The Town of Barnstable
Department of Public Works
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Daniel W. Santos, P.E.
Director

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Assistant Director

MEMORANDUM

To: Mark S. Ells, Town Manager

From: Daniel W. Santos, P.E., Director

Date: July 5, 2022

Subject: Shubael Pond Management Plan – Solution Recommendation

The Department of Public Works (DPW) retained the Coastal Systems Program at UMass Dartmouth School for Marine Science and Technology (SMAST) to conduct a nutrient diagnostic assessment of Shubael Pond and develop a management plan to address water quality issues. Please find the details of this study in the *Shubael Pond Nutrient Diagnostic Assessment and Management Plan* (April 2022).

This study found that Shubael Pond is being negatively impacted by excess phosphorus loading, the largest source of which is septic systems, and that management of phosphorus inputs is necessary to improve water quality.

Based on the report's conclusions, DPW is recommending the following actions to help mitigate the impact of phosphorus on Shubael Pond:

1. Sewers –
   - Advance the timeline for sewering the homes located the Shubael Pond contributing watershed from Phase 3 to Phase 2 of the Comprehensive Wastewater Management Plan.
2. Alum –
   - In the interim, prior to installation of the sewers it is recommended alum treatment(s) be used to address the internal phosphorus loading source and improve water quality.
   - It is expected that alum treatments in Shubael Pond are anticipated to last 3-7 years at a cost of ~$50,000 each treatment. DPW recommends incorporating adaptive management through water quality monitoring to evaluate the effectiveness of any given alum treatment and assess if additional treatments are needed.
   - Alum treatments will not eliminate all potential for cyanobacteria blooms, but will help reduce the available phosphorus, improve water quality, and reduce the frequency of blooms.
3. Stormwater Improvements –
   - DPW will continue to work to fund and expedite proposals to reduce stormwater inputs around the pond.
   - These inputs make up the smallest portion of the phosphorus load to the pond and stormwater improvements alone will not eliminate the potential for cyanobacteria blooms.

Shubael Pond Management Plan and Diagnostic Assessment

FINAL REPORT

April 2022

for the

Town of Barnstable

Prepared by:

Coastal Systems Group
School for Marine Science and Technology
University of Massachusetts Dartmouth
706 South Rodney French Blvd.
New Bedford, MA 02744-1221

Shubael Pond Management Plan and Diagnostic Assessment

FINAL REPORT

April 2022

Prepared for

Town of Barnstable
Department of Public Works

Prepared By

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Cover photo: Shubael Pond (9/28/21)

Acknowledgements

The authors acknowledge the contributions of the many individuals and boards who have worked tirelessly for the restoration and protection of the ponds and lakes within the Town of Barnstable. Without these pond stewards and their efforts, this project would not have been possible and restoration of Shubael Pond might not occur.

The authors also specifically recognize and applaud the generosity of time and effort spent by all Barnstable Pond and Lake Stewards (PALS), both past and present members. The individuals who participated in PALS Snapshots and supported pond and lake management activities within the town have provided reliable water quality data and advocacy support that has made the development of this management plan possible. Among these stewards particular thanks go to Lindsey Counsell, Meg Materne, and volunteers/staff at Barnstable Clean Water Coalition (nee Three Bays Preservation) and Dale Saad, former Town sampler. The authors thank all involved for their support and advocacy for Barnstable ponds.

In addition to these contributions, technical and project support has been freely and graciously provided by Griffin Beaudoin and Amber Unruh at the Town of Barnstable Department of Public Works and Sara Sampieri, Jennifer Benson, Roland Samimy, Micheline Labrie, Paul Mancuso, Lara Pratt, Alan Austin, Dale Goehringer, and others at the Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth.

Recommended Citation

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Executive Summary

Shubael Pond Management Plan and Diagnostic Assessment

FINAL REPORT
April 2022

Shubael Pond is a 56 acres Great Pond.[1] As such, Shubael Pond water quality management has to address local concerns, as well as regulatory requirements of the Massachusetts Department of Environmental Protection (MassDEP) in its implementation of the federal Clean Water Act. It thermally stratifies in the summer with deep water temperatures consistently low enough to meet the MassDEP cold water fishery criterion.

Prior to this project, water quality sampling of Shubael Pond has generally been limited to the annual, late-summer Cape-wide Pond and Lakes Stewards (PALS) Snapshot. Review of data from 13 Snapshots indicated that the Shubael Pond had "borderline impaired water quality in its shallow waters, but significantly impaired conditions in the deeper bottom waters due to low DO concentrations and high TP, TN, and chlorophyll a concentrations."[2] The Town's Health Division has also closed the pond in both 2019 and 2020 due to cyanobacteria concerns.[3] The 2021 pond data review was initiated as part of the Town Department of Public Works (DPW) effort to develop a comprehensive town-wide Pond and Lakes Program that would interface with the Comprehensive Wastewater Management Plan (CWMP). As a result of town-wide pond water quality data review, Barnstable DPW initially prioritized Shubael Pond, Long Pond (Marstons Mills) and Lovells Pond for management plans.

The present Shubael Pond Management Plan is primarily composed of two sections: 1) a Diagnostic Assessment of how the pond ecosystem generally functions based on the available historic water column data and 2020 data gap investigations and 2) a Management Options Summary, which identifies a proposed total phosphorus (TP) threshold for acceptable water quality and reviews applicable options to attain the threshold, their estimated costs, and likely regulatory issues. It is anticipated that the Town will work through a process to review the recommendations and choose a preferred implementation strategy for restoration of Shubael Pond water and habitat quality.

Data gaps surveys for Shubael Pond included: a) watershed delineation and watershed land use analysis, b) measurement of water quality conditions throughout a summer (*e.g.*, nine samplings between May and December 2020), c) measurements of direct stormwater discharge, d) collection of sediment cores and incubations to measure rates of TP and TN regeneration during different dissolved oxygen (DO) conditions, and e) collection of phytoplankton samples to understand how the population changes (including blue-green/cyanobacteria blooms) due to nutrient availability.

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[1] MGL c. 91 § 35 asserts that all ponds greater than 10 acres are "Great Ponds" and are publicly owned.

[2] Eichner, E. and B. Howes. 2021. Town of Barnstable Freshwater Ponds, 2021 Water Quality Monitoring Database: Development and Review. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 106 pp.

[3] Cyanobacteria are typically part of the phytoplankton population in impaired pond and are also variously referred to as blue-green algae, cyanophytes, blue-greens, etc.

Temperature profiles in 2020 showed regular, strong stratification with a warm, well-mixed upper layer and a cold deep bottom layer isolated from atmospheric mixing to replenish diminished DO. This temperature stratification began to weakly develop in May, was strongly in place by June and persisted through September. The deep layer consistently meets MassDEP temperature criterion for a cold water fishery, but once temperature stratification was established in June, anoxia (DO <1 mg/L) developed in this layer and increased throughout the summer. In the September 2020 profile, the whole cold layer was anoxic and anoxia was also measured in the transition zone between the cold and warm layers. Every completed PALS profile collected in August or September between 2001 and 2020 had anoxia in the deepest waters. DO concentrations less than the MassDEP 6 mg/L minimum are defined as impaired under state regulations and anoxia throughout the deep layer would not allow a cold water fishery to be sustained throughout the year.

Review of nutrient concentrations showed impairments throughout the water column of Shubael Pond and that phosphorus is the key nutrient for determining water quality conditions. TP concentrations in Spring 2020, prior to stratification, were generally acceptable with TP at or slightly greater than the Ecoregion threshold of 10 µg/L. Once stratification was established, anoxia caused sediment TP regeneration in the deep layer and TP concentrations increased throughout the water column. In September 2020, shallow and deep TP concentrations were greater than 14 µg/L and 40 µg/L, respectively. Trend analysis showed that watershed and sediment TP impacts are increasing each year; between 2001 and 2020 shallow PALS TP concentrations increased approximately 0.6 µg/L per year. With increased TP concentrations, chlorophyll a concentrations, which reflect phytoplankton growth, also increased with shallow concentrations regularly above the 1.7 µg/L Ecoregion threshold. Phytoplankton sampling showed that cyanobacteria were present in all monthly samples except in May and had a significant increase in July 2020, but cell counts were consistently less than 10% of the Massachusetts Department of Public Health criterion for pond closure throughout the summer. Project staff recommend that water column TP be limited to 11 kg; acceptable water quality was measured throughout the water column at this mass and meeting this goal should result in restoration of the system and elimination of the measured impairments.

Comparison of watershed and summer sediment nutrient inputs showed that septic system wastewater was the primary source of TP to Shubael Pond, but the parcels contributing to the pond needs to be refined. There is an established pond watershed delineated by the US Geological Survey (USGS) for the Massachusetts Estuaries Project (MEP), but there is new provisional USGS water table data near the pond, that is not yet publicly available, that suggests a smaller watershed. Review of land use and septic systems (*e.g.*, their age and distance to the pond) shows that septic system TP is the primary source of water column TP for either watershed delineation (77% to 86% of the spring TP contribution), but the watershed differences are important for determining the pond water residence time and associated water column concentrations, as well as defining which land areas should be managed to reduce TP sources (there are 27 or 13 septic systems contributing TP from the MEP watershed or the provisional watershed, respectively). Summer sediment TP additions vary depending on the depth and duration of bottom water anoxia, but the review shows that even at maximum sediment regeneration rates, septic systems remain the largest current source of water column TP (59% to 74% of the summer TP contribution). Sediment regeneration is estimated to account for 14% to 23% of the summer water column TP, while stormwater runoff varies between 4% and 7% and direct precipitation on the pond surface varies between 7% and 15%.

Review of wastewater options should be the primary part of a management plan since septic system TP are the largest source to the pond. Phase 3 of the Town CWMP, which is targeted for 21 to 30 years from now, includes sewering most of the parcels in the USGS/MEP watershed. This sewering will leave five parcels unsewered in either watershed version. Planned sewering plus average summer sediment contributions will achieve the recommended 11 kg TP restoration threshold goal for either watershed delineation. Sediments have the potential to become a larger management concern if the provisional watershed is considered. Although planned sewering can achieve the TP restoration goals for Shubael Pond, the current implementation schedule would lead to 20 to 30 years of worsening water quality prior to restoration.

TP-reducing septic systems were also evaluated and their use throughout both versions of the watersheds would also meet the recommended 11 kg TP restoration goal in most watershed and sediment loading scenarios. There are currently three types of these septic systems that are approved by MassDEP under "piloting" review. Their MassDEP approvals state that they reduce TP effluent concentrations to 0.3 mg/L or 1 mg/L. The piloting status means they are somewhat experimental and only 15 of each type of system can be installed throughout Massachusetts and each installation requires extensive performance monitoring. Preliminary cost estimates associated with replacing the 13 existing septic systems in the provisional watershed or 27 in the USGS/MEP watershed with the installation of one of the types of phosphorus-reducing septic systems are $332,000 and $689,000, respectively.

Although wastewater is the primary source of TP to Shubael Pond, project staff also reviewed applicable in-pond approaches to reduce sediment TP regeneration. These approaches could be combined with more limited wastewater reductions and included alum treatment, hypolimnetic aeration (*i.e.*, aeration only of the cold, deep layer), and sediment dredging. These approaches on their own resulted in a range of predicted water column TP masses from 13.9 kg to 16.5 kg under average sediment regeneration. It is not surprising that none of these approaches achieved the 11 kg remediation threshold since sediment TP load is only 14% to 23% of the overall load.

One additional insight gained from the water quality review is that Shubael Pond is removing 76% or 78% of its watershed nitrogen depending on which watershed delineation is considered. Incorporation of this insight into Three Bays and Centerville River N management could lead to changes in sewering strategies in the Town CWMP. Both the Three Bays MEP study[4] and 2021 MEP N loading update[5] assigned a conservative 50% N attenuation rate to Shubael Pond.

Based on these findings, CSP/SMAST staff recommends the following steps for implementation of an adaptive management approach for the restoration of Shubael Pond:

1. **Develop and implement a water column TP reduction strategy for the Shubael Pond.**
    - Septic system wastewater TP additions to the pond are the primary source of water column TP concentrations and pond impairments; phosphorus control is the key for managing water quality in Shubael Pond.

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

[5] CSP/SMAST Technical Memorandum. December 5, 2019. MEP Scenarios: Town of Barnstable Wastewater Plan and Land Use Updates. To: G. Beaudoin, Town Engineer, Barnstable Department of Public Works. From: B. Howes, E. Eichner, and J. Ramsey. 36 pp.

- The current Town CWMP includes sewering in the Pond watershed that will attain water quality restoration, but the implementation of the sewering is not planned until Phase 3 of the CWMP (*i.e.*, 21 to 30 years from now). Changes to the planned sewering schedule or an alternative wastewater treatment strategy are required to achieve acceptable water quality in Shubael Pond in the near-term.
- Development of an acceptable pond watershed delineation is key to appropriate wastewater strategies. The USGS/MEP watershed is included in the CWMP, but recent provisional data from USGS suggests a smaller watershed.
- Reductions in TP loads from sources other than wastewater are insufficient to achieve the restoration of pond water quality, but there may be other strategies that combine more limited wastewater TP reductions with other reductions.

2. Develop and implement an adaptive management monitoring program.

- Monitoring in 2020 for this project was the first complete summer of water quality monitoring for Shubael Pond.
- Implementation of a water column phosphorus reduction strategy should be accompanied by regular monitoring to assess its performance. This data should be collected for two to three summers and management strategies should be revisited if acceptable water quality is not achieved.

3. Utilize a water column mass of 11 kg TP as a target restoration threshold, but avoid a TMDL designation until attainment of satisfactory water quality.

- Shubael Pond is currently not listed as an impaired water for nutrients on MassDEP's most recent Integrated List, but the review of data in this report show that it fails to attain MassDEP minimum criterion for dissolved oxygen and has other impairments related to excessive phosphorus loading. Under the Clean Water Act, impaired waters are required to have a TMDL for the contaminant causing the impairment.
- Submitting TMDL-supporting information after implementation of a TP reduction strategy and subsequent adaptive management monitoring showing attainment of water quality goals. It is possible that MassDEP (or another party) may cause the Town to expedite a TMDL listing. If this occurs, the information in this Plan should be sufficient to meet the data requirements for a phosphorus TMDL submittal. If the Town develops and pursues an acceptable strategy, management of the pond would remain predominantly within local purview until the Town is ready to state that water quality impairments have been addressed.

Implementation of these recommendations will require funding sources and close coordination among local project planners and local regulatory boards. Potential funding sources include local funds, state grants, state budget directives, and county funds. It is further recommended that the town contact appropriate regulatory officials to explore these options. CSP/SMAST staff are available to further assist the town with implementation, adaptive monitoring, and regulatory activities.

Table of Contents

Shubael Pond Management Plan and Diagnostic Assessment
FINAL REPORT
April 2022

List of Figures

Shubael Pond Management Plan and Diagnostic Assessment
FINAL REPORT
April 2022

List of Figures (continued)

Shubael Pond Management Plan and Diagnostic Assessment
FINAL REPORT
April 2022

List of Tables

Shubael Pond Management Plan and Diagnostic Assessment
FINAL REPORT
April 2022

I. Introduction

The Town of Barnstable has numerous ponds and lakes scattered throughout the town. According to the Cape Cod Pond and Lake Atlas, Barnstable has over 180 ponds covering a total area of nearly 1,900 acres.[6] Of these ponds, 25 are greater than 10 acres and these are legally defined under Massachusetts law as Great Ponds, which are public waters. These ponds and lakes are important recreational areas for swimming, fishing, and boating. Their natural habitats provide important ecological and commercial services, including use for cranberry bogs, herring runs, and natural nitrogen attenuation that protects estuaries.

Management of pond and lake resources in Barnstable has been guided by a mix of municipal activities and citizen advocacy, typically through lake associations.[7] Prior to 2001, water quality monitoring of these resources was generally focused on individual pond assessments rather than long-term tracking of changes in water quality conditions and data based prioritization. In 2001, the Cape Cod Pond and Lake Stewards (PALS) program was initiated as a partnership between the Cape Cod Commission and the Coastal Systems Program at the School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) with in-kind support from most of the Cape towns and environmental organizations. The PALS program included a citizen-based, once a year water quality snapshot, a listing of all ponds on Cape Cod, and has become a focal point for pond and lake advocacy.

The goal of PALS Snapshots is to encourage development of basic, often initial, pond water quality data collected using consistent, scientifically-based, protocols and proper QA/QC. The resulting data can then support Town efforts to prioritize ponds for additional analysis and collection of more refined data, such as sediment nutrient regeneration, stream inputs and/or outputs, and watershed analysis. More refined targeted data collection can then be combined with the initial, citizen-collected water column data to develop active, appropriate, and pond-specific management strategies to ensure long-term sustainable high quality waters and aquatic habitats. The PALS program began by recruiting, training, and assisting Cape citizens to gather regular, long-term water column samples once a year during the critical late summer period. Water quality data collected through the PALS Snapshots has been used in numerous pond assessments and management efforts.

In 2020, the Town Department of Public Works (DPW) began a process to develop a comprehensive town-wide pond and lake water quality strategy that would complement and integrate with the Comprehensive Wastewater Management Plan.[8] The initial task under this process was the collection and review of available pond and lake water quality data, including PALS data.[9] This review identified data from 55 ponds and lakes collected from 2001 to 2019 PALS Snapshots and over 40 pond assessment reports. Although this water column data was useful, the review also identified data gaps that would need to be addressed in order to complete reliable pond management plans and actions.

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

[7] *e.g.*, the Indian Ponds Association, the Wequaquet Lake Protective Association, etc.

[8] https://barnstablewaterresources.com/documents/ (accessed 9/24/21)

[9] Eichner, E. and B. Howes. 2021. Town of Barnstable Freshwater Ponds, 2021 Water Quality Monitoring Database: Development and Review. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 106 pp.

DPW and CSP/SMAST used the water quality data compilation and review to begin to prioritize ponds for management plans. Initial prioritization identified Shubael Pond as the first pond in Barnstable to be addressed, followed by Long Pond in Marstons Mills and Lovells Pond. The present Shubael Pond Management Plan is primarily composed of two sections: 1) a Diagnostic Summary of how Shubael Pond generally functions based on the available historic water column data and data developed in the data gap investigations and 2) a Management Options Summary, which reviews applicable and best options, estimated implementation costs with applicable options, and likely regulatory issues associated with implementation. It is anticipated that the Town will work through a process to review the recommendations and choose a preferred implementation strategy for restoration of Shubael Pond water quality.

