrogen removal needs, Table 1 shows how these refinements decrease the removal need by 350 kg/yr, with most of the benefit accruing to Brewster.

In summary, the dis-aggregation and data refinement decrease the attenuated load in these four sub-watersheds from 15,694 kg/yr to 15,362 kg/yr, a 2% decrease. The nitrogen removal need decreases from 5,593 kg/yr to 5,243 kg/yr, a 6% reduction. Across the entire watershed, the load reduction is about 1% and the change in removal need is about 2%.

### Revisions to Tar Kiln Stream Attenuation

Table 2 presents these data in the same format, with the only change being the attenuation rate in the Tar Kiln Stream sub-watershed. The attenuated load in this sub-watershed decreases by 1,369 kg/yr, from 2,281 kg/yr to 912 kg/yr, a 60% reduction. Most of the load in this sub-watershed originates in Brewster, where the attenuated load reduction is 1,265 kg/yr.

The change in nitrogen removal requirement is not so straight-forward. With no attenuation in the Tar Kiln Stream sub-watershed, the attenuated load was 374 kg/yr higher than the threshold. Incorporation of the 1,369 kg/yr attenuation decreases the attenuated load to less than one-half the threshold load, taking away any removal need.

Taken together, the disaggregation process and the use of the 60% attenuation factor for Tar Kiln Stream result in a 1,700 kg/yr reduction in attenuated load and a 724 kg/yr reduction in load removal need. Overall, Brewster is the primary beneficiary, seeing a 662 kg/yr reduction in its removal requirement for these four sub-watersheds, compared to the TWMP which aggregated the sub-watersheds, and gave no credit for Tar Kiln Steam attenuation.

There has been significant discussion of this approach and these data, and I believe that this memo presents data that have benefited from multiple reviewers. Nonetheless, all interested parties should review this memo and attached tables and offer any further comments that are pertinent. I will draft a paragraph for the Watershed Annual Report that summarizes this analysis and notes the intent of the Towns to include these adjustments in a revised permit.

### Additional Discussion—16 October 2023

In the discussions of the disaggregation process, SMAST provided the attached Figure 1 to illustrate the allocation of attenuated watershed load to the Pleasant Bay Main and Little Pleasant Bay sub-embayments. To enable the calibration of the linked model, SMAST reallocated 25% of the loads from certain sub-watersheds (red-shaded in Figure 1) to the Little Pleasant Bay sub-embayment. This reallocation occurred in both the original MEP work (reported in 2006) and in the update conducted by SMAST as reported in 2021. The reallocation includes loads from sub-watersheds in Harwich and Chatham that otherwise would directly impact the Pleasant Bay Main sub-embayment. This explains the attribution of 922 kg/yr in attenuated loads from these two towns to Little Pleasant Bay.

## PLEASANT BAY ALLIANCE

Wednesday, June 14, 2023

**Sub-Watershed Loads, Attenuation and Removal Requirements, kg/yr**

***Table 1: Full Disaggregation of PB Sub-watershed*** ***No TKS attenuation***

| **Basis:** | | | | | |
|---|---|---|---|---|---|
| | Unattenuated loads | MEP 2006 and SMAST 2010 | | | |
| | Attenuation | MEP 2006, SMAST 2010, 2021 | TKS--0% | | |
| | Attenuated loads | MEP 2006 and SMAST 2010 | Modified as per HW memo of 22 Dec 2022 | | |
| | Threshold loads | MEP 2006 and SMAST 2010 | | | |
| | Load removals | Recomputed for PB sub-embayment | 5,243 | kg/yr total | 5,593 TWMP |

| **Subembayment** | | **Brewster** | | **Chatham** | | **Harwich** | | **Orleans** | | **TOTAL** |
|---|---|---|---|---|---|---|---|---|---|---|
| ***A. Basis for TWMP; 4 sub-embayments aggregated into one called "Pleasant Bay"; no TKS attenuation*** | | | | | | | | | | |
| Pleasant Bay (including Little Pleasant Bay, Horseshoe, Tar Kiln)--(same % removal for all towns) | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 6,212 | | 1,526 | | 4,743 | | 4,055 | | 16,536 |
| *Attenuation* | *2%* | 135 | *0%* | 0 | *4%* | 190 | *13%* | 517 | *5%* | 842 |
| *Attenuated Watershed Load* | | 6,077 | | 1,526 | | 4,553 | | 3,538 | | 15,694 |
| *Threshold Load* | | 3,913 | | 981 | | 2,932 | | 2,275 | | 10,101 |
| *Removal Requirement* | *35.6%* | 2,164 | *35.7%* | 545 | *35.6%* | 1,621 | *35.7%* | 1,263 | *35.6%* | 5,593 |
| ***B. All four sub-embayments considered separately, no Tar Kiln Stream attenuation*** | | | | | | | | | | |
| Pleasant Bay Main | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 3,085 | | 1,212 | | 3,740 | | 1,951 | | 9,988 |
| *Attenuation* | | 101 | | 0 | | 170 | | 239 | | 510 |
| *Attenuated Watershed Load* | | 2,984 | | 1,212 | | 3,570 | | 1,712 | | 9,478 |
| *Threshold Load* | | 1,910 | | 776 | | 2,285 | | 1,096 | | 6,067 |
| *Removal Requirement* | *36.0%* | 1,074 | *36.0%* | 436 | *36.0%* | 1,285 | *36.0%* | 616 | *36.0%* | 3,412 |
| Little Pleasant Bay | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 1,024 | | 381 | | 561 | | 1,538 | | 3,504 |
| *Attenuation* | | 34 | | 0 | | 20 | | 80 | | 134 |
| *Attenuated Watershed Load* | | 990 | | 381 | | 541 | | 1,458 | | 3,370 |
| *Threshold Load* | | 562 | | 216 | | 307 | | 828 | | 1,913 |
| *Removal Requirement* | *43.2%* | 428 | *43.2%* | 165 | *43.2%* | 234 | *43.2%* | 630 | *43.2%* | 1,457 |
| Tar Kiln Stream | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 2,109 | | | | | | 172 | | 2,281 |
| *Attenuation* | | 0 | | | | | | 0 | | 0 |
| *Attenuated Watershed Load* | | 2,109 | | | | | | 172 | | 2,281 |
| *Threshold Load* | | 1,763 | | | | | | 144 | | 1,907 |
| *Removal Requirement* | *16.4%* | 346 | | | | | *16.4%* | 28 | *16.4%* | 374 |
| The Horseshoe | | | | | | | | | | |
| *Unattenuated Watershed Load* | | | | | | | | 431 | | 431 |
| *Attenuation* | | | | | | | | 198 | | 198 |
| *Attenuated Watershed Load* | | | | | | | | 233 | | 233 |
| *Threshold Load* | | | | | | | | 233 | | 233 |
| *Removal Requirement* | | | | | | | *0%* | 0 | *0%* | 0 |
| Aggregated Pleasant Bay | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 6,218 | | 1,593 | | 4,301 | | 4,092 | | 16,204 |
| *Attenuation* | | 135 | | 0 | | 190 | | 517 | | 842 |
| *Attenuated Watershed Load* | | 6,083 | | 1,593 | | 4,111 | | 3,575 | | 15,362 |
| *Threshold Load* | | 4,235 | | 992 | | 2,592 | | 2,300 | | 10,120 |
| *Removal Requirement* | *30.4%* | 1,848 | *37.7%* | 601 | *36.9%* | 1,519 | *35.7%* | 1,275 | *34.1%* | 5,243 |
| *Change in atten. load* | | 6 | | 67 | | -442 | | 37 | | -332 |
| ***Summary of Removals*** | | | | | | | | | | |
| *Aggregated Pleasant Bay--TWMP* | | 2,164 | | 545 | | 1,621 | | 1,263 | | 5,593 |
| *Fully disaggregated Pleasant Bay* | | 1,848 | | 601 | | 1,519 | | 1,275 | | 5,243 |
| *difference--kg/yr* | | -316 | | 56 | | -102 | | 12 | | -350 |

# PLEASANT BAY ALLIANCE

Wednesday, June 14, 2023

**Sub-Watershed Loads, Attenuation and Removal Requirements, kg/yr**

***Table 2. Full Disaggregation of PB Sub-Watershed*** ***Tar Kiln Stream attenuation at 60%***

| | | | | | | |
|---|---|---|---|---|---|---|
| **Basis:** | Unattenuated loads | MEP 2006 and SMAST 2010 | | | | |
| | Attenuation | MEP 2006, SMAST 2010, 2021 | TKS--60% | | | |
| | Attenuated loads | MEP 2006 and SMAST 2010 | Modified as per HW memo of 22 Dec 2022 | | | |
| | Threshold loads | MEP 2006 and SMAST 2010 | | | | |
| | Load removals | Recomputed for PB sub-embayment | 4,869 | kg/yr total | 5,593 | TWMP |

## *A. Basis for TWMP; 4 sub-embayments aggregated into one called "Pleasant Bay"; no TKS attenuation*

| Subembayment | Brewster | | Chatham | | Harwich | | Orleans | | TOTAL | |
|---|---|---|---|---|---|---|---|---|---|---|
| Pleasant Bay (including Little Pleasant Bay, Horseshoe, Tar Kiln)--(same % removal for all towns) | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 6,212 | | 1,526 | | 4,743 | | 4,055 | | 16,536 |
| *Attenuation* | *2%* | 135 | *0%* | 0 | *4%* | 190 | *13%* | 517 | *5%* | 842 |
| *Attenuated Watershed Load* | | 6,077 | | 1,526 | | 4,553 | | 3,538 | | 15,694 |
| *Threshold Load* | | 3,913 | | 981 | | 2,932 | | 2,275 | | 10,101 |
| *Removal Requirement* | *35.6%* | 2,164 | *35.7%* | 545 | *35.6%* | 1,621 | *35.7%* | 1,263 | *35.6%* | 5,593 |

## *B. All four sub-embayments considered separately and Tar Kiln Stream attenuation = 60%*

| Subembayment | Brewster | | Chatham | | Harwich | | Orleans | | TOTAL | |
|---|---|---|---|---|---|---|---|---|---|---|
| Pleasant Bay Main | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 3,085 | | 1,212 | | 3,740 | | 1,951 | | 9,988 |
| *Attenuation* | | 101 | | 0 | | 170 | | 239 | | 510 |
| *Attenuated Watershed Load* | | 2,984 | | 1,212 | | 3,570 | | 1,712 | | 9,478 |
| *Threshold Load* | | 1,910 | | 776 | | 2,285 | | 1,096 | | 6,067 |
| *Removal Requirement* | *36.0%* | 1,074 | *36.0%* | 436 | *36.0%* | 1,285 | *36.0%* | 616 | *36.0%* | 3,412 |
| Little Pleasant Bay | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 1,024 | | 381 | | 561 | | 1,538 | | 3,504 |
| *Attenuation* | | 34 | | 0 | | 20 | | 80 | | 134 |
| *Attenuated Watershed Load* | | 990 | | 381 | | 541 | | 1,458 | | 3,370 |
| *Threshold Load* | | 562 | | 216 | | 307 | | 828 | | 1,913 |
| *Removal Requirement* | *43.2%* | 428 | *43.2%* | 165 | *43.2%* | 234 | *43.2%* | 630 | *43.2%* | 1,457 |
| Tar Kiln Stream | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 2,109 | | | | | | 172 | | 2,281 |
| *Attenuation* | *60%* | 1,265 | | | | | *60%* | 103 | | 1,369 |
| *Attenuated Watershed Load* | | 844 | | | | | | 69 | | 912 |
| *Threshold Load* | | 1,763 | | | | | | 144 | | 1,907 |
| *Removal Requirement* | *none* | 0 | | | | | *none* | 0 | *none* | 0 |
| The Horseshoe | | | | | | | | | | |
| *Unattenuated Watershed Load* | | | | | | | | 431 | | 431 |
| *Attenuation* | | | | | | | | 198 | | 198 |
| *Attenuated Watershed Load* | | | | | | | | 233 | | 233 |
| *Threshold Load* | | | | | | | | 233 | | 233 |
| *Removal Requirement* | | | | | | | *0%* | 0 | *0%* | 0 |
| Aggregated Pleasant Bay | | | | | | | | | | |
| *Unattenuated Watershed Load* | | 6,218 | | 1,593 | | 4,301 | | 4,092 | | 16,204 |
| *Attenuation* | | 1,400 | | 0 | | 190 | | 620 | | 2,211 |
| *Attenuated Watershed Load* | | 4,818 | | 1,593 | | 4,111 | | 3,472 | | 13,993 |
| *Threshold Load* | | 4,235 | | 992 | | 2,592 | | 2,300 | | 10,120 |
| *Removal Requirement* | *31.2%* | 1,502 | *37.7%* | 601 | *36.9%* | 1,519 | *35.9%* | 1,246 | *34.8%* | 4,869 |
| *Change in atten. load* | | -1,259 | | 67 | | -442 | | -66 | | -1,700 |
| ***Summary of Removals*** | | | | | | | | | | |
| *Aggregated Pleasant Bay--TWMP* | | 2,164 | | 545 | | 1,621 | | 1,263 | | 5,593 |
| *Fully disaggregated Pleasant Bay* | | 1,502 | | 601 | | 1,519 | | 1,246 | | 4,869 |
| *difference--kg/yr* | | -662 | | 56 | | -102 | | -17 | | -724 |

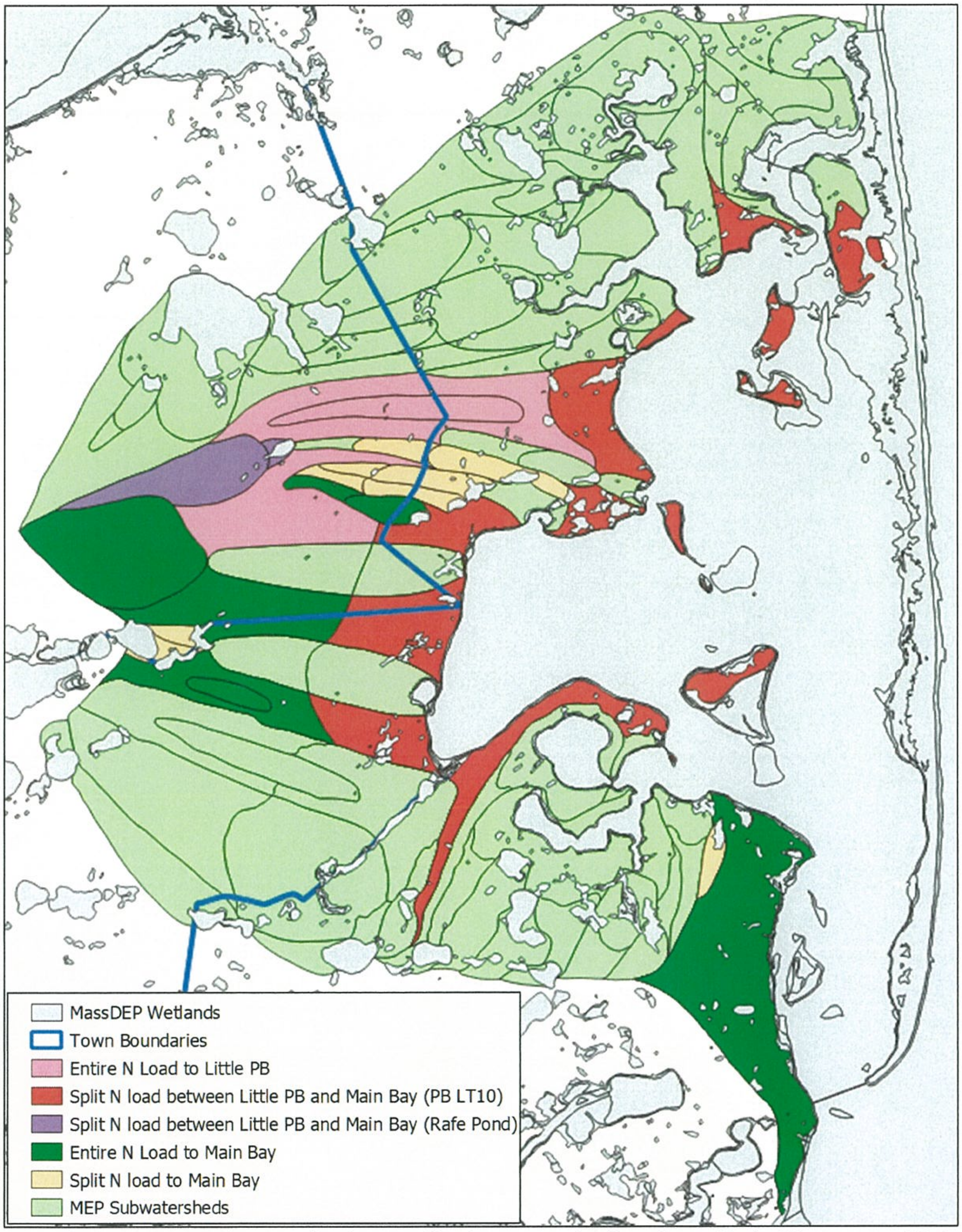

**Figure 1. Pleasant Bay Subwatersheds contributing N Loads directly to Little Pleasant or Main Bay.** Subwatersheds that contribute nitrogen loads directly to the Little Pleasant Bay are shown in pink (100% of their load), purple (a portion of their load), and 25% of the Pleasant Bay LT 10 subwatershed (red) The subwatersheds that contribute nitrogen loads directly to the Main Bay are shown in dark green (100% of their load) or tan (a portion of their load), and 75% of the Pleasant Bay LT 10 subwatershed (red). Light green subwatersheds discharge to subembayments, where N loads then interact with the Main Bay and Little Pleasant Bay through tidal exchange.

SMAST- 2023

# Appendix B

WRIGHT-PIERCE
Engineering a Better Environment

# Memorandum

Date: 11 July 2024 (Revised 4 September 2024)

Project No.: 13351E

To: Carole Ridley, Pleasant Bay Alliance

From: Mike Giggey

Subject: Changes to the Pleasant Bay Watershed Permit
Summary of Town Estimates of Watershed Growth

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One important step in updating the Pleasant Bay Watershed Permit is to estimate the increases in watershed nitrogen loads that have occurred since the 2006 MEP report, and to consider possible load increases into the future. This memo presents a summary of the growth estimates prepared by the four watershed towns to allow this factor to be considered in the upcoming modifications to the Watershed Permit.

Comments were received from DEP and the Commission on the 11 July 2024 draft of this memo, and it has been updated to address those comments.

Brewster, Harwich and Orleans have prepared reports to address the Watershed Permit changes they expect, and growth estimates are included in those reports. Chatham is preparing a similar report and has provided its growth projections while preparation of the full report is in progress.

The 2006 MEP report is based on water consumption data from the period of 2002 to 2004. In 2010, SMAST updated the Harwich watershed loads to reflect better land use data and a longer period of water use data. Taken together, those two SMAST documents establish the watershed loads that are the basis of the Targeted Watershed Management Plan and the Watershed Permit. SMAST completed an update to the MEP work in 2021 (the SNEP report) that includes watershed loads based on water consumption data for 2011 to 2015. The 2021 SMAST report thus provides some indication of growth in watershed loads from approximately 2003 (the midpoint of the MEP data) to 2013 (the midpoint of the SNEP data).

The general intent of the four towns is to look 20 years or more into the future so their nitrogen management plans can readily accommodate future growth. Looking 20 years beyond the existing Watershed Permit (2018) takes you to 2038. Looking 20 years beyond the expected date of modification of the permit (2024) takes you to 2044.

The towns' approaches to estimating growth in watershed nitrogen loads are summarized as follows:

**Brewster**. Horsley Witten, in its June 13, 2024 report, estimated a 99 kg/yr increase in attenuated watershed load in the Pleasant Bay sub-watersheds through the SNEP report. Horsley Witten also estimated that full development in these Brewster sub-watersheds would add another 388 kg/yr of attenuated nitrogen load from 78 homes and seven commercial/industrial parcels. Wright-Pierce has adjusted those numbers to 124 kg/yr and 429 kg/yr, respectively, so that the growth estimate is based on the same attenuation for Tar Kiln Stream as the Watershed Permit. The 429 kg/yr nitrogen load from future development is based on the full build-out in the Pleasant Bay watershed, which may not occur during the timeframe of the permit.

**Chatham**. GHD developed a growth estimate based on two parts. Water consumption data for the four-year period of 2019 to 2023 was evaluated to determine how wastewater flows have increased since the 2009 CWMP, which was based on early 2000s data, much like the MEP report. That analysis indicated that septic nitrogen loads have increased by about 6%. The 2009 CWMP estimate of build-out was deemed adequate for current use, indicating a further growth of about 18% through build-out. Applying these growth percentages to the Watershed Permit loads results in a build-out total load of 20,670 kg/yr.

**Harwich**. In its March 22, 2024 memo, Harwich presented estimates of 1) loading increases that occurred between the MEP report and the year 2020 (675 kg/yr), and 2) future increases for the period of 2020 to 2040 (568 kg/yr). These estimates were prepared by GHD and the Harwich Water & Sewer Department.

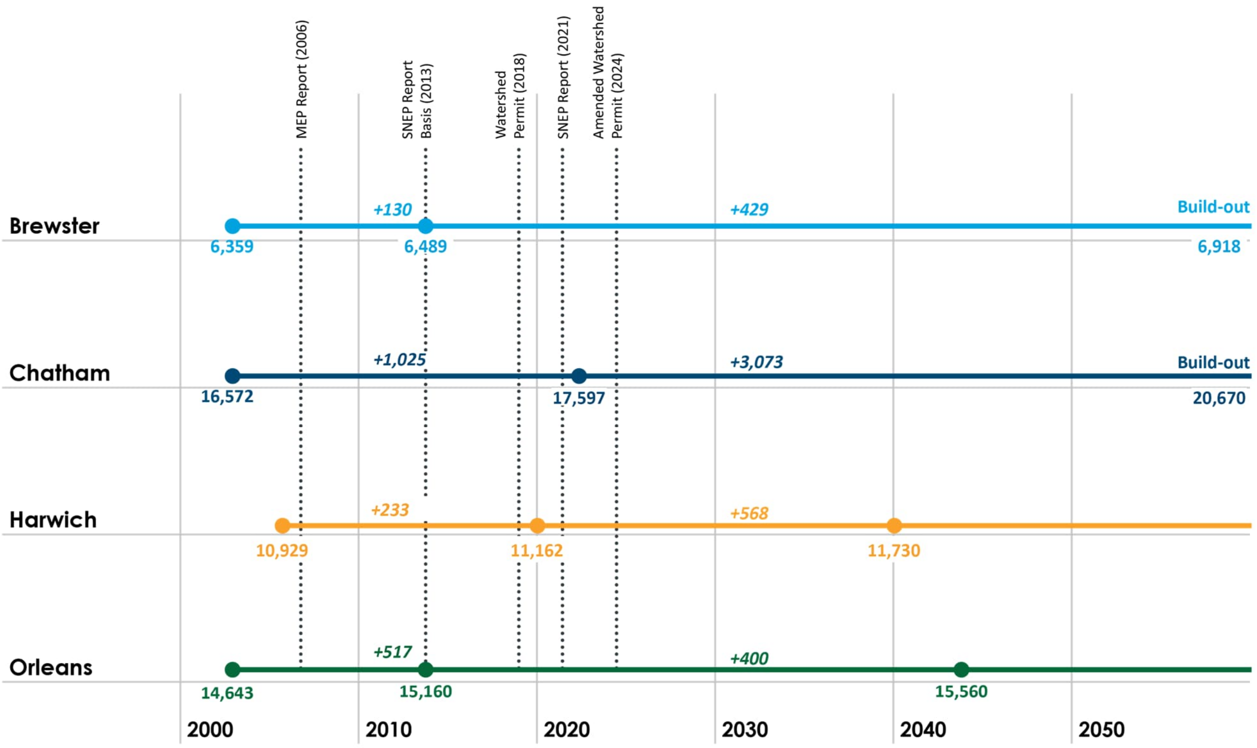
**Orleans**. AECOM reported growth estimates in its February 22, 2024 memo. Orleans used the load increase computed from the MEP and SNEP reports (480 kg/yr) and added 400 kg/yr to account for new homes expected on vacant lots in Pleasant Bay sub-watersheds in the 30 years following the basis of the SNEP estimate, that is, through 2043.

The growth estimates of the four towns are summarized in Table 1.

| **Table 1. Attenuated Watershed Load Increases by Town, kg/yr** | **Brewster** | **Chatham** | **Harwich** | **Orleans** | **Total** |
|---|---|---|---|---|---|
| **TWMP/Watershed Permit (2003)** | **6,359** | **16,572** | **10,929** | **14,643** | **48,503** |
| Adjustment for dis-aggregation | 6 | 67 | -442 | 37 | -332 |
| Growth: from 2003 | 124<br>to 2013 | 958<br>to 2021 | 675<br>to 2020 | 480<br>to 2013 | 2,237 |
| Growth: from 2013/2020/2021 to planning horizon | 429 | 3073 | 568 | 400 | 4,470 |
| Total growth (2003 to planning hor.) | 553 | 4,031 | 1,243 | 880 | 6,707 |
| **Updated loads for revised permit** | **6,918** | **20,670** | **11,730** | **15,560** | **54,878** |
| Growth as % of TWMP loads | 8.7% | 24.3% | 11.4% | 6.0% | 13.8% |
| Planning Horizon | Build out | Build out | 2040 | 2043 | |

Across the four towns, it is estimated that attenuated watershed loads have increased by 2,237 kg/yr since the basis of the Watershed Permit, and that future growth will be an additional 4,470 kg/yr. With these increases, the attenuated watershed load will have increased by about 14% from 48,503 kg/yr to 54,878 kg/yr. The percentage load increase is largest in Chatham (24%) and smallest in Orleans (6%).

The attached graphic illustrates the key dates associated with past nitrogen load estimates and shows the specific planning horizons adopted by each town. These are attenuated nitrogen loads, based on the same attenuation percentages used in the current Watershed Perit, for consistency. For all towns, the first segment of growth also includes the small correction in watershed loads associated with the dis-aggregation of the Pleasant Bay sub-watershed.



Growth in Attenuated Watershed Loads, kg/yr

Once DEP and the Cape Cod Commission complete their reviews of this memo, it will then be a straightforward matter to translate the load increases into changes in the towns' nitrogen load removal requirements. That important step will include revisions in attenuation percentages for Muddy Creek, Tar Kiln Stream and Pochet Neck from those used in the TWMP.

In 2023, the towns agreed to a proposed small change in watershed loads associated with the dis-aggregation of the previously-combined Pleasant Bay sub-watershed. Table 1 includes the reduction of 332 kg/yr from that dis-aggregation process. (See the Wright-Pierce memo of 14 June 2023, revised 10 October 2023.)

Town nitrogen management plans must be flexible enough to deal with future load increases, given that those increases are somewhat speculative, both in quantity and in timing. The future growth estimates reported here represent about 10% of the projected future nitrogen removal requirements, in the aggregate. When judging the progress of a town's compliance with the modified permit, it will be important to recognize that about 90% of the needs are firm, and about 10% are uncertain, in the aggregate. It is expected that actual growth will be regularly monitored, and these projections will be updated every five years.

Below are excerpts from Town reports describing methodologies for estimating growth in watershed loads.