II. Shubael Pond Background

Shubael Pond is a 56 acre Great Pond located in Marstons Mills. It is located east of Route 149 and south of Race Lane (**Figure II-1**). Shubael Pond is among the deepest fresh ponds and lakes in Barnstable (average depth in PALS snapshots was 11.8 m (n=12).[10] Review of historic US Geologic Survey topographic maps do not show any hydroconnections to adjacent ponds or wetlands, including Round Pond to the southeast. The 1944 topographic map shows only six buildings within 1,000 ft of the pond. The pond is not located within a designated Massachusetts Natural Heritage Priority Habitat, but is within a Centerville Osterville Marstons Mills Water District Zone II (*e.g.*, wellhead protection area). A Shubael Pond watershed was delineated by USGS as part of the Massachusetts Estuaries Project (MEP) Three Bays assessment[11] and the pond straddles the watershed boundary between Three Bays and Centerville River[12] MEP estuary watersheds.

Shubael Pond fisheries have been managed in the past by the Massachusetts Division of Fisheries and Wildlife (MassDFW). The first fisheries survey was in 1911 and found yellow perch, brown bullheads and chain pickerel.[13] MassDFW stocked the pond with brook trout, brown trout and rainbow trout between 1939 and 1946. The fishery was "reclaimed" for trout management in 1956, 1961 and 1974. Reclaiming for trout management means treatment with pesticide, typically rotenone, to kill other fish species and then introduction of trout to the altered habitat.

Given that it has a surface area greater than 10 acres, Shubael Pond is classified as a Great Pond under Massachusetts law. Great Ponds are publicly-owned waters of the Commonwealth. Shubael Pond is listed in the most recent EPA-approved Massachusetts Integrated List of surface

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[10] *Ibid.*

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

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

[13] https://www.mass.gov/files/documents/2016/08/tm/dfwshube_0.pdf (accessed 4/8/22).

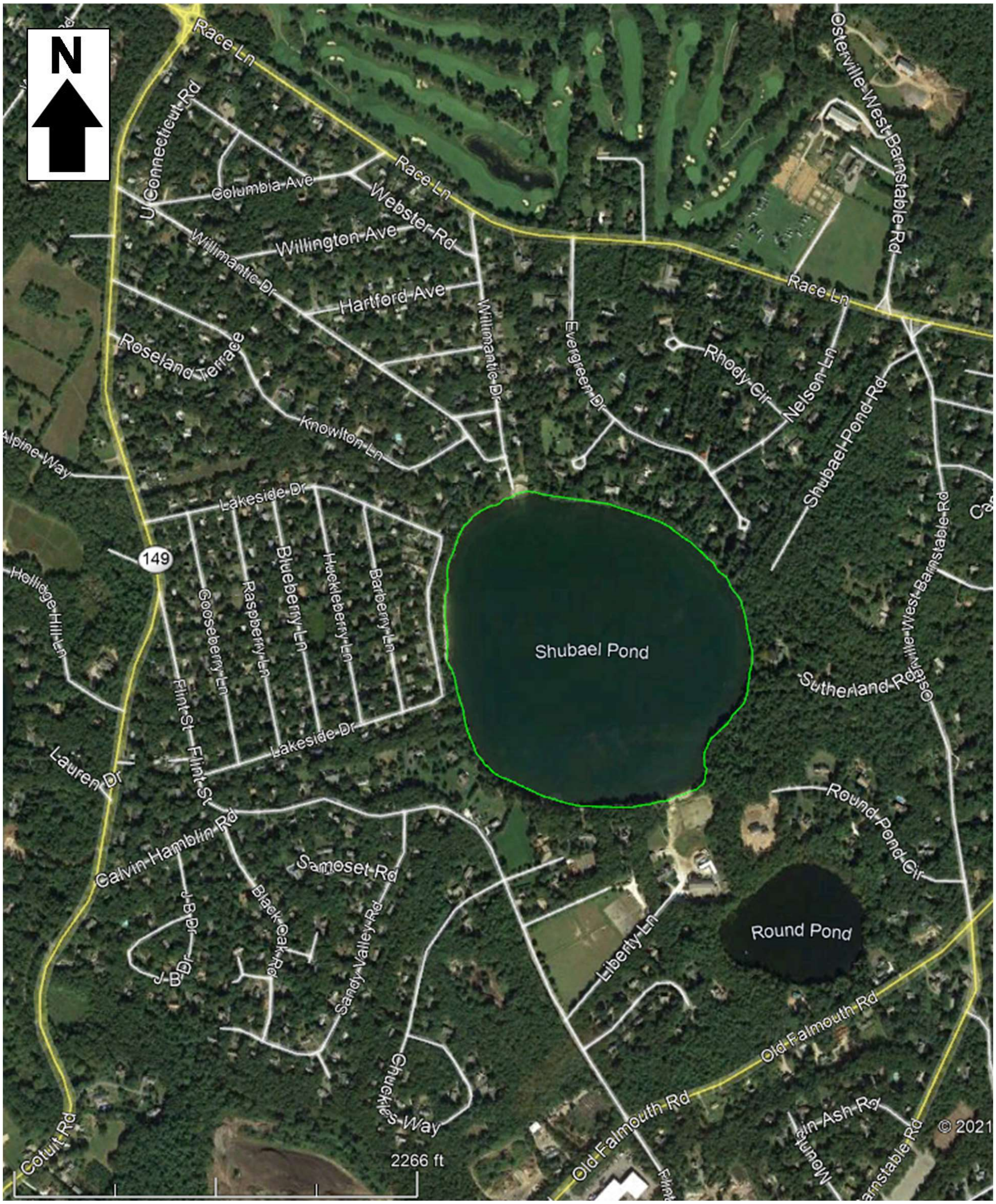

Figure II-1. Shubael Pond Locus. Shubael Pond is a 56-acre Great Pond located in Marstons Mills village in the Town of Barnstable. The pond is located approximately 450 m south of Race Lane and approximately 470 m east of Route 149/Cotuit Road. Map is aerial photograph from 10/5/18 (Google Earth).

waters as a category 3 surface water.[14] Category 3 is for waters with "No Uses Assessed." Shubael Pond continues to be assigned to this category in the 2018/2020 draft integrated list.

Shubael Pond is listed in the Cape Cod Pond and Lake Atlas as pond number BA-664.[15] The pond has been sampled 13 times during the annual PALS Snapshot: 2001-2003, 2007-2013, and 2017-2019.[16] The 2021 review of Shubael Pond water column data in the Town-wide review of pond water quality data found that the pond had "borderline impaired water quality in its shallow waters, but significantly impaired conditions in the deeper bottom waters based on low DO concentrations and high TP, TN, and chlorophyll a concentrations."[17] The 2021 water quality review also found that the water column generally was thermally stratified in late summer with a warm, well-mixed, upper layer of 6 to 8 m, a 1 to 2 m transition zone, and cold water, lower layer below the transition zone. Average DO concentrations in the upper layer were acceptable, while waters deeper than the transition layer (usually 9 m and deeper) were hypoxic (average = 1.2 mg/L DO; n=17). Clarity readings averaged 4.4 m or 38% of the water column. Review of N:P ratios found that phosphorus was the key nutrient determining water and habitat quality conditions in Shubael Pond. Average shallow TP concentration was at the Cape Cod ecoregion threshold (10 µg/L TP), but average TP concentration at 3 m, 9 m, and the deep sample exceeded the threshold. The average deep TP concentration was 3X the shallow average. Review of the Shubael Pond shallow PALS TP concentrations showed a significant increasing ($\rho<0.05$) temporal trend, but shallow TN did not, suggesting that the primary source of the TP increase is internal sediment regeneration rather than watershed inputs.

The 2021 water column data review noted that data was generally limited to late summer PALS snapshots and that additional water column sampling throughout a summer would help provide better context for understanding the impairments noted in the PALS readings. This review identified a number of data gaps that should addressed if the Town decided to pursue development of a Pond Management Plan. These data gaps included continuous monitoring to measure short-term water quality changes, characterization of phytoplankton species throughout the summer including cell counts (not just focused on blue-greens), a submerged aquatic plant survey to characterize potential water quality interactions with rooted plants, and measurement of sediment nutrient release rates to determine how much phosphorus could be added to the water column under oxic and anoxic conditions. These data gaps were addressed for this Management Plan and results are summarized below.

Shubael Pond was sampled 11 times (approximately twice a year) in 1986-1991 in support of an effort to raise the pH of the pond.[18] At the time, there was a lot of concern about acid rain impacts on surface waters and the naturally low pH of Shubael Pond caused it to be identified as acidified lake. As such, Living Lakes, Inc. recommended adding limestone to Shubael Pond and the pond was dosed twice with 13.1 tonnes of limestone. One pre-application and a number of

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[14] Massachusetts Department of Environmental Protection. December 2019. Massachusetts Year 2016 Integrated List of Waters. Final Listing. Massachusetts Division of Watershed Management, Watershed Planning Program. CN: 470.1. Worcester, MA. 375 pp.

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

[16] Eichner, E. and B. Howes. 2021. Town of Barnstable Freshwater Ponds, 2021 Water Quality Monitoring Database: Development and Review. pp. 82-83.

[17] *Ibid*.

[18] Living Lakes, Inc. 1992. Living Lakes Program, Final Report, Shubael Pond. Greenbelt, MD. 42 pp.

follow-up samplings were completed, although the report does not describe the laboratory or sampling methods. Laboratory assays were completed for pH, total nitrogen, total phosphorus, sodium, potassium, chloride, aluminum, and conductivity. Field data collection included dissolved oxygen at selected depths and Secchi/clarity, but no temperature readings.

III. Shubael Pond Regulatory and Ecological Standards

As mentioned above, much of the legal basis for management of ponds and lakes in Massachusetts is based on the surface area of a given water body. Shubael Pond has a surface greater than 10 acres, which means that it is a Great Pond under Massachusetts Law[19] and subject to Massachusetts regulations. As such, local Town decisions regarding management may be subject to state review. Massachusetts maintains regulatory standards for all its surface waters, which are administered by MassDEP.[20] These regulations include *descriptive* standards for various classes of waters based largely on how waters are used plus accompanying sets of selected *numeric* standards for: dissolved oxygen, pH, temperature, and indicator bacteria. For example, Class A freshwaters are used for drinking water and have a descriptive standard that reads, in part, that these waters "are designated as excellent habitat for fish, other aquatic life and wildlife, including for their reproduction, migration, growth and other critical functions, and for primary and secondary contact recreation, even if not allowed. These waters shall have excellent aesthetic value."[21] Additional distinctions are made between warm and cold water fisheries.

Under these state Surface Water Regulations, Shubael Pond would be classified as a Class B water and a cold water fishery. As noted above, deeper portions of the water column (≥8 m depth) in Shubael Pond generally meet the definition of a cold water fishery (*i.e.*, temperatures below 20°C throughout the year). Aside from temperature, the primary regulatory distinction between the warm and cold water fisheries is the difference in <u>minimum</u> dissolved oxygen (DO) concentrations: 6 mg/L for cold water fisheries and 5 mg/L for warm water fisheries. As such, for the purposes of the Shubael Pond diagnostic assessment and water quality management planning to address state regulatory standards, we have focused on the cold water regulatory standards, which means that the following numeric standards apply:

a) dissolved oxygen shall not be less than 6.0 mg/L,
b) temperature shall not exceed 68°F (20°C) (in deep waters),
c) pH shall be in the range of 6.5 to 8.3, and
d) bacteria (*Enterococci*) shall not exceed 61 colonies per 100 ml at bathing beaches (with variations available for multiple samples or use of different indicator species).

These numeric standards are accompanied by descriptive standards, which state the following are required for Class B waters: "designated as a habitat for fish, other aquatic life, and wildlife, including for their reproduction, migration, growth and other critical functions, and for primary and secondary contact recreation. Where designated in 314 CMR 4.06, they shall be suitable as a source of public water supply with appropriate treatment ("Treated Water Supply"). Class B waters shall be suitable for irrigation and other agricultural uses and for compatible industrial cooling and process uses. These waters shall have "consistently good aesthetic value."[22]

[19] MGL c. 91 § 35
[20] 314 CMR 4.00
[21] 314 CMR 4.05(3)(a)
[22] 314 CMR 4.05(3)(b)

Under the federal Clean Water Act, MassDEP is required to provide a listing of the status of all surface waters compared to the state regulatory standards. This "Integrated List" has waters assigned to five categories including Class 5 impaired waters failing to attain state standards. Class 5 waters are required to have a maximum concentration or load limit (also known as a Total Maximum Daily Load or TMDL) defined for the contaminant causing the impairment.[23] The Massachusetts Integrated List is updated every two years and submitted to and approved by the Environmental Protection Agency (EPA). As previously mentioned, Shubael Pond is listed in the most recent final Massachusetts Integrated List as a Category 3 water (No Uses Assessed).[24] Shubael Pond has been listed in this category since 2004, which was the first Massachusetts Integrated List.

Though a number of Cape Cod ponds have been identified as being impaired, no Cape Cod pond or lake nutrient TMDLs have been developed or approved by MassDEP as of 2021. In an effort to begin to define regionally-specific pond and lake nutrient standards, the Cape Cod Commission used the PALS sampling results from over 190 ponds and lakes during the first Snapshot in 2001 to develop potential Cape Cod-specific nutrient thresholds.[25] This effort used a recommended EPA method that relies on a statistical review of the available data within an ecoregion to develop nutrient thresholds.[26] This review suggested a target TP concentration range of 7.5 to 10 µg/L for sustaining unimpaired conditions in Cape Cod ponds. Potential target threshold ranges were also developed for total nitrogen (0.16 to 0.31 mg/L), chlorophyll-a (1.0 to 1.7 µg/L), and pH (5.19 to 5.62). These concentrations closely approximated the EPA reference criteria at the time for the east coast region that includes Cape Cod.[27] These Cape Cod-specific thresholds are guidance targets and have not been formally adopted as regulatory standards by MassDEP, the Cape Cod Commission, or any of the towns on the Cape. However, they provide the best estimate for thresholds for Cape Cod ponds at present.

A diagnostic assessment provides the opportunity, however, to review these thresholds based on the conditions within an individual pond. For example, a recent pond management review in Plymouth, which is in the same ecoregion as Barnstable, found that water quality in Savery Pond was acceptable up to 26 µg/L TP.[28] The individual circumstances of Savery Pond that favored acceptable water quality conditions at this high TP concentration were a very short residence time (48 days) and shallow conditions (maximum depth of 4 m). Data collected in Shubael Pond

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[23] 40 CFR 130.7 (CFR = Code of Federal Regulations)

[24] Massachusetts Department of Environmental Protection. December 2019. Massachusetts Year 2016 Integrated List of Waters. Final Listing. Massachusetts Division of Watershed Management, Watershed Planning Program. CN: 470.1. Worcester, MA. 375 pp.

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

[26] U.S. Environmental Protection Agency. 2000. Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs. First Edition. EPA-822-B00-001. US Environmental Protection Agency, Office of Water, Office of Science and Technology. Washington, DC.

[27] U.S. Environmental Protection Agency. 2001. Ambient Water Quality Criteria Recommendations. Information Supporting the Development of State and Tribal Nutrient Criteria for Lakes and Reservoirs in Nutrient Ecoregion XIV. EPA 822-B-01-011. US Environmental Protection Agency, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division. Washington, DC.

[28] Eichner, E., B. Howes, and D. Schlezinger. 2021. Savery Pond Management Plan and Diagnostic Assessment. Town of Plymouth, Massachusetts. TMDL Solutions LLC, Centerville, MA and Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth, New Bedford, MA. 101 pp.

identified when water quality conditions were acceptable and this provided guidance on management strategies to sustain acceptable conditions.

IV. Shubael Pond Diagnostic Review

During the development of the water quality database for Barnstable ponds and lakes, most (86%) of the available historic Shubael Pond data was PALS Snapshot data.[29] In addition to the PALS data, which was collected only in August and September, there were a) an August 13, 1948 snapshot set of DO and temperature profile readings[30] and b) data collected during 1986 to 1991 to support limestone additions to the pond that do not include full water column profiles or accompanying temperature readings.[31] PALS Snapshot data was collected 14 times since the start of the PALS program in 2001: 2001-2003, 2007-2013, 2017-2020. The Town has recently begun collecting spring PALS Snapshots to provide a more robust annual baseline when combined with the late summer PALS readings.

Since the available water column data was generally limited to late summer, a prominent data gap was the collection of water column data throughout the summer to better characterize how late summer water column conditions develop. Additional data gaps were addressed through the collection of key supplemental data including: bathymetric, rooted plant, and freshwater mussel surveys, and sediment nutrient regeneration measurements, and seasonal shifts in plankton communities. Supplemental data gap information was collected by CSP/SMAST in 2020 and included profile and water sample collection on 10 dates (including the September PALS sampling) between May and December. The data gap information combined with the historic data and other key information (*e.g.*, watershed assessment, stormwater measurements, etc.) collectively provide a more comprehensive understanding of the Pond ecosystem health and functions. With a better understanding of how the Shubael Pond ecosystem functions and how impairments occur, reliable water quality management strategies can be developed.

IV.A. Water Column Data Review

IV.A.1. *In Situ* Field Data: Temperature, Dissolved Oxygen, Secchi Clarity

Measurements of temperature and dissolved oxygen (DO) profiles provide insights into how portions of the Shubael Pond ecosystem function and how they change over the growing season. Profiles collected over a number of years or across a number of seasons show how the water column conditions change in response to atmospheric temperature changes (*i.e.*, whether it stratifies), whether there is notable sediment oxygen demand, and how nutrient conditions might vary in response to these changes. Loss of clarity in Cape Cod ponds and lakes (*i.e.*, reduced Secchi depth) is usually associated with enhanced phytoplankton growth due to phosphorus additions.

Historical PALS Secchi clarity readings show that Shubael Pond clarity is somewhat limited, but has not changed significantly over the past 20 years (**Figure IV-1**). Mean depth at the deepest location across all late summer surveys (2001-2020) was 11.8 m with a range of 11.0 to 13.4 m (n=16). Mean average Secchi transparency depth was 4.4 m (n=17) and averaged 38% of the total depth. Minimum and maximum recorded Secchi measurements were 20% and 60% of the

[29] Eichner, E. and B. Howes. 2021. Town of Barnstable Freshwater Ponds, 2021 Water Quality Monitoring Database: Development and Review. pp. 82-83.
[30] Collected by the Massachusetts Department of Fish and Game
[31] Living Lakes, Inc. 1992. Living Lakes Program, Final Report, Shubael Pond. Greenbelt, MD. 42 pp.

total depth of the pond (August 2020 and August 2002, respectively). Review of the Secchi readings over time shows no significant trend. The late summer average Secchi depth is approximately 0.5 m less than the available single August 1948 reading.[32] The six Secchi readings in 1986-1991 show better transparency (average = 6.8 m), but it is not clear whether this might be due to the two limestone additions coating the bottom.

Secchi readings collected in 2020 suggest that the loss of clarity measured in the PALS Snapshots tends to develop in earlier in the summer and is sustained throughout the summer. In 2020 monthly readings, Secchi readings decreased from 7 m (May 12) to 2.6 m (August 13) (**Figure IV-2**). Clarity in the May 20 and June 17 samplings was approximately 7 m and decreased to 3.8 on July 15 before decreasing to the August 13 minimum. The 2.6 m reading on August 13, 2020 was the lowest clarity recorded among all the late summer PALS readings.

Average historical PALS temperature profiles showed strong summer thermal stratification, but review of individual profiles occasionally showed no stratification. Average temperature profiles in August/September had a well-mixed upper layer (*i.e.*, epilimnion) to 6 m depth with strong stratification beginning at 7 m and transitioning to 9 m and a deep cold layer (*i.e.*, hypolimnion) from 10 m to the bottom (**Figure IV-3**). The depth of the bottom of the well-mixed upper layer varied between 3 m and 8.5 m. Review of individual August and September profiles shows, however, that 4 of the 16 profiles did not have thermal stratification and these occurred in both August and September. This finding suggests that there are years where the water column is warmed gradually enough to maintain mixing of the whole water column.

Historical PALS DO profiles were generally consistent with the temperature profiles with near-saturation levels in the epilimnion, hypoxia in the transition zone, and anoxia in the hypolimnion (see **Figure IV-3**). Individual snapshot DO profiles were generally consistent with average conditions, but shallow waters often had DO saturation levels greater than 105%, consistent with high phytoplankton growth and accompanying photosynthesis. DO in the hypolimnion was anoxic (*i.e.*, DO<1 mg/L) in both the average DO profile and each of the individual profiles with temperature stratification. Anoxic conditions occur in the hypolimnion because sediment oxygen demand consumes all available dissolved oxygen in the water column and atmospheric oxygen replenishment is prevented by the thermal stratification. Average August/September DO concentrations at 7 m and deeper are less than the MassDEP 6 mg/L DO minimum, which is consistent with impaired water quality conditions.

In 2020 profiles, thermal stratification isolated the deep colder waters and sediment oxygen demand gradually consumed all available dissolved oxygen in the deep, hypolimnion layer and in the shallower thermal transition zone. Hypoxia even reached the bottom of the epilimnion before water column mixing in the fall created isothermic, non-stratified conditions in the fall. Thermal stratification began weakly in May, was strong from June through September, and returned to weak stratification in October (**Figure IV-4**). DO concentrations in the hypolimnion were generally below the MassDEP DO minimum during periods of stratification with increasing proportions of the hypolimnion having anoxia as the summer progressed and stratification strengthened. DO concentrations in the May 8 and May 12 profiles were above the MassDEP

[32] Massachusetts Division of Fisheries and Game. 1948. Fisheries Report – Lakes of Plymouth, Berkshire and Barnstable Counties.

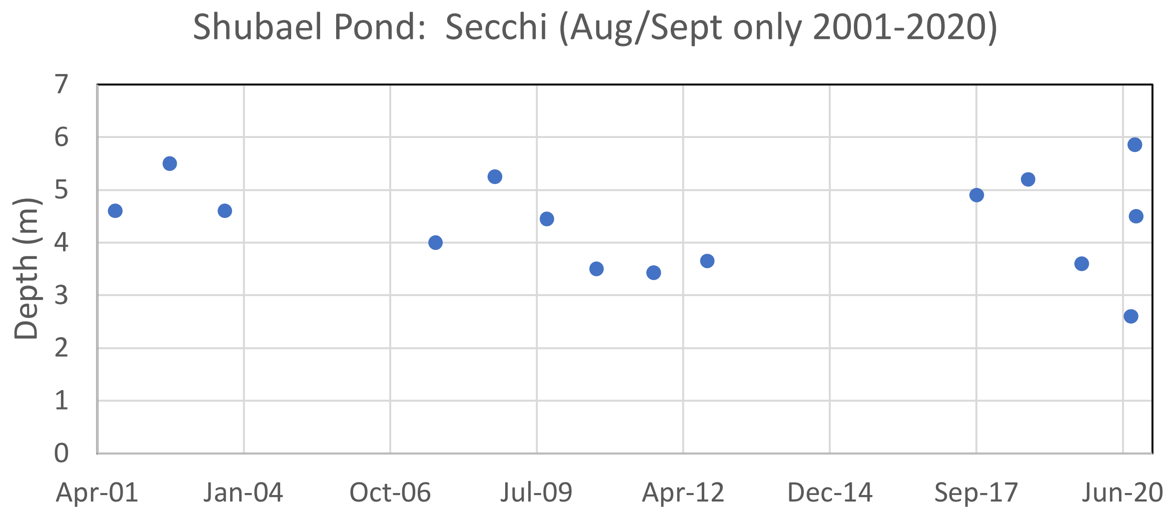


Figure IV-1. Shubael Pond Secchi Readings (2001 to 2020). Available historical Secchi clarity readings have mostly been collected through PALS Snapshots and, thus in August and September. These readings average 4.4 m with a range from 2.6 m to 5.9 m and have no statistically significant trend. Late summer 2020 readings were consistent with the historic readings.

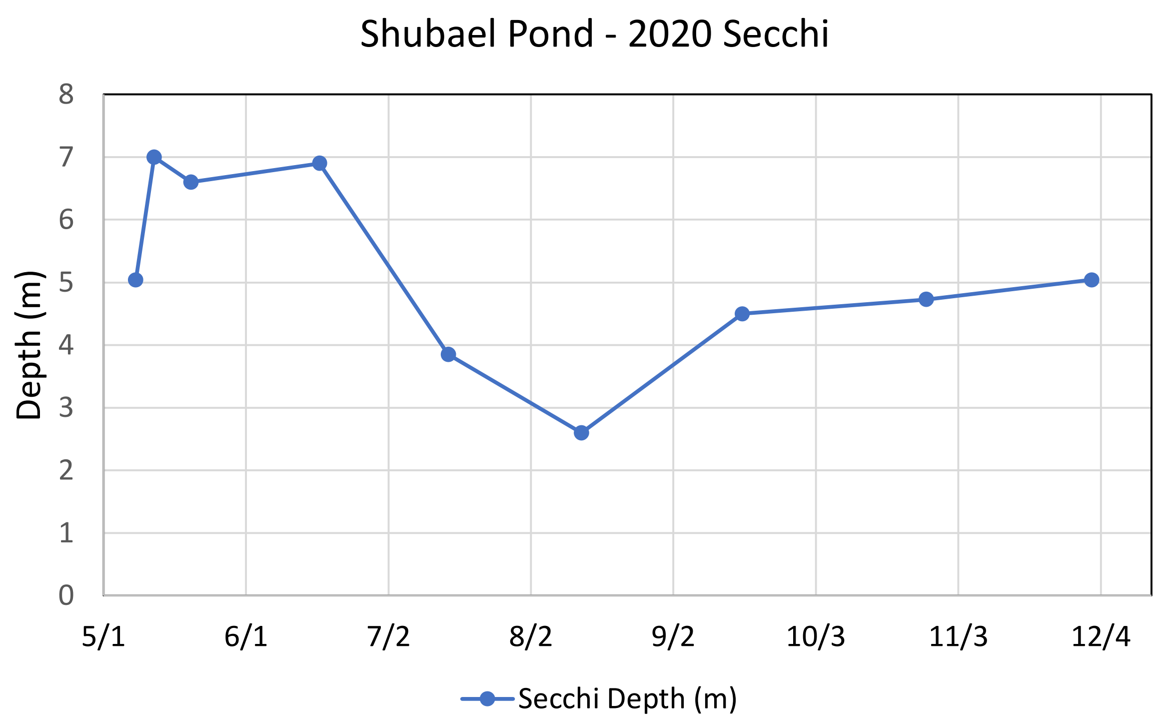


Figure IV-2. 2020 Shubael Pond Secchi Readings. Secchi clarity readings decreased from approximately 7 m measured from mid-May to mid-June to a minimum of 2.6 m on August 13. Readings in September, October, and December were consistent with average late summer historical PALS readings (*i.e.*, 4.5 to 5.0 m). The 2.6 m reading on August 13 was the lowest clarity recorded in late summer (n=15).

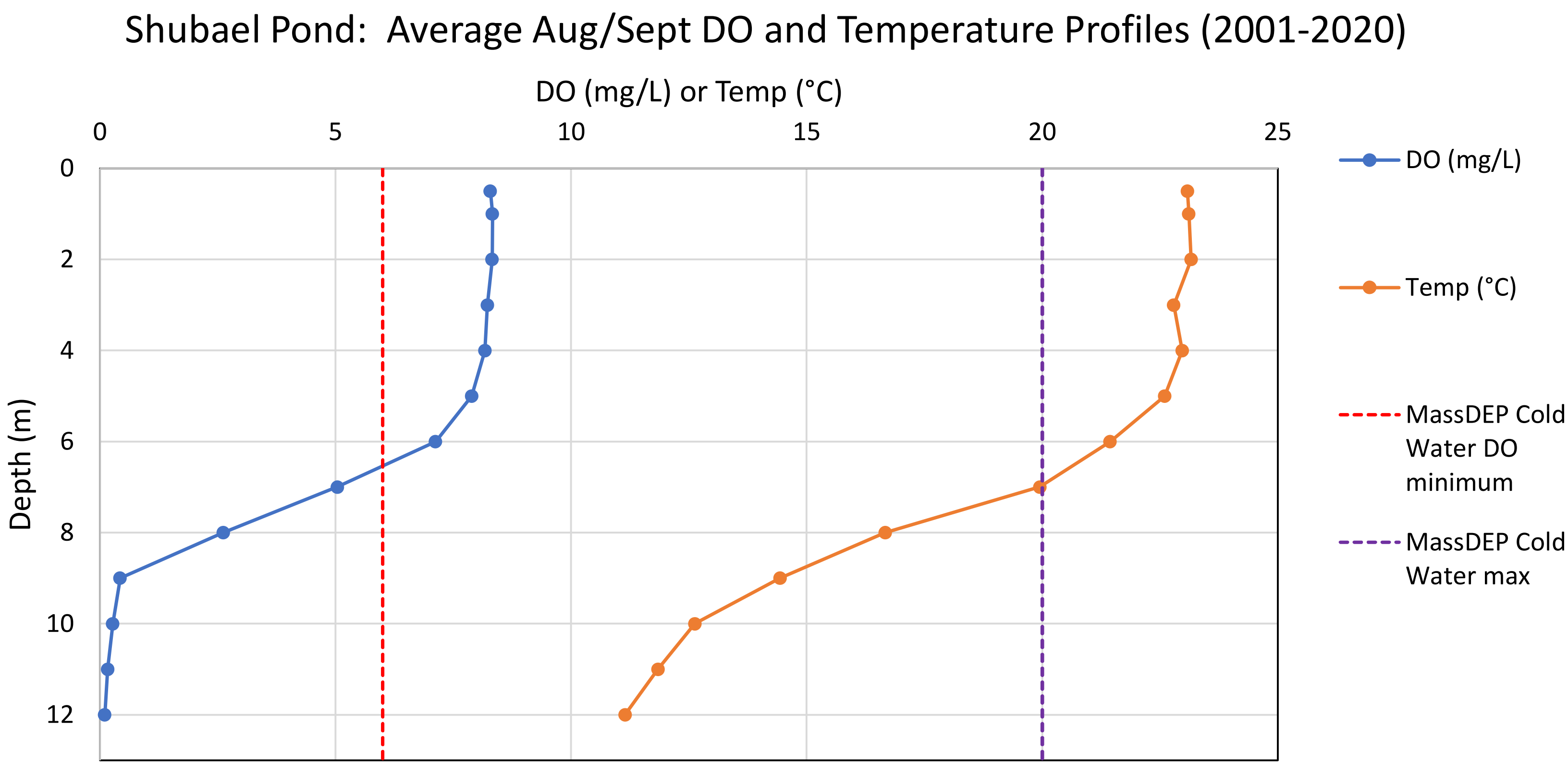
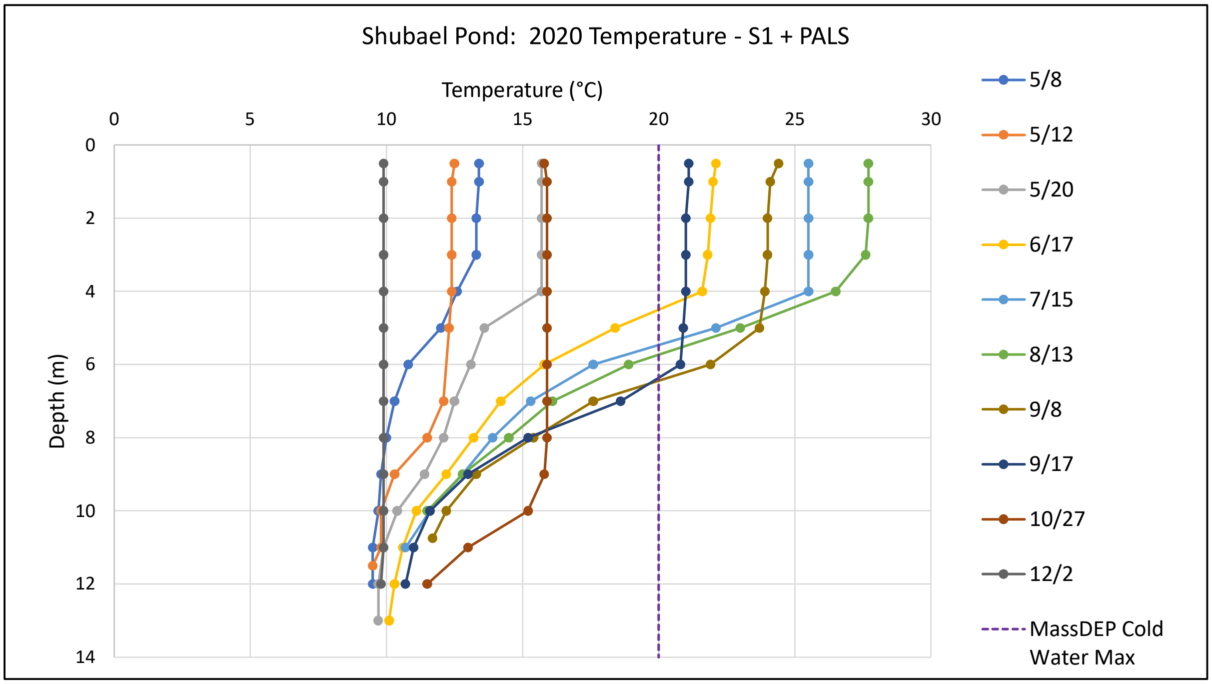


Figure IV-3. Average August/September Temperature and Dissolved Oxygen Profiles (2001-2020). Historical profile data for Shubael Pond is generally only available from PAL Snapshots, which occur only in August and September. Average water column temperature readings from this late summer data show strong thermal stratification beginning at 7 m depth with a well-mixed, warm upper layer, a transition zone between 7 m and 9 m depth, and a cold layer from 10 m to the bottom. Average August/September temperatures at 7 m and deeper meet the MassDEP temperature criterion for a cold water fishery. Average DO readings shallower than 7 m meet the MassDEP DO minimum (6 mg/L) and are not impaired. However, DO concentrations at 7 m and deeper do not meet the MassDEP minimum standard, meaning that average conditions in August/September are impaired throughout both the temperature transition zone and the cold layer. Average DO readings at 9 m and deeper are anoxic (<1 mg/L) meaning that the best cold water habitat cannot sustain a viable trout population in August and September.