**Brewster** (from Pleasant Bay Watershed 2024 Permit Update by Horsley Witten Group (HW), June 13, 2024)

*"HW worked with Ed Eichner of TMDL Solutions, LLC to refine buildout data for Brewster. This was done in two phases:*

1. *development that took place between the original 2006 MEP model and the 2021 SNEP model that provided updated information on developed properties; and*
2. *future buildout for properties developed from the 2021 model into the future.*

*The original MEP model used development information from 2006 and the SNEP model was based on land use data from 2018. The updated existing conditions SNEP model included nitrogen loads from new development since 2006 and also used updated information on the reduced fertilizer loading rates at Captains Golf Course. Therefore, to calculate the loads associated with just the new development, HW adjusted the golf course fertilizer use to match that in the MEP model and compared the changes in load between the MEP data and the SNEP data. Based on this analysis, there was an additional 99 kg/yr of load across Brewster from new development during that time frame. Table 1 shows the distribution of this new load throughout the Brewster subwatersheds. The SNEP model also included updates to the water use data for individual parcels, including those that were connected to Town water after the original MEP model was developed.*

*To calculate the additional buildout after the SNEP model, the Town reviewed the buildout information originally developed by TMDL Solutions, LLC and made adjustments based on which parcels can still be developed. Overall, the Town calculated that there can be an additional 78 homes built in the watershed as well as seven commercial/industrial parcels.*

*Using this information, TMDL Solutions, LLC updated the buildout information included in the SNEP buildout model. The nitrogen load for this future development was then calculated by comparing the SNEP existing conditions model results to the updated buildout results. Overall, there can be an additional 388 kg/yr of nitrogen associated with this future development in Brewster. The majority of this new development will be in the Pleasant Bay Man and Little Pleasant Bay subwatersheds."*

### Chatham

*GHD updated its 2009 CWMP analysis to estimate growth that has occurred since the early 2000s. The 2009 CWMP was based on water consumption data from the early 2000s, and the 2024 evaluation was based on water consumption data for the period 2019 to 2023. The growth in septic load in the Pleasant Bay watershed was found to be 5.8%. GHD also investigated the impact of residential irrigation by reviewing the properties that have separate irrigation water meters. Although the use of irrigation meters is not yet universal, early data indicate that 8% of the total water consumption may have been used for irrigation in the 2019-to-2023 period. The standard 10% consumption use factor was used to compute current nitrogen loads.*

*A review of the build-out analysis presented in 2009 CMWP indicated that it is a reasonable basis for updating the Pleasant Bay Watershed Permit. The septic nitrogen load is projected to be 17.9% higher at build-out than it was during the 2019-to-2023 period.*

*It is estimated that the total nitrogen loads will increase at the same rate as the septic loads, so the same 5.8% and 17.9% increases are appropriate for extending the Watershed Permit total loads from their 2003 basis out until Chatham's full build-out:*

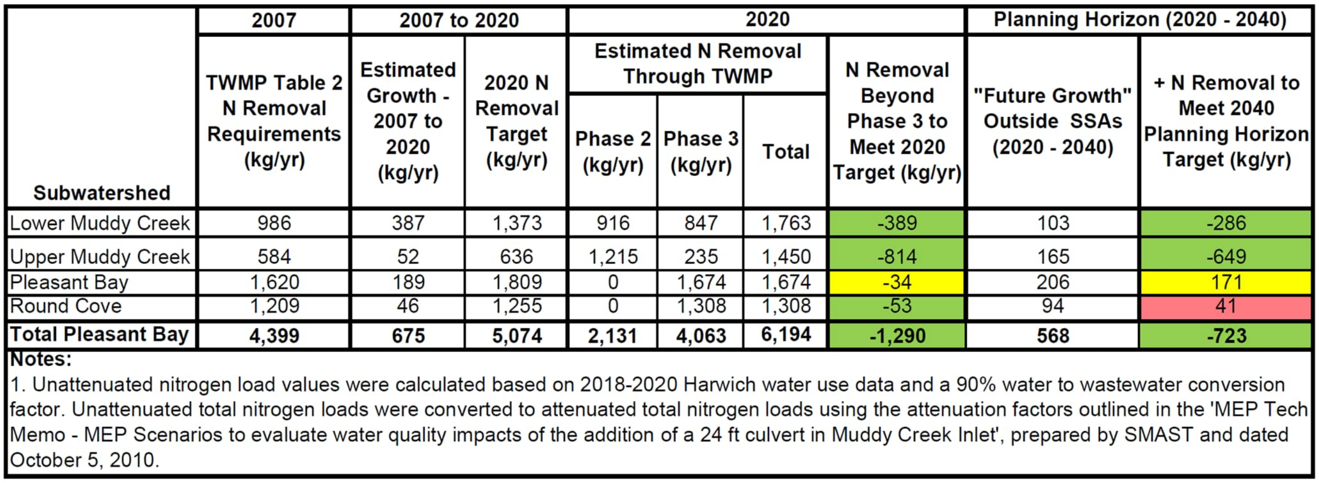
| | |
|---|---|
| *2009 CWMP (early 2000s basis)* | *16,572 kg/yr attenuated watershed load* |
| *2024 analysis (2019 to 2023 basis)* | *17,530 kg/yr attenuated watershed load* |
| *Build-out* | *20,670 kg/yr attenuated watershed load* |

*This same approach was used for each of the Pleasant Bay sub-watersheds impacted by Chatham.*

### **Harwich** (from Harwich Water & Sewer Department memo dated March 5, 2024)

*"As a mechanism to inform the design & limits of the Phase 3 wastewater collections system, the Town engaged its consultant GHD to perform a comprehensive evaluation of growth by sub-watershed. This evaluation considered both "past growth" occurring between the years 2007 – 2020, and "future growth" anticipated to occur within a 20-year planning horizon. The resulting data were converted to an annual N load and added to the previously defined removal requirements in {TWMP} Table 2 to derive new N removal goals. The growth projections were based on allowances for the development of vacant parcels and an*

*increase in water usage for all parcels (based on historical water use data trends). These new N removal goals were then used to evaluate the effectiveness of the Phase 2 & proposed Phase 3 sewer service areas and their ability to maintain continued compliance with the watershed permit & associated regulations. The table below summarizes the findings from this comprehensive evaluation and serves to inform & support recommendations for modifications to Harwich commitments in Phase 2 (years 2024-2028) TWMP Implementation Schedule."*



| | 2007 | 2007 to 2020 | | 2020 | | | | Planning Horizon (2020 - 2040) | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | Estimated N Removal Through TWMP | | | | | |
| Subwatershed | TWMP Table 2 N Removal Requirements (kg/yr) | Estimated Growth - 2007 to 2020 (kg/yr) | 2020 N Removal Target (kg/yr) | Phase 2 (kg/yr) | Phase 3 (kg/yr) | Total | N Removal Beyond Phase 3 to Meet 2020 Target (kg/yr) | "Future Growth" Outside SSAs (2020 - 2040) | + N Removal to Meet 2040 Planning Horizon Target (kg/yr) |
| Lower Muddy Creek | 986 | 387 | 1,373 | 916 | 847 | 1,763 | -389 | 103 | -286 |
| Upper Muddy Creek | 584 | 52 | 636 | 1,215 | 235 | 1,450 | -814 | 165 | -649 |
| Pleasant Bay | 1,620 | 189 | 1,809 | 0 | 1,674 | 1,674 | -34 | 206 | 171 |
| Round Cove | 1,209 | 46 | 1,255 | 0 | 1,308 | 1,308 | -53 | 94 | 41 |
| **Total Pleasant Bay** | **4,399** | **675** | **5,074** | **2,131** | **4,063** | **6,194** | **-1,290** | **568** | **-723** |

**Notes:**

1. Unattenuated nitrogen load values were calculated based on 2018-2020 Harwich water use data and a 90% water to wastewater conversion factor. Unattenuated total nitrogen loads were converted to attenuated total nitrogen loads using the attenuation factors outlined in the 'MEP Tech Memo - MEP Scenarios to evaluate water quality impacts of the addition of a 24 ft culvert in Muddy Creek Inlet', prepared by SMAST and dated October 5, 2010.

**Orleans** (from AECOM report dated August 20, 2024)

*"The current Pleasant Bay Watershed Permit is based on watershed loading data that were presented in the MEP report of 2006 which was based on 12 months of water consumption data for Orleans in 2002/2003. Orleans recognizes that watershed loads have increased since then and that there is potential for further growth through the next few decades. Accordingly, Orleans has estimated growth of nitrogen loads in Orleans in two parts:*

1. *Growth from the time of the 2006 MEP analysis to the updated loads presented in the SMAST 2021 report, and*
2. *Growth beyond the levels reported in the SMAST 2021 report to a future planning horizon of about 20 years from now.*

*Orleans consultant Wright-Pierce calculated the first segment of growth by subtracting the attenuated watershed loads in the 2006 MEP report from those computed in the 2021 SMAST report. For Orleans, that increase in watershed load is 480 kilograms/year (kg/yr).*

*The second segment of growth was based on the Town Planner's analysis conducted in late 2023. Historical data show the Orleans has historically grown at a rate of about nine dwellings per year in the Pleasant Bay watershed. As available parcels decline, it is expected that the future Pleasant Bay growth rate will be only about five dwellings per year, or about 150 units over a 30-year period. About one-third of those parcels are expected to be served by planned expansions of the public sewer system (with septic* *nitrogen transported outside the Pleasant Bay watershed), and about two thirds (100 homes) will contribute additional nitrogen loads to Pleasant Bay. A recent land set-aside has taken about 20 potential parcels from the vacant parcel inventory. Orleans' consultant Wright-Pierce has calculated that the net 80 new unsewered homes are estimated to contribute 5.0 kg/yr (including 4 kg/yr septic and 1 kg/yr fertilizer/stormwater load) in attenuated load to Pleasant Bay, or about 400 kg/yr over the loadings from the 2021 SNEP report.*

*Planning for current and future nitrogen needs will be based on the 2006 MEP loads, plus 480 kg/yr estimated by SMAST and 400 kg/yr estimated by the Town for a planning horizon 20 years from now {2043}. The MEP total watershed loading of 14,700 kg/yr from Orleans will be increased by 880 kg/yr to 15,580 kg/yr, a 6% rise, to account for Orleans' growth. The Town intends to update this growth estimate periodically and report revised figures every 5 years."*

# Appendix C

# REVIEW OF ESTIMATED ATTENUATED NITROGEN LOADS TO PLEASANT BAY SUB-EMBAYMENTS

MARCH 2022

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# REVIEW OF ESTIMATED ATTENUATED NITROGEN LOADS TO PLEASANT BAY SUB-EMBAYMENTS

## Treatment of Attenuation in the Linked Watershed-Embayment Model

The Massachusetts Estuaries Project (MEP) is based on modeling the relationship between nitrogen-generating activities on the land and impacts to estuarine embayments that receive water (and nitrogen) from the land (Howes et al., 2001, 2006). Processes on the land surface are addressed by a land-use-based watershed model. Groundwater flow was modeled by the U.S. Geological Survey (USGS) (Walter et al, 2004; Carlson et al., 2017) and the results were used to subdivide the land into subwatersheds, each leading to an estuarine embayment, freshwater pond, or public-supply well. Data on land use was then used to estimate the amount of nitrogen that would be generated within each subwatershed. This nitrogen load was then routed through successive downgradient subwatersheds until it reached the estuary. As discussed further below, nitrogen attenuation is assumed to occur within each freshwater pond along this travel path.

The estuarine portion of the model is a sophisticated representation of the bay using two simulation models. A hydrodynamic model using the RMA-2 computer code simulates how water flows within the estuary in response to tides and a water quality model using the RMA-4 code simulates the fate and transport of salinity and total nitrogen within the estuary. The two models share a common representation of the estuary as a two-dimensional array of finite elements, a spatially flexible representation that allows detailed representation of small coastal embayments and tidal streams. Together, these two models make up the embayment portion of the linked watershed-embayment model.

Attenuation, the topic of this report, is represented in only the watershed portion of the linked model. The linked watershed-embayment model takes no credit for the small amount of nitrogen attenuation that occurs within the groundwater aquifer. However, groundwater on Cape Cod is often intercepted by kettle-hole lakes and ponds. Groundwater flows through the ponds as surface water only to re-enter the aquifer on the lake's or pond's downgradient side (Walter et al., 2011). A significant amount of nitrogen can be removed by biochemical processes in the lakes, ponds, and wetlands that intercept groundwater. These complex biochemical processes are captured in a simplified way in the linked watershed-embayment model through an attenuation coefficient—a number that represents the fraction of the incoming nitrogen removed in the freshwater body.

An important distinction in the original linked watershed-embayment model is that attenuation is modeled only in freshwater bodies (Howes, 2021, personal communication). Attenuation coefficients are not applied to tidal waters according to Howes. (As discussed below, this approach was modified in updates subsequent to the original 2006 study.) Tidal waters included in the embayment model of Pleasant Bay are shown color-coded according to salinity in Figure 1. While attenuation coefficients were not applied to tidal waters, the embayment model accounted for benthic processes that affect nitrogen concentrations. Samples of bay mud were analyzed in the laboratory to determine the amount of nitrogen passing between the bay mud and water column as benthic flux within the estuary (Howes et al., 2006, Section IV.3) and those exchanges are included in the embayment water quality model. While the benthic flux is positive for most subembayments (meaning nitrogen goes into the water from the mud), for a few subembayments it is negative. Howes et al. (2006, pg. 79) state that bay sediments "with a net input to the sediments serve as an 'in embayment' attenuation mechanism for nitrogen." Thus, according to Howes et al. (2006) attenuation is accounted for in the embayment, but by a different algorithm than for freshwater bodies. The embayment water quality model does not include a process model for nitrogen. In essence, nitrogen is treated as a passive tracer, unaltered by biochemical reactions in the bay, but transported and diluted by currents.

As indicated above, the land draining to Pleasant Bay is subdivided into multiple subwatersheds based on groundwater modeling completed by the U.S. Geological Survey. The landscape of Cape Cod is dotted by many lakes and ponds, each of which captures flow from a separate subwatershed. Outflow from a lake or pond is often then divided among many other downgradient subwatersheds. This can lead to startling complexity. Consider the portion of the watershed that flows from the eastern side of The River (Figure 2). The tidal subembayment Kescayo Gansett Pond (also called Lonnie's Pond) receives outflows from freshwater Baker Pond (via subwatersheds 38 and 37), Crystal Lake (via 38), and Pilgrim Lake (via 38 and 40). But outflow from Baker Pond also flows into Crystal Lake (via subwatersheds 5 and 6) and Pilgrim Lake (via 28 and 13). Water flowing out from Baker Pond thus reaches Kescayo Gansett Pond by three different pathways, each of which would experience a different net attenuation. The pathway into Baker Pond is similarly complex. It receives inflow from Little Cliff Pond both directly and through Higgins Pond. Little Cliff Pond receives inflow from Cliff Pond which in turn receives inflow from Ruth Pond. Adding to the complexity, a significant portion of the outflow from Cliff Pond goes to the watershed to the north, which eventually drains to the north shore of Cape Cod. A portion of the outflow from Baker Pond also flows to the north eventually draining to Nauset Harbor.

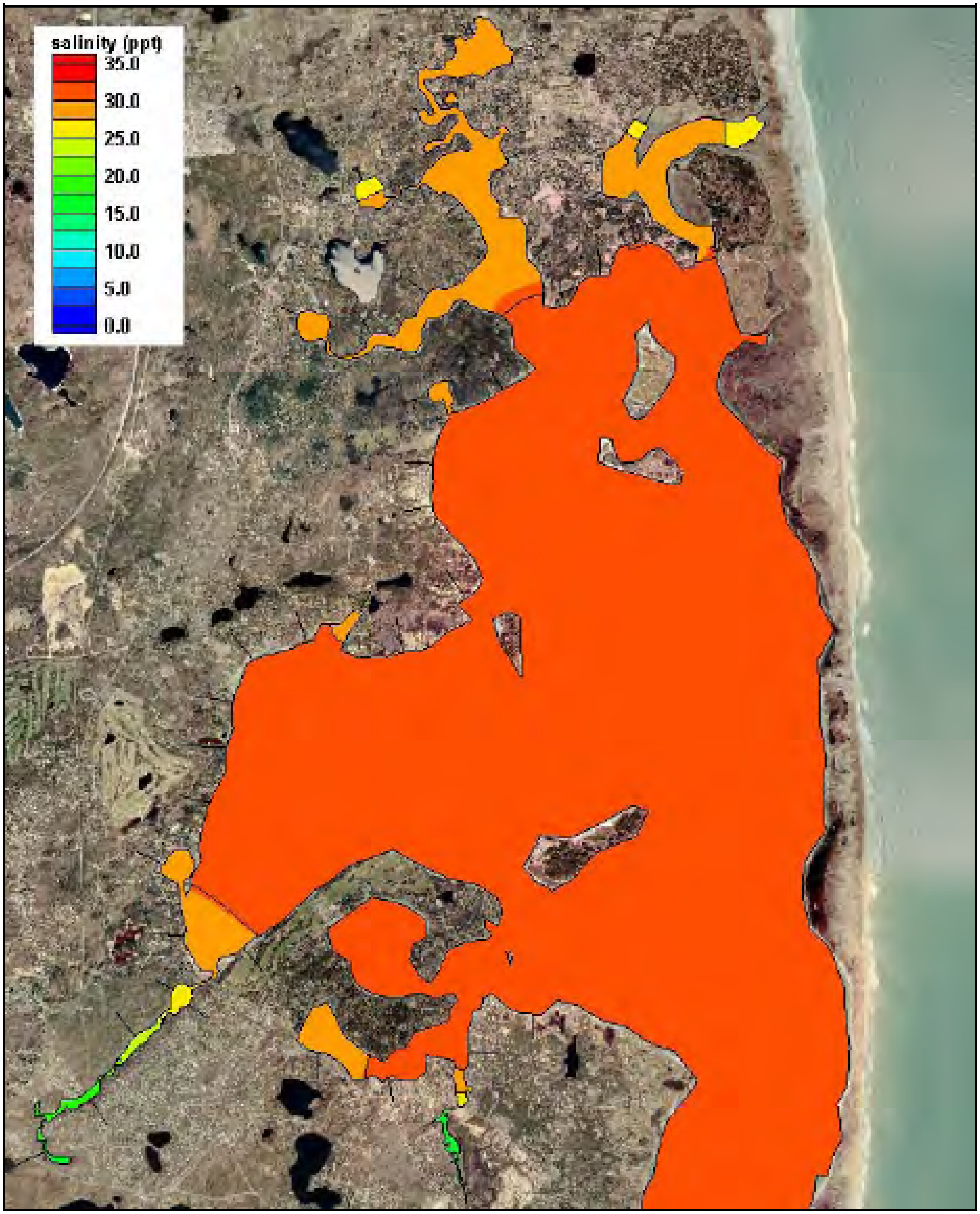

Figure 1

Embayment model with predicted salinity concentrations (Howes et al, 2006, Figure VI-7).

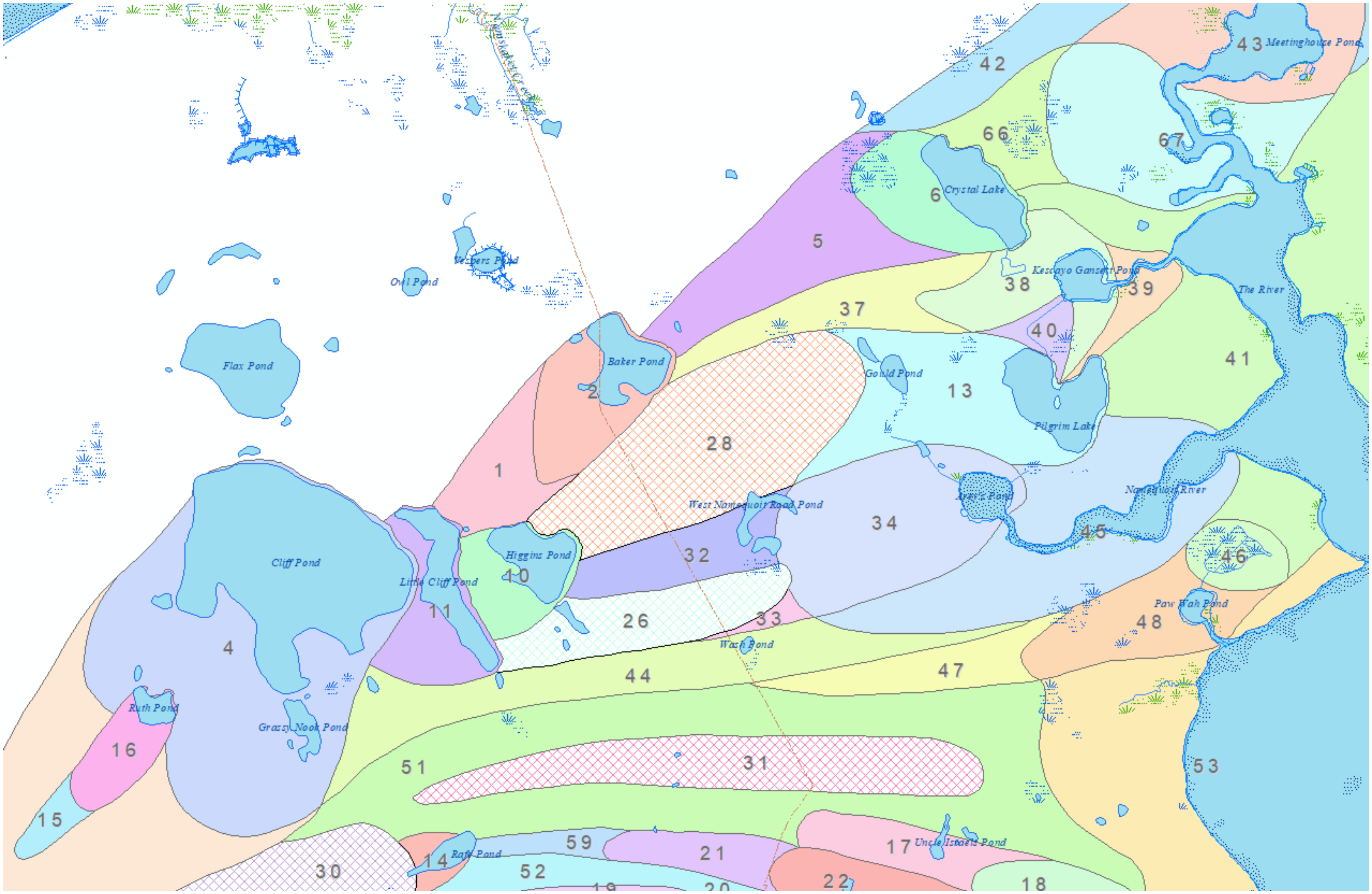

Figure 2
Portion of the subwatershed draining to The River.
Numbers indicate subwatershed number as assigned by Howes et al. (2006).

Each of the water bodies referenced above is assigned an attenuation coefficient in the watershed model. However, the complexity of the drainage patterns makes it difficult to determine the contribution of attenuation by each freshwater body to each receiving tidal subembayment. For example, the net attenuation of the nitrogen going to Keysaco Gansett Pond occurs in seven different ponds compounded by passage through as many as five ponds sequentially.

The various flow pathways are tracked in painstaking detail in the watershed model. Howes et al. (2006, Table IV-5) summarize the nitrogen loads to Pleasant Bay and its numerous subembayments tallied by the watershed model in their so-called "rainbow table." This 48-line table is, however, only a summary of a much larger table that is included on the Pleasant Bay Data Disk that accompanied the 2006 report. That table includes 145 lines to track subwatersheds plus an additional 71 lines solely to track lakes and ponds. I attempted to construct a summary of the effect of attenuation on the load reaching each subembayment but soon realized its construction would take many more hours than the project budget would support. Table 1 is a higher-level summary of the attenuation contribution of each water body. The various types of water bodies are differentiated by color-coded shading, a scheme that is used throughout this report.

The loads shown in Table 1 correspond to the loads presented as "Present N Loads" by Howes et al. (2006, Table IV-5). The total load shown in Table 1 to be removed by attenuation (3,656 kg/year) exceeds the difference (3,166 kg/year) between the attenuated (78,001 kg/year) and unattenuated loads (81,167 kg/year) in Table IV-5 of Howes et al. (2006) because some ponds tributary to other ponds are not explicitly tracked in Table IV-5. For example, the attenuation in far-upstream Ruth Pond is not tracked in Table IV-5 although the attenuated loads from Ruth Pond are correctly carried through the load budget shown in Table IV-5.

As can be seen in Table 1, an attenuation factor of 50% is used for all lakes and ponds except Stillwater Pond which was the subject of detailed field investigations discussed further below.

## Table 1
## Contribution of Ponds, Lakes, and Wetlands to Nitrogen Load Attenuation in 2006 Model (Howes et al., 2006).

| Water Body Name | Type of Water Body | Downgradient Receptors | Total Load into Pond (2006 values) (kg/year) | Portion of Load to Pleasant Bay (%) | Unattenuated Load to Pleasant Bay (kg/year) | Attenuation Factor (%) | Load after Attenuation (kg/year) | Load Removed by Attenuation (kg/year) |
|---|---|---|---|---|---|---|---|---|
| Baker Pond (BP) | Lake/pond | Crystal Lake, Pilgrim Lake, River System, *Nauset Harbor* | 373 | *60%* | 223 | 50% | 111 | 111 |
| Bassing Pond (BSP) | Lake/pond | PB Main, Ryder Cove | 160 | 100% | 160 | 50% | 80 | 80 |
| Cliff Pond (CP) | Lake/pond | Little Cliff Pond, River System, *Namskaket Marsh* | 2356 | *24%* | 573 | 50% | 286 | 286 |
| Crystal Lake (CL) | Lake/pond | Kescayo Gansett Pond, Upper River, Lower River | 596 | 100% | 596 | 50% | 298 | 298 |
| Deep Pond (DP) | Lake/pond | PB Main | 174 | 100% | 174 | 50% | 87 | 87 |
| Emery Pond (EP) | Lake/pond | Ryder Cove, *Stage Harbor* | 114 | *62%* | 71 | 50% | 36 | 36 |
| Frost Fish Creek | Salt Marsh | Ryder Cove | 1095 | 100% | 1095 | 0% | 1095 | 0 |
| Goose Pond (GOP) | Lake/pond | Muddy Creek, *Sulfur Springs, Bucks Creek* | 362 | *51%* | 183 | 50% | 92 | 92 |
| Grassy Pond (GP) | Lake/pond | PB Main, Round Cove | 183 | 100% | 183 | 50% | 92 | 92 |
| Hawksnest Pond (HWP) | Lake/pond | Muddy Creek, *Taylors Pond, Mill Creek, Cockle Cove, Bucks Creek* | 133 | *34%* | 45 | 50% | 23 | 23 |
| Higgins Pond (HP) | Lake/pond | Baker Pond, Cliff Pond Well, Arey's Pond | 324 | 100% | 324 | 50% | 162 | 162 |
| Little Cliff Pond (LCP) | Lake/pond | Cliff Pond Well, Baker Pond, Higgins Pond, Cliff Pond, *Namskaket Marsh* | 466 | *84%* | 391 | 50% | 196 | 196 |
| Lovers Lake (LL) | Lake/pond | Ryder Cove, Stillwater Pond | 559 | 100% | 559 | 50% | 279 | 279 |
| Mill Pond Fresh (MPF) | Lake/pond | Muddy Creek, *Taylors Pond, Mill Creek, Cockle Cove, Bucks Creek* | 669 | *29%* | 191 | 50% | 96 | 96 |
| Mud Pond (MP) | Lake/pond | PB Main, Round Cove | 62 | 100% | 62 | 50% | 31 | 31 |
| Muddy Creek, Upper | Salt Marsh | Muddy Creek | 3860 | 100% | 3860 | 0% | 3860 | 0 |
| Muddy Creek, Lower | Salt Marsh | Muddy Creek | 7027 | 100% | 7027 | 0% | 7027 | 0 |
| Pah Wah Pond Bog | Freshwater wetland | Pah Wah Pond | 709 | 100% | 709 | 0% | 709 | 0 |
| Pilgrim Lake (PL) | Lake/pond | Kescayo Gansett Stream and River, Namequoit River, Lower River | 994 | 100% | 994 | 50% | 497 | 497 |
| Pochet Neck | Salt Marsh | Pochet Neck | 3718 | 100% | 3718 | 0% | 3718 | 0 |
| Rafe Pond (RFP) | Lake/pond | PB Main, Quanset Pond | 79 | 100% | 79 | 50% | 40 | 40 |
| Ruth Pond (RP) | Lake/pond | Cliff Pond | 267 | 100% | 267 | 50% | 134 | 134 |
| Quanset Pond Bog (QPB) | Freshwater wetland | PB Main, Quanset Pond | 105 | 100% | 105 | 50% | 52 | 52 |
| Sarahs Pond (SP) | Lake/pond | The Horseshoe | 397 | 100% | 397 | 50% | 198 | 198 |
| Schoolhouse Pond (SCP) | Lake/pond | Ryder Cove, Crow's Pond, Stillwater Pond | 195 | 100% | 195 | 50% | 97 | 97 |
| Shoal Pond (SHP) | Lake/pond | PB Main, Quanset Pond | 409 | 100% | 409 | 50% | 204 | 204 |
| Stillwater Pond (SWP) | Lake/pond | Ryder Cove | 734 | 100% | 734 | 5% | 697 | 37 |
| Tar Kiln Marsh | Salt Marsh | Tar Kiln Stream | 2259 | 100% | 2259 | 0% | 2259 | 0 |
| Trout Pond (TTP) | Lake/pond | Muddy Creek | 357 | 100% | 357 | 50% | 178 | 178 |
| Twinings Pond (TP) | Lake/pond | Quanset Pond | 378 | 100% | 378 | 50% | 189 | 189 |
| Uncle Harvey Pond | Lake/pond | Pochet Neck | 123 | 100% | 123 | 50% | 61 | 61 |
| Uncle Seths Pond (USP) | Lake/pond | PB Main | 202 | 100% | 202 | 50% | 101 | 101 |
| Total (2006) | | | 29,437 | | 26,641 | | 22,985 | 3,656 |

Note: Downgradient receptors not within the drainage to Pleasant Bay are shown in italics.

Table 1 should be viewed in comparison to the total load predicted to reach Pleasant Bay by Howes et al. (2006). The amount of nitrogen attenuated in freshwater ponds and lakes within the watershed (3,656 kg/year) is less than 5% of the total load that is predicted to reach the bay (78,001 kg/year). That said, the loading distribution is uneven and attenuation at some water bodies (for example, Muddy Creek, Pochet Neck, and Tar Kiln Marsh) could be a significant factor in the load that reaches Pleasant Bay. Also noteworthy in Table 1 are the water bodies that are not included in computing attenuation. Among the water bodies that are not considered to contribute to attenuation are Kescayo Gansett Pond, Arey's Pond, Upper and Lower Muddy Creek, and Frost Fish Creek. These water bodies, which are shown in Figure 1 to be brackish, are included in the embayment model but not the watershed model. Nitrogen attenuation in these water bodies, if any, is captured by the benthic flux in the embayment water quality model and not by attenuation in the watershed model. Although not treated as a part of the embayment model, attenuation was also not considered for Tar Kiln Marsh or Pah Wah Pond Bog.

Although error checking was not an intended part of this review, I was required to review the rainbow table and its supporting calculations in great detail in order to understand how attenuation factored into the nitrogen loads as they cascaded from pond to pond within the watershed. I came to appreciate that the table was constructed with great care and attention to detail. I found no errors in my review, which I find extraordinary given the complexity of the table and of the nitrogen-load bookkeeping that underlies it.

## Revisions to the MEP Model

The original MEP model (Howes et al., 2006) has subsequently been revised. Eichner et al. (2010a) presented a revised excerpt of the "rainbow" loading table for Muddy Creek and Round Cove while Eichner et al. (2010b) incorporate attenuation into the Muddy Creek calculations. Howes et al. (2021) completed a wholesale revision of the model to incorporate new information on land and water use as well as new findings concerning attenuation. The 2010 and 2021 revisions are discussed in the following paragraphs.

Eichner et al. (2010a) revisited loading estimates for Muddy Creek after receiving new information on land and water use for Harwich. They used this information to construct a revised "rainbow table" for Muddy Creek and Round Cove, with substantially higher loads than in the original 2006 study. The caption on the rainbow table states (Eichner et al., 2010a, Table 1): "Muddy Creek attenuated loads do not include attenuation assigned to within the wetlands and sediments of the Muddy Creek." The memorandum indicates that attenuation rates of 57% and 2% were applied to Upper and Lower Muddy Creek respectively (Eichner et al., 2010a, pg. 2) but the attenuated loads are not presented other than for the portion of the watershed within Harwich (Eichner et al., 2010a, Table 2).

Eichner et al. (2010b) evaluated the potential impact of a restoration project then being contemplated for Muddy Creek. They added no new analysis of attenuation but presented modified loads for Upper and Lower Muddy Creek. Loads were not presented in the form of a rainbow table but were provided in Table 1 in a different format and in units of kg/day rather than kg/year. Detailed versions of the watershed loading tables, as included on the data disk for the 2006 report, are not available for the 2010 updates which precludes my detailed analysis. But the aggregated watershed loads presented in Table 1 of Eichner et al. (2010b) are directly comparable with those in the prior rainbow tables. The total load for Upper Muddy Creek is simply the attenuated load ("Atten N Load") in Table 1B of Eichner et al. (2010a) reduced by an attenuation factor of 57% and that for Lower Muddy Creek reduced by an attenuation factor of 2.5%. These are essentially the same attenuation factors as those stated in Eichner et al. (2010a) and this is consistent with a statement by Eichner et al. (2010b) that they did not alter the attenuation coefficients in their new analysis. Significantly, in using these attenuation factors for Muddy Creek, Eichner et al. (2010b) stepped away from the prior practice of applying attenuation factors only to freshwater bodies. Eichner et al. (2010a, Table 2) show a negative benthic flux term for Upper Muddy Creek and in this way attenuation occurs in both the watershed and embayment models, which may constitute double-counting. Eichner et al. (2010b) also used the embayment model in evaluating the proposed restoration and found that nitrogen concentrations would be lowered in Muddy Creek as the result of increased tidal flushing (rather than by increased attenuation).

In the spring of 2016, the Muddy Creek Marsh Restoration Project was completed (Ruthven and Kelley, 2017). Two 2.5-foot-wide, 100-foot long box culverts were replaced by a 22-foot-wide single-span bridge that allowed much greater tidal flow with the goal of restoring a salt marsh habitat to Upper Muddy Creek. Howes (2021, personal communication) said that opening up the hydraulic connection between Upper and Lower Muddy Creek made both portions into salt marshes and thus excluded the saltwater portion of Muddy Creek from the attenuation calculations.