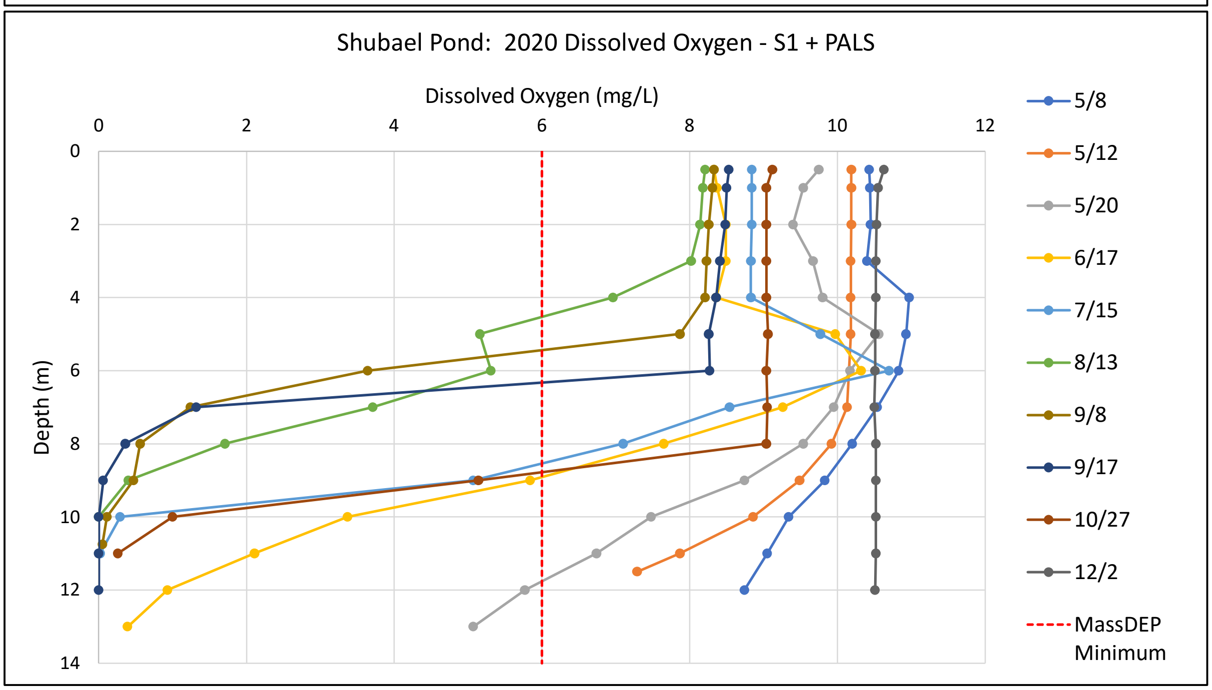


Figure IV-4. 2020 Temperature and Dissolved Oxygen Profiles. Temperature and dissolved oxygen readings throughout Shubael Pond water column were collected on 10 dates in 2020 over the deepest point in the pond (S1). Temperature readings show relatively well-mixed water column conditions in early May, weak stratification in the May 20 profile, and then initial thermal stratification (*i.e.*, layering) in June. Stratification was sustained throughout the summer before returning to weak stratification in October. In December, the whole water column was isothermic with no stratification. The water column at 7 m and deeper met MassDEP temperature criterion to be a cold water fishery in all profiles. Deep DO readings decreased below the MassDEP minimum concentration in June and became more impaired throughout the summer. Anoxia (*i.e.*, DO<1 mg/L) began in the deepest waters in June and gradually included more of the cold water layer in each subsequent profile.

minimum throughout the water column and the temperature readings showed no thermal stratification. DO concentrations at 12 and 13 m in the May 20 profile were less than the MassDEP minimum and the first anoxic concentrations were measured at the same depths in the June 17 profile. The DO at the top of the hypolimnion at 7 m on June 17 was 9.3 mg/L and concentrations between 7 and 9 m were greater than the MassDEP minimum. By July 15, strong thermal stratification had been established and anoxia was recorded at 10 m and deeper. By August 13, anoxia was recorded at 9 m and deeper and DO concentrations throughout the hypolimnion and the transition zone between the epilimnion and hypolimnion were less than the MassDEP minimum. By September 8, anoxia was first recorded in the transition zone at 8 m and in the September 17 profile a sharp DO interface between the warm, well-oxygenated epilimnion and the top of the transition zone had formed with DO at 8.3 mg/L at 6 m depth and 1.3 mg/L at 7 m depth. In the October 27 profile, temperatures had decreased so that the thickness of the epilimnion had increased to most of the water column (to 10 m), but anoxia remained at 11 m and waters at 9 m and deeper were less than the MassDEP DO minimum. By the December 2 profile, the pond water column was well-mixed with isothermic conditions and acceptable DO throughout. Waters deeper than 7 m were consistently less than the MassDEP cold water fisheries upper limit (20°C) in all 2020 profiles; maximum temperature in the cold water layer was 14.5°C at 8 m in the August 13 profile.

Review of DO % saturation levels show that the anoxia in the bottom waters also impacted water quality conditions in the upper, warmer waters. Warm, upper waters in stratified ponds are generally well-mixed by winds blowing across the surface. As such, these waters have regular contact with atmospheric oxygen and their dissolved oxygen concentrations are generally around 100% saturation or in equilibrium with atmospheric oxygen. Most of the 2020 profiles for Shubael Pond had DO saturation levels around 100% to a depth of approximately 4 m (**Figure IV-5**). However, in the June 17 and July 15 profiles, DO concentrations were above 105% and peaked 112% in the July profile. Saturation levels above 105% are indicative of high phytoplankton biomass and photosynthetic rates. A mid-depth bulge in DO profiles is caused by photosynthesis adding more DO to the water column than what would be caused by atmospheric mixing alone. It is also notable that the DO bulge is not present in the August 13 profile as waters at 5 m and deeper had hypoxia.

Overall, the historic temperature and DO profiles and Secchi clarity readings show that Shubael Pond has impaired conditions in late summer during most years. The 2020 readings suggest these impaired conditions began in late May and worsened in each subsequent summer month. In 2020, acceptable DO concentrations throughout the water column were not measured again until December 2020 after the breakdown of temperature stratification. DO concentrations are consistent with significant sediment oxygen demand and were sustained long enough in 2020 to likely mobilize and release sediment-bound phosphorus. Temperature profiles show that Shubael Pond could support and sustain a cold water fishery if deep DO concentrations are increased to acceptable levels throughout the summer.

IV.A.2. Water Column: Laboratory Water Quality Assays

Water quality samples were also collected during the 14 PALS Snapshot profiles between 2001 and 2020, the 11 1986-1991 Living Lakes samplings, and the nine additional 2020 data gap profiles. All water quality samples during the PALS and 2020 samplings were assayed at the

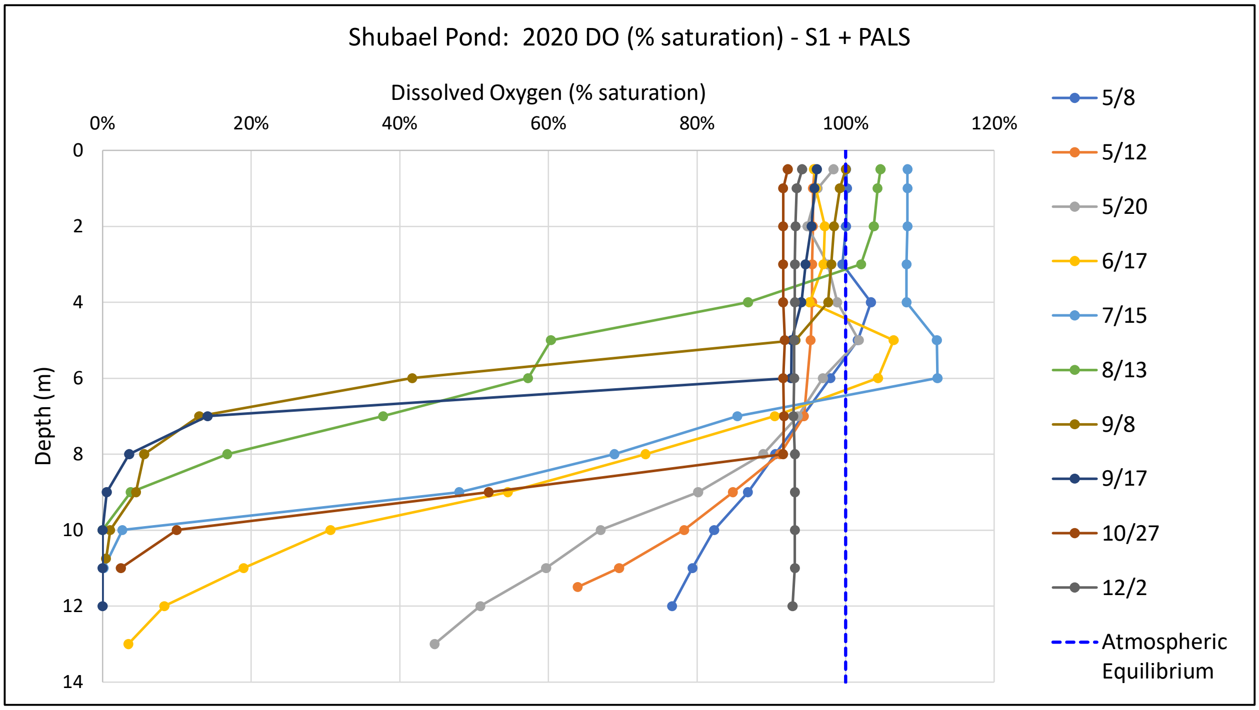


Figure IV-5. 2020 Dissolved Oxygen Saturation Profiles. Most profiles show DO saturation levels to 4 m depth at atmospheric equilibrium (*i.e.*, 100% saturation = atmospheric equilibrium). In the June 17 profile, saturation levels peak at 105% at 5 m depth, which is indicative of phytoplankton photosynthesis producing DO in excess of atmospheric equilibrium. In the July 16 profile, this bulge increases to 112% at 5 m and 6 m depth. Photosynthesis/growth in these situations typically is due to phytoplankton utilizing high phosphorus content in deep, anoxic waters seeping through the temperature transition zone between upper and deep layers. It is notable that the DO bulge is not present in the August 13 profile, where sediment oxygen demand had begun to impact DO in both the deep layer and the transition zone between the upper and deep layers.

Coastal Systems Analytical Facility at SMAST-UMass Dartmouth using the same procedures used in all PALS Snapshot samples. No assay details are provided in the Living Lakes report. Compilation and analysis of the PALS Snapshot assay results through 2019 was summarized in the 2020 Pond Monitoring Database report, which also details assay procedures that were followed.[33] The summary below updates the data analysis in the Pond Monitoring Database report by including the results from the sampling events in 2020, including the data gap survey results, as well as providing additional insights about the pond characteristics.

Water quality samples collected during the August/September PALS Snapshots were generally collected at the following depths: 0.5 m, 3 m, 9 m and a deep sample. Deep sample averaged 10.8 m depth among the Snapshot data. Snapshot samples were assayed for: pH, alkalinity, chlorophyll a, pheophytin a, total phosphorus (TP), and total nitrogen (TN). Data gap samples collected in 2020 were collected at the same depths except the deep samples were consistently collected at 11 m. Data gap water column samples were collected on 10 dates in 2020 (9 dates + 2020 PALS) and assayed for the same constituents as the PALS Snapshots.

IV.A.2.a Water Column: Laboratory Water Quality Assays: Phosphorus and Nitrogen

Historical August/September TP and TN PALS Snapshot averages were consistent with the impaired conditions measured in the DO/temperature profiles. Shallow (0.5 m) and 3 m total phosphorus (TP) and total nitrogen (TN) concentrations were not significantly different reflecting the average well-mixed conditions at these depths measured in the temperature profiles (**Figure IV-6**). Average readings at both depths exceeded their respective Cape Cod Ecoregion thresholds (*i.e.*, 10 µg/L TP and 0.31 mg/L TN).[34] Review of individual readings showed that 56% of the shallow TP concentrations and 87% of the shallow TN concentrations exceeded their respective Ecoregion thresholds. Average TP and TN concentrations at 9 m and the deepest depth, which typically experience anoxia in August/September, were significantly higher ($\rho<0.05$) than the 0.5 m and 3 m averages. Review of individual Snapshot temperature profiles show that waters at 9 m depth are either in the transition zone or in the hypolimnion. Deep TP and TN concentrations were higher than the 9 m averages, but only the deep TN concentration was significantly higher. Almost all of the PALS Snapshot TN and TP concentrations at 9 m and deep exceeded their respective Ecoregion thresholds. Living Lakes 1986-1991 data was reviewed and has some quality control issues: more than a third of the TP concentrations were reported as below detection limit concentrations, including deep readings in August.[35]

Comparison of historical TP and TN concentrations show that phosphorus is the key nutrient stimulating plant growth in Shubael Pond and, thus, is the primary focus for managing its water and habitat quality. Average N:P ratios based on 2001 to 2020 PALS Snapshot data were greater than 50 throughout the water column with shallow average ratios even greater: 0.5 m samples averaged 95, while 3 m samples averaged 77. Deep and 9 m averages were 56 and 53, respectively, which shows how relatively more phosphorus than nitrogen is released from the sediments during anoxic conditions.

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[33] Eichner, E. and B. Howes. 2021. Town of Barnstable Freshwater Ponds, 2021 Water Quality Monitoring Database: Development and Review.

[34] Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas.

[35] Living Lakes, Inc. 1992. Living Lakes Program, Final Report, Shubael Pond. Greenbelt, MD. 42 pp.

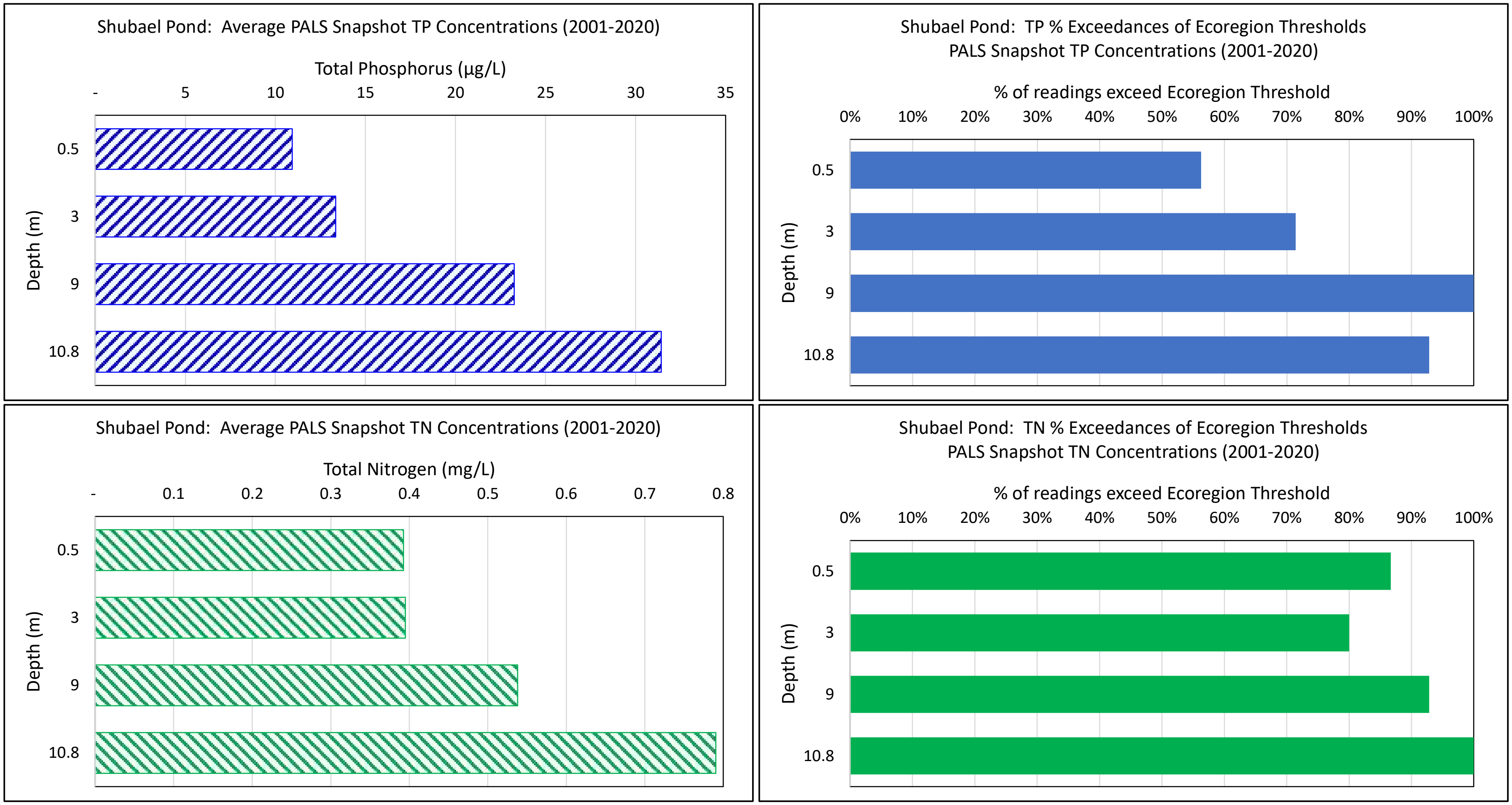
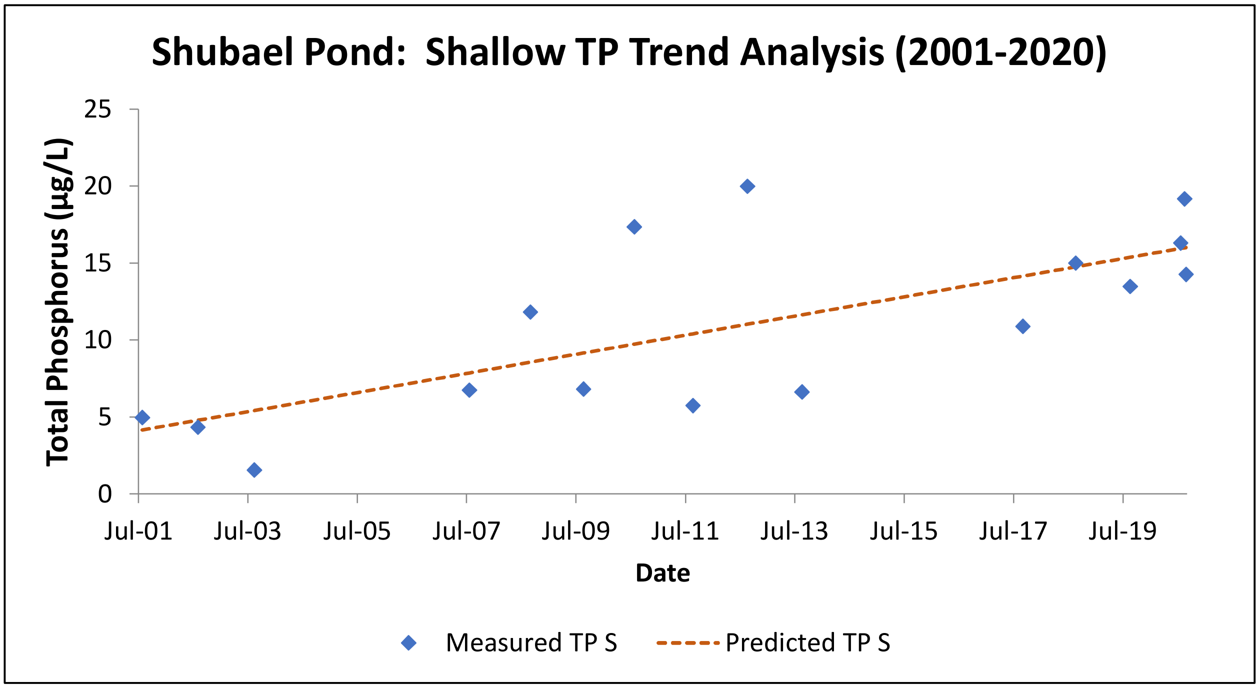


Figure IV-6. Shubael Pond Average Snapshot TP and TN Concentrations (2001-2020) and Exceedances of Respective Ecoregion Thresholds by Depth. TP and TN average concentrations based on PALS Snapshot data collected between 2001 and 2020 at 0.5 m, 3 m, 9 m, and deep (10.8 m) sampling depths exceed the respective Ecoregion thresholds. Review of individual concentrations show that more than 80% of the TN concentrations at all depths were greater than the TN threshold (0.31 mg/L). Individual 0.5 m TP concentrations exceeded the threshold (10 µg/L) 56% of the time, while 71% of the 3 m concentrations exceeded the threshold. Individual deep TP and TN concentrations exceeded the respective thresholds most (>93%) of the time. The higher concentrations in the deep waters in August/September is consistent with sediment regeneration of these nutrients under prolonged anoxia.

Trend analysis of the historical August/September PALS Snapshot TN and TP data from 2001 through 2020 shows that nutrient inputs have increased significantly over the past two decades and that the primary source of the increase appears to be watershed inputs. Trend analysis of shallow (0.5 m) TP concentrations show a statistically significant increasing trend (+0.62 µg/L per year; $\rho<0.002$), which would translate to a 6.2 µg/L TP increase over 10 years (**Figure IV-7**). A significant trend was also noted in the TP data at 3 m: +0.47 µg/L per year; $\rho<0.03$. Review of shallow TN concentrations also showed a statistically significant increasing trend, but the rate is very low: +0.0047 mg/L per year; $\rho<0.05$, which would translate to only a 0.05 mg/L TN increase over 10 years. TN concentrations at 3 m do not have a significant trend. Trend analysis of deep TP samples also do not have a significant trend.

Collectively, the increasing trend of shallow TP between 2001 and 2020 without significant changes in deep TP concentrations would be consistent with slowly increasing watershed inputs likely from septic systems. Septic system inputs would increase as phosphorus plumes from existing houses gradually reach and discharge into the pond. Phosphorus plumes from the newest houses generally take decades to reach the pond. The relatively small increase in TN concentrations supports this contention that the TP increase is not due to new septic systems being added or increases in population, but rather a gradual increase in the number of existing septic systems discharging phosphorus to the pond.

Review of 2020 TP data collected between May and December shows summer increases throughout the water column (**Figure IV-8**). All of the individual 2020 TP concentrations except for December 2 samplings were greater than the Ecoregion TP threshold. In the first (May 8) sampling, TP concentrations at 0.5 m, 3 m, and 7 m varied between 10.2 µg/L and 12.2 µg/L, while concentrations at 9 m and 11 m were 18.3 µg/L and 16.3 µg/L, respectively. Shallow (0.5 m) TP concentrations increased into the 14 to 19 µg/L range beginning in the July 15 sampling and remained within that range until the December 2 sampling when the shallow concentrations returned to the 10 to 12 µg/L range (12.1 µg/L). The TP samples at 3 m and 7 m followed a similar pattern. TP concentrations at 9 m also followed this pattern, but had peak concentrations of 21.1 µg/L on both August 13 and September 17. Deep TP concentrations were 16.3 µg/L on May 8, then increased to 26.4 µg/L on May 20, decreased to 16.3 µg/L on June 17 and then gradually increased in each subsequent sampling until September 17 when it peaked at 42.3 µg/L. The deep sample on December 2, when the whole pond water column was well-mixed, had a TP concentration of 8.8 µg/L or approximately half of the May 8 result. The lowering of TP after the water column mixes is typically due to 1) the reoxidation of the surface sediments, which can then sorb phosphate, and 2) the deposition of phytoplankton and organic particulate matter to the sediments. The low temperature conditions slow the amount of organic matter decomposition and release of P until spring/return of anoxia. The increase in TP throughout the water column during 2020 seems to be largely coincident with the notable increase in the deep TP concentrations. This pattern could be the result of a number of processes or combination of processes including sediments adding phosphorus to the water column during the summer, the deep increases due to anoxia are causing the TP increases in shallower depths, and/or the shallow pond volume is decreasing significantly.



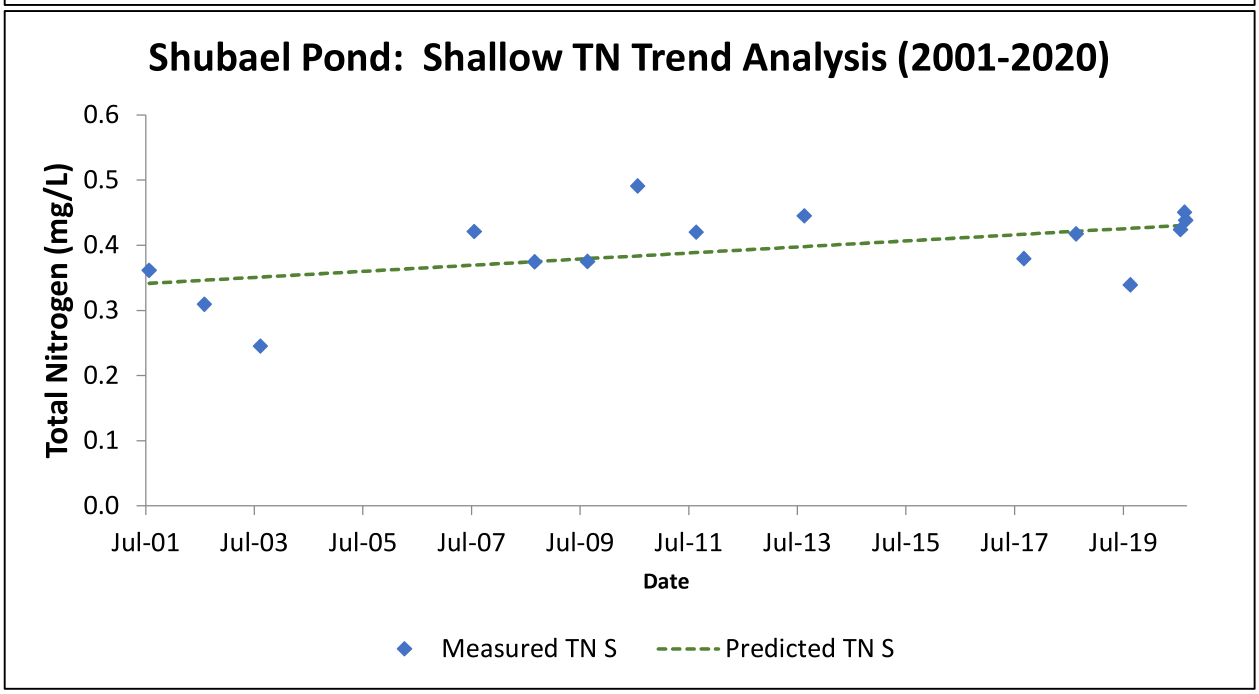
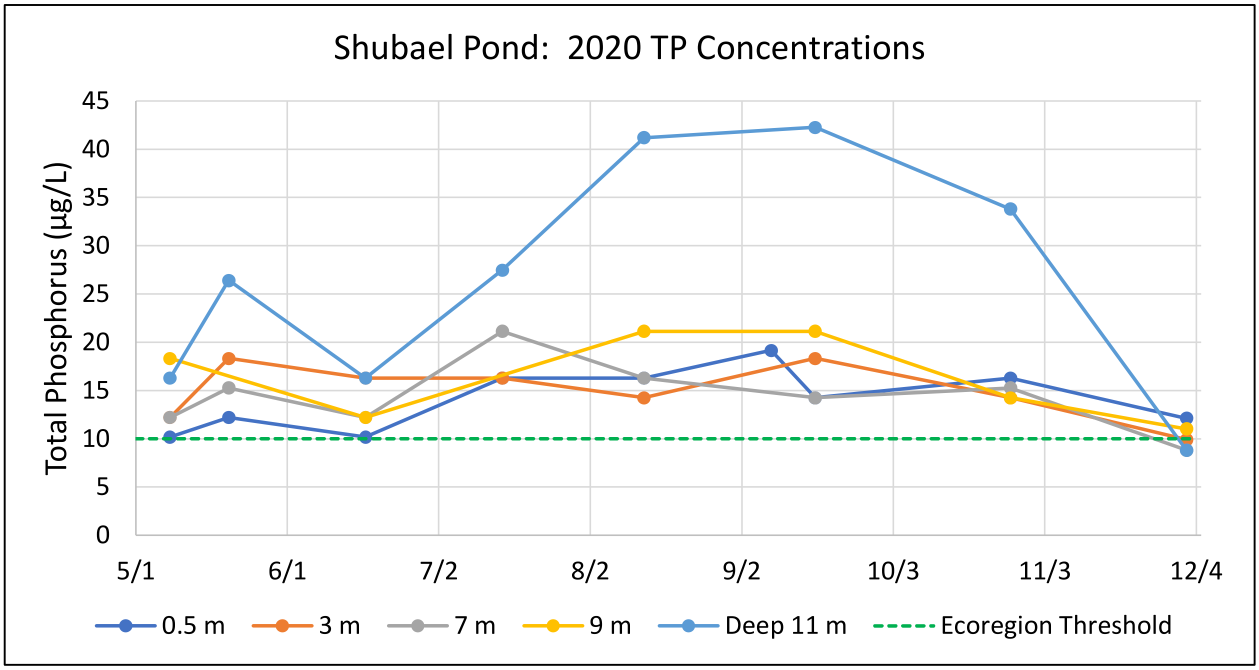


Figure IV-7. Shubael Pond: Shallow TP and TN August/September Trends (2001 to 2020). Trend analysis of shallow TP and TN concentrations in PALS Snapshots between 2001 and 2020 show that both have statistically significant increasing trends. The shallow TP trend is +0.62 µg/L per year ($\rho<0.002$), while the shallow TN trend is +0.0047 mg/L per year ($\rho<0.05$). The shallow TP trend is more notable because 10 years of the current trend would represent a 6.2 µg/L increase or more than half of the 10 µg/L TP Ecoregion threshold, while the TN concentration increase over ten years would only be 0.05 mg/L or less than 20% of the 0.31 mg/L TN Ecoregion threshold. TP concentrations at 3 m also had a significant increasing trend, but 3 m TN concentrations did not. Deep TP concentrations also did not have a significant trend.



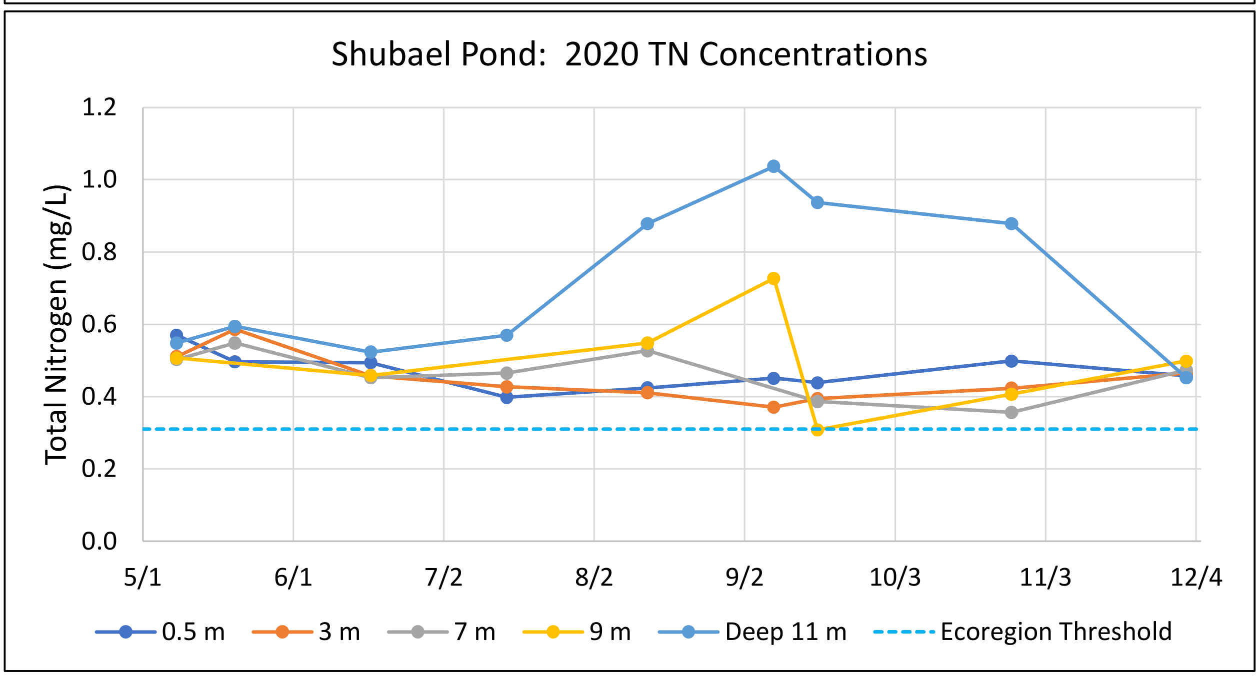


Figure IV-8. Shubael Pond 2020 Water Column TP and TN Concentrations. TP water column concentrations collected between May and December 2020 shows summer increases throughout the water column and all individual TP concentrations were greater than the Ecoregion threshold (except for December 2). The summer TP increase throughout the water column seems to be largely coincident with the notable increase in the deep TP concentrations. TN water column concentrations decreased in shallower depths throughout the summer, while increasing in the deep depths and all of the individual TN concentrations at all depths were greater than the Ecoregion threshold. Deep TP and TN concentration increases suggest impacts of prolonged anoxia during the summer.

Shallow water column TN levels during 2020 decreased throughout the summer, while increasing in the deep depths. All of the individual TN concentrations at all depths were greater than the Ecoregion threshold throughout the year. In the May 8 sampling, the shallow (0.5 m) TN concentration was 0.57 mg/L, which then decreased to 0.50 mg/L and 0.49 mg/L in the May 20 and June 17 samplings, respectively, decreased further to 0.40 mg/L on July 15 and then varied between 0.42 mg/L and 0.45 mg/L in the August 13, September 8, and September 17 samplings. In the October 27 sampling, the TN concentration returned to 0.50 mg/L. Concentrations at 3 m followed a similar pattern, but TN concentrations at 7 m and 9 m had a decrease in the June 17 and July 15 samplings and then an increase in the August 13 sampling that was consistent with a notable increase in the deep (11 m) TN concentration. In the September 17 sampling, the TN concentrations at 7 m and 9 m decreased again before gradually increasing in the October 27 and December 2 samplings. The deep TN concentrations remained consistent with the August 13 levels until decreasing with mixing by the December 2 sampling. The pattern of deep TN concentrations suggest that deep anoxia is prolonged throughout the summer, since sediment nitrogen regeneration only typically occurs once available nitrate-nitrogen is utilized. The decrease in TN concentrations seen in the shallower depths suggests that nitrogen is being preferentially removed from the water column during the summer, likely by rooted or floating aquatic plants, which can prompt sediment denitrification around their roots,[36] or by shellfish growth and biodeposition.[37]

The ratios of 2020 TP and TN concentrations show that phosphorus is the key nutrient controlling water and habitat quality conditions throughout the year. The Redfield ratio threshold of 16 typically defines whether water quality conditions are controlled more by nitrogen or phosphorus; ratios of greater than 16 (more N than P) indicate that phosphorus determines water quality conditions in a pond. Freshwater ponds and lakes typically have N:P ratios 2X to 3X the Redfield ratio. Average 2020 N:P ratios in Shubael Pond at all depths were greater than 60 and review of individual ratios during each of the samplings show that the minimum ratio was 32 (**Figure IV-9**). This review confirms that phosphorus is the key management nutrient in Shubael Pond throughout the summer management period and is consistent with the 2001 to 2020 PALS Snapshot data.

IV.A.2.b Water Column: Laboratory Water Quality Assays: Chlorophyll a and Phaeophytin

Chlorophyll a is the primary pigment used in photosynthesis and is a reasonable proxy for phytoplankton concentrations. Phaeophytin is the first breakdown product of chlorophyll a once it begins to degrade. The sum of the two concentrations is an alternative estimate of the total phytoplankton population. The Cape Cod Ecoregion threshold concentration for chlorophyll a is 1.7 µg/L.[38] Although measurable concentrations of both pigments are usually present throughout the water column, chlorophyll a concentrations tend to be higher in shallower portions of the water column where phytoplankton are actively growing, while phaeophytin concentrations tend to be higher in deeper portions of the water column as degrading phytoplankton settle to the sediments.

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[36] Lu Y, Zhou Y, Nakai S, Hosomi M, Zhang H, Kronzucker HJ, Shi W. 2014. Stimulation of nitrogen removal in the rhizosphere of aquatic duckweed by root exudate components. *Planta*. 239(3): 591-603.

[37] Bingchang Tan, Hu He, Jiao Gu, Kuanyi Li. 2018. Eutrophic water or fertile sediment: which is more important for the growth of invasive aquatic macrophyte Myriophyllum aquaticum? *Knowl. Manag. Aquat. Ecosyst.* 419(3)

[38] Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas.