# Table 2
## Contribution of Ponds, Lakes, and Wetlands to Nitrogen Load Attenuation in 2021 Model (Howes et al., 2021).

| Water Body Name | Type of Water Body | Downgradient Receptors | Total Load into Pond (2021 values) (kg/year) | Portion of Load to Pleasant Bay (%) | Unattenuated Load to Pleasant Bay (kg/year) | Attenuation Factor (%) | Load after Attenuation (kg/year) | Load Removed by Attenuation (kg/year) |
|---|---|---|---|---|---|---|---|---|
| Baker Pond (BP) | Lake/pond | Crystal Lake, Pilgrim Lake, River System, *Nauset Harbor* | 495 | *60%* | 296 | 50% | 148 | 148 |
| Bassing Pond (BSP) | Lake/pond | PB Main, Ryder Cove | 174 | 100% | 174 | 50% | 87 | 87 |
| Cliff Pond (CP) | Lake/pond | Little Cliff Pond, River System, *Namskaket Marsh* | 2457 | *24%* | 597 | 50% | 299 | 299 |
| Crystal Lake (CL) | Lake/pond | Kescayo Gansett Pond, Upper River, Lower River | 644 | 100% | 644 | 50% | 322 | 322 |
| Deep Pond (DP) | Lake/pond | PB Main | 184 | 100% | 184 | 50% | 92 | 92 |
| Emery Pond (EP) | Lake/pond | Ryder Cove, *Stage Harbor* | 154 | *62%* | 96 | 50% | 48 | 48 |
| Frost Fish Creek | Salt Marsh | Ryder Cove | 1353 | 100% | 1353 | 0% | 1353 | 0 |
| Goose Pond (GOP) | Lake/pond | Muddy Creek, *Sulfur Springs, Bucks Creek* | 432 | *51%* | 219 | 50% | 109 | 109 |
| Grassy Pond (GP) | Lake/pond | PB Main, Round Cove | 154 | 100% | 154 | 50% | 77 | 77 |
| Hawksnest Pond (HWP) | Lake/pond | Muddy Creek, *Taylors Pond, Mill Creek, Cockle Cove, Bucks Creek* | 136 | *34%* | 46 | 50% | 23 | 23 |
| Higgins Pond (HP) | Lake/pond | Baker Pond, Cliff Pond Well, Arey's Pond | 511 | 100% | 511 | 50% | 255 | 255 |
| Little Cliff Pond (LCP) | Lake/pond | Cliff Pond Well, Baker Pond, Higgins Pond, Cliff Pond, *Namskaket Marsh* | 762 | *84%* | 639 | 50% | 320 | 320 |
| Lovers Lake (LL) | Lake/pond | Ryder Cove, Stillwater Pond | 501 | 100% | 501 | 50% | 251 | 251 |
| Mill Pond Fresh (MPF) | Lake/pond | Muddy Creek, *Taylors Pond, Mill Creek, Cockle Cove, Bucks Creek* | 1015 | *29%* | 290 | 50% | 145 | 145 |
| Mud Pond (MP) | Lake/pond | PB Main, Round Cove | 63 | 100% | 63 | 50% | 31 | 31 |
| Muddy Creek, Upper | Salt Marsh | Muddy Creek | 5062 | 100% | 5062 | **10%** | 4556 | 506 |
| Muddy Creek, Lower | Salt Marsh | Muddy Creek | 8577 | 100% | 8577 | 0% | 8577 | 0 |
| Pah Wah Pond Bog | Freshwater wetland | Pah Wah Pond | 709 | 100% | 709 | 0% | 709 | 0 |
| Pilgrim Lake (PL) | Lake/pond | Kescayo Gansett Stream and River, Namequoit River, Lower River | 1132 | 100% | 1132 | 50% | 566 | 566 |
| Pochet Neck | Salt Marsh | Pochet Neck | 3790 | 100% | 3790 | 0% | 3790 | 0 |
| Rafe Pond (RFP) | Lake/pond | PB Main, Quanset Pond | 84 | 100% | 84 | 50% | 42 | 42 |
| Ruth Pond (RP) | Lake/pond | Cliff Pond | 142 | 100% | 142 | 50% | 71 | 71 |
| Quanset Pond Bog (QPB) | Freshwater wetland | PB Main, Quanset Pond | 214 | 100% | 214 | 50% | 107 | 107 |
| Sarahs Pond (SP) | Lake/pond | The Horseshoe | 342 | 100% | 342 | 50% | 171 | 171 |
| Schoolhouse Pond (SCP) | Lake/pond | Ryder Cove, Crow's Pond, Stillwater Pond | 199 | 100% | 199 | 50% | 99 | 99 |
| Shoal Pond (SHP) | Lake/pond | PB Main, Quanset Pond | 451 | 100% | 451 | 50% | 226 | 226 |
| Stillwater Pond (SWP) | Lake/pond | Ryder Cove | 1053 | 100% | 1053 | 5% | 1000 | 53 |
| Tar Kiln Marsh | Salt Marsh | Tar Kiln Stream | 1525 | 100% | 1525 | **60%** | 610 | 915 |
| Twinings Pond (TP) | Lake/pond | Quanset Pond | 403 | 100% | 403 | 50% | 201 | 201 |
| Uncle Harvey Pond | Lake/pond | Pochet Neck | 128 | 100% | 128 | 50% | 64 | 64 |
| Uncle Seths Pond (USP) | Lake/pond | PB Main | 274 | 100% | 274 | 50% | 137 | 137 |
| Total (2006) | | | 33,119 | | 29,851 | | 24,486 | 5,365 |

Note: Downgradient receptors not within the drainage to Pleasant Bay are shown in italics.

Howes et al. (2021) report on an update of the Pleasant Bay study that incorporates new information on land and water use as well as findings on attenuation developed since the 2006 MEP study. Nitrogen loads were revised throughout the Pleasant Bay watershed, in many case substantially. A portion of the data disk for this study was available for review, allowing detailed deconstruction of the role of attenuation in the model. Table 2 is a revised tabulation of the contribution of ponds, lakes, and wetlands to attenuation in the 2021 update and is directly comparable to the summary of the 2006 study in Table 1. As can be seen, the computed watershed loads to attenuating water bodies increased by almost 4000 kg/year. As a result, the load removed by attenuation also increased, from 3700 kg/year to 5400 kg/year, but this increase of 1700 kg/year of attenuation is less than half the increase in load and the attenuated load predicted in 2021 is higher than that predicted in 2006.

As far as the attenuation provided by individual water bodies in the 2021 update, the percentage of attenuation remained at 50% for the freshwater ponds and lakes. The only changes from the 2006 attenuation factors were to Upper Muddy Creek, which changed from 0% to 10%, and Tar Kiln Stream, from 0% to 60%.

Attenuation in Muddy Creek thus changed significantly in 2021 from what used in 2010 (57% in Upper and 2.5% in Lower). This apparently reflects the reversion of Muddy Creek to more of a salt marsh following the Muddy Creek Restoration Project. The salt marsh portion of the creek is assumed to have zero attenuation and the small attenuation for Upper Muddy Creek (10%) captures attenuation in freshwater wetlands upstream of the saltwater portion. Attenuation is no longer considered for Lower Muddy Creek in the 2021 update.

The evolving analysis of attenuation in Tar Kiln Stream is further discussed below.

## Review of Attenuation Factors

Attenuation is computed in the MEP watershed model as the difference between the mass of nitrogen that flows into the surface-water body and the mass of nitrogen that flows out divided by mass that flows in:

$$Attenuation = \frac{Inflowing\ mass - Outflowing\ mass}{Inflowing\ mass} \qquad (1)$$

Attenuation is expressed as a percentage and represents the percentage of the mass entering the water body that is removed by environmental mechanisms within the water body. Attenuation is also expressed in the literature as an area-specific rate, that is the rate of attenuation per unit area of sediment or water body. That formulation of attenuation is used to compute nitrogen exchange with benthic sediment in embayments and Pleasant Bay for the MEP embayment model

Nitrogen is attenuated in the environment mostly by two processes. In environments that are devoid of oxygen, such as pond and wetland mud, nitrate nitrogen is converted to nitrogen gas and removed from the water body by a process known as denitrification. Elsewhere in the pond or wetlands, growing plants and algae take up nitrogen to fuel growth processes, converting inorganic nitrogen to organic nitrogen. Subsequent settling of dead organisms removes organic nitrogen by sedimentation. The importance of denitrification, sedimentation, and other less important processes varies with the type of water body, the time it takes for water to pass through the water body (hydraulic residence time), the magnitude of the nitrogen loading to the water body, and the biochemical characteristics of the water body.

The scientific literature reports widely varying degrees of attenuation in water bodies of the same type and between different types of water bodies (Table 3). Jansson et al. (1994) contend that lakes are generally more effective than wetlands in removing nitrogen because they have longer travel times even though wetlands have higher area-specific attenuation rates. Saunders and Kalff (2001), who give regression relations between area-specific attenuation and nitrogen load, show wetlands have area-specific attenuation rates about twice as high as lakes. Seitzinger (1988) indicates that coastal marine sediments have higher area-specific attenuation rates than lake and river sediments, but that all vary widely.

Saunders and Kalff (2001) develop regression equations for nitrogen retention (i.e., attenuation) in wetlands and lakes. Their equation for lakes is:

$$A_S = 2.53 + 0.34L_S \tag{2}$$

where, $A_S$ is the area-specific attenuation rate [g-N/m$^2$/year], and

$L_S$ is the area-specific loading rate [g-N/m$^2$/year].

### Table 3
### Attenuation Factors from the Literature.

| Source | Type of Water Body | Attenuation Factor (%) | Area-Specific Attenuation Rate ($g\text{-}N/m^2/year$) | Notes |
|---|---|---|---|---|
| Hill and Sanmugadas, 1983 | Stream | | 40 - 90 | Cited by Woods Hole Group, 2007 |
| Seitzinger, 1988 | Stream | | 0 - 30 | |
| Saunders and Kalff, 2001 | Lake | | 20 | Value at 50 $g\text{-}N/m^2/year$ loading |
| Seitzinger, 1988 | Lake | | 0.2 - 20 | Sediment denitrification |
| Seitzinger, 1988 | Lake | 0 - 62 | 2 - 180 | Whole lake denitrification |
| Ahlgren et al., 1994 | Lake | 29 - 51 | | Lake Vallentuna |
| Ahlgren et al., 1994 | Lake | 13 - 26 | | Lake Norrviken |
| Durand et al., 2010 | Lake | 10 - 60 | | Function of depth and residence time |
| Ginger, 2017 | Lake | | 0.1 - 300 | Denitrification |
| Grantz, 2011 | Lake | 49 - 84 | 3.5 - 19 | |
| Müller et al., 2021 | Lake | 25 | 22 ± 6 | Lake Baldegg |
| Müller et al., 2021 | Lake | 10 | 3.2 ± 4.2 | Lake Sarnen |
| Jansson et al., 1994 | Lake | 50 + | | |
| Johnston, 1990 | Freshwater wetland | | 0.1 - 1.0 | Cited by Woods Hole Group, 2007 |
| Phipps and Crumpton, 1994 | Freshwater wetland | 78 - 84 | | Cited by Woods Hole Group, 2007 |
| Howard-Williams, 1985 | Freshwater wetland | | 4 | Cited by Woods Hole Group, 2007 |
| Saunders and Kalff, 2001 | Freshwater wetland | | 32 | Value at 50 $g\text{-}N/m^2/year$ loading |
| Nowicki et al., 1999 | Salt marsh | | 0.5 - 5.5 | Nauset Marsh |
| Kroeger and Charette, 2008 | Salt marsh | 65 | | Waquoit Bay |
| Seitzinger, 1988 | Salt marsh | | 6 - 30 | Typical range for sediment denitrification |
| Seitzinger, 1988 | Salt marsh | | 0 - 130 | "Extreme" range for sediment denitrification |

Saunders and Kalff (2001) fit this equation to a dataset of 23 lakes with a coefficient of determination ($R^2$) of 0.80. Saunders' and Kalff's equation for wetlands is:

$$A_S = 0.42 + 0.64 L_S \tag{3}$$

which was fit to a dataset of 23 wetlands with an $R^2$ value of 0.82. Moriasi et al. (2015) rate $R^2$ values greater than 0.7 as "very good" for nitrogen prediction in watershed models so both the lake and wetlands equations should have satisfactory predictive ability.

If Equations 2 and 3 are multiplied by the area of the pond or wetland, they become equations for the attenuation as a fractional value that is a function of the total annual nitrogen loading. Thus, they show that attenuation in highly loaded lakes is proportional to about 34% of the annual loading and in highly loaded wetlands to about 64% of the annual loading. These are comparable to the 50% attenuation used by Howes et al. (2006) for attenuation in lakes and wetlands.

Steingruber (2020) also evaluates regression equations for predicting total nitrogen attenuation in lakes. She bases her equations on the areal hydraulic load, which is the water flow rate divided by the pond area. She evaluates ten alternative equations, some of which require data not available for the Pleasant Bay watershed from the MEP study or other sources. Of the equations she evaluates, the applicable equation providing the best fit ($R^2$ = 0.64) is:

$$R = 0.44 - 0.27\mathrm{q} + 0.39 \frac{L_{DIN}}{L_{TN}} \tag{3}$$

where, $R$ is the attenuation rate [%];

$q$ is the areal hydraulic load [m/year]; and,

$L_{DIN}$ is the area-specific load of dissolved inorganic nitrogen [kg/year]; and,

$L_{TN}$ is the area-specific load of total nitrogen [kg/year].

Since the loading to lake and ponds in the Pleasant Bay watershed is presumed to be predominantly dissolved inorganic nitrogen in groundwater, $L_{DIN} = L_{TN}$ in this application. This equation is based on data from 39 lakes and reservoirs.

For Pleasant Bay, Howes et al. (2006, Section IV.2) determined attenuation in selected freshwater water bodies that were the subject of field-monitoring programs for 16 to 24 months. The outflowing nitrogen mass was computed from their measurements. Flow was monitored continuously by measuring water level with a recording gauge and translating water level into flow rate using a rating curve. The concentrations of nitrogen and other water-quality attributes were measured in water samples collected weekly. Mass flow was determined by multiplying the measured water flow by the nitrogen concentration interpolated between the weekly concentration measurements.

The inflowing mass to each water body was taken as the estimate developed from land-use-based nitrogen loading analysis within the watershed model (Howes et al., 2006, Section IV.1). Those nitrogen loads are presented in the "rainbow table" (Howes et al., 2006, Table IV-5).

The attenuation factors determined by this methodology are inherently but necessarily approximate. Measuring the nitrogen load that flows into water bodies via groundwater is a practical impossibility and thus approximations are required. Estimating the mass into the ponds using the watershed model is one of only a few practical alternatives and has the advantage of being consistent with the loads that form the basis for the subsequent TMDL and Watershed Permit (MADEP, 2007, 2018). The outflowing mass is determined by field measurements, but using nitrogen concentrations that are measured only weekly and which show significant fluctuation. The fluctuations do not appear to be systematic seasonal variation but rather predominantly simple statistical "noise." (The data record for each water body is examined in more detail below.) Attenuation is therefore calculated based on the difference between a noisy number and an estimated number, and therefore is itself highly approximate. It is important to recognize that the resulting estimates of attenuation are necessarily, but unavoidably, highly uncertain.

## Attenuation in Specific Water Bodies

Howes et al. (2006, Section IV.2) report on detailed assessments of attenuation in five water bodies: Pilgrim Lake (tributary to Kescayo Gansett Pond), Pah Wah Pond Bog (tributary to Pah Wah Pond), Tar Kiln Marsh which discharges to Pleasant Bay, Lovers Lake and Stillwater Pond which discharge, in that sequence, to Ryder Cove, and Frost Fish Creek which discharges to Bassing Harbor. In addition, Eichner et al. (2018, 2019) assessed attenuation in Uncle Harvey's Pond and Pilgrim Lake, and White et al. (2008) and Eichner et al. (2010a, 2010b) assessed Muddy Creek. These assessments are reviewed in the following.

Pilgrim Lake. Pilgrim Lake is unlike many of the other ponds and lakes in the watershed in that it has a surface-water outlet that drains into Kescayo Gansett Pond.

Howes et al. (2006) monitored the outflow from June 2002 to October 2003 and used the twelve-month record from October 2002 to October 2003 to assess attenuation. A continuous record of flow and weekly measurements of total nitrogen and combined nitrate and nitrite are plotted in Figure IV-8 of the 2006 report. The raw field data were not available for my analysis. The plotted record shows higher flow during the winter and spring, consistent with seasonal groundwater flow patterns, and occasional spikes of flow apparently due to stormwater inflows. The resolution of the graph is insufficient to determine the extent to which measured nitrogen concentrations coincide with stormwater flows. Visual inspection of the graph indicates that total nitrogen concentrations fluctuate in a seemingly random pattern between about 0.5 and 1.3 mg/L with three outliers between about 1.6 and 2.3 mg/L. The average concentration is 0.8 mg/L (Howes et al., 2006, Table IV-7). The load calculated to flow from Pilgrim Lake is 285 kg/year compared to an unattenuated load of 562 kg/year (Eichner et al., 2019, pg. 57; Howes et al., 2006, pg. 50). The measured load is only about 50% of the estimated load, which implies an attenuation rate of 50%. Based on the range in the observed concentrations, the attenuation rate likely lies within a range between 17% and 68%. This should be considered an extreme range since it is based on the minimum and maximum concentrations (excluding outliers) and not a statistical determination of concentration variation. Attenuation is often expressed in the literature in terms of grams of nitrogen per square meter per year. For Pilgrim Lake, with an area of 38 acres (per MassGIS, 2019), the nitrogen attenuation rate is 4.3 g-N/m$^2$/year, which is on the modest side compared to values from the literature in Table 1.

Pah Wah Pond Bog. The outflow from this small freshwater bog was monitored from June 2002 to April 2004; data for the year between September 2002 to September 2003 were used to compute attenuation. The patterns of flow and concentration for this site (Howes et al., 2006, Figure IV-9) were similar to those for Pilgrim Lake except that the spikes in flow associated with surface-water runoff were considerably milder. The concentration of total nitrogen averaged 1.6 mg/L (Table IV-7) and, based on visual inspection, ranged between about 0.6 and 2.6 mg/L excepting one high and three low outliers. The average measured flow (388 m$^3$/day) exceeded that predicted by the watershed model (271 m$^3$/day). The load predicted by the watershed model was 710 kg/year while the measured load was only 229 kg/year (Howes et al, 2006, pg. 55), implying an attenuation rate of 60%. Considering the uncertainty associated with the range of observed concentrations, the attenuation rate could be as high as 88% or as low as 52%. With an area of 15 acres, Paw Wah Pond Bog has an attenuation rate of 7.9 g-N/m$^2$/year.

Tar Kiln Marsh. The outflow from Tar Kiln Marsh, which is a salt marsh, was monitored between July 2003 and May 2005. A twelve-month record from May 2004 to May 2005 was analyzed to determine an attenuation coefficient (Howes et al., 2006, pg. 57). Water quality samples were collected at low tide when the marsh outlet lies above the tide and freshwater flows from the marsh. The measured outflow matched the flow predicted by the watershed model within 9%. Total nitrogen concentrations in the outflow were high, averaging 0.69 mg/L. As with the other field measurements plotted by Howes et al. (2006), nitrogen concentrations varied seemingly randomly, between about 0.3 and 1 mg/L, based on visual inspection. The measured outflow load was 764 kg/year, compared to 2258 kg/year estimated in the watershed model. This is equivalent to an attenuation rate of 66% (Howes et al., 2006, pg. 58, give a slightly different value of 69%). Accounting for the range in observed concentrations, the attenuation rate could vary between 51% and 85%. In fact however, no attenuation was included in the 2006 analysis for Tar Kiln Marsh. Howes et al. (2021, pg. 14) explain "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." Howes et al. (2021, pg. 14) indicated that a subsequent study (Howes et al., 2020) showed the original attenuation coefficient to be reasonable and 60% attenuation was employed in the 2021 update of the Pleasant Bay analysis (Howes et al., 2021). MassGIS (2019) gives the area of Tar Kiln Marsh as 8.1 acres, for an area-specific attenuation rate of 45 g-N/m$^2$/year, which is somewhat high compared to values in Table 3.

Lovers Lake. Lovers Lake discharges via a surface-water stream to Stillwater Pond. The outflow was monitored from November 2000 to Summer 2002 but with significant interruptions due instrument failures (Howes et al., 2006, pg. 60). A composite year of record (Figure IV-12) was constructed by filling gaps in the available record with data from the same calendar period of other years. The flow hydrograph showed typical seasonality and relatively minor apparent influence from surface runoff. The measured flow from Lovers Lake was equal to 91% of the inflow computed by the watershed model. Visual inspection of measured total nitrogen concentrations shows more scatter, and likely outliers, than at the locations discussed above. Concentrations mostly varied between 0.3 and about 1.0 mg/L, but with concentration excursions as high as 2.3 mg/L. The average outflow concentration was 0.85 mg/L (Howes et al., 2006, pg. 61). The predicted load from the watershed was reduced in Lovers Lake from 559 to 296 kg/year (converted from units of g/day in Table IV-9), an attenuation of 47%. This equates to an area-specific attenuation of 1.7 g-N/m$^2$/year over the 37-acre lake.

Stillwater Pond. The outflow from Lovers Lake flows into Stillwater Pond from which it discharges to Ryder Cove. The flow from Stillwater Pond was monitored during the same period as Lovers Lake and was also assessed using a coinciding constructed composite record. The measured flow from Stillwater Pond was only about a third (34%) of the inflow computed by the watershed model (Howes et al., 2006, Table IV-9), suggesting that much of the outflow from the pond is by groundwater. Table IV-9 gives the average nitrogen load discharged from Stillwater Pond as equivalent to 262 kg/yr. Presuming this represents only 34% of the pond's outflow, the total outflow load would be 770 kg/day, slightly higher than the inflow load of 751 kg/day and implying about a 2.5% addition of nitrogen (i.e., negative attenuation). Nonetheless, Table IV-9 states the attenuation as 7%, a value I am unable to replicate from the numbers in the table and report or the data disk. This attenuation was approximated as 5% in the watershed model (Table 1).

Frost Fish Creek. Although Frost Fish Creek is tidal, Howes et al. (2006, pg. 66) evaluated attenuation for this water body also. The monitoring program for this water body differed from those above due in part to its tidal character. Flow measurements were made over two tidal periods each on four separate days (about four days' time in total), showing an average flow of 1097 $m^3$/day, which is roughly similar to that predicted by the watershed model, 1274 $m^3$/day. Freshwater flow per tidal period ranged between 900 and 1258 $m^3$/day. Water quality samples were collected hourly during ebb and flood tide and half-hourly at the turn of tide and analyzed for total nitrogen concentration. Based on a comparison of measured nitrogen load to that estimated by the watershed model, Howes et al. (2006, pg. 67) concluded that there was no nitrogen attenuation in Frost Fish Creek.

Uncle Harvey's Pond. As part of a diagnostic study for Uncle Harvey's Pond, Eichner et al. (2018) constructed nutrient budgets for nitrogen and phosphorus. Based on the mass of nitrogen in the pond estimated from measured springtime concentrations (47 kg) and the computed hydraulic residence time of the pond (0.86 year), Eichner et al. computed an average nitrogen loading of 54 kg/year after attenuation. This was compared to an unattenuated loading of 130 kg/year (Eichner et al., 2018, pg. 60), a value updated from the rainbow table in Howes et al. (2006) based on new information on land use. The difference in load equates to nitrogen attenuation of 58%. The average nitrogen loading was calculated from the springtime nitrogen mass, which varied between 32 and 65 kg over the years 2002 to 2017, with an average of 47 kg. This variation implies an extreme maximum range in nitrogen attenuation between 50 and 75% over the 16 years of available data. Eichner et al. (2018, Figure IV-10) show values for the springtime nitrogen concentration for 11 of those years. A statistical analysis of those data place the 95% confidence interval for attenuation between 56% and 62%. The average attenuation of 76 kg/year is equivalent to an area-specific attenuation rate of 3.0 g-N/m$^2$/year over the 6.4-acre pond.

Muddy Creek. As discussed above, Muddy Creek has been addressed by a series of reports. White et al. (2008) evaluated the character of the wetlands in the two portions of the creek: Upper Muddy Creek which had low salinity and Lower Muddy Creek which was considerably saltier. At the time, the two portions of the creek were separated by a culvert that restricted tidal flows between Upper and Lower Muddy Creek. White et al. (2008, pg. 12) conducted one-day field studies in June and July 2008 to measure the flow of water, salt, and nutrients through a complete tidal cycle. From the June and July measurements, they found attenuation factors of 55% and 57% for Upper Muddy Creek and factors of 41% and 1% for the combined effects of Upper and Lower Muddy Creek. They attributed the large difference in the combined attenuation to the fact the creek holds a large volume of water compared to the tidal exchange. Thus, monitoring tidal flow during a single tidal cycle could be unrepresentative of the system's average behavior.

Summary. Table 4 summarizes the attenuation coefficients determined for the specific water bodies discussed above with loads presented in consistent units (the unspecified incoming load for Stillwater Pond was back-calculated). The loads into the water bodies are those used in the original analyses of the field data and are similar but not identical to the 2006 loads in the Table 1. With the exception of Stillwater Pond, attenuation in the lakes and ponds varies between 47 and 58%, lending credence to the generic 50% attenuation rate used by Howes et al. (2006). Nonetheless, the low observed attenuation in Stillwater Pond and potential ranges in attenuation discussed above point out that attenuation in any particular pond may vary substantially from year to year and differ from 50%.

Wetlands show greater variability than lakes in Table 4, but some were more difficult to monitor because of reversing tidal flow. Pah Wah Pond Bog, Upper Muddy Creek, and Tar Kiln Marsh posed the least monitoring issues and showed generally higher attenuation than the lakes. Lower Muddy Creek showed less attenuation and it was highly variable. Frost Fish Creek showed negligible attenuation, but is not a wetland per se. Rather, it is a tidal basin with a fringing salt marsh according to Howes et al. (2006, pg. 66). As such, it would not be considered within the watershed portion of the linked watershed-embayment model.

## Table 4
## Attenuation Factors for Specific Water Bodies.

| Name of Water Body | Type of Water Body | Estimated Load In (kg/year) | Measured Load Out (kg/year) | Load Removed by Attenuation (kg/year) | Attenuation Factor (%) | Pond Area (MassGIS, 2019) ($m^2$) | Pond Area (acres) | Area-Specific Attenuation Rate (g-N/$m^2$/year) | Predicted Area-Specific Attenuation Rate[1] (g-N/$m^2$/year) |
|---|---|---|---|---|---|---|---|---|---|
| Pilgrim Lake | Lake/pond | 562 | 285 | 277 | 49% | 154,300 | 38 | 1.8 | 3.8 |
| Pah Wah Pond Bog | Freshwater wetland | 710 | 229 | 481 | 68% | 61,090 | 15 | 7.9 | 7.9 |
| Tar Kiln Marsh | Salt marsh | 2258 | 764 | 1494 | 66% | 32,900 | 8.1 | 45 | |
| Lovers Lake | Lake/pond | 559 | 296 | 263 | 47% | 151,400 | 37 | 1.7 | 3.8 |
| Stillwater Pond | Lake/pond | 828 | 770 | 58 | 7% | 74,060 | 18 | 0.8 | 6.3 |
| Frost Fish Creek | Salt Marsh | 1060 | 1286 | -226 | 0% | 40,471 | 10 | 0.0 | |
| Uncle Harvey's Pond | Lake/pond | 130 | 54 | 76 | 58% | 25,750 | 6.4 | 3.0 | 4.2 |
| Upper Muddy Creek (June) | Freshwater wetland | 3869 | 1752 | 2117 | 55% | 52,100 | 12.9 | 40.6 | 47.9 |
| Upper Muddy Creek (July) | Freshwater wetland | 3869 | 1679 | 2190 | 57% | 52,100 | 12.9 | 42.0 | 47.9 |
| Upper and Lower Muddy Creek (June) | Freshwater and salt marsh | 7045 | 6935 | 110 | 2% | 124,650 | 30.8 | 0.9 | |
| Upper and Lower Muddy Creek (July) | Freshwater and salt marsh | 7045 | 4125 | 2920 | 41% | 124,650 | 30.8 | 23.4 | |

1. Predicted based on equations by Saunders and Kalff, 2001

## Evaluation of Waterbody Attenuation Factors

Lakes. Virtually all of the attenuation in the Pleasant Bay linked watershed-embayment model occurs in lakes which, with the exception of Stillwater Pond, Howes et al. (2006) assume remove 50% of the incoming nitrogen load. The technical literature indicates that attenuation in lakes is a function of the lakes' characteristics including the nitrogen loading rate (Saunders and Kalff, 2001) and hydraulic residence time (Steingruber, 2020). I applied the empirical equations developed by these authors to the water bodies in the Pleasant Bay watershed, with the results shown in Table 5. (More detail is included in Tables A1 and A2 appended to this report.) Table 5 includes Frost Fish Creek Pond, a pond tributary to Frost Fish Creek that is identified by Walters and Masterson (2011) but not included in the MEP model.

The area-specific loading rates in the Pleasant Bay tributary lakes and ponds are, with a few exceptions, 20 g/m$^2$/year or less, which is on the lower end of the range evaluated by Saunders and Kalff (2001), 0 to 160 g/m$^2$/year. As shown in Table 5, the average attenuation coefficient predicted using the Saunders and Kalff equation for the lakes and ponds (but excluding wetlands) is 80%, substantially higher than that used by Howes et al. (2006). This suggests that the approach used for the linked watershed-embayment model is conservative and employs lower attenuation rates than may actually apply. That said, the Saunders and Kalff equation predicts complete attenuation of nitrogen in lakes with very light incoming load per unit area (less than 4 g-N/m$^2$/year), which includes many of the lakes in Table 5. It might be a useful exercise to test this result in one of the actual lakes. Pore-water sampling on the downgradient side of a lake using push-point samplers as used in Ashumet Pond by Stoliker et al. (2016) could be a relatively inexpensive means to evaluate nitrogen concentrations in the groundwater exiting the lake.

Applying the Steingruber equation to the lakes and ponds tributary to Pleasant Bay predicts attenuation factors in a range between 37 and 84% with an average attenuation of 65% (Table 5). As with the Saunders and Kalff (2001) predictions, this average attenuation is higher than the 50% figure used by Howes at al. (2006) but not as high as that based on Saunders and Kalff (2001). Unlike the results from the Saunders and Kalff equations, which are approximately 50% or higher for all ponds and lakes, the Steingruber equation predicts one lake with attenuation less than 50%, Pilgrim Lake at 37%. Also unlike Saunders and Kalff, no lakes are predicted to attenuate 100% of the load with the Steingruber equation.