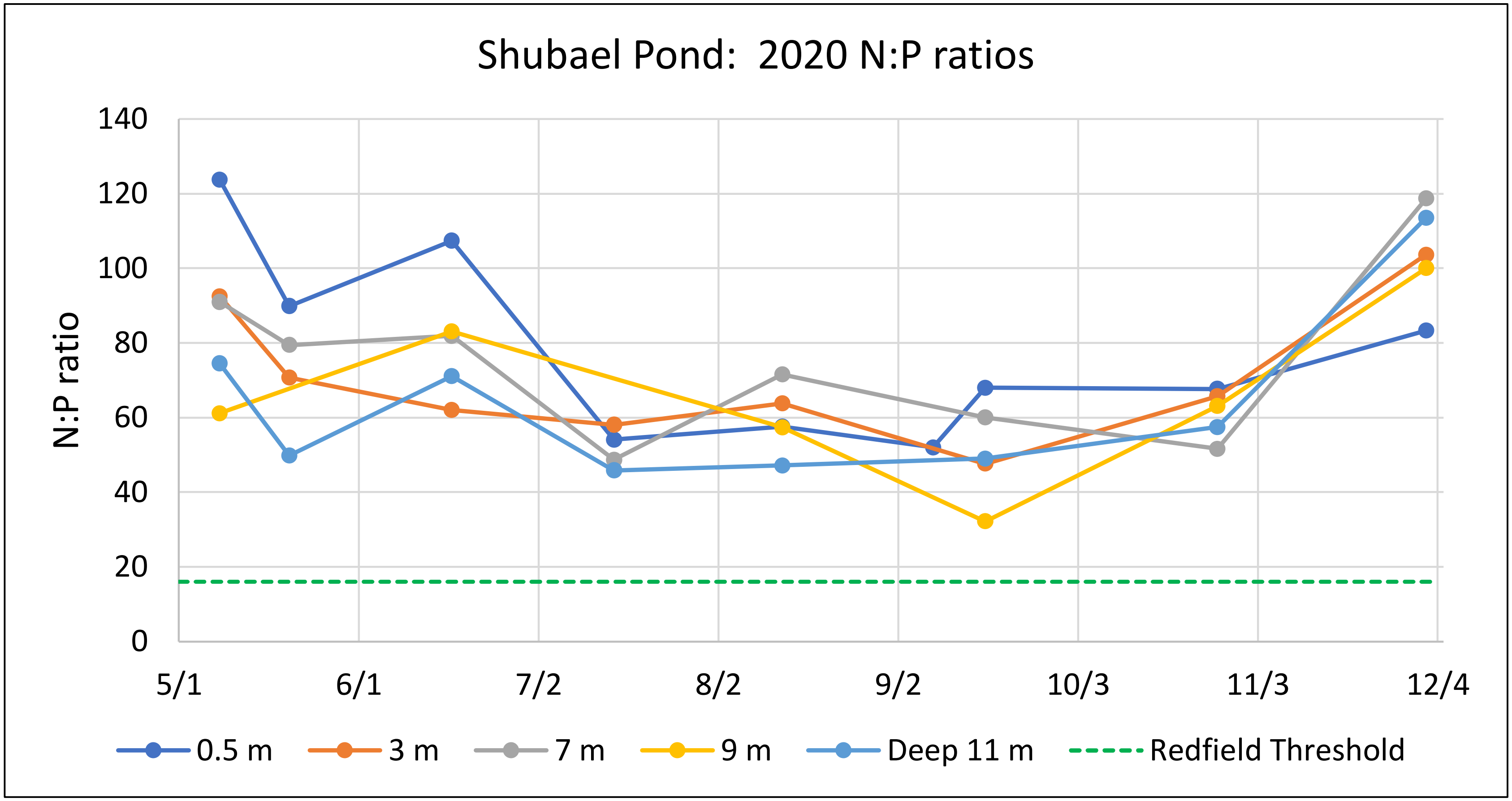
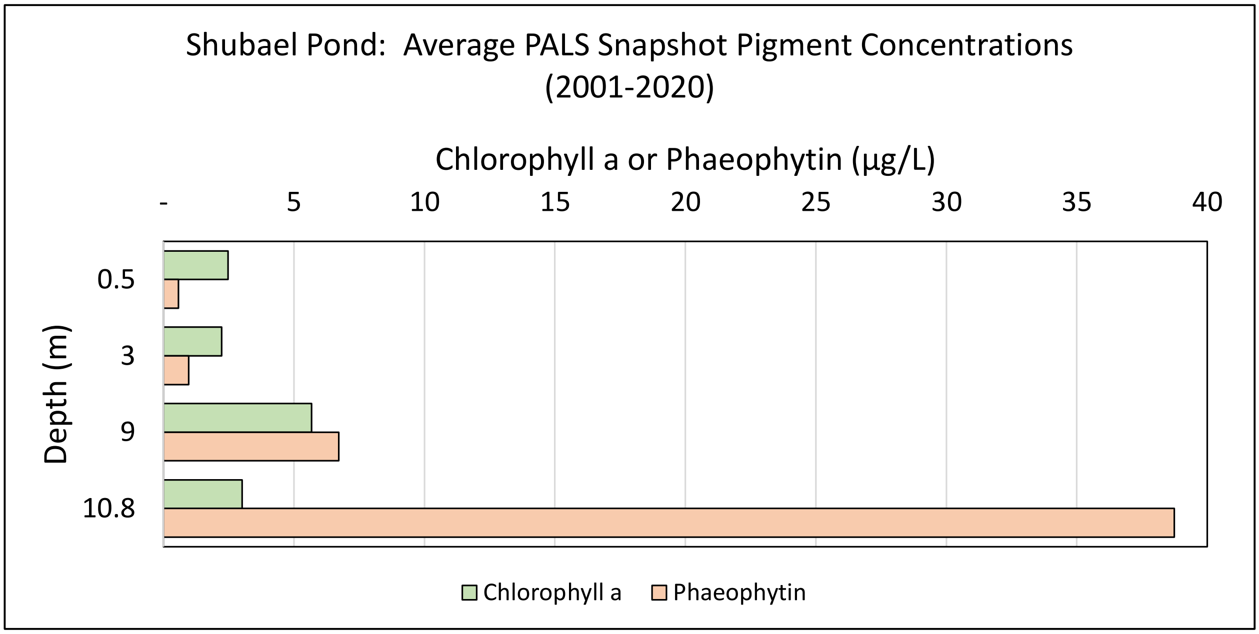


Figure IV-9. Shubael Pond 2020 N to P ratios. The ratio of TP and TN concentrations at all depths show that phosphorus is the key nutrient controlling water quality conditions in Shubael Pond throughout 2020. The Redfield ratio threshold of 16 typically defines whether water quality conditions are controlled more by nitrogen or phosphorus; ratios of greater than 16 (more N than P) indicate that phosphorus determines water quality conditions in a pond. Average N:P ratios in Shubael Pond at all depths during 2020 were greater than 60.

Historical August/September chlorophyll a (CHLa), phaeophytin (PHA), and total pigment PALS Snapshot averages were consistent with the impaired conditions in Shubael Pond. Shallow (0.5 m) and 3 m CHLa and PHA concentrations were not significantly different reflecting the average well-mixed conditions at these depths (**Figure IV-10**). Average CHLa concentrations from both shallow depths exceeded their respective Cape Cod Ecoregion thresholds and review of individual readings showed that 81% of the shallow CHLa concentrations exceeded the Ecoregion threshold. Average PHA concentrations were low at 0.5 m and 3 m (*i.e.*, <1 µg/L). At 9 m, the PALS average CHLa was 5.7 µg/L, while the PHA concentration was 6.7 µg/L. The increases at this depth are consistent with both degrading shallower phytoplankton and the active phytoplankton noted by the 2020 mid-depth DO bulge (see **Figure IV-5**). At the deep (10.8 m) depth, the average PALS CHLa concentration was 3.0 µg/L, while the PHA concentration was 38.7 µg/L. This decrease in CHLa concentration would be expected given phytoplankton would not be growing at this depth, while the large PHA increase compared to the 9 m average would also be expected reflecting degrading phytoplankton settling into the deepest waters. Average total pigment concentrations increased from 13.9 µg/L at 9 m to 46.3 µg/L at the deep depth.

CHLa and PHA 2020 concentrations in May to December generally show that acceptable concentrations throughout the water column through June and increasing concentrations throughout the rest of the summer especially in deeper samples, which developed very high PHA concentrations. Shallow 2020 CHLa concentrations in the May 8, May 12, May 20, and June 17 samplings were all less than the 1.7 µg/L Ecoregion threshold (**Figure IV-11**). All CHLa concentrations at 1 m, 3 m, and 9 m on the same dates were also less than the threshold. CHLa concentrations at 7 m and 11 m (deep) were less than the threshold in all May samplings, but exceeded the threshold in June. CHLa concentrations at 1 m, 3 m, and 9 m in the July 15 sampling all exceeded 2.4 µg/L, while the 7 m and 11 m concentrations were less than 1.5 µg/L. In the August 15 sampling, the 1 m, 3 m, 7 m and 9 m CHLa concentrations all increased, while the deep concentration decreased to 0.02 µg/L. This pattern of CHLa concentrations increasing is consistent with the increasing TP concentrations measured in the summer (see **Figure IV-8**). The decreases in deep CHLa concentrations are consistent with active growth of shallower phytoplankton populations. Deep PHA concentrations had notable increases in the July 15 sampling consistent with senescence and settling of phytoplankton from the shallower waters. In the August 15 sampling, the deep PHA concentration increased by >7X over July 15 further reinforcing that phytoplankton in the shallower waters were growing and settling extensively between the two samplings. In the September 8 sampling, CHLa concentrations at 9 m peaked at 13.1 µg/L and the deep sample was again 0.02 µg/L. The 2020 DO profile on September 8 had anoxia throughout the hypolimnion and hypoxia through the transition zone; this means the high deep TP concentrations could support phytoplankton growth at the bottom of the epilimnion and that productivity of that growth was causing phytoplankton to cycle quickly and senescing phytoplankton to begin to settle. This is consistent with the high PHA concentration on September 8 (71.9 µg/L). The September 17 sampling seems to confirm these processes by having an exceptional increase in the deep CHLa concentration (to 69.3 µg/L). After these September concentration peaks, CHLa and PHA concentrations decrease in subsequent samplings, although CHLa concentrations still remained above the Ecoregion threshold in December.



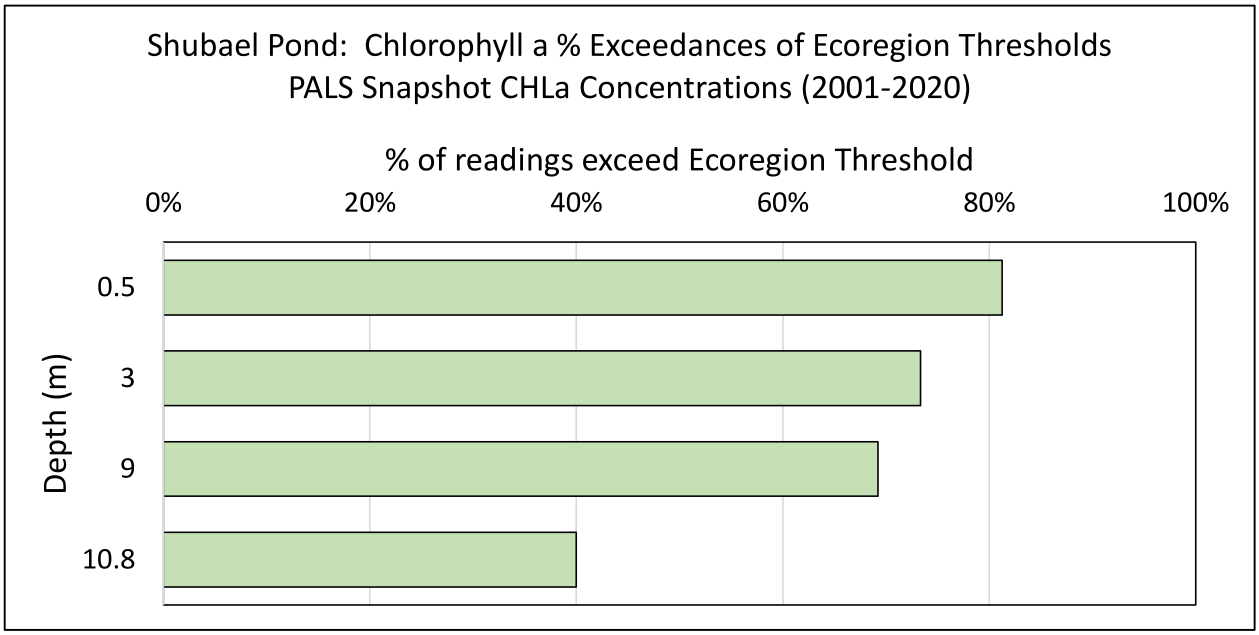


Figure IV-10. Historical Shubael Pond Average Snapshot Pigment Concentrations (2001-2020) and Exceedances of Chlorophyll Ecoregion Threshold by Depth. Average historical August/September chlorophyll a (CHLa) and pheophytin a (PHA) concentrations were consistent with the impaired conditions measured in TP, TN, and DO concentrations. Shallow 0.5 m and 3 m CHLa and PHA concentrations were not significantly different, consistent with well-mixed conditions seen in the temperature profiles and >70% of the CHLa concentrations at these depths in the individual Snapshots exceed the Cape Cod Ecoregion threshold (1.7 µg/L). Average PHA concentrations were low at 0.5 m and 3 m (*i.e.*, <1 µg/L) as the phytoplankton were actively growing. At 9 m, the PALS average CHLa was 5.7 µg/L, while the PHA concentration was 6.7 µg/L (a 7X increase from 3 m). The increases at the 9 m depth are consistent with an active and senescing phytoplankton population at the upper edge of the hypolimnion. At deth (10.8 m), the average PALS CHLa concentration was 3.0 µg/L, while the PHA concentration was 38.7 µg/L. The large increase in deep PHA concentration is consistent with senescing/degrading phytoplankton settling from shallower depths.

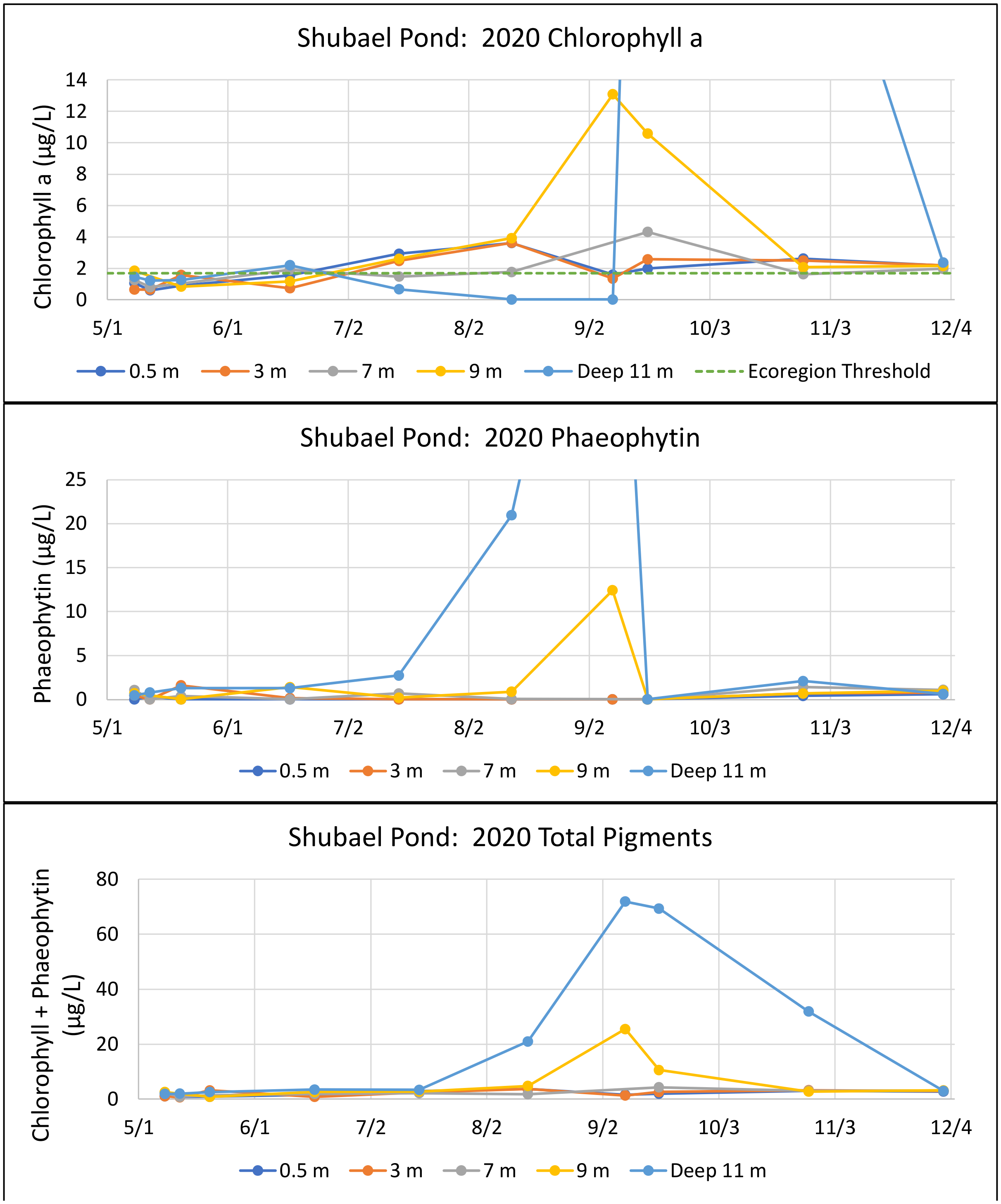


Figure IV-11. Shubael Pond 2020 Water Column Chlorophyll a, Phaeophytin a, and Total Pigment Concentrations. CHLa and PHA concentrations were generally acceptable throughout the water column in both May and June. Concentrations increase throughout the rest of summer, especially at the 9 m and deep 11 m depths, as phytoplankton settling and high TP concentrations in the deep waters prompt phytoplankton growth at the bottom of the epilimnion and within the transition zone. This growth raises CHLa concentrations and population turnover prompts higher PHA concentrations and settling of PHA into deeper depths. CHLa and PHA graphs have limited y-axes to show more detail during most of the samplings.

IV.A.2.c Water Column: Laboratory Water Quality Assays: pH and Alkalinity

Alkalinity and pH are somewhat linked parameters: pH is the negative log of the hydrogen ion concentration and is traditionally used to determine whether a liquid is acidic (pH<7) or basic (pH>7), while alkalinity (ALK) is a measure of the capacity of water to neutralize acid (*e.g.*, high alkalinity waters can absorb the impacts of acid inputs without significant changes in pH). Compounds providing ALK are bicarbonates, carbonates, and hydroxides. Cape Cod ponds and lakes typically have naturally low pH and ALK.

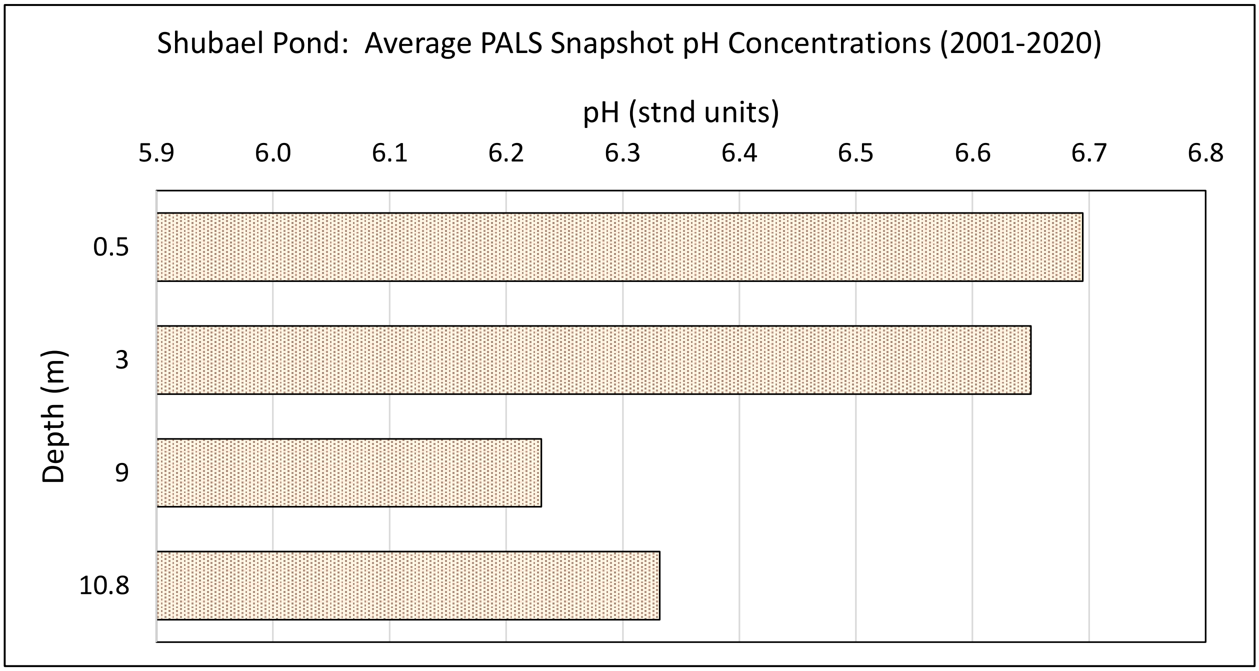
As mentioned above, MassDEP regulations specify that pond water should have a pH of 6.5 to 8.3, but the regulations have allowances for acceptable pH outside of this range if it is naturally occurring. Since Cape Cod is mostly glacially-deposited sand, there is little natural carbonate material (*e.g.*, limestone) to reduce the naturally low pH of rain (*i.e.*, 5.7). Review of data from 193 Cape Cod ponds and lakes sampled during the first PALS Snapshot had a median pH concentration of 6.28 and a median alkalinity concentration of 7.2 mg/L as $CaCO_3$.[39] An earlier sampling of Cape Cod groundwater in public and private drinking water wells had a median pH of 6.1.[40] Cape Cod ponds with higher pH readings typically have higher nutrient levels, since photosynthesis consumes hydrogen ions and higher nutrient levels prompt more phytoplankton photosynthesis.

During the late 1980's, when little pond water quality data existed on Cape Cod and decreases in rain pH had been measured throughout the Northeast due to industrial combustion in the Midwest, there was a concern that the low pH in Cape Cod ponds was due to increases in acid rain. In response, a Living Lakes effort was conducted to raise the pH of Shubael Pond by adding 13.1 tonnes of limestone to the pond on two occasions, November 1986 and July 1991. This effort raised the average pH to 7.0 in the shallow pond waters (n=11), but later monitoring showed that this increase was temporary. Comparison of shallow 1986-1991 August pH readings to shallow 2001-2020 PALS pH readings show that pH after the limestone treatment was significantly higher, but the change was relatively small: August 1986-1991 average = 7.0 while 2001-2020 August/September average = 6.7. Although the averages were statistically different, review the individual 1986-1991 shallow August readings showed that none of the pH readings were notably different from those collected between 2001 and 2020 and none would have been statistically outliers if they were included in the PALS database.

Historical August/September pH and ALK PALS Snapshot averages in Shubael Pond were consistent with the impaired conditions. Shallow pH readings were significantly higher than deep readings, consistent with greater photosynthesis in shallower waters, while ALK levels were higher in deeper waters consistent with greater carbon availability due to settling biomass. Shallow 0.5 m and 3 m pH and ALK readings were not significantly different from each other consistent with the average well-mixed conditions in the upper portion of the water column (**Figure IV-12**). Deep and 9 m averages were also not significantly different from each other consistent with the late summer conditions where anoxic DO had typically risen to 9 m (see **Figure IV-3**). Average shallow and 3 m pH from the 2001 to 2020 PALS data were 6.69 and 6.65, respectively, while average 9 m and deep 10.8 m pH readings were 6.23 and 6.33,

[39] Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas.

[40] Frimpter, M.H. and F.B. Gay. 1979. Chemical Quality of Ground Water on Cape Cod, Massachusetts. US Geological Survey, Water-Resources Investigations 79-65. Boston, MA. 20 pp. + 2 plates.



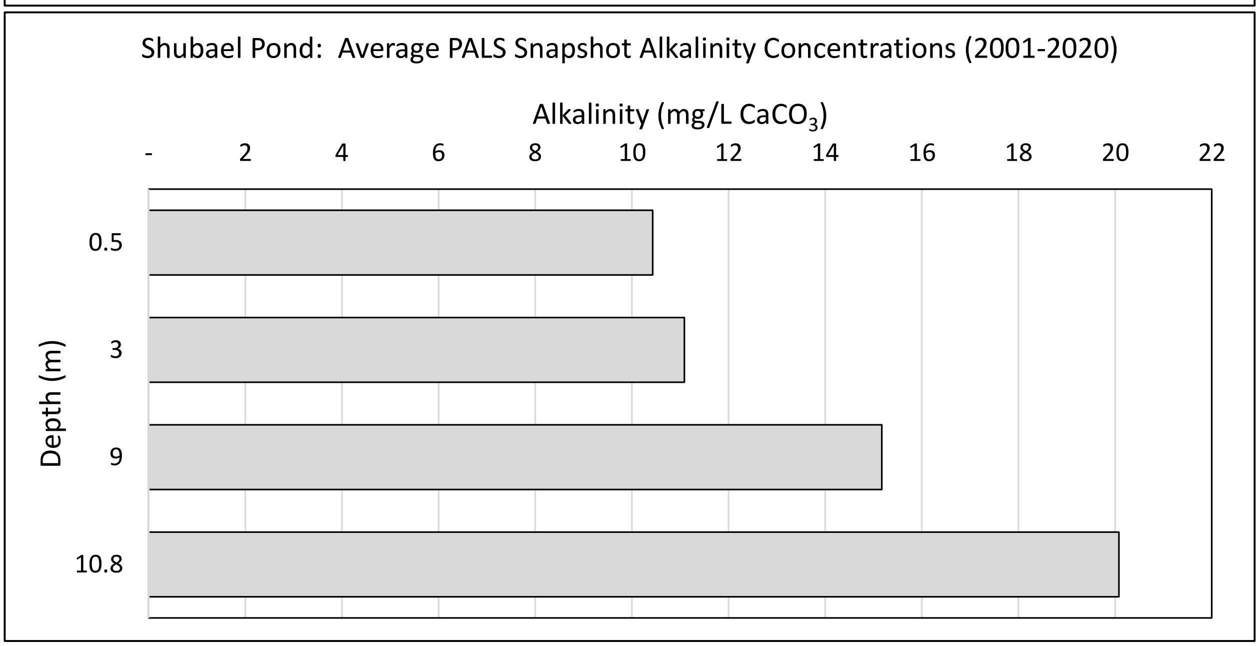
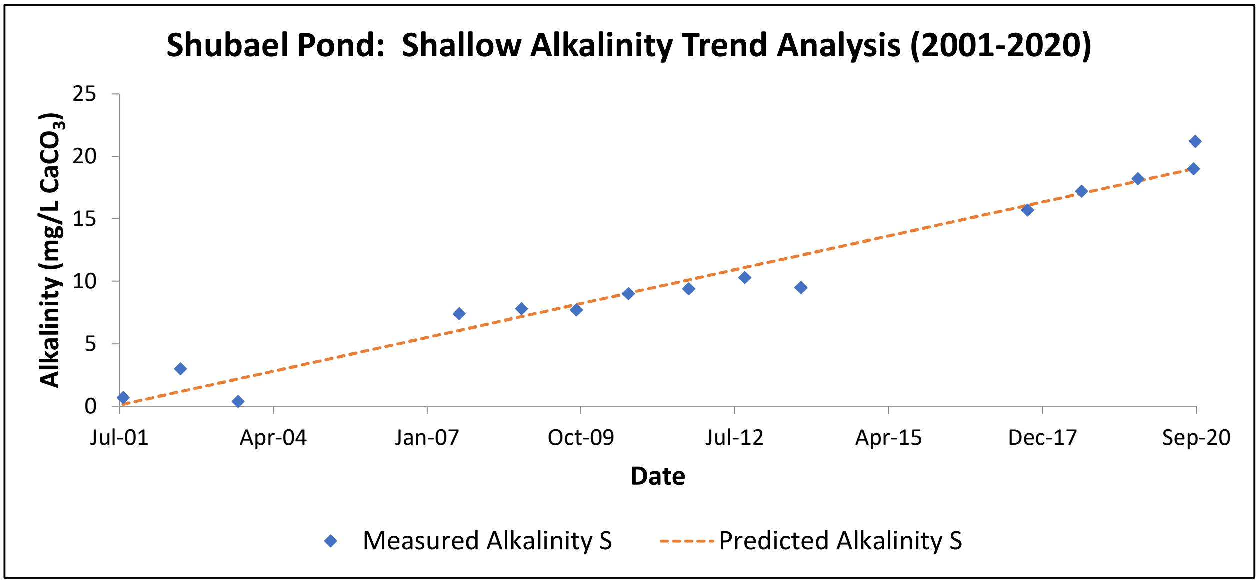


Figure IV-12. Historical Shubael Pond Snapshot pH and Alkalinity Concentrations (2001-2020). Shallow August/September pH readings from the PALS Snapshots were significantly higher than deep readings consistent with greater photosynthesis in shallower waters. Average pH from 0.5 m and 3 m samples were not significantly different and 9 m and 10.8 m average readings also were not significantly different. Alkalinity concentrations were significantly higher in deeper waters due to settling of biomass from shallower waters (mostly phytoplankton). As with pH, shallow alkalinity averages were not significantly different nor were deep averages.

respectively. Average shallow and 3 m ALK concentrations were 10.4 and 11.1 mg/L as $CaCO_3$, respectively, while average 9 m and deep (10.8 m) ALK readings were 15.1 and 20.1 mg/L as $CaCO_3$, respectively.

Trend analysis of the historical PALS Snapshot pH and ALK data from 2001 through 2020 shows that ALK has a significant increasing trend, while pH does not. Trend analysis of shallow (0.5 m) ALK concentrations show a statistically significant increasing trend (+1.0 mg/L $CaCO_3$ per year; $\rho<1.0E-10$) (**Figure IV-13**). Significant increasing trends in ALK were also noted at 3 m, 9 m, and the deep PALS Snapshot data, though the rate of increase per year at the deep station was 2X the shallow rate. No significant trends were noted in the pH readings at the various depths. The increasing ALK is likely mostly related to the increasing plant productivity in Shubael Pond, as noted in the TP and TN concentrations. Additional TP would increase the amount of carbon that could be stored in the pond as biomass (*i.e.*, phytoplankton, zooplankton, macrophytes, fish, etc). The increasing rate with depth would be due to settling of this increasing biomass into the smaller volume of the pond in the deeper water. Overall, the increase in ALK is consistent with the increase in nutrients and impaired conditions.

May to December 2020 ALK concentrations generally showed increases paralleling the summer TP increases, while pH readings were relatively similar throughout the 2020 sampling period though with higher shallow readings than deep readings. ALK began to increase beginning in June, peaked in August, before slowly decreasing to June levels in December (**Figure IV-14**). As noted, higher TP concentrations would allow greater amounts of biomass to be developed and retained within the pond. ALK readings in May were generally between 15 and 16 mg/L $CaCO_3$, rose slightly in June to 15 to 17 mg/L $CaCO_3$, then 16 to 22 mg/L $CaCO_3$ in July (with higher concentrations in shallow samples) and peaked in August with a range of 17 to 63 mg/L $CaCO_3$. September through December readings decreased sequentially with December slightly lower than those in July, but higher than June. Highest pH readings (*i.e.*, 7.0) occurred in July. Average 2020 pH at the sampled depths varied between 6.7 (0.5 m, 1 m, and 3 m) and 6.4 (11 m).



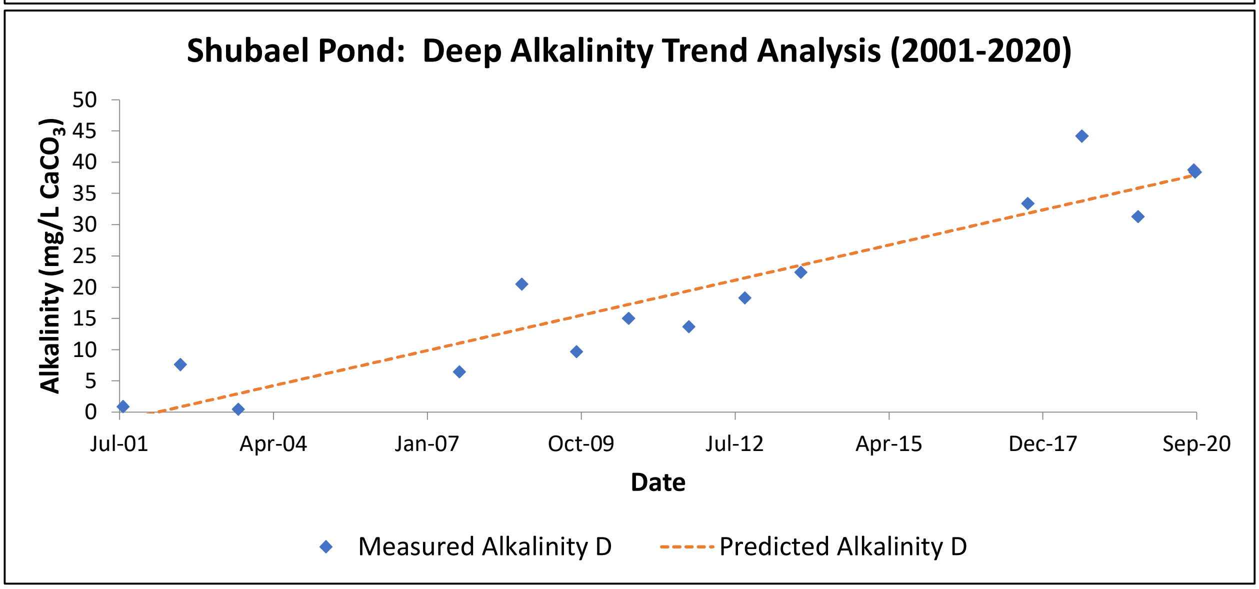


Figure IV-13. Shubael Pond: Shallow and Deep Alkalinity August/September Trends (2001 to 2020). Trend analysis of shallow and deep alkalinity concentrations in PALS Snapshots between 2001 and 2020 show that both have statistically significant increasing trends. The shallow alkalinity trend is +1.0 mg/L $CaCO_3$ per year (ρ<1.0E-10), while the deep alkalinity trend is +2.0 mg/L $CaCO_3$ per year (ρ<2E-07). Increasing trends were also noted at 3 m and 9 m readings. The increase in shallow alkalinity is consistent with increasing organic matter in the pond and measured TP trends. The deep readings have a higher increasing rate because of biomass settling and the reduced volume of deeper waters. No significant trends were noted in pH readings over the same period.

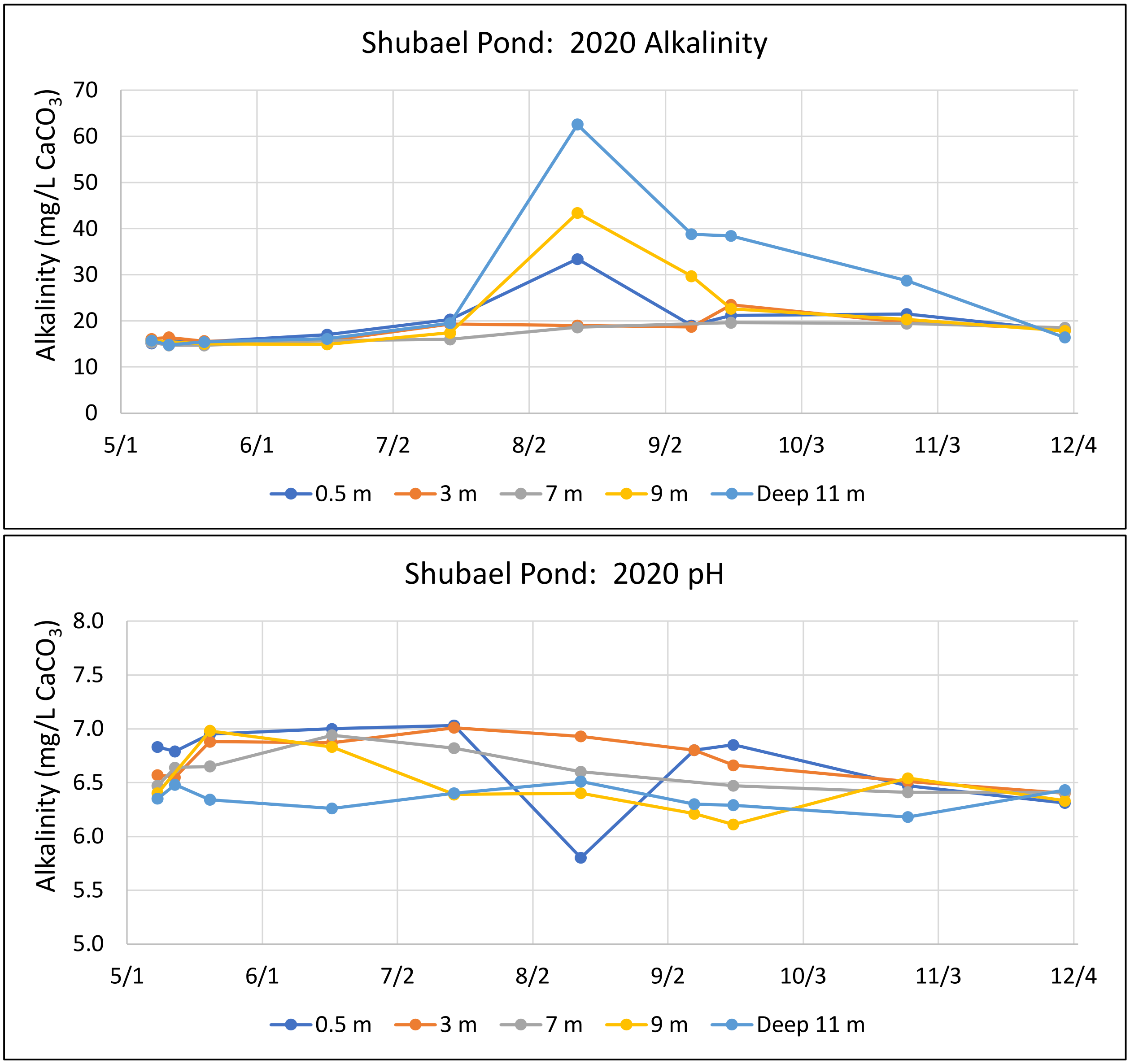


Figure IV-14. Shubael Pond 2020 Water Column Alkalinity and pH Concentrations. Alkalinity concentrations in May to December 2020 generally showed increases paralleling the summer TP increases. Alkalinity began to increase beginning in June, peaked in August, before slowly decreasing to June levels in December. The average shallow (0.5 m) alkalinity concentration (19.7 mg/L $CaCO_3$) was higher than mid-depth readings (1 m and 3 m), but lower than 9 m or 11 m readings (20.9 mg/L $CaCO_3$ and 25.3 mg/L $CaCO_3$, respectively). pH readings were relatively similar throughout the 2020 sampling period with shallow readings higher than deep readings. Average pH at 0.5 m, 1 m, and 3 m were all 6.7, while 7 m average was 6.6, 9 m was 6.5, and 11 m (deep) was 6.4.