## Table 5
## Computed Attenuation Factors for Pleasant Bay Lakes and Wetlands based on Empirical Equations.

| Water Body Name | Type of Water Body | Downgradient Receptors | Attenuation Factor in 2020 Linked Model (%) | Predicted Attenuation Factor (Saunders & Kalff, 2001) (%) | Predicted Attenuation Factor (Steingruber, 2020) (%) |
|---|---|---|---|---|---|
| Baker Pond (BP) | Lake/pond | Crystal Lake, Pilgrim Lake, River System, *Nauset Harbor* | 50% | 100% | 64% |
| Bassing Pond (BSP) | Lake/pond | PB Main, Ryder Cove | 50% | 75% | 69% |
| Cliff Pond (CP) | Lake/pond | Little Cliff Pond, River System, *Namskaket Marsh* | 50% | 100% | 71% |
| Crystal Lake (CL) | Lake/pond | Kescayo Gansett Pond, Upper River, Lower River | 50% | 87% | 69% |
| Deep Pond (DP) | Lake/pond | PB Main | 50% | 56% | 51% |
| Emery Pond (EP) | Lake/pond | Ryder Cove, *Stage Harbor* | 50% | 100% | 84% |
| Frost Fish Creek | Salt Marsh | Ryder Cove | 0% | 65% | |
| Frost Fish Creek Pond | Lake/pond | Ryder Cove, Frost Fresh Creek | 0% | 86% | 69% |
| Goose Pond (GOP) | Lake/pond | Muddy Creek, *Sulfur Springs, Bucks Creek* | 50% | 100% | 73% |
| Grassy Pond (GP) | Lake/pond | PB Main, Round Cove | 50% | 100% | |
| Hawksnest Pond (HWP) | Lake/pond | Muddy Creek, *Taylors Pond, Mill Creek, Cockle Cove, Bucks Creek* | 50% | 100% | 82% |
| Higgins Pond (HP) | Lake/pond | Baker Pond, Cliff Pond Well, Arey's Pond | 50% | 83% | 63% |
| Little Cliff Pond (LCP) | Lake/pond | Cliff Pond Well, Baker Pond, Higgins Pond, Cliff Pond, *Namskaket Marsh* | 50% | 80% | |
| Lovers Lake (LL) | Lake/pond | Ryder Cove, Stillwater Pond | 50% | 100% | 73% |
| Mill Pond Fresh (MPF) | Lake/pond | Muddy Creek, *Taylors Pond, Mill Creek, Cockle Cove, Bucks Creek* | 50% | 100% | 57% |
| Mud Pond (MP) | Lake/pond | PB Main, Round Cove | 50% | 100% | |
| Muddy Creek, Upper | Salt Marsh | Muddy Creek | 10% | 64% | |
| Muddy Creek, Lower | Salt Marsh | Muddy Creek | 0% | 64% | |
| Pah Wah Pond Bog | Freshwater wetland | Pah Wah Pond | 0% | 68% | |
| Pilgrim Lake (PL) | Lake/pond | Kescayo Gansett Stream and River, Namequoit River, Lower River | 50% | 68% | 37% |
| Pochet Neck | Salt Marsh | Pochet Neck | 0% | 70% | |
| Rafe Pond (RFP) | Lake/pond | PB Main, Quanset Pond | 50% | 100% | 67% |
| Ruth Pond (RP) | Lake/pond | Cliff Pond | 50% | 82% | 61% |
| Quanset Pond Bog (QPB) | Freshwater wetland | PB Main, Quanset Pond | 0% | 66% | |
| Sarahs Pond (SP) | Lake/pond | The Horseshoe | 50% | 49% | 58% |
| Schoolhouse Pond (SCP) | Lake/pond | Ryder Cove, Crow's Pond, Stillwater Pond | 50% | 100% | 79% |
| Shoal Pond (SHP) | Lake/pond | PB Main, Quanset Pond | 50% | 53% | 59% |
| Stillwater Pond (SWP) | Lake/pond | Ryder Cove | 5% | 52% | 69% |
| Tar Kiln Marsh | Salt Marsh | Tar Kiln Stream | 60% | 65% | |
| Trout Pond (TTP) | Lake/pond | Muddy Creek | 50% | 60% | |
| Twinings Pond (TP) | Lake/pond | Quanset Pond | 50% | 55% | 57% |
| Uncle Harvey Pond | Lake/pond | Pochet Neck | 50% | 85% | 75% |
| Uncle Seths Pond (USP) | Lake/pond | PB Main | 50% | 51% | 57% |
| | | Average for lakes and ponds | 50% | 81% | 66% |
| | | Average for wetlands | 10% | 66% | |

While the predictions using the Saunders and Kalff (2001) and Steingruber (2020) regression equations provide a useful touchstone, it is important to recognize they are based on curve-fitting to a relatively small number of data points and are highly approximate. Despite this qualification, the results in Table 5 confirm that the 50% attenuation rate used by Howes et al. (2006) is reasonable but conservative.

One aspect of lake attenuation that I was asked to examine is the potential for groundwater underflow—i.e., flow groundwater beneath lakes such that the groundwater does not discharge into the lake. This is a demonstrated phenomenon elsewhere on Cape Cod; for example, a contaminant plume from the Massachusetts Military Reservation was discovered to pass beneath Ashumet Pond and instead discharge to downgradient Johns Pond (Savoie et al., 2000). In the context of the linked watershed-embayment model, the concern was that groundwater underflow could lead to an incorrect accounting of the nutrient load entering and being attenuated within ponds or lakes. My review of reports on the groundwater modeling that supported the MEP study (Walter et al, 2004; Carlson et al., 2017; Walter and Masterson, 2011) indicates there is little likelihood of unaccounted underflow. The USGS groundwater model is a three-dimensional model that is able to discern water intercepted by lakes and ponds from that which flows below. Although subwatersheds are mapped in two dimensions (as, for example, in Figure 2) the horizontal extent of the watersheds was determined in the model by back-tracking groundwater from the ponds and lakes and thus reflects the three-dimensional aspects of their capture zones. This is reflected by the limited extent of watersheds draining to lakes and ponds. For example, the subwatershed for Ruth Pond ends a relatively short distance upgradient.

In the final analysis, the use of a 50% attenuation coefficient for lakes and ponds appears to be reasonable, likely conservative, but also uncertain. Table 1 shows that attenuation within the watershed model, which is predominantly from lakes and ponds, accounts for less than 5% of the total watershed load. Thus, total nitrogen attenuation in lakes and ponds is well within the margin of error of the loading estimates made by the watershed model.

Freshwater Wetlands. Howes et al. (2006) include only a few wetlands in the attenuation calculations in the MEP watershed model (Table 1). This is consistent with Figure 3, which shows that freshwater wetlands are less prevalent in the watershed than lakes and ponds. The extents of water bodies in Figure 3, including the shoreline of Pleasant Bay, are based on current data from MassGIS (2019).

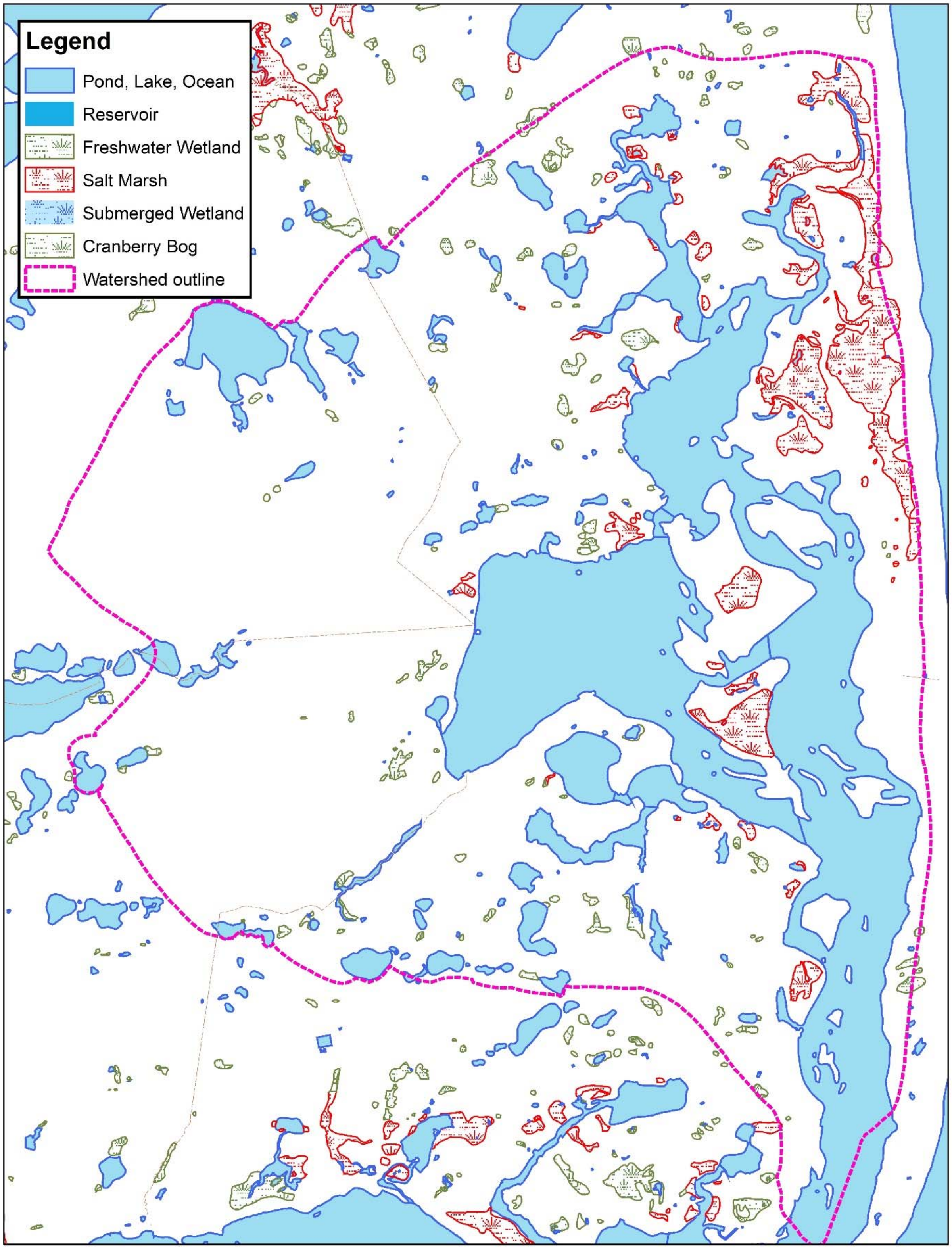

Figure 3

Wetlands within the Pleasant Bay watershed (MassGIS, 2019).

Some mapped wetlands were not considered in the watershed model including those to the east of Quanset Bog, north and south of Round Cove, and south of Ryder Cove. These wetlands may provide limited additional attenuation. However, they were not included in the USGS groundwater model (Carlson et al., 2017) and adding them to the watershed loading model would require considerable additional effort. By their nature, wetlands are shallow features on the landscape and thus can be expected to intercept less groundwater than deeper lakes and ponds. Thus, their exclusion is unlikely to be significant.

Salt Marshes. As discussed above, tidal water bodies are included in the embayment portion but not the watershed portion of the linked watershed-embayment model. As such, attenuation is not considered for salt marshes and tidal water bodies as it is for lakes and ponds. Although not attenuation per se, the embayment model does include a benthic load term to account for the nitrogen load either added or removed by interaction between the water column and the bay mud. The benthic load is negative—and would attenuate nitrogen—in Pochet Neck, Lower Muddy Creek, Chatham Harbor Channel, Frost Fish Creek, Bassing Harbor, and Chatham Harbor in the original MEP model (Howes et al., 2006, Table VI-2). Elsewhere the benthic load is positive and creates additional nitrogen loading to Pleasant Bay. Benthic loads were revised in the recent update based on new field sampling and laboratory measurements (Howes et al., 2021). The field data reported in Table II-7 of Howes et al. (2021) shows Arey's Pond, Round Cove, Upper Muddy Creek, and portions of Pleasant Bay with negative benthic loads. The reversal of a number of benthic loads illustrates the uncertainty of the benthic load estimates. Seemingly contrary to the field data, none of the benthic loads listed in Table IV-2 as inputs to the embayment model show negative values. Some of this may be because Table IV-2 aggregates water bodies, resulting in net positive rates, but this would still not explain the discrepancy between the tables for Round Cove.

While the benthic load does account for nitrogen uptake by bay sediments, the biochemical process differs from that captured in the watershed model. The benthic loads in the embayment model envision an exchange between the sediments and bay water driven by diffusion and chemical gradients, but not involving active flow of groundwater. This is implicit in the methods used to quantify the benthic load: laboratory tests that measure the exchange between collected sediment and overlying stirred water (Howes et al., 2006, pg. 76). Attenuation in ponds, lakes, and freshwater wetlands results from a different dynamic: the flow of groundwater through anoxic lake-bottom sediments in which denitrification removes nitrogen. (Sedimentation is also an attenuation process in lakes). The key difference here is between a model with the active flow of groundwater (attenuation in lakes, pond, and freshwater wetlands) and without the active flow of groundwater (benthic exchange in tidal waters).

The different dynamics envisioned between freshwater and saltwater bodies are generally consistent with the known characteristics of submarine groundwater discharge. While groundwater discharges to the bay just as it discharges to lakes and ponds, most of the flow is to a narrow strip of water along the shoreline (Knee and Payton, 2011). In one example from Cape Cod, Michael et al. (2003, 2005) monitored groundwater discharge into Waquoit Bay within tens of meters from the shoreline. Assuming a relatively narrow discharge zone into the bay, attenuation of groundwater nitrogen would be most likely in shoreline fringing salt marshes and less likely in the more offshore basin. Figure 3 shows that salt marshes are limited on the western shore of Pleasant Bay but more prevalent along the eastern side of the bay. Areas where groundwater is likely to pass through salt marshes, particularly Pochet Neck, should be considered as potential sites for attenuation similar to that in freshwater bodies. A calculation of attenuation for Pochet Neck is further discussed below.

Attenuation in salt marshes should be considered only in those circumstances where groundwater discharge is likely to be dominant over benthic exchange—i.e., in salt marshes within the designated watersheds or that fringe the bay. In other words, in water bodies that lie on the land side of the solid-blue shoreline in Figure 3. As an example, as a shallow inland wetland Muddy Creek likely experiences groundwater discharge over most if not all of its area. My recommendation for Muddy Creek is that only the attenuation associated with groundwater discharge should be considered (i.e., in the watershed model) and not attenuation associated with benthic exchange (in the embayment model). The inclusion of attenuation for Muddy Creek by Eicher et al. (2010b) and Howes et al. (2021, Table II-7) in addition to the negative benthic exchange already considered for that waterbody seems like double-counting.

## Uncertainty in Attenuation

As is implied by the preceding discussion, there is considerable uncertainty in the prediction of attenuation coefficients for any particular waterbody. Unfortunately, it is difficult to quantify that uncertainty with the few data available. Saunders and Kalff (2001) give the standard estimate of error (SEE) for each of their equations (also called the standard error of regression). This corresponds to the standard deviation of the prediction error and can be used to set plus-or-minus bounds on the predicted attenuations. Plus or minus the SEE corresponds to the 68% confidence limits; plus or minus twice the SEE corresponds to the 95% confidence limits. Saunders and Kalff (2001) give the SEE for lakes as 8.3 g-N/m$^2$/year and for wetlands as 13.8 g-N/m$^2$/year.

Applying the SEE to Muddy Creek gives a 68% confidence interval of 50 to 79% for Upper Muddy Creek (vs. attenuation of 64% predicted by the Saunders and Kalff (2001) model) and 53 to 76% for Lower Muddy Creek (vs. predicted 64%). For Tar Kiln Marsh, the range is 35 to 95% (vs. predicted 65%). But for most other water bodies, the 68% confidence interval (i.e., plus or minus the SEE) is 0 to 100% or nearly so (Table A1). This extreme range illustrates the considerable uncertainty in the predictions, but is of little practical utility in setting attenuation factors. The range largely stems from the fact that the Pleasant Bay lakes and ponds are lightly loaded compared to those considered by Saunders and Kalff (2001), and thus lie in a portion of their dataset with great sensitivity.

In contrast to the situation with the Saunders and Kalff (2001) equation, the Pleasant Bay lakes and ponds lie more within the midrange of the data used by Steingruber (2020) to develop her equation. While she does not provide goodness-of-prediction information, the range of the predictions made with her equation for the Pleasant Bay lakes and ponds—37% to 84% attenuation—can be taken generally indicative of the potential uncertainty in the attenuation in lakes and ponds.

## Conclusions and Recommendations

This review has found the treatment of attenuation in the linked watershed-embayment model developed by the Massachusetts Estuaries Project to be generally sound. Attenuation coefficients for lakes and ponds are reasonable, probably conservative, but also uncertain. As such, they should be used with caution in planning future measures to control nitrogen discharges. As stated by Bierman et al. (2011), "A healthy recognition that there is uncertainty would encourage planning bodies to pursue an adaptive monitoring and management strategy as they move forward to understand and remedy the impacts of nitrogen on bays and estuaries. Such an adaptive strategy is wise in light of the uncertainties in predicting the response of bays and estuaries to future load reductions." Plans to manage nitrogen within the watershed should thus include a margin of safety in their considerations. Values provided above place that margin as very roughly plus and minus 50% of the attenuation factor. For example, for the 50% attenuation factor used for lakes, a range of 25% to 75% could be considered.

The scope of work for this review asked for specific attention to Tar Kiln Marsh, Muddy Creek, and Pochet Neck, which are addressed in the following:

- Tar Kiln Stream, to which Tar Kiln Marsh is tributary, has one of the higher watershed loads shown in Tables 1 and 2. I found the revised attenuation factor assigned by Howes et al. (2021) to Tar Kiln Marsh, 60%, to be consistent with literature sources and founded on actual field studies. I see no reason to alter that attenuation factor but every reason to consider it to be uncertain just as the attenuation assigned to lakes and ponds is uncertain.

- Attenuation in Muddy Creek is a puzzle. On the one hand, it is considered a salt marsh and part of the embayment model and thus should have no attenuation assigned (although its benthic flux load could be negative and thus attenuating). On the other hand, Eichner et al. (2010b) assigned Upper Muddy Creek an attenuation factor but, as I understand it, only to capture attenuation in freshwater wetlands upstream of the salt marsh. However, the physical setting of Muddy Creek implies that it receives groundwater inflow throughout. As such, attenuation, rather than benthic exchange, is likely the dominant process in Muddy Creek. If this is so, then it would be appropriate to assign an attenuation factor to Muddy Creek much as attenuation factors have been assigned to freshwater bodies throughout the watershed. As seen in Tables 1 and 2, Muddy Creek receives a large nitrogen load and thus attenuation within Muddy Creek could have significant implications for meeting nitrogen goals. Unfortunately, the attenuation in Muddy Creek is unknown—past field studies have given inconsistent results and the road crossing between Upper and Lower Muddy Creek has been substantially altered since those field studies were conducted. As shown in Table 5, the current attenuation factors (10% and 0% for Upper and Lower Muddy Creek) are much less than those predicted by the Saunders and Kalff (2001) equation (64%). For all of these reasons, I recommend that consideration be given to new field studies to better quantify attenuation in Muddy Creek. A new field study to evaluate attenuation in Muddy Creek could be a cost-effective investment given the potential substantial costs to otherwise reduce loads to Muddy Creek.

- Since it is part of the embayment model, Pochet Neck is not assigned an attenuation factor in the MEP model. However, unlike most of the subwatersheds, Pochet Neck includes a significant area of salt marsh (roughly 125 acres) within its mapped watershed to the landside of the shoreline in Figure 3. As shown in Table 5, the loading equation from Saunders and Kalff (2001) indicates this area would attenuate roughly 70% of the incoming nitrogen load. Since the salt marshes are separate from the embayment, including this attenuation would not constitute double-counting with benthic flux. I therefore recommend that an attenuation factor be added to the watershed model for the Pochet Neck subwatersheds. In keeping with the conservatism elsewhere in the model, an attenuation factor of 50% seems reasonable.

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Table A1. Computed Attenuation Factors for Pleasant Bay Lakes based on Saunders and Kalff (2001).

| **Freshwater Body Name** | **Pond Area** (MassGIS, 2019) ($m^2$) | **Total Load into Pond (2021 values)** (kg/year) | **Area-Specific Loading Rate** (g-N/$m^2$/year) | **Predicted Area-Specific Attenuation Rate** (g-N/$m^2$/year) | **Predicted Attenuation Factor** (Saunders & Kalff, 2001) (%) | **Predicted Attenuation Factor minus SEE** (%) | **Predicted Attenuation Factor plus SEE** (%) | **Attenuation Factor in Linked Model** (%) |
|---|---|---|---|---|---|---|---|---|
| Baker Pond (BP) | 108,937 | 296 | 2.7 | 3.5 | 100% | 0% | 100% | 50% |
| Bassing Pond (BSP) | 28,476 | 174 | 6.1 | 4.6 | 75% | 0% | 100% | 50% |
| Cliff Pond (CP) | 775,470 | 597 | 0.8 | 2.8 | 100% | 0% | 100% | 50% |
| Crystal Lake (CL) | 133,990 | 644 | 4.8 | 4.2 | 87% | 0% | 100% | 50% |
| Deep Pond (DP) | 16,194 | 184 | 11.4 | 6.4 | 56% | 0% | 100% | 50% |
| Emery Pond (EP) | 49,090 | 96 | 2.0 | 3.2 | 100% | 0% | 100% | 50% |
| Frost Fish Creek | 40,471 | 1353 | 33.4 | 21.8 | 65% | 24% | 100% | 0% |
| Frost Fish Creek Pond | 59,597 | 291 | 4.9 | 4.2 | 86% | 0% | 100% | 0% |
| Goose Pond (GOP) | 143,295 | 219 | 1.5 | 3.0 | 100% | 0% | 100% | 50% |
| Grassy Pond (GP) | 46,499 | 154 | 3.3 | 3.7 | 100% | 0% | 100% | 50% |
| Hawksnest Pond (HWP) | 103,725 | 46 | 0.4 | 2.7 | 100% | 0% | 100% | 50% |
| Higgins Pond (HP) | 99,819 | 511 | 5.1 | 4.3 | 83% | 0% | 100% | 50% |
| Little Cliff Pond (LCP) | 116,870 | 639 | 5.5 | 4.4 | 80% | 0% | 100% | 50% |
| Lovers Lake (LL) | 151,400 | 501 | 3.3 | 3.7 | 100% | 0% | 100% | 50% |
| Mill Pond Fresh (MPF) | 81,317 | 290 | 3.6 | 3.7 | 100% | 0% | 100% | 50% |
| Mud Pond (MP) | 38,216 | 63 | 1.6 | 3.1 | 100% | 0% | 100% | 50% |
| Muddy Creek, Upper | 52,096 | 5062 | 97.2 | 62.6 | 64% | 50% | 79% | 10% |
| Muddy Creek, Lower | 72,548 | 8577 | 118.2 | 76.1 | 64% | 53% | 76% | 0% |
| Pah Wah Pond Bog | 61,090 | 709 | 11.6 | 7.8 | 68% | 0% | 100% | 0% |
| Pilgrim Lake (PL) | 154,300 | 1132 | 7.3 | 5.0 | 68% | 0% | 100% | 50% |
| Pochet Neck | 508,606 | 3790 | 7.5 | 5.2 | 70% | 0% | 100% | 0% |
| Rafe Pond (RFP) | 30,809 | 84 | 2.7 | 3.5 | 100% | 0% | 100% | 50% |
| Ruth Pond (RP) | 26,755 | 142 | 5.3 | 4.3 | 82% | 0% | 100% | 50% |
| Quanset Pond Bog (QPB) | 9,371 | 214 | 22.8 | 15.0 | 66% | 5% | 100% | 0% |
| Sarahs Pond (SP) | 20,060 | 342 | 17.1 | 8.3 | 49% | 0% | 98% | 50% |
| Schoolhouse Pond (SCP) | 81,196 | 199 | 2.4 | 3.4 | 100% | 0% | 100% | 50% |
| Shoal Pond (SHP) | 33,118 | 451 | 13.6 | 7.2 | 53% | 0% | 100% | 50% |
| Stillwater Pond (SWP) | 74,060 | 1053 | 14.2 | 7.4 | 52% | 0% | 100% | 5% |
| Tar Kiln Marsh | 32,900 | 1525 | 46.4 | 30.1 | 65% | 35% | 95% | 60% |
| Trout Pond (TTP) | 38,473 | 372 | 9.7 | 5.8 | 60% | 0% | 100% | 50% |
| Twinings Pond (TP) | 33,240 | 403 | 12.1 | 6.6 | 55% | 0% | 100% | 50% |
| Uncle Harvey Pond | 25,750 | 128 | 5.0 | 4.2 | 85% | 0% | 100% | 50% |
| Uncle Seths Pond (USP) | 18,285 | 274 | 15.0 | 7.6 | 51% | 0% | 100% | 50% |

Table A2. Computed Attenuation Factors for Pleasant Bay Lakes based on Steingruber (2020).

| Freshwater Body Name | Pond Area, A (MassGIS, 2019) ($m^2$) | Pond Flow, Q (Walter & Masterson, 2011) ($m^3$/year) | q = Q/A (m/year) | Total Load into Pond (2021 values) (kg/year) | Area-Specific Loading Rate (g-N/$m^2$/year) | Predicted Area-Specific Attenuation Rate (g-N/$m^2$/year) | Predicted Attenuation Factor (Steingruber, 2020) (%) | Attenuation Factor in Linked Model (%) |
|---|---|---|---|---|---|---|---|---|
| Baker Pond (BP) | 108,937 | 529,563 | 4.9 | 495 | 4.5 | 4.1 | 64% | 50% |
| Bassing Pond (BSP) | 28,476 | 95,873 | 3.4 | 174 | 6.1 | 4.6 | 69% | 50% |
| Cliff Pond (CP) | 775,470 | 2,202,224 | 2.8 | 2457 | 3.2 | 3.6 | 71% | 50% |
| Crystal Lake (CL) | 133,990 | 457,423 | 3.4 | 644 | 4.8 | 4.2 | 69% | 50% |
| Deep Pond (DP) | 16,194 | 249,632 | 15.4 | 184 | 11.4 | 6.4 | 51% | 50% |
| Emery Pond (EP) | 49,090 | 46,463 | 0.9 | 154 | 3.1 | 3.6 | 84% | 50% |
| Frost Fish Creek | 40,471 | | | | | | | 0% |
| Frost Fish Creek Pond | 59,597 | 201,695 | 3.4 | 291 | 4.9 | 4.2 | 69% | 0% |
| Goose Pond (GOP) | 143,295 | 340,733 | 2.4 | 432 | 3.0 | 3.6 | 73% | 50% |
| Grassy Pond (GP) | 46,499 | N/A | | | | | | 50% |
| Hawksnest Pond (HWP) | 103,725 | 116,049 | 1.1 | 136 | 1.3 | 3.0 | 82% | 50% |
| Higgins Pond (HP) | 99,819 | 550,814 | 5.5 | 511 | 5.1 | 4.3 | 63% | 50% |
| Little Cliff Pond (LCP) | 116,870 | N/A | | | | | | 50% |
| Lovers Lake (LL) | 151,400 | 343,980 | 2.3 | 501 | 3.3 | 3.7 | 73% | 50% |
| Mill Pond Fresh (MPF) | 81,317 | 728,508 | 9.0 | 1015 | 12.5 | 6.8 | 57% | 50% |
| Mud Pond (MP) | 38,216 | N/A | | | | | | 50% |
| Muddy Creek, Upper | 52,096 | | | | | | | 10% |
| Muddy Creek, Lower | 72,548 | | | | | | | 0% |
| Pah Wah Pond Bog | 61,090 | | | | | | | 0% |
| Pilgrim Lake (PL) | 154,300 | 7,790,295 | 50.5 | 1132 | 7.3 | 5.0 | 37% | 50% |
| Pochet Neck | 508,606 | | | | | | | 0% |
| Rafe Pond (RFP) | 30,809 | 116,370 | 3.8 | 84 | 2.7 | 3.5 | 67% | 50% |
| Ruth Pond (RP) | 26,755 | 180,020 | 6.7 | 142 | 5.3 | 4.3 | 61% | 50% |
| Quanset Pond Bog (QPB) | 9,371 | | | | | | | 0% |
| Sarahs Pond (SP) | 20,060 | 175,614 | 8.8 | 342 | 17.1 | 8.3 | 58% | 50% |
| Schoolhouse Pond (SCP) | 81,196 | 118,004 | 1.5 | 199 | 2.4 | 3.4 | 79% | 50% |
| Shoal Pond (SHP) | 33,118 | 249,632 | 7.5 | 451 | 13.6 | 7.2 | 59% | 50% |
| Stillwater Pond (SWP) | 74,060 | 248,644 | 3.4 | 1053 | 14.2 | 7.4 | 69% | 5% |
| Tar Kiln Marsh | 32,900 | | | | | | | 60% |
| Trout Pond (TTP) | 38,473 | N/A | | | | | | 50% |
| Twinings Pond (TP) | 33,240 | 303,235 | 9.1 | 403 | 12.1 | 6.6 | 57% | 50% |
| Uncle Harvey Pond | 25,750 | 51,499 | 2.0 | 128 | 5.0 | 4.2 | 75% | 50% |
| Uncle Seths Pond (USP) | 18,285 | 169,730 | 9.3 | 274 | 15.0 | 7.6 | 57% | 50% |

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# Technical Memorandum

To: Pleasant Bay Alliance Working Group
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Date: March 23, 2023 (revised final 8/9/23)

RE: Pochet Neck and Muddy Creek Nitrogen Mass Exchange

## I. Introduction and Background

In 2021, the Coastal Systems Program from the School for Marine Science and Technology at UMass-Dartmouth (CSP/SMAST) in partnership with the rest of the Massachusetts Estuaries Project (MEP) Technical Team completed an update of the 2006 Pleasant Bay MEP model[1] through a FY18 Southeast New England Watershed Grants Program (SNEP) grant to the Pleasant Bay Alliance (PBA). This 2020 update of the Pleasant Bay MEP model utilized the same model development procedures previously approved by Massachusetts Department of Environmental Protection (MassDEP) and that serve as the basis for the Pleasant Bay regulatory water quality threshold concentrations and nitrogen loads (*e.g.*, TMDLs[2]). Results from the 2020 update project included revisions to the Tar Kiln and Muddy Creek nitrogen attenuation, as well as Pochet Neck nitrogen concentrations above the recommended levels in the TMDL. [3]

Subsequent discussions among SNEP Pleasant Bay partners suggested that it would be worthwhile to measure the nitrogen exchange in Muddy Creek and Pochet Neck to provide more refined characterization of the conditions in these portions of the Pleasant Bay system and to help gauge any N attenuation that may be lowering N loads to lower Muddy Creek and to upper Pleasant Bay from Pochet. CSP/SMAST project staff completed nitrogen mass exchange measurements over three complete tidal cycles at both locations to evaluate site-specific nitrogen interactions. This Technical Memo summarizes the results of these measurements to help provide necessary guidance for modeling and future management decisions.

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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.

[3] Howes, B., E. Eichner, and S. Kelley. 2021. Ecosystem Monitoring and Modeling for Implementation (Task 3) of Regional Watershed Permit Implementation Project for Nitrogen Management in Pleasant Bay, Cape Cod, MA. For the Pleasant Bay Alliance, Massachusetts. Technical Report by the Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 92 pp.

## II. Muddy Creek Nitrogen Mass Exchange

Muddy Creek is a complex coastal ecosystem that has been altered since the initial MEP characterization. During the MEP, Muddy Creek functioned as a saltwater marsh with lower tidal flushing in its uppermost section (*i.e.*, above the historical dike). As a saltwater marsh, it removed nitrogen and based on the available watershed water use data, MEP staff determined that the upper and lower portions of Muddy Creek attenuated 4% and none (0%) of the watershed nitrogen load inputs.[4] These attenuation rates were based on all of the data inputs to the water quality model, including measured water column water quality data, sediment core incubation measurements of nitrogen additions, and tidal flushing within Muddy Creek.

In 2008, CSP/SMAST completed a more refined assessment of the Muddy Creek ecosystem in order to evaluate whether a new water control structure should be installed at the site of the historical dike separating upper and lower Muddy Creek. This assessment included: 1) measuring elevations and determining plant types to the freshwater/saltwater marsh border throughout the system, 2) collection, characterization, and incubation of 16 sediment cores to measure sediment nitrogen additions to the water column, 3) collection and characterization of benthic animal communities in 6 sediment samples (3 above and 3 below the dike), 4) two tidal flux/nitrogen mass exchange samplings at the dike and the Route 28 outlet, and 5) a projection of potential changes in various portions of the wetland community and water levels in response to restoring the dike and the measured changes due to the 2007 breach and creation of a new Pleasant Bay inlet.[5]

In 2010, MEP staff received a request from the Town of Harwich to review the impact on the MEP modeling of updated watershed water use and land use data, as well as the 2008 refined assessment of Muddy Creek.[6] During the original MEP, the Town only had one year of municipal water use data (2004) and the Town had collected three additional years (*i.e.*, 2004 through 2007 data) and wanted to review the impact of a more complete dataset that was more consistent with the available data provided by the other towns during the MEP assessment. This 2010 update also included other information supplied by the Town: a) changes in the treatment of both existing and buildout conditions at the Wequassett Inn, b) nitrogen load additions from farm animals, c) nitrogen loads from a cranberry bog in Lower Muddy Creek watershed that was previously excluded, d) inclusion of innovative/alternative septic systems in the Upper Muddy Creek subwatersheds, and e) updated land use coverages from 2006. The net result of incorporating these changes/refinements showed higher watershed nitrogen loads, which in turn, required higher nitrogen attenuation rates in Muddy Creek to match measured MEP water quality: 57% attenuation in Upper Muddy Creek and 2% attenuation in Lower Muddy Creek. The Upper Muddy Creek was more consistent with what might be expected in salt marshes. The overall loads in the water quality model and the nitrogen threshold concentrations remained similar to the MEP, but the increased attenuation decreased the watershed load reductions required to meet the threshold concentration in Upper

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

[5] 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.

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

Muddy Creek. Lower Muddy Creek saw no change in watershed nitrogen load reduction to meet the threshold concentration.

In 2016, the Muddy Creek system was substantially altered by the installation of a new Route 28 bridge at the system inlet. Based on tidal measurements and the 2021 hydrodynamic model update, this increased the Muddy Creek tidal prism volume by ~4X and decreased the residence time of water within the Creek system from 3.6 days to 0.8 days.[7] These alterations, combined with the other alterations in the larger Pleasant Bay system, showed that the nitrogen attenuation rates to match measured water quality measurements in Upper and Lower Muddy Creek were 10% and 0%, respectively.[8] This finding means that the Upper Creek system is functioning less like a salt marsh and more like an enclosed basin, although it is not completely like other Pleasant Bay basins like Round Cove or Ryder Cove where fringing wetland nitrogen removal is minimal. At the time of the 2021 MEP update, it was unclear whether the Muddy Creek system was still transitioning to a new equilibrium following the impacts of the new bridge and Pleasant Bay inlet breach.

In order to provide more refined understanding of the Muddy Creek system, CSP/SMAST staff conducted three measurements of nitrogen mass exchange (June 12, July 8, August 8, 2022) at the location of former dike dividing Upper and Lower Muddy Creek, which is also the dividing line between the MEP watershed delineations (**Figure 1**). Measurements included hourly velocity transects at this location using an electromagnetic flow meter (Marsh-McBirney Flo-Mate) and a continuous stage recorder. Muddy Creek had a maximum transect of 57 feet (at high tide) and a minimum transect of 40 ft (at low tide). Velocity readings were measured in 5-foot increments regardless of the transect width. These measurements applied the same methods utilized in 2008.[9]

These flow transects were coupled to water quality sampling over a complete tidal cycle (low tide-high tide-low tide). On each sampling date, samples were collected at mid-depth hourly at three locations along the transect then pooled for a single time sample. Among the three mass exchange dates, 14-16 samples were collected (**Table 1**). Water quality samples were assayed at the Coastal Systems Analytical Laboratory at SMAST/UMASS Dartmouth using the same assay procedures used for Pleasant Bay water quality monitoring program. Samples were assayed for ammonium-N and nitrate/nitrite N, dissolved nitrogen, particulate organic nitrogen, particulate organic carbon, ortho-phosphate, chlorophyll a, salinity, and salinity/specific conductivity.

### *Muddy Creek Tides*

Flood and ebb current velocity measurements were made concurrently with water sampling in Muddy Creek to determine flow characteristics during both flood and ebb tides. These flow data were then interpolated with stage data to yield a detailed record of flow in and out of Upper Muddy Creek. Total flow into the upper creek was calculated between slack low tide and slack high tide. Total flow out was calculated from slack high tide to the point at which the tidal height, as measured by a tide gauge during ebb reached the same level as that recorded at the previous slack low tide. Flow estimates during flood and ebb tides were used to calculate salt and nutrient flux into and out of Muddy Creek transect site during the tidal cycle on each of the three sampling dates. Data from each collected water sample was paired with the corresponding flow rate to

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[7] Howes, B., E. Eichner, and S. Kelley. 2021. Tables III-8 and III-9.

[8] Howes, B., E. Eichner, and S. Kelley. 2021. Table II-3.

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

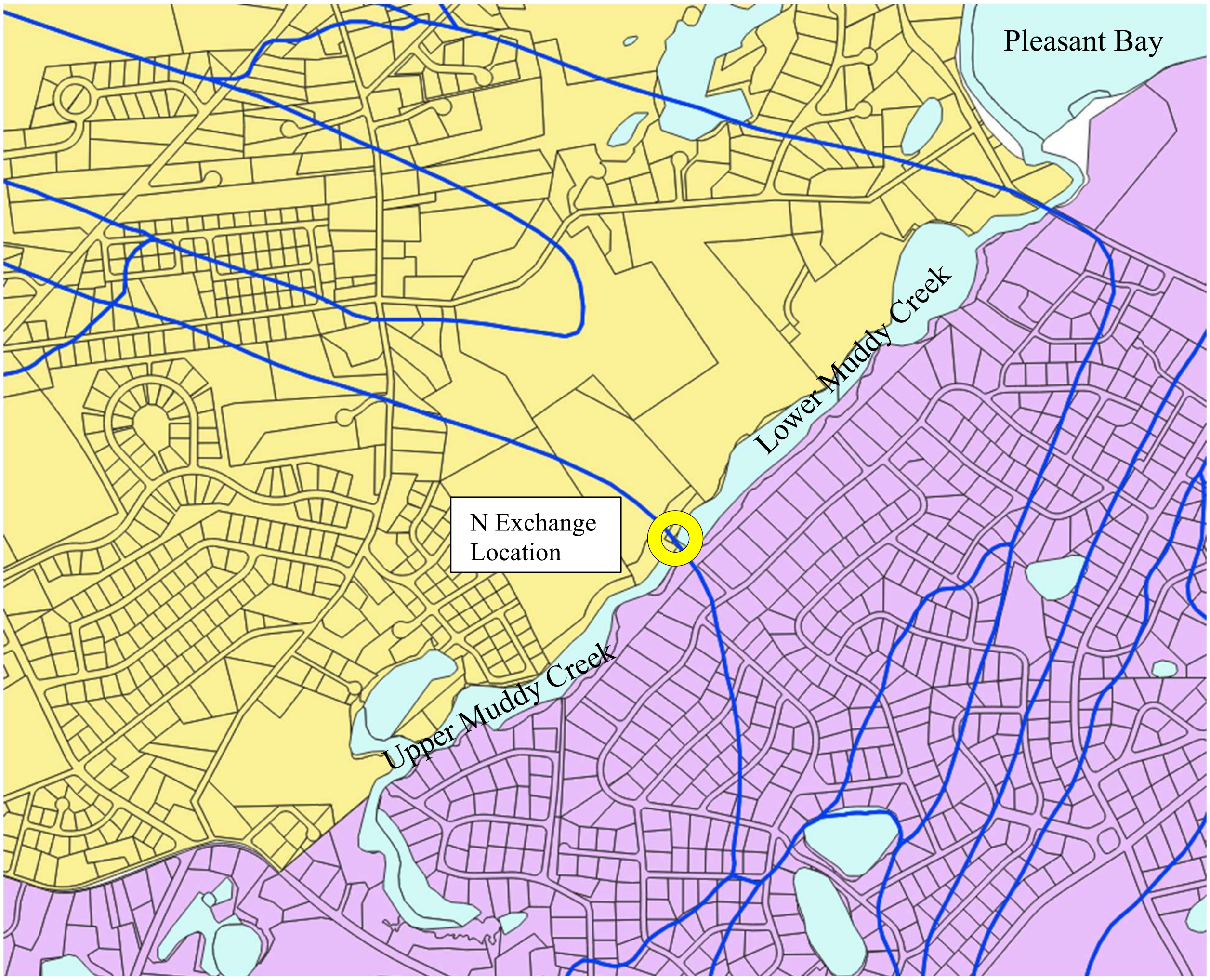

**Figure 1. Muddy Creek Location of Nitrogen Mass Exchange Measurements.** Water quality samples, flow velocities, and stage readings were collected hourly over a complete tidal cycle (low tide-high tide-low tide) during the three events at the former dike dividing Upper and Lower Muddy Creek (yellow circle in figure). Hourly measurements were collected across a transect at this location during three tidal cycles in 2022: June 12, July 8, and August 8. Water quality samples (14-16 per date) were created from pooled samples from 3 positions across the transect. A continuous stage recorder was also deployed during sampling events.

**Table 1. Muddy Creek sampling dates for water quality and laboratory assays performed on samples.** Each water quality sample consisted of water collected and pooled from 3 locations along the transect. Note that TDN is Total Dissolved Nitrogen, POCN is particulate organic carbon and nitrogen, CHLA is total chlorophyll-*a* pigments.

| **Sample Date** | **# samples** | **Assays** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **NH4** | **PO4** | **NO3/NO2** | **TDN** | **POCN** | **CHLA** | **Salinity** | **Velocity** |
| 6-12-22 | 16 | X | X | X | X | X | X | X | X |
| 7-8-22 | 14 | X | X | X | X | X | X | X | X |
| 8-8-22 | 15 | X | X | X | X | X | X | X | X |
| **Total** | **45** | | | | | | | | |

calculate a mass flux for each sampling event. These results were interpolated to yield a total mass flux for the entire tidal cycle. From these flux data, the magnitude and direction of the net flux of salt and nutrients were calculated.

A continuous stage recorder and a staff gauge were deployed during each of the three 2022 sampling events in close vicinity to the transect location for the Muddy Creek tidal studies to measure the differences between the tides on each date. This stage data shows the tide delay between predicted Pleasant Bay tides and Muddy Creek (**Table 2**). There was a morning low tide delay from the Pleasant Bay station to Muddy Creek ranging from 1 hour 56 minutes (June 12) to 2 hours and 35 minutes (August 8). The evening low tide lag ranged from 44 minutes to 1 hour 14 minutes, while the delay in high tide was consistently shorter and ranged from 37 minutes to 55 minutes. The June 12 tides were measured two days before a full moon (spring tide), while July 8 was two days after the first quarter moon (neap tide). The August 8 sampling occurred three days before a full moon spring tide.

**Table 2. Muddy Creek measured tide height compared to predicted low and high tides.** Tides were compared to predicted tides at a Pleasant Bay South station (US Harbors.com) along with the corresponding lag times. Tide ranges on the three dates varied from 0.48 to 2.05 ft.

| Date | Tide | Predicted (time) | Measured (time) | Gauge Depth (ft) | Lag (hr:min) |
|---|---|---|---|---|---|
| 6/12/2022 | Low | 7:14 | 9:10 | 0.54 | 1:56 |
| | High | 12:23 | 13:00 | 2.59 | 0:37 |
| | Low | 19:26 | 20:40 | 0.55 | 1:14 |
| 7/8/2022 | Low | 3:55 | 6:07 | 0.12 | 2:12 |
| | High | 9:02 | 9:57 | 0.60 | 0:55 |
| | Low | 16:13 | 16:57 | 0.08 | 0:44 |
| 8/8/2022 | Low | 5:26 | 8:01 | 0.89 | 2:35 |
| | High | 10:36 | 11:21 | 2.33 | 0:45 |
| | Low | 17:38 | 18:31 | 0.87 | 0:53 |

### *Muddy Creek Water Flux*

Water flux data generally showed that tides in Muddy Creek were flood dominant. Current velocities were applied to the cross-sectional area of the creek to obtain an instantaneous flow rate of water through the culvert. The flooding tide into Muddy Creek on each of the three sampling dates was shorter in duration and typically stronger in flow rate compared to the ebbing tides. The peak flow rate on the flooding tides were: 3,036 liters per second (L/s) on June 12 , 3,984 L/s on July 8, and 3,855 L/s on August 8 (**Figure 2**). Flow rate ebbing from Muddy Creek was longer in duration and typically weaker. The maximum ebbing flow rates were: 2,782 L/s recorded on June 12, 2,144 L/s on July 8 and 1,644 L/s on August 8.

The hourly flow rates were then interpolated with stage information over the course of each of the single tidal cycles to yield an estimate of total water flux for both flood and ebb tides. Total flow into the upper creek during the tidal cycle was calculated between slack low tide and slack high tide. Total flow out of the upper creek was calculated from slack high tide to the point at which the tidal height reached the same level as that recorded at the previous slack low tide, as measured by a tide gauge during ebb. Water flux during flood tide ranged from 24,099 to 35,662 cubic

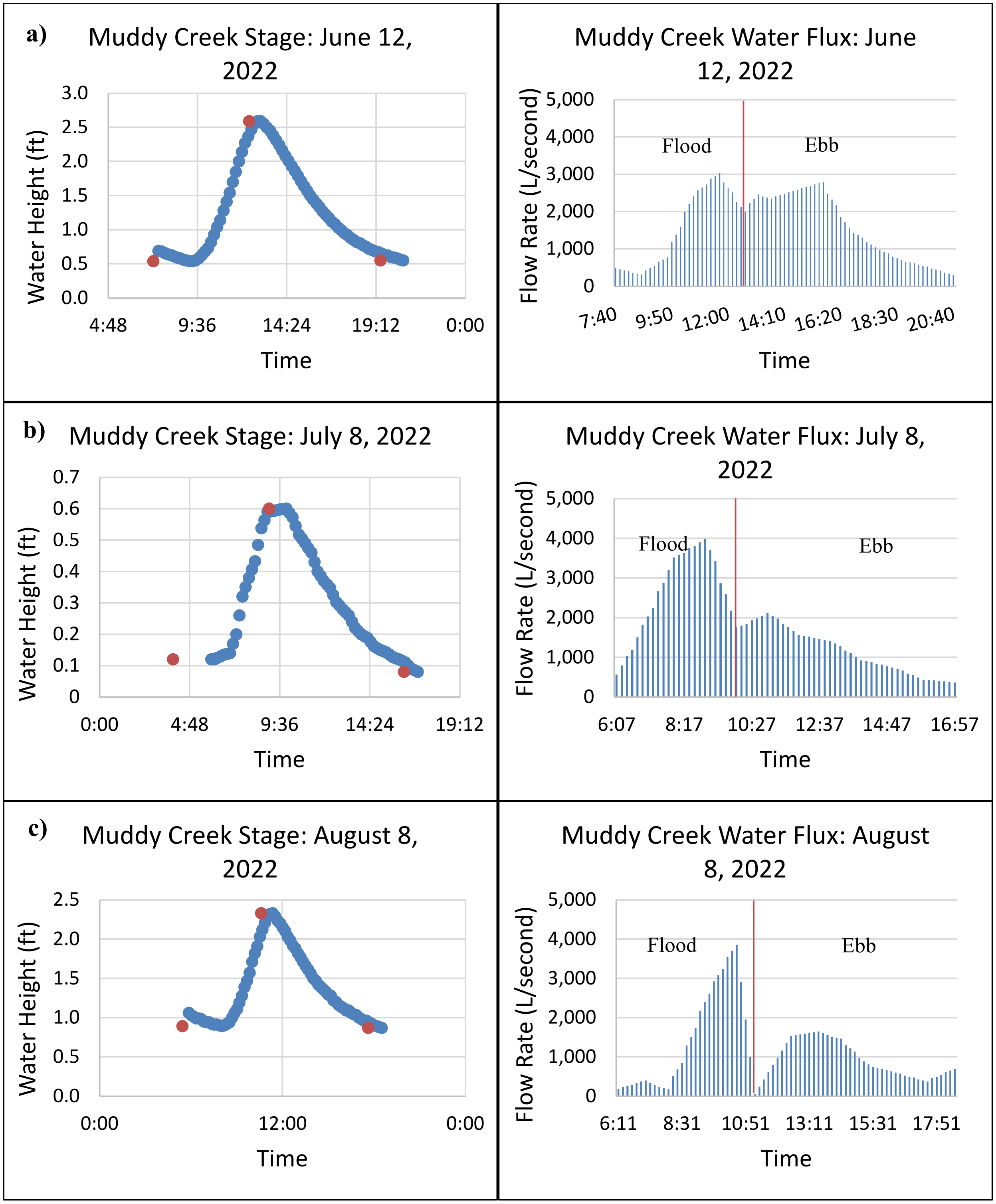

**Figure 2. Muddy Creek measured tide height and water flows over the period of a single tidal cycle on three 2022 sampling events: June 12, July 8, and August 8.** Flow rates show higher floods rates, but longer ebb periods. The predicted low, high, and low tide on each date is shown by the red dots on the stage graphs (USHarbors.com, South Pleasant Bay station).

meters ($m^3$) (August 8 and July 8, respectively) (**Table 3**). Water flux during tidal ebb was of a longer duration than during tidal flooding and resulted in larger fluxes of water, ranging from 25,662 to 41,874 $m^3$ (August 8 and June 12, respectively). As a result of this tidal asymmetry, there was a net flux of water out of the upper marsh on two of the three dates. This finding would be expected given watershed inputs to the marsh, although the variability shows that on individual tides, other factors (*i.e.*, precipitation, winds, evapotranspiration, groundwater fluctuations, etc.) can have a large day-to-day impact. For example, the elevated volume of water exiting Muddy Creek on June 12 could be due to the 1.7 inches of rain that fell from June 8 through June 9 (**Figure 3**). Depending on the characteristics of individual salt marshes, summer conditions can often result in less water leaving than entering due to evapotranspiration, wind, and light availability.[10] It should be noted, however that the water flux entering and leaving Upper Muddy Creek in 2022 was 3X-5X larger than the exchange in 2008.[11]

**Table 3. Muddy Creek cumulative water volume flux for 2022 tidal samplings: June 12, July 10, and August 9.** Water flux in and out varied with flux out greater than flux in on two of the three samplings. Flood durations were less then ebb durations with relatively small differences in duration of the two components. Volume readings show variability of individual tides.

| | **Water Volume** | **Time Range** | **Tide Time** |
|---|---|---|---|
| | **$m^3$** | | **hr:min** |
| **June 12** | | | |
| **Flux In** | 30,624 | 9:00-13:10 | 4:10 |
| **Flux Out** | 41,874 | 13:20-20:40 | 7:20 |
| **Net Flux** | 11,250 | OUT | |
| **July 8** | | | |
| **Flux In** | 35,662 | 6:07-9:47 | 3:40 |
| **Flux Out** | 31,026 | 9:57-16:57 | 7:00 |
| **Net Flux** | -4,636 | IN | |
| **August 8** | | | |
| **Flux In** | 24,099 | 7:51-11:11 | 3:20 |
| **Flux Out** | 25,662 | 11:21-18:31 | 7:10 |
| **Net Flux** | 1,562 | OUT | |

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[10] *e.g.*, Huang, Y., H. Guo, X. Chen, Z. Chen, C. van der Tol, Y. Zhou, and J. Tang. 2019. Meteorological controls on evapotranspiration over a coastal salt marsh ecosystem under tidal influence. *Agricultural and Forest Meteorology*. 279:107755.

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

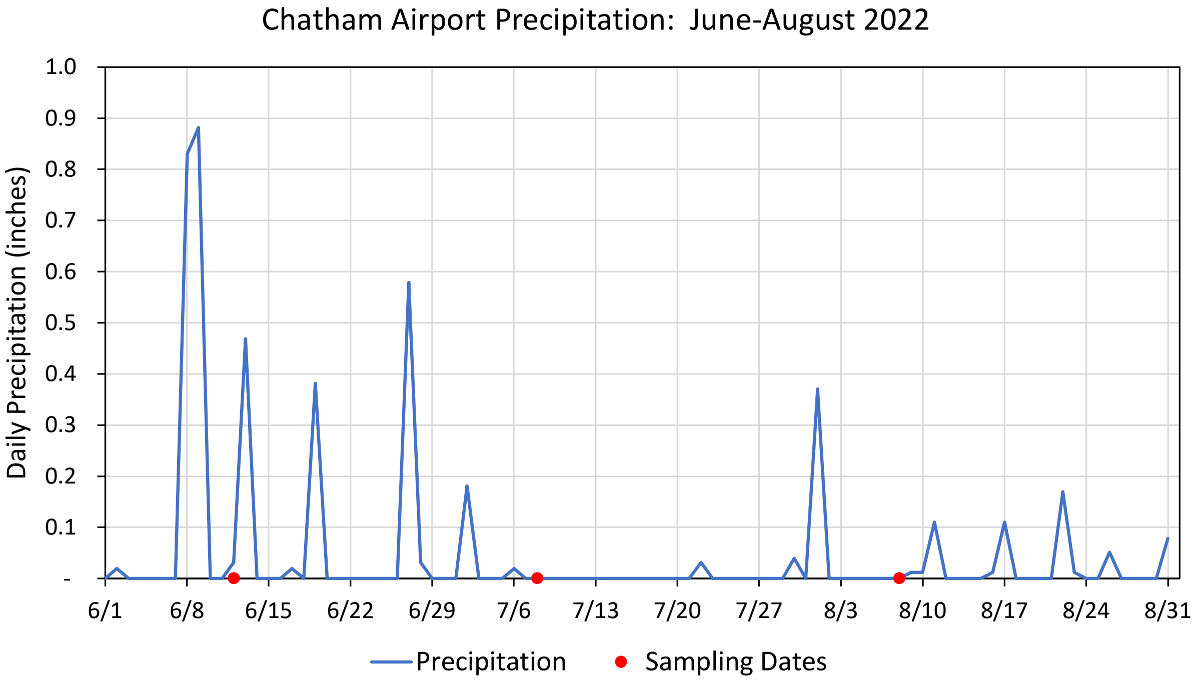

**Figure 3. Daily precipitation amounts and the Muddy Creek sampling events June-August 2022.** Daily rain totals were measured at Chatham Airport (NOAA, downloaded 3/15/22). Muddy Creek sampling events occurred on June 12, July 8, and August 8, 2022.

### *Muddy Creek Nutrient Flux*

Muddy Creek nutrient flux measurements showed that results varied on each of the dates, but all results suggesting that Muddy Creek is now functionally more a part of Pleasant Bay since the 2016 changes in the Route 28 bridge. Salt measurements showed greater export mass than input mass on June 12, greater import mass on July 8, and close to balanced mass on August 8 (**Table 4**). These types of fluctuations usually occur in systems where differing amounts of water remain in the system, which often occurs in salt marsh systems where temperature and tidal variations can impact the wetting and drying of the marshes. This type of fluctuation can also impact nitrogen fluxes.

Nitrogen flux showed some of the same sort of fluctuations with more TN leaving the Creek than entering it on the flood tide during July measurements, but less leaving than entering in June and August. In all flux readings, the TN mass leaving the Creek was approximately 3X to 4X of the watershed input. This finding suggests that the sediments in the Creek are adding TN to the water column, which is consistent with highly variable sediment core readings from the two cores collected in Upper Muddy Creek in 2020.[12] It also means that nitrogen flux in Muddy Creek more closely approximates conditions in the Main Bay, where benthic contributions are greater than watershed inputs. Nitrogen concentrations at mid-ebb were generally consistent with most recent (2015-2019) water quality measurements used in the 2020 update of the MEP model (**Figure 4**). This suggests that the increase in mass over watershed inputs is mostly due to greater volumes of water entering and leaving the Creek.

If salt measurements are balanced to try to account for some of the variation in the water fluxes, the June 12 flux measurements showed a net removal of 970 g of TN during the tidal cycle, of which 460 g were bioactive N (DIN+PON). If this were converted into an annual removal it would be a 708 kg TN removal. This TN removal rate would match the estimated attenuation rate in the 2020 Pleasant Bay Update of watershed nitrogen loading, which had a 704 kg attenuation in Upper Muddy Creek based on a 10% attenuation rate.[13]

If the same sort of salinity balancing is done on the July 8 flux measurements, the attenuation was removed and the net TN flux exported from Muddy Creek was greater than the N than entered the system. These flux measurement showed an increase of 5,606 g of TN exported from Upper Muddy Creek (1,690 g of which were bioactive N). Based on this date, the annual nitrogen export from Upper Muddy Creek to Lower Muddy Creek would be 14,684 kg or 2.8X the watershed input. It is unclear why these measurements are different than the June 12 flux readings, but it was likely due to the differences in water/nitrogen retention in Muddy Creek. The amount of water and salt in and out of the system was lower than June 12, potentially due to change in tidal characteristics: flood tide was 30 minutes shorter, but with a 16% greater volume. July readings also show a notable increase in DON and a decrease in PON and DIN, perhaps indicating a fluctuation in the phytoplankton population, scour impacts within the wetland due to the larger and faster flood tide volume, and/or activation of DIN uptake/conversion processes in sediments or biota. Temperatures had also increased between the two measurements, so perhaps this is also playing a role in the changing conditions (*e.g.*, changes in sediment and water column interactions).

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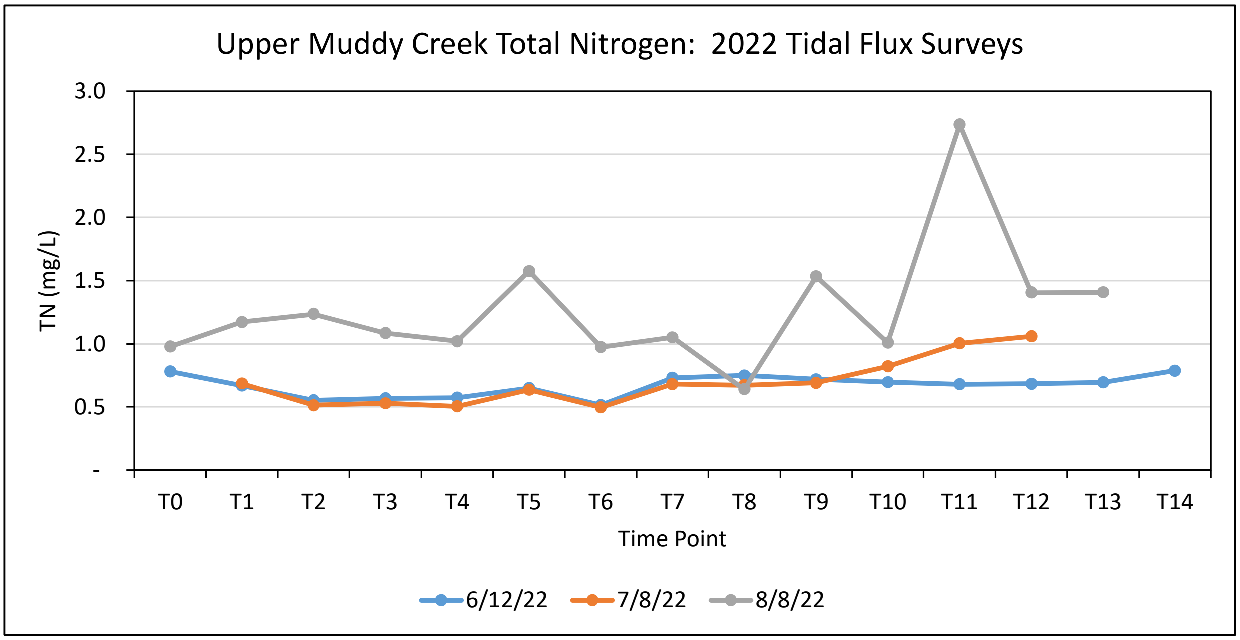
[12] Howes, B., E. Eichner, and S. Kelley. 2021. Table II-7, p. 33.

[13] Howes, B., E. Eichner, and S. Kelley. 2021. Table II-5, p. 19.

**Table 4. Upper Muddy Creek salt, water and nutrient flux during three 2022 sampling events: June 12, July 8, and August 8.** Salt balanced water volume and nutrient mass into (flood tide) and out of (ebb tide) the Creek are shown. The mass of each measured hourly constituent was interpolated for every ten minutes based on hourly samples and tidal stage and then summed from slack low to high tide for In totals and high tide to slack low for the Out totals. Salt is a conservative tracer and the mass in and out on each tide has been balanced. Negative net flux (in parentheses) indicates retention or attenuation within Upper Muddy Creek. The June 12 and August 8 events had total nitrogen attenuation approximating the 10% used in the 2020 update (Howes, *et al.*), while the July 8 event showed a net export of TN out of the Creek. Differences in tidal characteristics include volume exchanged, the rate of exchange (length of flood and ebb cycles are shown in first column), and other factors (*e.g.*, benthic infauna, wetting and drying of wetlands, decreases in watershed inputs, etc.) likely account for variations in many of the measurements.

| **Tide Length (hr:min)** | | **Salt (kg)** | **Water (m3)** | **PO4 (g)** | **NH4 (g)** | **NOx (g)** | **DIN (g)** | **DON (g)** | **TDN (g)** | **PON (g)** | **TON (g)** | **TN (g)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **6/12/22** | | | | | | | | | | | | |
| 4:10 | **In/Flood** | 1,009,134 | 39,356 | 561 | 18 | 1,953 | 1,971 | 9,347 | 11,318 | 11,846 | 21,193 | 23,165 |
| 7:20 | **Out/Ebb** | 1,009,134 | 41,874 | 534 | 39 | 2,303 | 2,342 | 8,837 | 11,179 | 11,015 | 19,852 | 22,195 |
| | **Net Flux** | - | 2,519 | (28) | 21 | 350 | 371 | (510) | (139) | (831) | (1,341) | (970) |
| | **Direction** | balanced | OUT | IN | OUT | OUT | OUT | IN | IN | IN | IN | IN |
| **7/8/22** | | | | | | | | | | | | |
| 3:40 | **In/Flood** | 717,071 | 26,522 | 440 | 194 | 260 | 453 | 8,297 | 8,750 | 5,759 | 14,055 | 14,509 |
| 7:00 | **Out/Ebb** | 717,071 | 31,026 | 406 | 192 | 211 | 404 | 12,213 | 12,617 | 7,498 | 19,711 | 20,115 |
| | **Net Flux** | - | 4,504 | (34) | (1) | (48) | (49) | 3,916 | 3,867 | 1,739 | 5,656 | 5,606 |
| | **Direction** | balanced | OUT | IN | IN | IN | IN | OUT | OUT | OUT | OUT | OUT |
| 8/8/22 | | | | | | | | | | | | |
| 3:20 | **In/Flood** | 621,599 | 24,201 | 1,083 | 157 | 424 | 581 | 24,548 | 25,130 | 6,657 | 31,205 | 31,787 |
| 7:10 | **Out/Ebb** | 621,599 | 25,662 | 1,050 | 180 | 192 | 372 | 18,755 | 19,128 | 11,858 | 30,613 | 30,986 |
| | **Net Flux** | - | 1,461 | (33) | 23 | (232) | (209) | (5,793) | (6,002) | 5,201 | (592) | (801) |
| | **Direction** | balanced | OUT | IN | OUT | IN | IN | IN | IN | OUT | IN | IN |



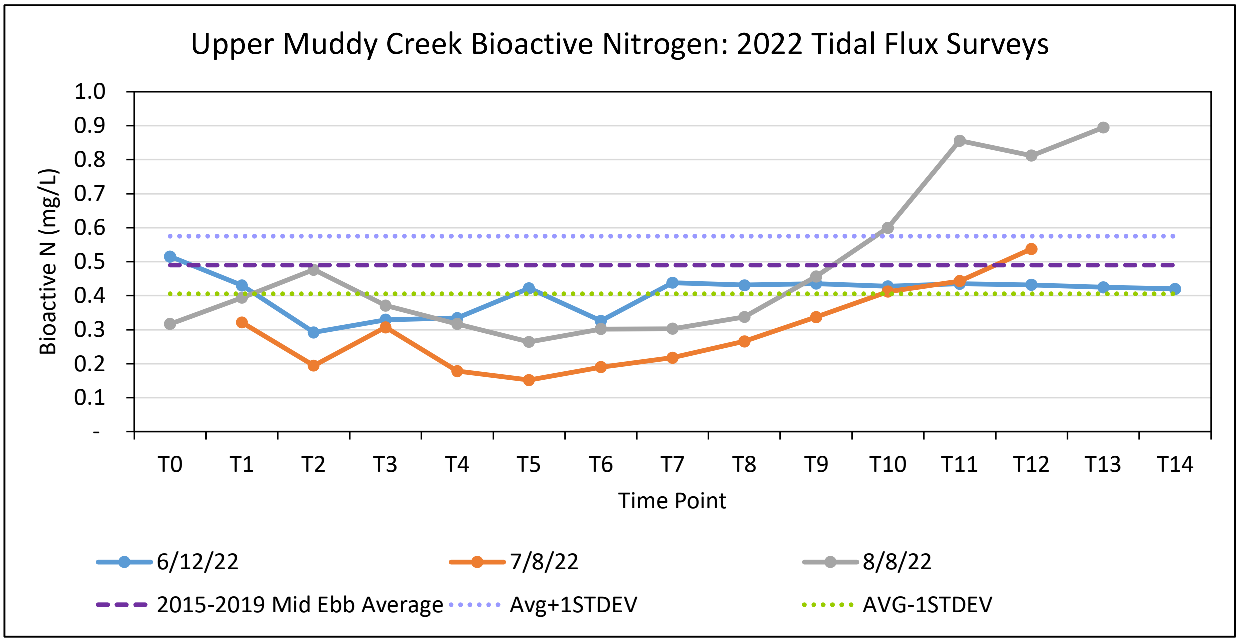


**Figure 4. Time Course Total Nitrogen and Bioactive Nitrogen during 2022 Upper Muddy Creek Tidal Flux Surveys: June 12, July 8, and August 8.** Flood tide occurred until T5 or T6 time points. Bioactive N concentration increased substantially during the ebb tides on July 8 and August 8 surveys reflecting relatively greater watershed inputs, but June 12 was fairly stable perhaps because of the greater volumes in this survey. Bioactive N concentrations in mid-ebb were consistent the average mid-ebb concentrations used in the 2020 Pleasant Bay update (Howes, *et al*., 2021).

The August 8 flux measurements had the best balance between salinity and water fluxes and generally showed similar TN mass entering and leaving Upper Muddy Creek. Net difference between the salinity-corrected and non-corrected TN export loads and import loads was 3% and 2%. The net annual N difference between flood tide and ebb tide was similar to the June 12 reading with 585 kg with the salinity-corrected estimate and 488 kg in the non-corrected estimate. The August 8 readings showed a notable increase in DON flux in and out compared to July 8. Both July 8 and August 8 readings had a notable decrease in DIN mass compared to June 12 readings suggesting an increase in phytoplankton, but PON masses were lowest in the July 8 measurements. Perhaps the benthic infauna is changing in the system and this is altering N dynamics (benthic infauna was not updated in the 2020 Update).

### ***Upper Muddy Creek Conclusions***

The three flux surveys completed at the location of the former dike dividing Upper and Lower Muddy Creek had differing results, but two of the three surveys largely confirmed that the 10% nitrogen attenuation used for Upper Muddy Creek in the 2020 update of the Pleasant Bay MEP model was appropriate.

## III. Pochet Neck Nitrogen Mass Exchange

Pochet Neck is a component of the overall Pleasant Bay system defined in the MEP model as a section north of a peninsula split by Payson Lane and Pochet Island. The area north of the line includes open waters with fringing salt marshes and an interior salt marsh north of Pochet Road. Comparison of MEP and 2020 data showed that TN concentrations had not changed significantly, but the sediment nitrogen contributions measured at the same locations had changed from net removals[14] to net additions.[15]

In order to provide more refined understanding of how the Pochet Neck system had changed, CSP/SMAST staff conducted three measurements of nitrogen mass exchange (June 12, July 10, August 9, 2022) at the MEP dividing line between the Pochet Neck system and the main portion of Pleasant Bay (**Figure 5**). Measurements included hourly velocity transects at this location using an electromagnetic flow meter (Marsh-McBirney Flo-Mate) and a stage recorder nearby. On each sampling date, a minimum of 15 water quality samples were collected hourly from the whole water column. These water quality samples were pooled from three locations across the channel transect and were collected over a complete tidal cycle (low tide-high tide-low tide). A total of 141 samples (47 pooled) were collected during the three mass exchange dates (**Table 5**). Water quality profile samples were assayed at the Coastal Systems Analytical Laboratory at SMAST/UMASS Dartmouth using the same assay procedures used for Pleasant Bay water quality monitoring program. Samples were assayed for ammonium-N and nitrate/nitrite N, dissolved nitrogen, particulate organic nitrogen, particulate organic carbon, ortho-phosphate, chlorophyll a, salinity, and salinity/specific conductivity.

*Pochet Neck Tides*

Flood and ebb current velocity measurements were made concurrently with water sampling at the Pochet Neck transect to determine flow characteristics during both flood and ebb tides. These flow data were then interpolated with stage data to yield a detailed record of flow in and out. Total flow into Pochet Neck was calculated between slack low tide and slack high tide. Total flow out was calculated from slack high tide to the point at which the tidal height, as measured by a tide gauge during ebb reached the same level as that recorded at the previous slack low tide. Flow estimates during flood and ebb tides were used to calculate salt and nutrient flux into and out of Pochet Neck transect site during the tidal cycle on each of the three sampling dates. Data from each collected water sample was paired with the corresponding flow rate to calculate a mass flux for each sampling event. These results were interpolated to yield a total mass flux for the entire tidal cycle. From these flux data, the magnitude and direction of the net flux of salt and nutrients were calculated.

A stage recorder was deployed in close proximity to the Pochet Neck transect location prior to the sampling events to measure the differences between the tides on each date. This stage data shows the tide delay between predicted Pleasant Bay tides and Pochet Neck (**Table 6**). The recorded morning low tide levels had a time delay ranging from 35 minutes (June 12) to 49 minutes (August 9) compared to the corresponding predictions at a tide station in the southern section of Pleasant Bay. High tide was experienced within minutes of the predicted high tide while the evening low tide had a time delay ranging from 3 to 17 minutes on the three dates. The June 12 tides were measured two days before a full moon (spring tide), while July 10 was four days after the first quarter moon (neap tide). The August 9 sampling occurred four days before a full moon spring tide. The lowest high tide elevation (3.9 ft) was on August 9.

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[14] Howes B., S.W. Kelley, J.S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner. 2006. Pleasant Bay MEP Report. Table IV-11, p. 82.

[15] Howes, B., E. Eichner, and S. Kelley. 2021. Table II-7, p. 33.

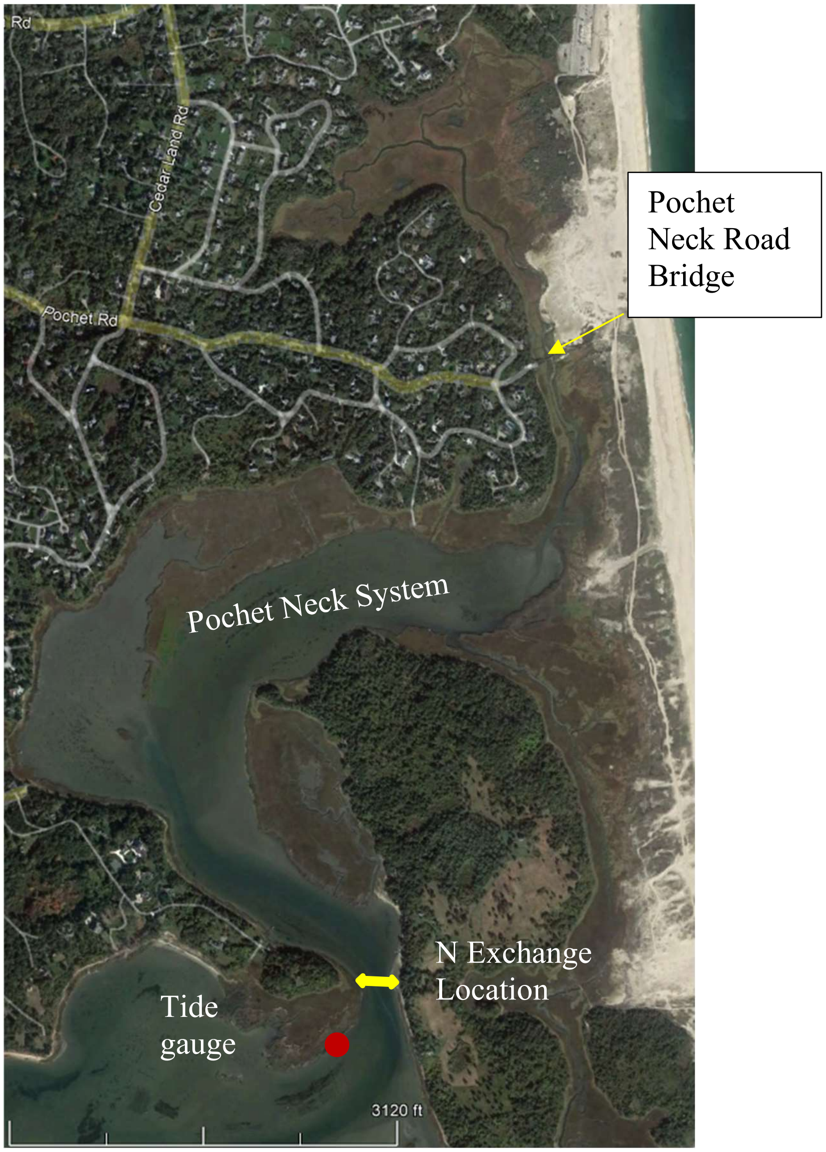

**Figure 5. Pochet Neck Location of Nitrogen Mass Exchange Measurements. Water quality** Water quality samples, flow velocities, and stage readings were collected hourly over a complete tidal cycle (low tide-high tide-low tide) during the three events across Pochet channel (location of yellow arrow in figure). Hourly measurements were collected across a transect at this location during three tidal cycles in 2022: June 12, July 10, and August 9. Water quality samples (minimum of 15 per date) were created from pooled samples from 3 positions across the transect. A continuous stage recorder was also deployed during sampling events (red circle). The main tidal creek for the Pochet Neck system extends north of the Pochet Neck Road bridge.

**Table 5. Pochet Neck sampling dates for water quality and laboratory assays performed on samples.** Each water quality sample consisted of water collected and pooled from three locations along the transect. Note that TDN is Total Dissolved Nitrogen, POCN is particulate organic carbon and nitrogen, CHLA is total chlorophyll-*a* pigments.

| Sample Date | # samples | Assays | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | NH4 | PO4 | NO3/NO2 | TDN | POCN | CHLA | Salinity | Velocity |
| 6-12-22 | 16 | X | X | X | X | X | X | X | X |
| 7-10-22 | 16 | X | X | X | X | X | X | X | X |
| 8-9-22 | 15 | X | X | X | X | X | X | X | X |
| **Total** | **47** | | | | | | | | |

**Table 6. Pochet Neck measured tide height compared to predicted low and high tides at the US Harbors Pleasant Bay South station and the corresponding lag time between predicted and measured tides. Tide ranges on the three dates varied from 2.85 to 3.19 ft.**

| Date | Tide | Predicted (time) | Measured (time) | Gauge Depth (ft) | Lag (hr:min) |
|---|---|---|---|---|---|
| 6/12/2022 | Low | 7:14 | 7:49 | 1.4 | 0:35 |
| | High | 12:23 | 12:19 | 4.59 | -0:04 |
| | Low | 19:26 | 19:29 | 1.47 | 0:03 |
| 7/10/2022 | Low | 5:50 | 6:28 | 1.30 | 0:38 |
| | High | 10:58 | 10:58 | 4.15 | 0 |
| | Low | 18:02 | 18:18 | 1.28 | 0:16 |
| 8/9/2022 | Low | 6:28 | 7:17 | 0.97 | 0:49 |
| | High | 11:40 | 11:37 | 3.90 | -0:03 |
| | Low | 18:40 | 18:57 | 0.94 | 0:17 |

### *Pochet Neck Water Flux*

Water flux data generally showed that tides at the Pochet Neck transect were flood dominant, just as they were in the Muddy Creek measurements. Current velocities were applied to the cross-sectional area of the channel to obtain an instantaneous flow rate of water at the transect. The flooding tide at the Pochet Neck transect on each of the three sampling dates was shorter in duration and typically stronger in flow rate compared to the ebbing tides. The peak flow rate on the flooding tides were: 47,167 liters per second (L/s) on June 12, 33,457 L/s on July 10, and 34,326 L/s on August 9 (**Figure 6**). Flow rate ebbing from Pochet Neck was longer in duration and typically weaker. The maximum ebbing flow rates were: 24,251 L/s recorded on June 12, 14,638 L/s on July 10 and 17,641 L/s on August 9.

The hourly flow rates were then interpolated with stage information over the course of each of the single tidal cycles at the Pochet Neck transect to yield an estimate of total water flux for both flood and ebb tides. Total flow into Pochet Neck during the tidal cycle was calculated between slack low tide and slack high tide. Total flow out of Pochet Neck was calculated from slack high tide to the point at which the tidal height reached the same level as that recorded at the previous slack low tide, as measured by a tide gauge during ebb. Water flux during flood tide ranged from 307,287 to 451,217 cubic meters (m$^3$) (July 10 and June 12, respectively) (**Table 7**). Water flux during tidal ebb was of a longer duration (~7 hrs) than during tidal flooding (4-5 hrs), same as Muddy

**Table 7. Pochet Neck cumulative water volume flux for 2022 tidal samplings: June 12, July 10, and August 9.** Water flux in and out varied with flux out greater than flux in on two of the three samplings. Ebb durations were longer than flood durations with relatively small differences in duration of each of the two components (<1 hr). Volume readings show variability of individual tides.

| | Water Volume | Time Range | Tide Time |
|---|---|---|---|
| | m³ | | hr:min |
| **June 12** | | | |
| **Flux In** | 451,217 | 7:19-12:19 | 5:00 |
| **Flux Out** | 451,965 | 12:29-19:29 | 7:00 |
| **Net Flux** | 748 | OUT | |
| **July 10** | | | |
| **Flux In** | 307,287 | 6:28-10:48 | 4:20 |
| **Flux Out** | 278,473 | 10:48-18:38 | 7:50 |
| **Net Flux** | -28,814 | IN | |
| **August 9** | | | |
| **Flux In** | 342,546 | 7:27-11:27 | 4:00 |
| **Flux Out** | 328,599 | 11:37-18:57 | 7:20 |
| **Net Flux** | -13,946 | IN | |

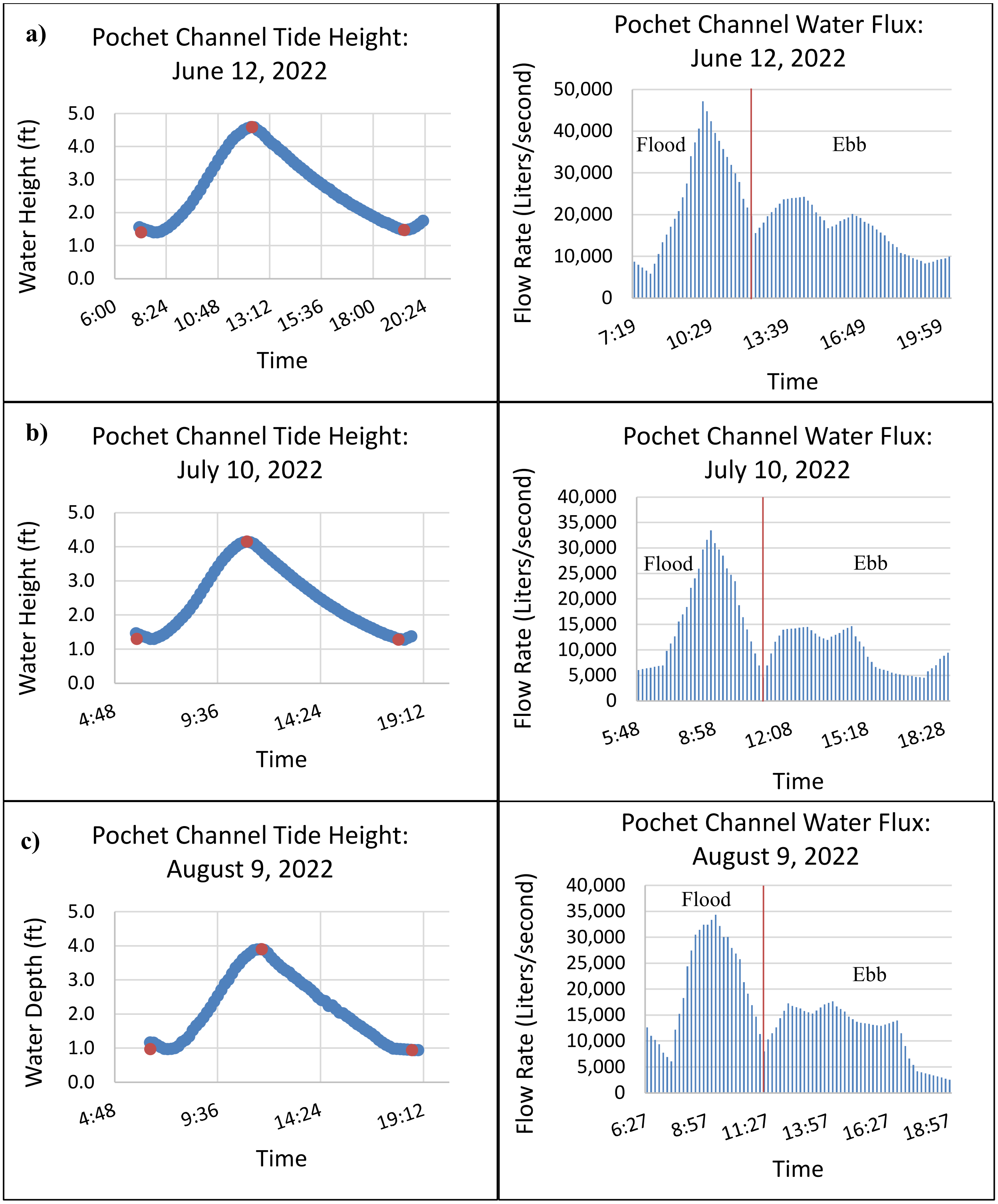

**Figure 6. Pochet Neck channel measured tide height and water flows over the period of a single tidal cycle on three 2022 sampling events: June 12, July 10, and August 9.** Flow rates show higher floods rates, but longer ebb periods. The predicted low, high, and low tide on each date is shown by the red dots on the stage graphs (USHarbors.com, South Pleasant Bay station).

Creek. Flood tide volumes ranged from 307,727 to 451,217 $m^3$ (July 10 and June 12, respectively), while ebb tide volumes ranged from 278,473 to 451,965 $m^3$ (July 10 and June 12, respectively).

Comparison of flood and ebb tide volumes showed two dates of the three dates where more water entered the system than left (4% difference on August 9 and 9% difference on July 10), while the third date was balanced (0.2% difference on June 12). Greater flows on June 12 may be a result of the 1.65 inches of rain that fell from June 8 through June 10 (**Figure 7**). The net loss of water in the Pochet Neck marsh would be consistent with estimated evapotranspiration rates under high light conditions.[16] One of the key features of the Pochet Neck system compared to the Muddy Creek system is the extensive marsh plain, especially the large marsh area north of Pochet Road.

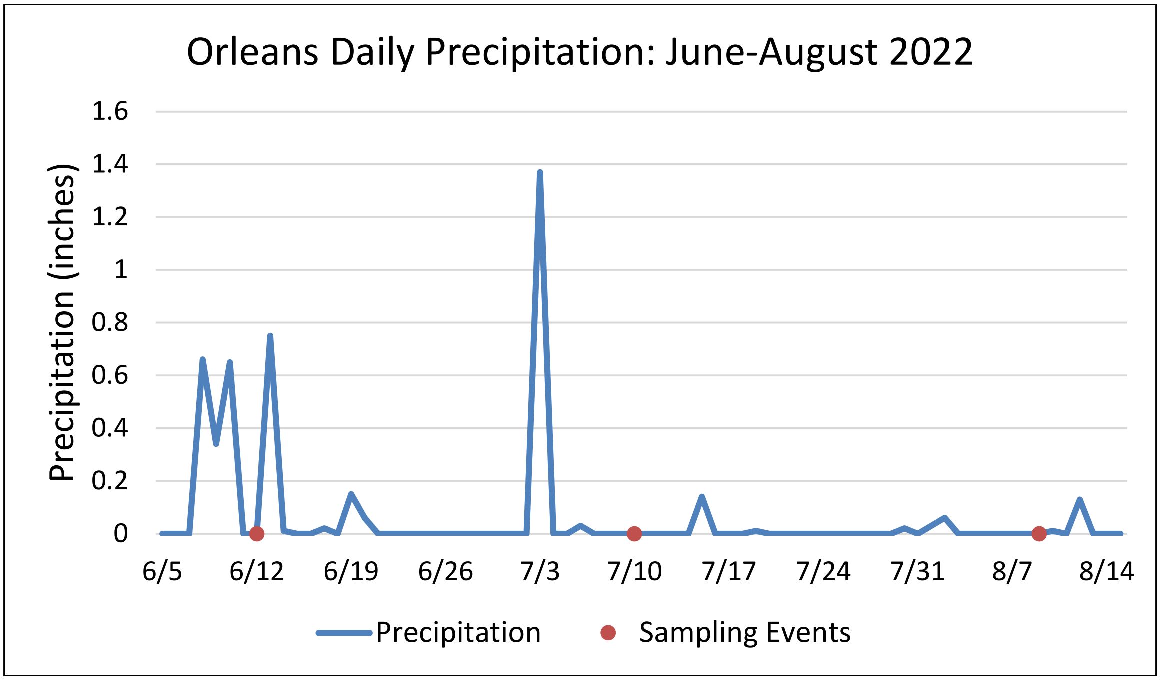

**Figure 7. Daily precipitation amounts and the Pochet Neck sampling events June-August 2022.** Daily rain totals were measured from an Orleans meteorological station just to the south of Town Cove (cocorahs.org, downloaded 3/9/23). Pochet Neck sampling events occurred on June 12, July 10, and August 9, 2022.

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[16] *e.g.*, Shen, C., Zhang, C., Xin, P., Kong, J., and Li, L. 2018. Salt dynamics in coastal marshes: Formation of hypersaline zones. *Water Resources Research*, 54:3259–3276. https://doi.org/10.1029/2017WR022021

### *Pochet Neck Nutrient Flux*

Nitrogen measurements at the Pochet Neck transect present a number of issues related to its future management. DIN loads are consistently higher (>2X) during flood tides than ebb tides (**Table 8**), which would be consistent with transformations of inorganic forms (typically found in groundwater) to organic forms that occur in salt marshes. However, all three sampling events had greater bioactive N (DIN+PON) on ebb tides than entered Pochet Neck on the flood tides. This net bioactive N mass export varied within a relatively consistent range from 8,219 g to 12,763 g. Translating these masses to annual loads results in a range of 6,000 kg to 9,317 kg. Given these changes, most of the increase in bioactive nitrogen export was due to additions of PON.

This increase in PON is greater than the projected watershed TN input. The Pochet Neck watershed nitrogen load in the 2020 Pleasant Bay Update was 3,074 kg. As mentioned, this watershed input would tend to be DIN (mostly nitrate-N), but some of this would be lost to denitrification and the rest would be transformed to ammonium-N as it discharges with groundwater through the salt marshes at the margins of Pochet Neck. But even if it all reached the open waters of Pochet Neck, it would only account for a maximum of approximately 50% of the bioactive N exported from the system. This finding also means that the remaining N mass exported from Pochet Neck is from internal sources (*i.e.*, sediments). It is also likely that portions of the system have different N cycles: the marsh above Pochet Road is likely attenuating N, but the open water south of the road is likely functioning more like the rest of Pleasant Bay. As an aside, it is also notable that much of the DIN entering on flood tides is ammonium-N (82% - 93%) likely indicating local watershed inputs outside of Pochet Neck, transformation of those inputs from groundwater NOx to estuary NH4-N, and readily available forms for phytoplankton growth.

Review of TN and bioactive N concentrations during flood and ebb portions of the tides on the three dates showed that mid-ebb concentrations tended to match average 2015-2019 concentrations at WMO-5,[17] which is the interior Pochet Neck station, as opposed to WMO-3, which is in the portion of Pleasant Bay just outside of the Pochet Neck transect site (~700 m WSW of the transect) (**Figure 8**). Average bioactive-N from 2015-2019 monitoring data was 0.152 mg/L at WMO-3 and 0.267 mg/L at WMO-5. Average bioactive N concentrations during ebb tide on June 12, July 10, and August 9, 2022, sampling dates were 0.27 mg/L, 0.24 mg/L, and 0.24 mg/L, respectively. Corresponding TN concentrations on the 2022 sampling dates were 0.63 mg/L, 0.65 mg/L, and 0.53 mg/L, respectively.

### ***Pochet Neck Conclusions***

The three flux surveys completed at the Pochet Neck transect, which corresponds to the MEP watershed delineation, were relatively consistent and found that the Pochet Neck system generally exports 13-17% more bioactive N than enters the system on flood tides. The mass of exported bioactive N is 1.6X to 2.5X greater than the watershed nitrogen load meaning that the sediments within the system are adding additional N to flood tides. This finding is consistent with the change in the nitrogen regeneration measurements from the sediment cores in MEP and the altered 2020. There may be differences in how and where nitrogen is being added in the Pochet Neck system (*e.g.*, above and below Pochet Road; the marsh above the road is likely removing N), but these types of refinements would require measurements within different segments of the system.

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[17] Howes, B., E. Eichner, and S. Kelley. 2021. Table IV-1, p. 50.

**Table 8. Pochet Neck salt, water and nutrient flux during three 2022 sampling events: June 12, July 10, and August 9.** Salt balanced water volume and nutrient mass into (flood tide) and out of (ebb tide) the Pochet Neck transect are shown. The mass of each measured hourly constituent was interpolated for every ten minutes based on hourly samples and tidal stage and then summed from slack low to high tide for In totals and high tide to slack low for the Out totals. Salt is a conservative tracer and the mass in and out on each tide has been balanced. Negative net flux (in parentheses) indicates retention or attenuation within Pochet Neck. The June 12 event had total nitrogen attenuation of approximately 3%, but net bioactive N (DIN+PON) export of +13%. Bioactive N export was +14% on July 10 and +17% on August 9; both of these dates also had net TN export of +10% and +7%, respectively. TN export on July 10 and August 9 was 3.2X and 2.1X the watershed N inputs, suggesting that the sediments in Pochet Neck are the primary source of TN exported from Pochet Neck.

| **Tide Length (hr:min)** | | **Salt (kg)** | **Water (m3)** | **PO4 (g)** | **NH4 (g)** | **NOx (g)** | **DIN (g)** | **DON (g)** | **TDN (g)** | **PON (g)** | **TON (g)** | **TN (g)** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **6/12/22** | | | | | | | | | | | | |
| 5:00 | **In/Flood** | 13,556,704 | 450,333 | 7,273 | 9,553 | 2,112 | 11,665 | 172,974 | 184,639 | 90,287 | 263,261 | 274,926 |
| 7:00 | **Out/Ebb** | 13,556,704 | 451,965 | 3,925 | 235 | 793 | 1,028 | 152,094 | 153,122 | 113,687 | 265,781 | 266,809 |
| | **Net Flux** | - | 1,632 | (3,348) | (9,318) | (1,319) | (10,637) | (20,880) | (31,516) | 23,400 | 2,520 | (8,117) |
| | **Direction** | balanced | OUT | IN | IN | IN | IN | IN | IN | OUT | OUT | IN |
| **7/10/22** | | | | | | | | | | | | |
| 4:20 | **In/Flood** | 8,728,405 | 276,146 | 30,773 | 17,891 | 1,439 | 19,317 | 103,178 | 122,484 | 40,042 | 143,553 | 162,870 |
| 7:50 | **Out/Ebb** | 8,728,405 | 278,473 | 30,342 | 6,379 | 1,497 | 7,876 | 78,337 | 122,163 | 59,702 | 171,344 | 179,212 |
| | **Net Flux** | - | 2,327 | (432) | (11,512) | 58 | (11,441) | (24,841) | (321) | 19,660 | 27,791 | 16,342 |
| | **Direction** | balanced | OUT | IN | IN | OUT | IN | IN | IN | OUT | OUT | OUT |
| **8/9/22** | | | | | | | | | | | | |
| 4:00 | **In/Flood** | 10,638,523 | 330,596 | 22,393 | 11,408 | 2,498 | 13,906 | 94,649 | 108,555 | 49,465 | 144,114 | 158,019 |
| 7:10 | **Out/Ebb** | 10,638,523 | 328,599 | 22,291 | 3,657 | 2,659 | 6,316 | 94,679 | 100,995 | 67,986 | 162,665 | 168,981 |
| | **Net Flux** | - | (1,997) | (102) | (7,750) | 161 | (7,590) | 30 | (7,560) | 18,521 | 18,551 | 10,962 |
| | **Direction** | balanced | IN | IN | IN | OUT | IN | OUT | IN | OUT | OUT | OUT |

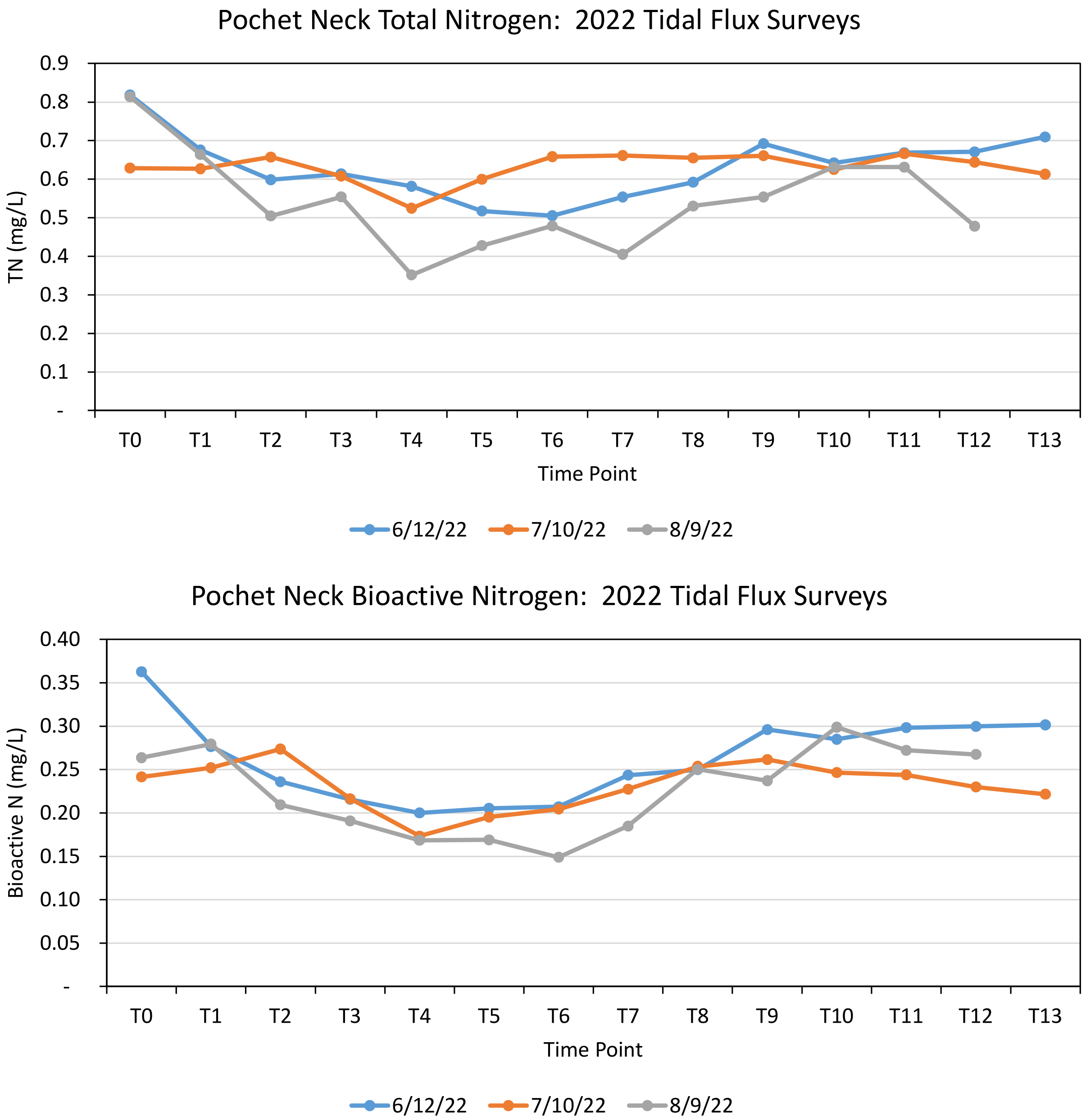

**Figure 8. Time Course Total Nitrogen and Bioactive Nitrogen during 2022 Pochet Neck Tidal Flux Surveys: June 12, July 10, and August 9.** Flood tides occurred through the T5 time point during each survey. Bioactive N concentration increased during the ebb tides reflecting greater watershed inputs, but also inputs from the interior portions of the system. TN concentrations were relatively consistent on both flood and ebb portions of the tides; consistent with findings in the MEP and the primary reason for relying on bioactive N in MEP water quality modeling. Bioactive N concentrations in mid-ebb were generally consistent with the average mid-ebb concentrations at the inner Pochet Neck station (WMO-5), which had a 2015-2019 average mid-ebb concentration of 0.267 mg/L bioactive N (Howes, *et al*., 2021).

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# Technical Memorandum

To: Pleasant Bay Alliance Working Group
Carole Ridley, Coordinator, Pleasant Bay Alliance

From: Ed Eichner, Principal, TMDL Solutions/Adjunct Professor, CSP/SMAST
Sean Kelley, PE, Senior Coastal Engineer, Sustainable Coastal Solutions

Date: June 5, 2023 (revised final 8/9/23)

RE: Impact of Changes in Tar Kiln and Upper Muddy Creek Nitrogen Attenuation Scenarios (SNEP20: modified Task 4)

## I. Introduction and Background

In 2021, the Coastal Systems Program from the School for Marine Science and Technology at UMass-Dartmouth (CSP/SMAST) in partnership with the rest of the Massachusetts Estuaries Project (MEP) Technical Team completed an update of the 2006 Pleasant Bay MEP model[1] through a FY18 Southeast New England Watershed Grants Program (SNEP) grant to the Pleasant Bay Alliance (PBA). This SNEP18 update of the Pleasant Bay MEP model utilized the same MEP model development procedures previously approved by Massachusetts Department of Environmental Protection (MassDEP) and that serve as the basis for the Pleasant Bay regulatory water quality threshold concentrations and nitrogen loads (*e.g.*, TMDLs[2]). Results from the SNEP18 project included updates to the Tar Kiln and Upper Muddy Creek nitrogen attenuation rates based on post-MEP data: 60% and 10%, respectively. [3]

Subsequent discussions among CSP/SMAST and PBA Working Group led to some additional questions about the system-wide and local impacts of the updated revisions to the Tar Kiln and Muddy Creek nitrogen attenuation. As a result of these discussions, PBA has asked CSP/SMAST to complete two (2) additional water quality scenarios using the SNEP18 linked models (*i.e.*, hydrodynamics and watershed nitrogen loads) to evaluate the impact of:

a) Reducing the Tar Kiln marsh attenuation to zero (*i.e.*, no attenuation; same as the MEP),
b) Reducing both Tar Kiln and Upper Muddy Creek attenuations to MEP rates (0% and 4%, respectively)

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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.

[3] Howes, B., E. Eichner, and S. Kelley. 2021. Ecosystem Monitoring and Modeling for Implementation (Task 3) of Regional Watershed Permit Implementation Project for Nitrogen Management in Pleasant Bay, Cape Cod, MA. For the Pleasant Bay Alliance, Massachusetts. Technical Report by the Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 92 pp.

## II. Scenario 1: SNEP18 existing watershed loading with no Tar Kiln Marsh nitrogen attenuation (*i.e.*, same as MEP)

This scenario utilized the existing conditions watershed loads and tidal hydrodynamics developed through the SNEP18 update except for changing the Tar Kiln Marsh nitrogen attenuation from 60% to 0%. This change is a return to the historical Tar Kiln Marsh nitrogen attenuation assigned in the original MEP Pleasant Bay assessment and the 2010 update. During the data collection for the original MEP, Tar Kiln Marsh stream had a continuous gauge and regular water quality sampling. These results were synthesized and reported in the MEP report. 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 were high. However in 2020 and prior to the SNEP18 update, CSP/SMAST was asked by the Orleans Conservation Trust to complete a more refined review and assessment of the Tar Kiln Marsh system.[4] This 2020 review addressed some of the uncertainties about the Tar Kiln system at the time of the MEP, including tidal flow characteristics of the marsh, whether the Marsh was stable, and whether there were signs of impairment within the marsh. As a result of this more refined review and data collection, the SNEP project team determined that a 60% nitrogen attenuation within the Tar Kiln Marsh system was appropriate and sufficiently conservative.

For this scenario, the SNEP18 water quality model was utilized with SNEP18 watershed nitrogen loads incorporating no nitrogen attenuation in the Tar Kiln Marsh (**Table 1**). No changes were made in the hydrodynamic portion of the SNEP18 linked model or its water quality calibration. SNEP18 benthic nitrogen loads were not adjusted since Tar Kiln Marsh did not have a benthic load in the SNEP18 model.

Changing the Tar Kiln Marsh attenuation from 60% to 0% in the SNEP18 water quality model had little to no impact on nitrogen concentrations throughout Pleasant Bay (**Table 2**). Modeled bioactive nitrogen concentrations (*i.e.*, dissolved inorganic nitrogen + particulate organic nitrogen) changed by less than 1% at four of the 25 monitoring stations and did not change at the remaining 21 other stations. Bioactive nitrogen concentrations at the three primary sentinel stations did not change at all in this scenario (**Figure 1**). This outcome is consistent with the small nitrogen load change from the attenuation change relative (<2%) to the overall Little Pleasant Bay loads (*i.e.*, the portion of the system that would be mostly impacted by a watershed load change).

## III. Scenario 2: SNEP18 existing watershed loading with no Tar Kiln Marsh attenuation and 4% attenuation in Upper Muddy Creek (*i.e.*, same as MEP)

This scenario utilized the existing conditions watershed loads and tidal hydrodynamics developed through the SNEP18 update and changed the nitrogen attenuation in Tar Kiln Marsh and Upper Muddy Creek to the attenuation rates used in the original MEP Pleasant Bay assessment (0% and 4%, respectively). Tar Kiln Marsh attenuation is discussed above and Upper Muddy Creek was assigned a 4% nitrogen attenuation rate in the MEP assessment based on water quality data, benthic flux, hydrodynamics prior to the 2007 breach, watershed nitrogen loading.

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[4] 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.

In 2008-2010, refinements to Muddy Creek were added to the MEP water quality model based on updated data. In 2010, the Town of Harwich provided updated water use information to the MEP team and the watershed nitrogen loads were altered to reflect the update, including in the Muddy Creek watershed. In 2008, CSP/SMAST completed a refined assessment of the Upper Muddy Creek ecosystem, including measurements of nitrogen export to assess attenuation within the system.[5] The updated nitrogen loads and refined system characterization were combined within the MEP model and, as a result, the nitrogen attenuation rates in Upper and Lower Muddy Creek were adjusted to match the measured 2008 water quality data.[6] Upper Muddy Creek nitrogen attenuation was changed from 4% to 57% and Lower Muddy was assigned an attenuation rate of 2%. The net result of these changes was that Lower Muddy Creek still needed to remove 100% of the watershed septic load to meet the threshold load, while Upper Muddy Creek removal was reduced from 75% to 66%. During this same time period, PBA asked the MEP team to evaluate the impact of incorporating a 24 ft culvert at the Muddy Creek inlet into the MEP model in anticipation of the changes planned on Route 28. The culvert addition reduced the nitrogen concentration from 43% above the threshold to 23% above the threshold (0.21 mg/L bioactive N) at the Lower Muddy Creek secondary threshold station (PBA-05).[7] No changes were made to the nitrogen attenuation rates, but it was noted that there was some uncertainty how the fringing Upper Muddy Creek salt marshes would respond to the increased tidal range. The increase in Mean High Water (+1.2 ft) due to the increase in the culvert width might expand the salt marsh area over what was measured in the 2008 study and increase nitrogen attenuation, but there were uncertainties because available marsh elevation contours were greater (2 ft) than the change in MHW.

For the current scenario, the SNEP18 water quality model was utilized with SNEP18 watershed nitrogen loads (**Table 3**) incorporating no nitrogen attenuation in the Tar Kiln Marsh and 4% attenuation in Upper Muddy Creek (*i.e.*, original MEP attenuation rates). As mentioned above, the SNEP18 update of the Pleasant Bay MEP model included updated watershed attenuation rates for Tar Kiln Marsh and Upper Muddy Creek: 60% and 10%, respectively. No changes were made in the hydrodynamic portion of the SNEP18 linked model or its water quality calibration.

The combined impact of changing the attenuation rates in both Tar Kiln Marsh and Upper Muddy Creek had the largest impact at the two Muddy Creek monitoring stations. The bioactive N concentration at the Upper Muddy Creek station (PBA-05A) increased by 4.8%, while the concentration at the Lower Muddy Creek station (PBA-05) increased by 1.8% (**Table 4**). The Lower Muddy Creek station is one of the secondary threshold stations, which have a bioactive N threshold concentration of 0.21 mg/L. This threshold concentration was exceeded in the SNEP18 existing conditions and the change in attenuation rates increased the exceedance of the threshold. The bioactive N concentration at the PBA-12 primary threshold station (Little Pleasant Bay) did not change compared to the SNEP18 update and the Ryders Cove concentration increased <1% over the primary threshold concentration (0.16 mg/L) compared to the SNEP18 update. Overall,

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[5] 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.

[6] 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] 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 Coordinator and B. Duncanson, Chair, Technical Resource Committee, PBA. 8 pp.

nine stations had increases in bioactive N concentrations in this scenario compared to SNEP18 existing conditions concentrations, but only the two Muddy Creek stations had increases greater than 1%. The system-wide bioactive N concentrations for this scenario are shown in **Figure 2**.

Comparison between the results from Scenario 1 (see Table 2) and Scenario 2 (see Table 4) shows the increases in bioactive N concentrations at five additional stations as a result of adding the change in attenuation in Upper Muddy Creek. The removal of the Tar Kiln N attenuation impacted concentrations at four stations, albeit all with <1% changes, but the addition of the change in the Upper Muddy Creek attenuation in Scenario 2 did not change the Scenario 1 concentrations at these four stations. The change in the Upper Muddy Creek attenuation impacted bioactive N concentrations at Little Quanset Pond, Round Cove and Upper Ryders Cove in addition to the two Muddy Creek stations. These changes at the three non-Muddy Creek stations were not significant, but reinforce how changes in one part of the Pleasant Bay watershed may impact other portions.

**Table 1. Nitrogen Loads for Scenario 1: SNEP18 existing loading scenario with no Tar Kiln Marsh attenuation.** For this scenario, all watershed nitrogen loads and direct atmospheric loads are the same as those developed and assessed in the SNEP18 Pleasant Update (Howes and others, 2021) except for Tar Kiln Marsh. Tar Kiln Marsh watershed nitrogen load was changed by reducing the 60% attenuation in the SNEP18 update to no attenuation. The SNEP18 update includes updated tidal flushing, bathymetry, and sediment benthic flux.

| 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 |
| Pah 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 | 4.178 | 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** | 140.216 | 83.962 | 476.362 |

**Table 2. Modeled average bioactive N (DIN+PON) concentrations for Scenario 1: SNEP18 existing loading scenario with no Tar Kiln Marsh nitrogen attenuation.** Scenario bioactive N concentrations are compared to SNEP18 bioactive N concentrations, which included a 60% nitrogen attenuation in Tar Kiln Marsh. Both the SNEP18 and the scenario results are based on the updated Pleasant Bay water quality model developed during SNEP18. 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 sentinel station threshold is set as the average of the PBA-03 and CM-13 concentrations. The change in the Tar Kiln Marsh from 60% to 0% resulted in changes in concentrations at 4 stations with all changes less than 1%. There were no changes in concentrations at the primary sentinel stations.

| Sub-Embayment | monitoring station | SNEP18 existing (mg/L) | SNEP18 Scenario 1 (mg/L) | % change |
|---|---|---|---|---|
| Meetinghouse Pond | PBA-16 | 0.288 | 0.288 | 0% |
| Mtghse@Rattles Dock | WMO-10 | 0.238 | 0.238 | 0% |
| Mtghse@Off Lonnie's Inlet | WMO-08 | 0.192 | 0.192 | 0% |
| Lonnie's Pond | PBA-15 | 0.246 | 0.246 | 0% |
| Areys Pond | PBA-14 | 0.334 | 0.334 | 0% |
| Namequoit River Upper | WMO-6 | 0.239 | 0.239 | 0% |
| The River-Mouth | PBA-13 | 0.148 | 0.148 | 0% |
| Pochet - Upper off Town Landing | WMO-05 | 0.279 | 0.279 | 0% |
| Pochet - Basin@ Mouth | WMO-03 | 0.146 | 0.146 | 0% |
| Little Pleasant Bay - Head | PBA-12 | 0.139 | 0.139 | 0% |
| Little Pleasant Bay - Main Basin | PBA-21 | 0.132 | 0.133 | +0.8% |
| Pah Wah Pond | PBA-11 | 0.207 | 0.208 | +0.5% |
| Little Quanset Pond | WMO-12 | 0.185 | 0.185 | 0% |
| Quanset Pond | WMO-01 | 0.153 | 0.154 | +0.7% |
| Round Cove | PBA-09 | 0.254 | 0.254 | 0% |
| Muddy Creek - Upper | PBA-05A | 0.503 | 0.503 | 0% |
| Muddy Creek - Lower | PBA-05 | 0.224 | 0.224 | 0% |
| Pleasant Bay-Head | PBA-08 | 0.121 | 0.121 | 0% |
| Pleasant Bay- Upper Strong Island | PBA-19 | 0.104 | 0.104 | 0% |
| Pleasant Bay off Muddy Creek | PBA-06 | 0.140 | 0.141 | +0.7% |
| Pleasant Bay lower Strong Island | PBA-20 | 0.103 | 0.103 | 0% |
| Ryders Cove Upper | PBA-03 | 0.218 | 0.218 | 0% |
| Ryders Cove Lower | CM-13 | 0.113 | 0.113 | 0% |
| Crows Pond | PBA-04 | 0.116 | 0.116 | 0% |
| Chatham Harbor - Upper | PBA-01 | 0.099 | 0.099 | 0% |

**Table 3. Nitrogen Loads for Scenario 2: SNEP18 existing loading scenario with no Tar Kiln Marsh nitrogen attenuation and 4% nitrogen attenuation in Upper Muddy Creek.** For this scenario, all watershed nitrogen loads and direct atmospheric loads are the same as those developed and assessed in the SNEP18 Pleasant Update (Howes and others, 2021) except for Tar Kiln Marsh and Upper Muddy Creek. The SNEP18 update includes updated tidal flushing, bathymetry, and sediment benthic flux.

| 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 |
| Pah 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 | 4.178 | 0.000 | - |
| Round Cove | 5.745 | 0.170 | 0.206 |
| The Horseshoe | 0.570 | 0.063 | - |
| Muddy Creek - upper | 13.142 | 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** | 141.047 | 83.962 | 476.399 |

**Table 4. Modeled average bioactive N (DIN+PON) concentrations for Scenario 2: SNEP18 existing loading scenario with no Tar Kiln Marsh nitrogen attenuation and 4% nitrogen attenuation in Upper Muddy Creek.** Scenario bioactive N concentrations are compared to SNEP18 existing conditions bioactive N concentrations, which included a 60% nitrogen attenuation in Tar Kiln Marsh and 10% nitrogen attenuation in Upper Muddy Creek. Both the SNEP18 and the scenario results are based on the updated Pleasant Bay water quality model developed during SNEP18. 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 sentinel station threshold is set as the average of the PBA-03 and CM-13 concentrations. The combined impact of the change in the nitrogen attenuation in Tar Kiln Marsh and Upper Muddy Creek changed concentrations at 9 stations, but only at the Muddy Creek stations were changes greater than 1%: +4.8% at Upper Muddy Creek (PBA-05A) and +1.8% at Lower Muddy Creek (PBA-05). The Ryder Cove primary sentinel station average concentration remained slightly above the threshold concentration and the Little Pleasant Bay primary sentinel station concentration did not change. Concentrations at the secondary threshold stations did not change relative to the 0.21 mg/L bioactive N threshold in this scenario: those greater than the threshold remained greater than the threshold and those less than the threshold remained less than the threshold.

| Sub-Embayment | monitoring station | SNEP18 existing (mg/L) | SNEP18 Scenario 2 (mg/L) | % change |
|---|---|---|---|---|
| Meetinghouse Pond | PBA-16 | 0.288 | 0.288 | 0% |
| Mtghse@Rattles Dock | WMO-10 | 0.238 | 0.238 | 0% |
| Mtghse@Off Lonnie’s Inlet | WMO-08 | 0.192 | 0.192 | 0% |
| Lonnie’s Pond | PBA-15 | 0.246 | 0.246 | 0% |
| Areys Pond | PBA-14 | 0.334 | 0.334 | 0% |
| Namequoit River Upper | WMO-6 | 0.239 | 0.239 | 0% |
| The River-Mouth | PBA-13 | 0.148 | 0.148 | 0% |
| Pochet - Upper off Town Landing | WMO-05 | 0.279 | 0.279 | 0% |
| Pochet - Basin@ Mouth | WMO-03 | 0.146 | 0.146 | 0% |
| Little Pleasant Bay - Head | PBA-12 | 0.139 | 0.139 | 0% |
| Little Pleasant Bay - Main Basin | PBA-21 | 0.132 | 0.133 | +0.8% |
| Pah Wah Pond | PBA-11 | 0.207 | 0.208 | +0.5% |
| Little Quanset Pond | WMO-12 | 0.185 | 0.186 | +0.5% |
| Quanset Pond | WMO-01 | 0.153 | 0.154 | +0.7% |
| Round Cove | PBA-09 | 0.254 | 0.255 | +0.4% |
| Muddy Creek - Upper | PBA-05A | 0.503 | 0.527 | +4.8% |
| Muddy Creek - Lower | PBA-05 | 0.224 | 0.228 | +1.8% |
| Pleasant Bay-Head | PBA-08 | 0.121 | 0.121 | 0% |
| Pleasant Bay- Upper Strong Island | PBA-19 | 0.104 | 0.104 | 0% |
| Pleasant Bay off Muddy Creek | PBA-06 | 0.140 | 0.141 | +0.7% |
| Pleasant Bay lower Strong Island | PBA-20 | 0.103 | 0.103 | 0% |
| Ryders Cove Upper | PBA-03 | 0.218 | 0.219 | +0.5% |
| Ryders Cove Lower | CM-13 | 0.113 | 0.113 | 0% |
| Crows Pond | PBA-04 | 0.116 | 0.116 | 0% |
| Chatham Harbor - Upper | PBA-01 | 0.099 | 0.099 | 0% |

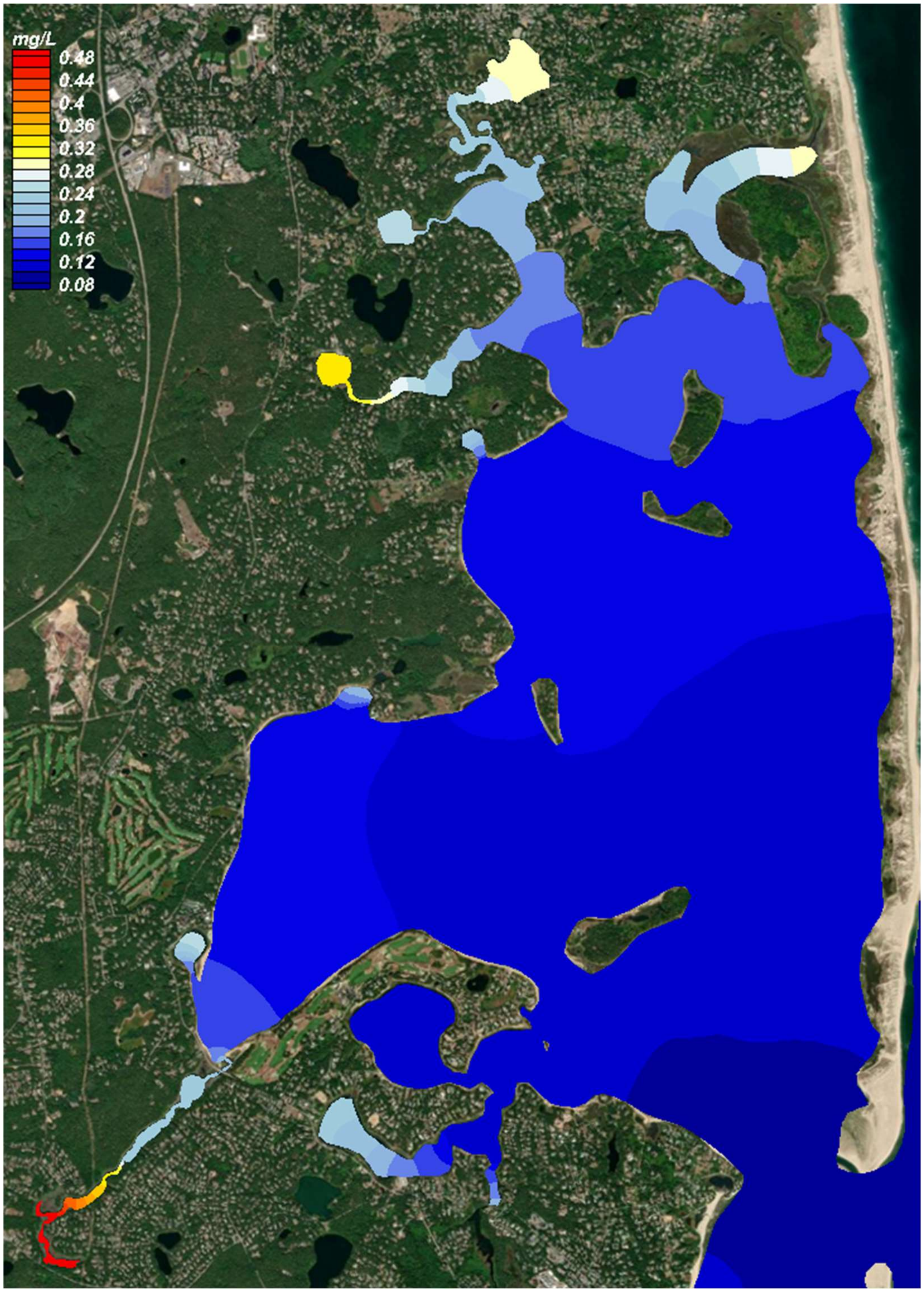

**Figure 1. Tidally averaged Bioactive N concentration (mg/l) throughout the Pleasant Bay system for Scenario 1: SNEP18 existing watershed loading with no Tar Kiln Marsh attenuation.** These concentrations are based on the SNEP18 update, which included updated bathymetry and hydrodynamics, which include the 2019 configuration of the post-2007 breach of north inlet. The selected nitrogen attenuation rate for Tar Kiln Marsh is the same as used in the original MEP assessment. Bioactive N concentrations changed by <1% at 4 of the 25 key monitoring stations and did not change at the other 21 monitoring stations.

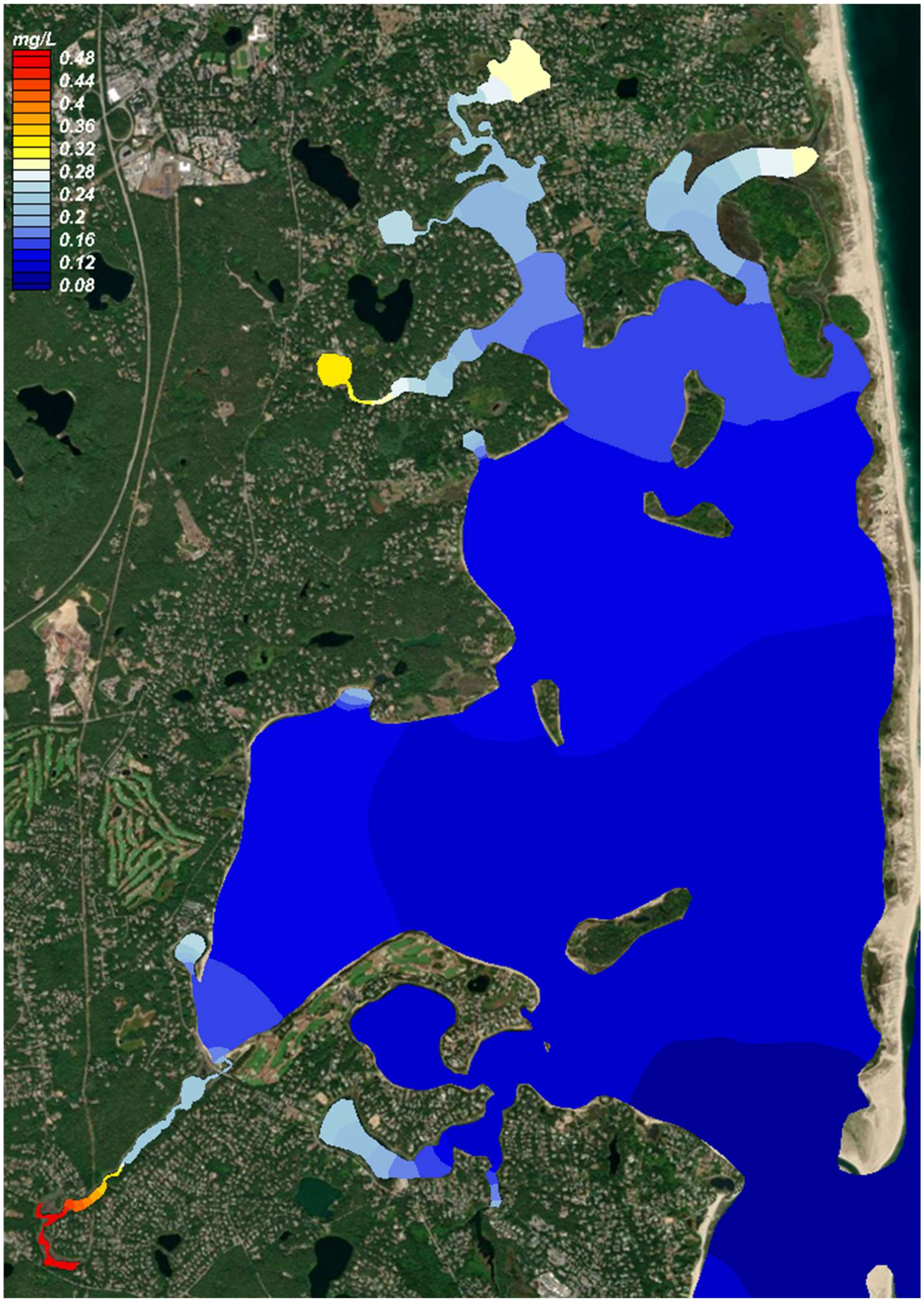

**Figure 2. Tidally averaged Bioactive N concentration (mg/l) throughout the Pleasant Bay system for Scenario 2: SNEP18 existing watershed loading with no Tar Kiln Marsh attenuation and Upper Muddy Creek attenuation reduced to 4%.** These concentrations are based on the SNEP18 update, which included updated bathymetry and hydrodynamics, which include the 2019 configuration of the post-2007 breach of north inlet. The selected nitrogen attenuation rates for Upper Muddy Creek and Tar Kiln Marsh are the same as those in the original MEP assessment. The largest changes in bioactive N concentrations were at the Muddy Creek stations: +4.8% at Upper Muddy Creek (PBA-05A) and +1.8% at Lower Muddy Creek (PBA-05). Another 7 of the 25 stations had concentration changes of <1% and 16 stations had no change.

# REVIEW OF ESTIMATED NITROGEN ATTENUATION IN PLEASANT BAY SUB-EMBAYMENTS

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# REVIEW OF ESTIMATED NITROGEN ATTENUATION IN PLEASANT BAY SUB-EMBAYMENTS

## Introduction

This review was completed for the Pleasant Bay Alliance in response to a request to evaluate two recent reports by the School of Marine Science and Technology (SMAST) of the University of Massachusetts Dartmouth (Eichner et al., 2023; Eichner and Kelley, 2023). The SMAST reports build on prior work for the Massachusetts Estuaries Project (MEP) to develop and apply a linked watershed-embayment model of Pleasant Bay (Howes et al., 2006; Howes et al., 2011). In the first of the two recent reports, Eichner et al. (2023) presented results from new field studies to assess nitrogen attenuation in the Muddy Creek and Pochet Neck sub-embayments of Pleasant Bay. In the second of the two reports, Eichner and Kelley (2023) completed new simulations with the MEP model incorporating different assumptions about attenuation in the Tar Kiln Brook and Upper Muddy Creek sub-embayments. The second report includes no new field data with which to reassess attenuation for those sub-embayments. For that reason, I am not providing a review of that document. The remainder of this review provides an in-depth look at the report by Eichner et al. (2023).

Eduard Eichner of SMAST reviewed drafts of this report and provided helpful discussions and comments on the drafts.

Eichner et al. (2023) completed field studies at two transects to measure the fluxes of water, salinity, and nitrogen components between Pleasant Bay and tributary sub-embayments over the course of several complete tidal cycles. Transects were established between Upper and Lower Muddy Creek and between Pochet Neck and Pleasant Bay. These measurements provided estimates of the net flux of nitrogen from which estimates of attenuation could be inferred. Multiple steps were involved in this process of collecting and processing the data:

1. Continuous measurements were made of water elevation (i.e., tide) and hourly measurements of current velocities. In addition, hourly samples were collected for analysis of salinity, nitrogen and phosphorus species, and chlorophyll-a.
2. The hourly current measurements were used to estimate the corresponding flow through the transect. There is necessarily a degree of approximation in this calculation since current velocities can be measured only at selected locations within the transect cross section.

3. The continuous stage measurements were then used to interpolate flow between the hourly values to construct a continuous record of flow and compute the total volume of water passing through the transect on the ebb and flood tides.
4. The measured salinity and computed flows were then combined to compute salt fluxes for the ebb and flood tides. Based on the salt fluxes, the flow volumes for the incoming flood tide were adjusted up or down such that there was a balance between the incoming salt on the flood tide and outgoing salt on the ebb tide. This procedure thus corrected the estimated water fluxes based on the assumption that the total amount of salt flowing into the sub-embayment would equal the total amount of salt flowing out. This is a reasonable but approximate assumption; while salt content in the sub-embayment could vary from tide cycle to tide cycle, variations are likely to be small. Salinity-based corrections were as high +29% and -26% for Upper Muddy Creek, but only a few percent for Pochet Neck.
5. The salinity-corrected flows were then combined with the hourly nitrogen measurements to compute total nitrogen fluxes on flood and ebb tides.

The nitrogen fluxes computed from this multi-step process provide a field-based estimate of how much nitrogen passes into and out of the sub-embayment on the incoming flood tide and outgoing ebb tide, respectively. I use these newly-measured fluxes in the analysis below to evaluate attenuation.

## Mass Balances

The Massachusetts Estuaries Project (MEP) linked watershed-embayment model (Howes et al., 2006, 2021) considers several different flows of nitrogen into sub-embayments. Nitrogen enters sub-embayments via the flow of groundwater, a load that is computed using the watershed model component of the linked model. Howes et al. (2021, Table II-5) tabulate the annual watershed loads computed with the watershed model for each subwatershed to Pleasant Bay. (One note on terminology: loads and fluxes differ in that loads are measured as mass but fluxes as mass per time. The annual loads tabulated by Howes et al. are reported in kilograms per year and thus are fluxes using a strict definition of that term. For consistency with Howes et al., I retain the term loads here.) Nitrogen also enters each sub-embayment from atmospheric deposition (atmospheric load) and by nitrogen exchange with the mud underlying the sub-embayment (benthic load). Howes et al. (2021, Table IV-2) provide these loads as well.

The fluxes of nitrogen into and out of a sub-embayment can be estimated as the combination of the fluxes that go into the sub-embayment from the watershed, atmosphere, and with the incoming flood tide, the fluxes that go out with the outgoing ebb tide, and the exchange of nitrogen with the mud in the bottom of the sub-embayment (the benthic flux). Benthic flux may be either positive (incoming) or negative (outgoing) but is generally positive within Pleasant Bay. This mass balance is shown in the equation below with benthic flux included as an incoming flux. In principle, the fluxes into and out of the sub-embayment, if fully accounted for, should balance. Equation 1 below defines any imbalance as "lost flux."

Lost Flux = (Fluxes In) – (Fluxes Out)

(Watershed Flux + Atmospheric Flux + Benthic Flux + Flood Tide Flux) – (Ebb Tide Flux) (1)

Flux may be lost due to errors in the estimates or measurements of the component fluxes. Assuming there is no error, a positive value of the lost flux indicates that a portion of the total load into the sub-embayment has been eliminated by various natural processes that have not been fully accounted for. One particular unknown factor in the flux of nitrogen to the sub-embayments is the degree to which the watershed loads may be reduced (attenuated) by biochemical processes in nearshore sediments and wetlands as groundwater discharges to the sub-embayment. Attenuation is factored into calculations in the watershed component of the MEP linked model and as such is applied only to the watershed and atmospheric loads. However, achieving a balance of all fluxes to a sub-embayment may also require reconsideration of the benthic load, which is a component of the embayment model component of the linked model.

## Upper Muddy Creek

The nitrogen fluxes to Upper Muddy Creek are compiled in Table 1 in units of kilograms per day. Table 1 includes the watershed, atmospheric, and benthic loads derived by Howes et al. (2021) plus the tidal fluxes determined by Eichner et al. (2023) from field data collection. The incoming and outgoing tidal fluxes in grams over a tidal cycle were divided by the time in hours between subsequent low tides so as to compute a rate in grams per hour that was then converted to kilograms per year.

## Table 1
## Nitrogen Balances for Upper Muddy Creek

### Total Nitrogen

| Field measurements | | | | Other incoming loads | | | | Mass balance | | | Attenuation | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Survey date | Flood TN flux | Ebb TN flux | Net TN flux out | Watershed flux[1] | Atmospheric flux[2] | Benthic flux[3] | Total non-tidal flux | Total flux in | Total flux out | Lost flux | As percentage of total flux in | As percentage of watershed + atmospheric flux |
| | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | % | % |
| 06/12/2022 | 17,646 | 16,907 | -739 | 5,000 | 62 | 458 | 5,520 | 23,166 | 16,907 | 6,259 | 27% | 100% |
| 07/10/2022 | 11,732 | 16,265 | 4,533 | 5,000 | 62 | 458 | 5,520 | 17,252 | 16,265 | 987 | 6% | 19% |
| 08/09/2022 | 26,519 | 25,851 | -668 | 5,000 | 62 | 458 | 5,520 | 32,040 | 25,851 | 6,188 | 19% | 100% |

### Bioactive Nitrogen

| Field measurements | | | | Other incoming loads | | | | Mass balance | | | Attenuation | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Survey date | Flood Bioactive N flux | Ebb Bioactive N flux | Net Bioactive N flux out | Watershed flux | Atmospheric flux | Benthic flux | Total non-tidal flux | Total flux in | Total flux out | Lost flux | As percentage of total flux in | As percentage of watershed + atmospheric flux |
| | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | % | % |
| 06/12/2022 | 10,525 | 10,175 | -350 | 5,000 | 62 | 458 | 5,520 | 16,045 | 10,175 | 5,871 | 37% | 100% |
| 07/10/2022 | 5,023 | 6,390 | 1,367 | 5,000 | 62 | 458 | 5,520 | 10,543 | 6,390 | 4,154 | 39% | 82% |
| 08/09/2022 | 6,039 | 10,203 | 4,165 | 5,000 | 62 | 458 | 5,520 | 11,559 | 10,203 | 1,355 | 12% | 27% |

[1] Howes et al., 2021, Table II-5 (Existing N load, attenuated) without 10% attenuation for Upper Muddy Creek. This retains attenuation from upstream ponds, but removes it for Muddy Creek itself.

[2] Howes et al., 2021, Table IV-2 (Direct atmospheric deposition).

[3] Howes et al., 2021, Table IV-2 (Benthic flux net).

The "Field measurements" columns in upper portion of Table 1 show that the total nitrogen balance for Upper Muddy Creek is strongly influenced by nitrogen carried in and out of Upper Muddy Creek with the tide. On June 12 and August 9, 2022, the total nitrogen (TN) carried into Upper Muddy Creek by the flood tide exceeded the nitrogen carried out by the ebb tide, indicating a net loss of nitrogen within Upper Muddy Creek ("Net TN flux out" is negative in Table 1). The opposite occurred on July 10, which showed a relatively larger net gain of nitrogen despite lesser in and out tidal fluxes.

The "Other incoming loads" columns of Table 1 tally the watershed, atmospheric, and benthic loads as reported by Howes et al. (2021). (The atmospheric flux is separated out in Table IV-2 by Howes et al. (2021) but is in fact included as part of the watershed load in the underlying calculations and is thus modified by attenuation along with the watershed load.)

The "Mass balance" columns in Table 1 add up the various loads into Upper Muddy Creek according to Equation 1. On all three dates, the total nitrogen flux into Upper Muddy Creek exceeds the total out, indicating a net loss of total nitrogen within Upper Muddy Creek.

Eichner et al. (2023) evaluate both total nitrogen and bioactive nitrogen in their analysis of the results of the field survey. The bottom portion of Table 1 provides a mass balance for Upper Muddy Creek based on only bioactive nitrogen species. Bioactive nitrogen (also called bioavailable nitrogen) is taken by Eichner et al. as the sum of inorganic nitrogen and particulate organic nitrogen. Jørgensen et al. (2014) also include a fraction of dissolved organic nitrogen (DON) as bioactive, but the bioactive fraction of ocean-derived DON is small and neglecting the contribution of DON to bioactive nitrogen is a practical approach. In some respects, bioactive nitrogen is a superior indicator of attenuation than total nitrogen in that the watershed and atmospheric load are essentially all bioactive nitrogen while a substantial portion of the nitrogen carried into the sub-embayment by the flood tide is non-bioactive dissolved organic nitrogen.

Table 1 shows a seeming discrepancy with respect to benthic flux in Howes et al. (2021). Table II-7 of that report shows the mean nitrogen flux from Upper Muddy Creek sediments to be –2.7 mg N/m$^2$/day based on sediment sampling, where the minus sign indicates that nitrogen is taken up by the sediments. However, Table IV-2, which is the source of the benthic loads in Table 1, shows the net benthic flux in Upper Muddy Creek to be 1.255 kg/day—a positive rather than negative load. Eduard Eichner (personal communication) explained that these are indeed opposite in sign since the benthic fluxes used in the embayment model (Table IV-2) were adjusted in the process of calibrating the model and superseded those determined from sediment sampling.

The two right-hand columns of Table 1 compute attenuation by comparing the lost flux to the total incoming flux and to the watershed flux (including atmospheric flux). Computing attenuation as a percentage of the total flux recognizes that attenuation processes in Upper Muddy Creek are agnostic as to the source of nitrogen and will act on nitrogen from the incoming tide and watershed loads alike. In this sense, the lost flux in Table 1 should be taken as being lost from watershed and tidal fluxes more or less equally. This is also a conservative approach in that it would tend to lead to more stringent measures to control watershed nitrogen. The attenuation computed based on total flux in varies between 6% and 39% over both total nitrogen and bioactive nitrogen. A rough average of 25% attenuation appears justified based on Table 1.

An alternative but much less conservative interpretation is that based on comparing the lost nitrogen to the watershed (including atmospheric) flux only. In Table 1, the field surveys show the lost flux exceeded the watershed flux for total nitrogen on June 12 and August 8 and for bioactive nitrogen on June 12. These comparisons could be taken to imply complete attenuation of the watershed total nitrogen load. However, the error in that interpretation can be seen in the nitrogen concentrations provided by Eichner et al. in Figure 4. Figure 4 shows that nitrogen concentrations tend to be higher on the outgoing tide than on the incoming tide, particularly for bioactive nitrogen. The difference is most dramatic between the concentrations just before tidal reversals. Concentrations at the field transect over the tidal cycle will represent a variation in the mix of inflowing Lower Muddy Creek/Pleasant Bay water and outflowing Upper Muddy Creek water. Concentrations at the end of flood tide (at T5 and T6 in Figure 4) are most representative of Lower Muddy Creek/Pleasant Bay water while concentrations at the end of ebb tide (at T12 to T14) are most representative of Upper Muddy Creek water. Ebb tide tends to show much higher concentrations of bioactive nitrogen than flood tide, implying that bioactive watershed fluxes into Upper Muddy Creek are incompletely attenuated. Dissolved inorganic nitrogen, which is the form of nitrogen presumed to dominate the watershed load, shows a similar trend of higher ebb tide concentrations (Eduard Eichner, personal communication).

Based on Table 1, I recommend an attenuation factor of 25% for Upper Muddy Creek. While there is variation in the results from the different field surveys and depending on whether the analysis is made with total nitrogen or bioactive nitrogen, the average of the results points to attenuation in this general range. Attenuation of this magnitude is unsurprising. A fair portion of Upper Muddy Creek is wetlands (White et al., 2008) and would be expected to assimilate nitrogen as plant life grows. This is in fact the concept behind constructed wetlands as a best management practice for stormwater treatment (Massachusetts DEP, 2008) and that concept appears to apply here as well.

## Lower Muddy Creek

The field surveys conducted in 2022 made measurements at the weir between Upper and Lower Muddy Creek but not the culvert between Lower Muddy Creek and Pleasant Bay. Field surveys were completed at both transects in 2008 (White et al., 2008), but those precede the reconstruction of the culvert at the mouth of Lower Muddy Creek. Tidal flushing has increased dramatically since the culvert reconstruction and the older survey results represent much different conditions than currently exist and are no longer applicable.

The two field surveys completed in June and July 2008 by White et al. (2008) showed significant attenuation in Upper Muddy Creek (55% and 57%) but much less for Muddy Creek as a whole (1% and 41%). Attenuation rates for Muddy Creek were revisited by Eichner et al. (2010a) and Howes et al. (2021) after the watershed loads to Muddy Creek were recalculated based on updated information on water use and land use. Loads increased from the model by Howes et al. (2006), which led to still higher attenuation rates when compared to the fluxes measured in the field; a footnote to Table II-3 in Howes et al. (2021) gives the revised rates from 2010 as 2% and 59% for Muddy Creek as a whole. These were further revised by Howes et al. (2021) based on water quality data to 10% for Upper Muddy Creek and 0% for Lower Muddy Creek. Unfortunately, none of these previously determined rates can still be considered applicable since conditions in Muddy Creek have been changed.

In my previous analysis of attenuation (Shanahan, 2022), I used a formula from the literature (Saunders and Kalff, 2001) to estimate an attenuation factor of 64% for both Upper and Lower Muddy Creek. As I note in my earlier report, the estimate should be considered "highly approximate."

The fact that recent field surveys point to potentially significant attenuation in Upper Muddy Creek since the installation of the new culvert suggests there may be attenuation in Lower Muddy Creek as well. This conclusion is tempered by the observation that there is less wetland area in Lower Muddy Creek than in Upper (White et al., 2008). Nonetheless, there may be value in conducting additional field studies to measure nitrogen fluxes across a transect at the outlet culvert of Lower Muddy Creek and develop attenuation rates for Lower Muddy Creek that reflect current conditions.

## Pochet Neck

Field surveys were also conducted in 2022 at a transect at Pochet Neck (Eichner et al., 2023). The field data were processed and analyzed by Eichner et al. in the same way as for Upper Muddy Creek.

A summary of the field-measured fluxes along with the watershed, atmospheric, and benthic fluxes is provided in Table 2. The results for Pochet Neck differ significantly from those for Upper Muddy Creek in that tidal fluxes dwarf those from other sources, particularly for total nitrogen. Watershed flux is less than 2.5% of the ebb tide flux during all three surveys. This implies that the computed attenuation will be very sensitive to errors in the field-determined fluxes.

The results of the total nitrogen mass balances for Pochet Neck are mixed. The "lost flux" for June 12 survey exceeds the total non-tidal flux, implying that those loads were completely attenuated. However, the lost fluxes for the July and August surveys are negative, implying zero attenuation plus potential additional incoming fluxes. The July and August surveys are potentially more accurate than the June survey because the tidal fluxes were less. However, any potential improvement in accuracy is minor since the watershed flux remains a small fraction of the tidal fluxes during those surveys as well.

The mass balances for bioactive nitrogen in the lower portion of Table 2 are relatively consistent in that the lost flux is small relative to the flood and ebb tide fluxes.

My conclusion from the collected data and the analysis above is that there is no clear indication in the data that attenuation is reducing watershed loads from Pochet Neck. However that conclusion comes with the strong caveat that the large tidal fluxes at the field transects make any estimates of attenuation highly uncertain.

Table 2
Nitrogen Balances for Pochet Neck

| Field measurements | Other incoming loads | Mass balance |
|---|---|---|

## Total Nitrogen

| Survey date | Flood TN flux | Ebb TN flux | Net TN flux out | Watershed flux[1] | Atmospheric flux[2] | Benthic flux[3] | Total non-tidal flux | Total flux in | Total flux out | Lost flux |
|---|---|---|---|---|---|---|---|---|---|---|
| | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year |
| 06/12/2022 | 206,430 | 200,335 | -6,095 | 3,074 | 651 | 4,796 | 7,870 | 214,300 | 200,335 | 13,964 |
| 07/10/2022 | 127,010 | 139,753 | 12,744 | 3,074 | 651 | 4,796 | 7,870 | 134,879 | 139,753 | -4,874 |
| 08/09/2022 | 118,650 | 126,813 | 8,163 | 3,074 | 651 | 4,796 | 7,870 | 126,519 | 126,813 | -294 |

## Bioactive Nitrogen

| Survey date | Flood BioN flux | Ebb BioN flux | Net BioN flux out | Watershed flux[1] | Atmospheric flux[2] | Benthic flux[3] | Total non-tidal flux | Total flux in | Total flux out | Lost flux |
|---|---|---|---|---|---|---|---|---|---|---|
| | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year | kg/year |
| 06/12/2022 | 76,551 | 86,135 | 9,583 | 3,074 | 651 | 4,796 | 7,870 | 84,421 | 86,135 | -1,713 |
| 07/10/2022 | 46,289 | 52,699 | 6,409 | 3,074 | 651 | 4,796 | 7,870 | 54,159 | 52,699 | 1,460 |
| 08/09/2022 | 47,583 | 55,790 | 8,208 | 3,074 | 651 | 4,796 | 7,870 | 55,452 | 55,790 | -338 |

1 Howes et al., 2021, Table II-5 (Existing N load, attenuated)

2 Howes et al., 2021, Table IV-2 (Direct atmospheric deposition).

3 Howes et al., 2021, Table IV-2 (Benthic flux net).

One final observation is that roughly half of the Pochet Neck watershed load enters upstream of where Pochet Road crosses the estuary. At least on the map, Pochet Road crosses a narrow stretch of open water and may be a workable location for a field transect. There is extensive salt marsh upstream of Pochet Road and thus potentially significant attenuation capacity. There is also much less open water north of Pochet Road than south, which would reduce the magnitude of tidal fluxes at a Pochet Road transect. For these reasons, an additional field survey at the Pochet Road transect has the potential to identify meaningful attenuation and reduce or eliminate the need to control watershed loads from north of Pochet Road.

The loads north of Pochet Road originate from Subwatersheds 56 and 57 as well as portions of 54 and 55 in the MEP model. Were strong attenuation identified in a field survey, it could be worthwhile to subdivide Subwatersheds 54 and 55 to separate the portions of the watershed that lie north and south of the Pochet Road transect and develop a more precise prediction of the watershed loads.

## Conclusions and Recommendations

Nitrogen-exchange field surveys completed by Eichner et al. (2023) provide new information on potential attenuation of watershed loads into Muddy Creek and Pochet Neck. This information is valuable because nitrogen-exchange surveys have not previously been completed at Pochet Neck and were completed at Muddy Creek before construction of a new culvert that substantially modified its tidal exchange with Pleasant Bay.

My assessment of the survey results along with other data from prior SMAST reports is that an attenuation factor of 25% can be applied to watershed loads entering Upper Muddy Creek. This is an approximate number because there is considerable variability between the three different field surveys conducted on Upper Muddy Creek and because the attenuation estimate depends on watershed, atmospheric, and benthic loads from the MEP models that are inherently approximate.

No new data were collected for Lower Muddy Creek and no new conclusions can be drawn regarding attenuation to that portion of Muddy Creek. A field survey of Lower Muddy Creek could be useful to collect new information on Lower Muddy Creek, which has been extensively altered by construction of the new culvert.

The survey results for Pochet Neck provide no clear indication that a non-zero attenuation factor can be applied to those watershed loads. However, this conclusion is tempered by the fact that tidal loads greatly exceed watershed loads and thus could mask any attenuation effects. An additional field survey at a more inland transect at Pochet Road would be less dominated by tidal flows and could yield useful information on attenuation in the upper reaches of Pochet Neck.

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# Appendix D

WRIGHT-PIERCE
Engineering a Better Environment

# Memorandum

Date: **12 September 2024 (Draft)**

Project No.: **13351E**

To: **Carole Ridley, Pleasant Bay Alliance**

From: **Mike Giggey**

Subject: **Changes to the Pleasant Bay Watershed Permit**
**Revised Nitrogen Removal Requirements**

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One of the principal reasons to modify the Pleasant Bay Watershed Permit is to address changes in the nitrogen removal requirements that result from the new watershed permitting regulations and the technical findings of studies completed since the original permit. This memo summarizes the analyses and results of the efforts to revise the nitrogen removal requirements. (This memo supersedes a similar Wright-Pierce memo dated 17 July 2024 and reflects changes in the towns' growth and attenuation estimates since that initial evaluation.)

Table 2 of the Targeted Watershed Management Plan (TWMP) sets forth the current nitrogen removal requirements for each town in each sub-watershed. I have prepared an updated version of the TWMP Table 2 for consideration by the Watershed Work Group; see attached. I have labeled this as Table 2 (Revised). (There is no Table 1 attached to the memo.)

Table 2 (Revised) reflects changes in three areas:

- Incorporation of **growth** in watershed loads beyond those included in current Watershed Permit
- **Disaggregation** of the previously-combined Pleasant Bay sub-watershed into four parts, and
- Revisions to estimated **attenuation** amounts in Muddy Creek, Tar Kiln Stream and Pochet Neck

The Watershed Permit requires the four towns to remove 17,717 kg/yr across the entire watershed. Changes in these three areas increase that requirement by 8,216 kg/yr (46%) to 25,933 kg/yr. The individual town changes are:

| | | | |
|---|---|---|---|
| Brewster | reduction of | 223 kg/yr | ( 10%) |
| Chatham | increase of | 4,869 kg/yr | (120%) |
| Harwich | increase of | 3,235 kg/yr | ( 74%) |
| Orleans | increase of | 335 kg/yr | ( 5%) |
| Overall | increase of | 8,216 kg/yr | ( 46%) |

## Growth

The four watershed towns have conducted analyses to estimate the increase in watershed loads that 1) have occurred since the 2006 MEP report and SMAST's 2010 refinements, and 2) are expected to occur into the future. The Wright-Pierce memo dated 4 September 2024 provides details on the methodology and results of this exercise. Comments previously made by DEP and the Commission were addressed in that 4 September memo, and both DEP and the Commission provided approval of that document on 11 September 2024.

The increases in attenuated watershed loads are detailed as follows, along with the planning horizons adopted by each town. These growth figures include the same attenuation percentages that are the basis of the current Watershed Permit, to allow a direct comparison and the computation of percentage increases.

| | | Brewster | Chatham | Harwich | Orleans | Total |
|---|---|---|---|---|---|---|
| Growth in Attenuated Watershed Load, kg/yr | | 553 | 4,031 | 1,243 | 880 | 6,707 |
| % increase from MEP | | 8.7% | 24.3 | 11.4% | 6.0% | 13.8% |
| Planning Horizon | | Build out | Build out | 2040 | 2043 | |

## Dis-Aggregation of Pleasant Bay Sub-Watershed

In the Targeted Watershed Management Plan, which is the basis of the current Watershed Permit, the "Pleasant Bay" sub-watershed was treated as a single sub-watershed because then-available data required the aggregation of load and thresholds for four of the sub-watersheds evaluated the MEP report (Pleasant Bay Main, Little Pleasant Bay, Tar Kiln Stream and the Horseshoe). An analysis was conducted in 2023 to allow the dis-aggregation of "Pleasant Bay" into its four parts. That analysis resulted in small changes in attenuated watershed loads as follows.

| | | Brewster | Chatham | Harwich | Orleans | Total |
|---|---|---|---|---|---|---|
| Change in Attenuated Watershed Load due to Dis-aggregation, kg/yr | | 6 | 67 | -442 | 37 | -332 |
| % reduction from TWMP | | 0.1% | 0.4% | -4.2% | 0.3% | -0.7% |

While the changes in attenuated loads are small, the dis-aggregation process has allowed the separate consideration of new attenuation data for the Tar Kiln Stream sub-watershed.

## Attenuation

The Alliance has conducted several studies to better understand the amount of nitrogen reduction that occurs naturally as nitrogen loads pass though the sub-watersheds and at the watershed-embayment boundaries. The modified attenuation rates decrease the overall attenuation amounts by 612 kg/yr, as follows:

| Change in Natural Attenuation, kg/yr | | Brewster | Chatham | Harwich | Orleans | Total |
|---|---|---|---|---|---|---|
| Muddy Creek—Upper (from 57% to 10%) | | | -580 | -1,790 | | -2,370 |
| Muddy Creek—Lower (from 2% to 0%) | | | -30 | -50 | | -80 |
| Tar Kiln Stream (from 0% to 60%) | | 1,265 | | | 103 | 1,368 |
| Pochet Neck (from 0 to 470 kg/yr) | | | | | 470 | 470 |
| Total | | 1,265 | -610 | -1,840 | 573 | -612 |

While the overall net change in attenuation amounts is small (about 10% of the amount used in the current Watershed Permit), these changes have significant impacts on the towns' nitrogen removal responsibilities in these specific sub-watersheds.

The changes in load removal requirements reflect these modifications:

- Growth increases watershed load by 7,028 kg/yr (with revised atten.)
- Disaggregation decreases watershed load by 332 kg/yr
- Changes in attenuation increase watershed load by 612 kg/yr

Table 2 (Revised) has 33 entries. In 22 entries, the increase in load removal requirement is numerically equal to the growth in watershed load. In the other entries, 2 or 3 of the factors influence the net change.

Given the importance of these changes in nitrogen removal requirements, I have prepared this Table 2 (Revised) as a draft for consideration at the next Watershed Work Group meeting. Because town plans must address these changes, it will be important for this draft to receive early and thorough review.

**PLEASANT BAY ALLIANCE**

**Table 2 (Revised): Nitrogen Removal Requirements** *Draft #2* *12-Sep-24*

| | | Nitrogen Load Removal Requirements, kg/yr | | | | | |
|---|---|---|---|---|---|---|---|
| **Sub-Watershed** | **Basis** | **Brewster** | **Chatham** | **Harwich** | **Orleans** | **Total** | **Increase** |
| MtgHouse Pond | TWMP | | | | 1,876 | 1,876 | |
| | Revised | | | | 2,265 | 2,265 | 21% |
| Lonnnie's Pond | TWMP | 14 | | | 284 | 298 | |
| | Revised | 44 | | | 251 | 295 | -1% |
| Arey's Pond | TWMP | 29 | | | 113 | 142 | |
| | Revised | 39 | | | 236 | 275 | 94% |
| The River--Upper | TWMP | 3 | | | 375 | 378 | |
| | Revised | 11 | | | 305 | 316 | -16% |
| The River--Lower | TWMP | 6 | | | 518 | 524 | |
| | Revised | 20 | | | 495 | 515 | -2% |
| Namequoit River | TWMP | 19 | | | 348 | 367 | |
| | Revised | 42 | | | 353 | 395 | 8% |
| Pah Wah Pond | TWMP | - | | | 413 | 413 | |
| | Revised | - | | | 435 | 435 | 5% |
| Quanset Pond | TWMP | 29 | | | 227 | 256 | |
| | Revised | 51 | | | 98 | 149 | -42% |
| Round Cove | TWMP | 1 | | 1,209 | | 1,210 | |
| | Revised | 2 | | 1,349 | | 1,351 | 12% |
| Muddy Ck--Upper | TWMP | | 193 | 584 | | 777 | |
| | Revised | | 1,050 | 2,835 | | 3,885 | 400% |
| Muddy Ck--Lower | TWMP | | 584 | 986 | | 1,570 | |
| | Revised | | 924 | 1,536 | | 2,460 | 57% |
| Ryder's Cove | TWMP | | 1,954 | | | 1,954 | |
| | Revised | | 2,939 | | | 2,939 | 50% |
| Crows Pond | TWMP | | - | | | - | |
| | Revised | | 354 | | | 354 | |
| Bassing Harbor | TWMP | | - | | | - | |
| | Revised | | 178 | | | 178 | |
| Frost Fish Ck | TWMP | | 803 | | | 803 | |
| | Revised | | 1,099 | | | 1,099 | 37% |

| | | Nitrogen Load Removal Requirements in kg/yr | | | | | |
|---|---|---|---|---|---|---|---|
| **Sub-Watershed** | **Basis** | **Brewster** | **Chatham** | **Harwich** | **Orleans** | **Total** | **Increase** |
| Pochet Neck | TWMP | | | | 1,569 | 1,569 | |
| | Revised | | | | 1,170 | 1,170 | -25% |
| PB-aggregated | TWMP | 2,161 | 542 | 1,620 | 1,257 | 5,580 | |
| | Revised | | | | | - | |
| The Horseshoe | TWMP | | | | | - | |
| | Revised | | | | - | - | |
| Pleasant Bay Main | TWMP | | | | | - | |
| | Revised | 1,348 | 704 | 1,627 | 761 | 4,440 | |
| Little Pleasant Bay | TWMP | | | | | - | |
| | Revised | 482 | 249 | 287 | 946 | 1,964 | |
| Tar Kiln Stream | TWMP | | | | | - | |
| | Revised | - | | | - | - | |
| Chatham Harbor | **TWMP** | | **-** | | | **-** | |
| | **Revised** | | **1,448** | | | **1,448** | |
| **Total** | TWMP | 2,262 | 4,076 | 4,399 | 6,980 | 17,717 | |
| | Revised | 2,039 | 8,945 | 7,634 | 7,315 | 25,933 | |
| | Incr, kg/yr | (223) | 4,869 | 3,235 | 335 | 8,216 | |
| | *Incr, %* | *-9.9%* | *119.5%* | *73.5%* | *4.8%* | *46.4%* | |