IV.B. Shubael Pond Data Gap Surveys

During the 2021 review of available pond water quality in the Town of Barnstable ponds and lake,[41] project staff identified a number of Shubael Pond data gaps that would need to be addressed in order to better characterize and quantify the sources of the water column nutrient levels, the processes that cause ecosystem changes seasonally and year-to-year, and to provide a more complete understanding of the system in order to select management strategies that will reliably address the identified water and habitat quality impairments. These data gaps tasks included: a) measuring seasonal changes in the phytoplankton community, b) measuring the nutrient loads from stormwater runoff into the pond, c) surveying the bathymetry, rooted plant community, and freshwater mussel populations, and d) continuously measuring the changes in water column water quality conditions. Results from each of these data gap surveys are summarized in this section.

IV.B.1. Bathymetry, Groundwater Fluctuations, and Water Column Nutrient and DO Mass

CSP/SMAST staff completed a bathymetric survey on September 15, 2021 using a differential GPS mounted on a boat for positioning coupled to a survey-grade fathometer and underwater video camera. This approach provided thousands of depth readings throughout the pond, which is a significant data density increase over previous bathymetric mapping. This data collection determined that the total volume of Shubael Pond is 1,098,269 cubic meters with a maximum depth of 13 m (**Figure IV-15**). This volume is essentially the same (<0.3% difference) as a previous estimate developed by the Cape Cod Commission based on the MassDFW bathymetric map[42] and the Living Lakes 1992 estimate.[43]

Groundwater levels at the time of the bathymetry survey were slightly below average (**Figure IV-16**). Review of groundwater measurements since 1975 show that the pond level could increase approximately 1 m above what was measured in mid-September 2021. An increase in pond elevation of 1 m would increase the overall pond volume by approximately 19%. Based on the groundwater records, the overall historic range of pond water fluctuations has been approximately 2 m suggesting that pond water levels could decrease another meter from September 2021 levels.

Combining the volume of the pond with available water quality data provides additional insights into the availability of nutrient and dissolved oxygen mass within the water column. Water column DO loss incorporates shallow DO additions from phytoplankton photosynthesis with deep DO loss from bottom water and sediment oxygen demand. Late summer PALS Snapshot (August/September) water column DO loss from 2001 to 2020 has increased since 2010 (**Figure IV-17**). The difficulty with definitive trend statements is the lack of sufficient water column DO profiles between 2014 and 2020. Average water column DO loss based on 100% saturation levels from 2001 to 2020 is 2,140 kg (n=10), while average hypolimnion loss is 1,309 kg. During the 2020 samplings from May to December, water column DO loss generally increased from May to August and decreased slightly in each of the remaining profiles (**Figure IV-18**).

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[41] Eichner, E. and B. Howes. 2021. Town of Barnstable Freshwater Ponds, 2021 Water Quality Monitoring Database: Development and Review.

[42] https://www.mass.gov/info-details/massachusetts-pond-maps (accessed11/3/21); maximum depth in the MassDFW map is 47 ft (14.3 m)

[43] Living Lakes, Inc. 1992. Living Lakes Program, Final Report, Shubael Pond. Greenbelt, MD. 42 pp.

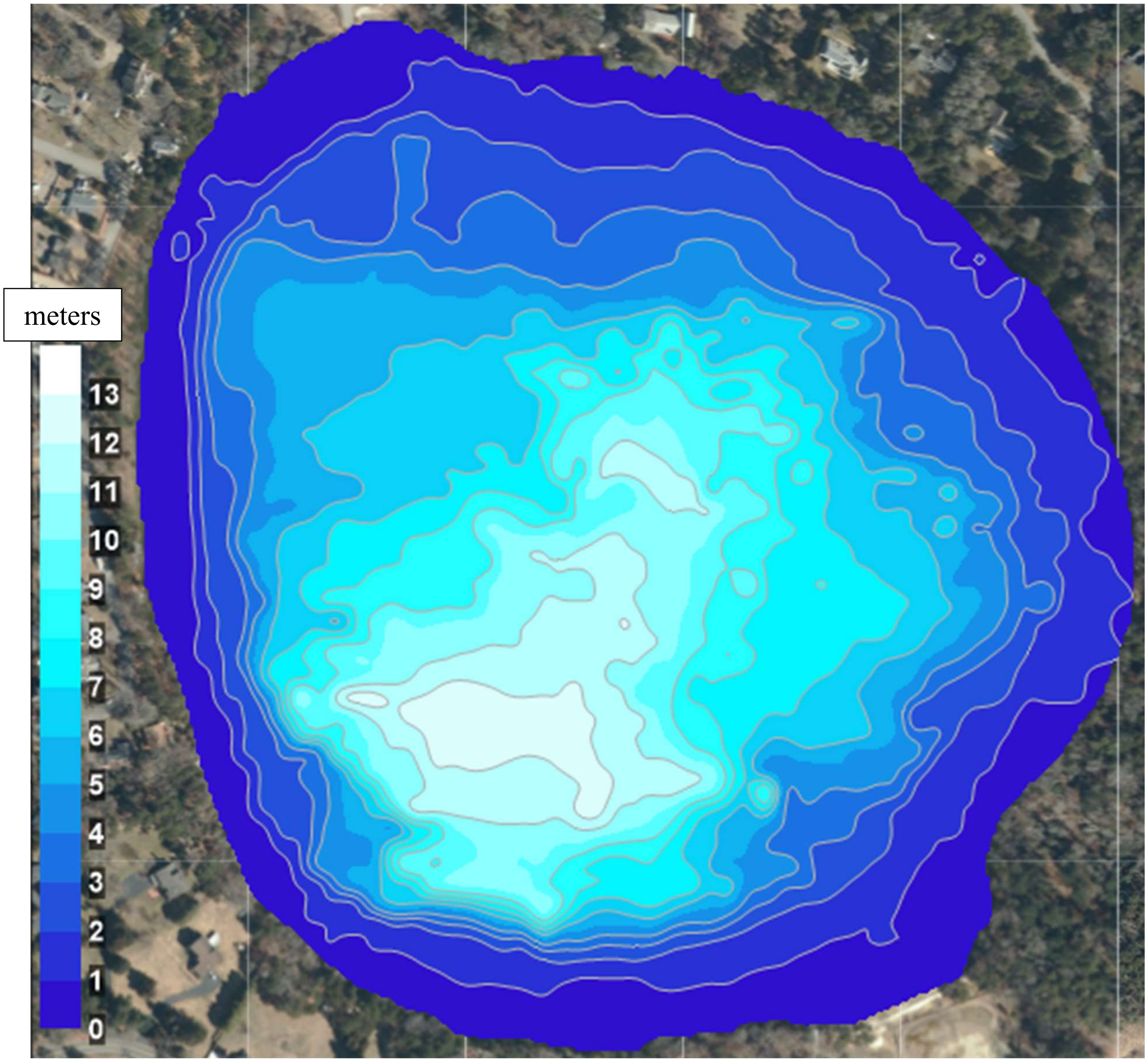

Figure IV-15. Shubael Pond 2021 Bathymetry. CSP/SMAST staff completed a bathymetry survey on September 15, 2021 using a boat with a differential GPS for positioning coupled to a survey-grade fathometer and submerged video camera. Data collection resulted in more than 200,000 depth points and synthesis of this data determined the total volume of Shubael Pond is 1,098,269 cubic meters with a maximum depth of 13 m. Figure shows depth contours in meters.

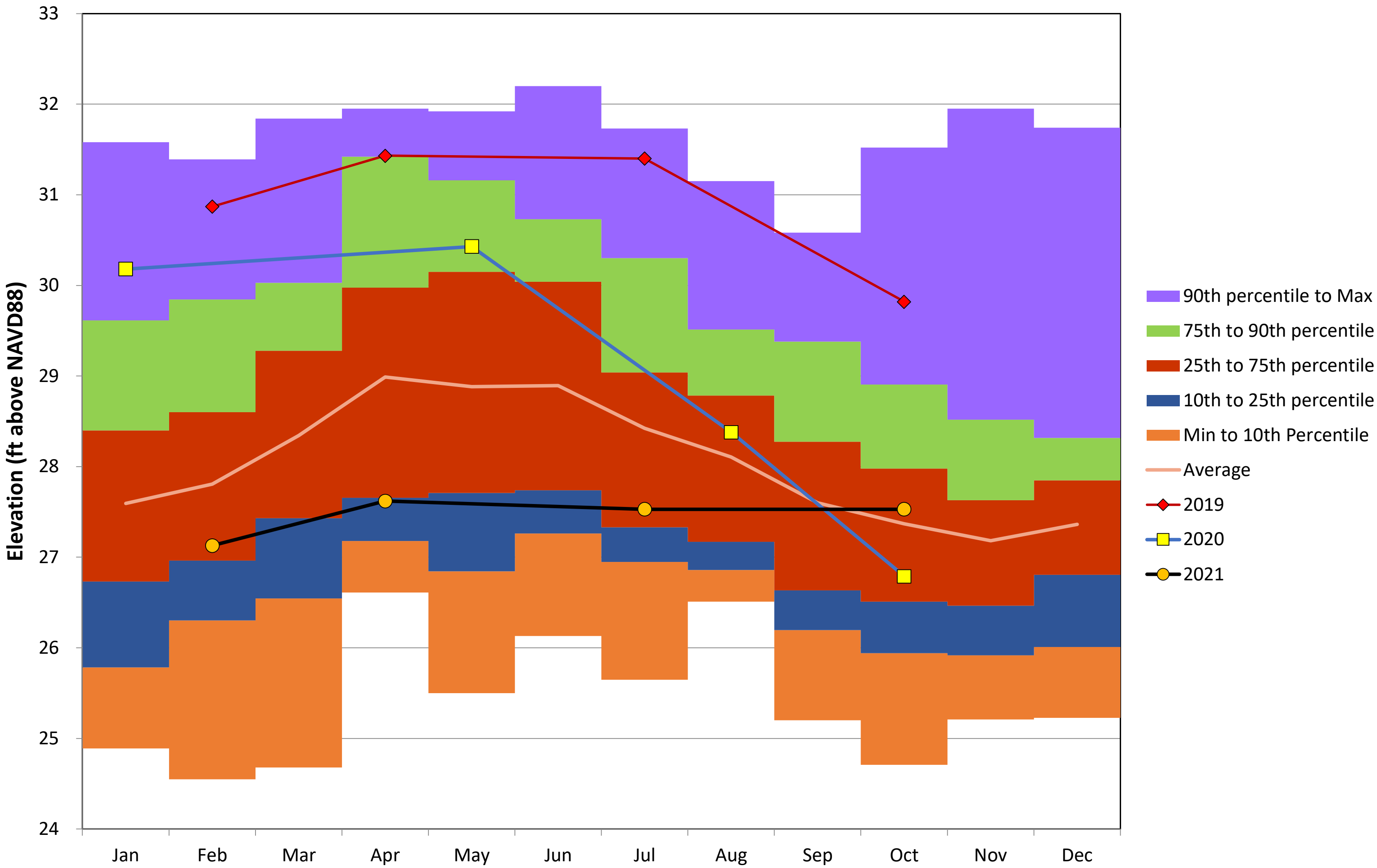

Figure IV-16. Barnstable Groundwater Elevations (A1W306: 1975 to 2021). Monthly percentile breakdowns and average elevations of groundwater based on data collected at a well located north of Barnstable High School between 1975 and 2021 (n=432). Water levels were generally well above average in in 2019 before decreasing notably in the second half of 2020. They were generally below average throughout 2021. Overall range of water elevations is 2.3 m. Water quality collected in Shubael Pond throughout 2020, while bathymetric readings for Shubael Pond were collected in September 2021 when water levels approximated average conditions. These readings suggest that Shubael Pond would have approximately 1 m additional depth in high groundwater conditions.

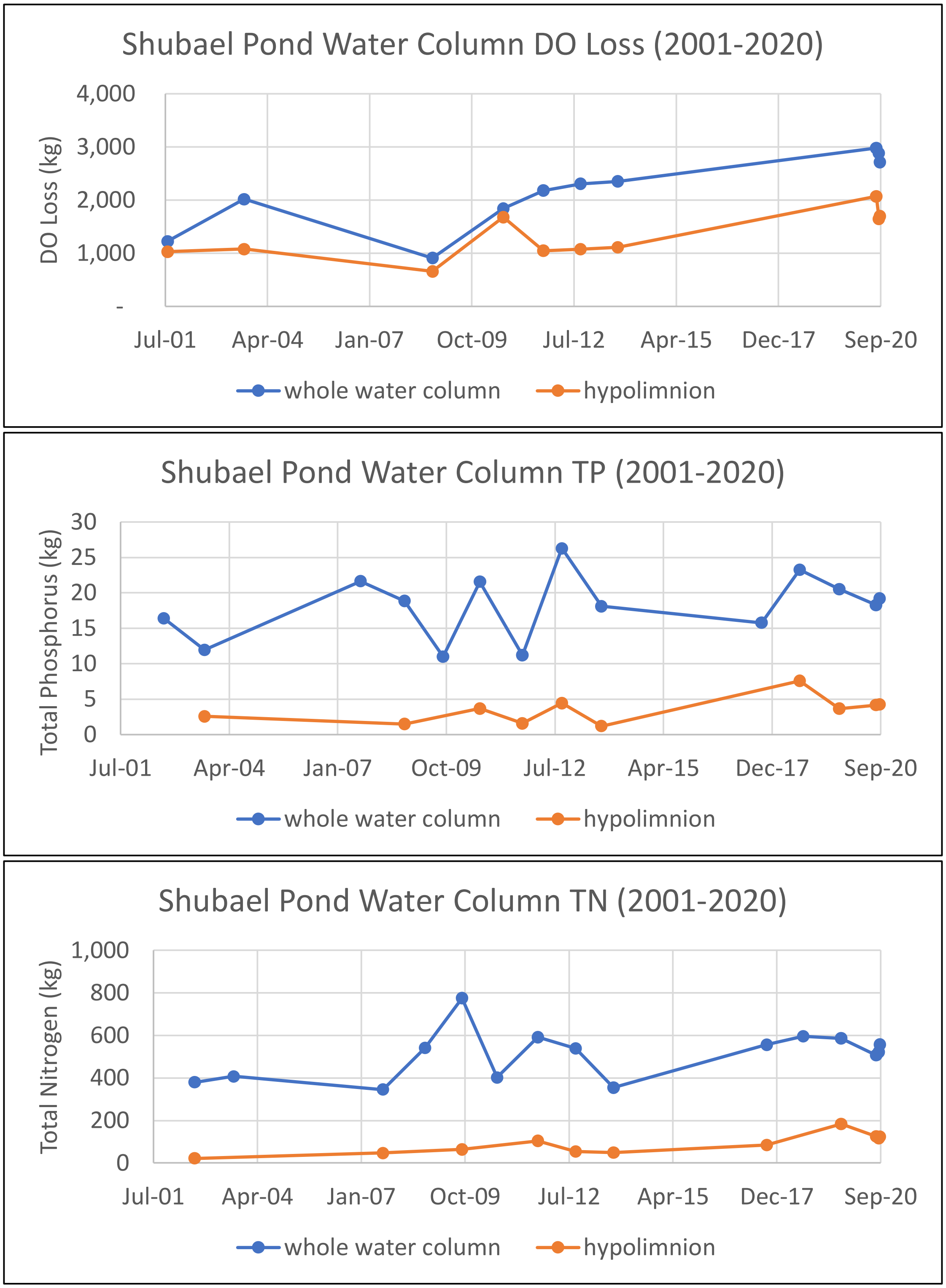

Figure IV-17. Shubael Pond Water Column DO Loss and TP and TN Mass (August/September 2001-2020). Data mostly from PALS Snapshots showed that average water column DO loss from 2001 to 2020 was 2,140 kg (n=10) with average hypolimnion loss of 1,309 kg. Trend analysis suggests a more recent increase, but is limited by lack of data from 2014 to 2019. Water column TP averaged 18.2 kg with maximum of 26.3 kg. Water column TN averaged 508 kg with a maximum of 776 kg. Hypolimnetic TP and TN masses both showed small, but statistically significant, increasing trends.

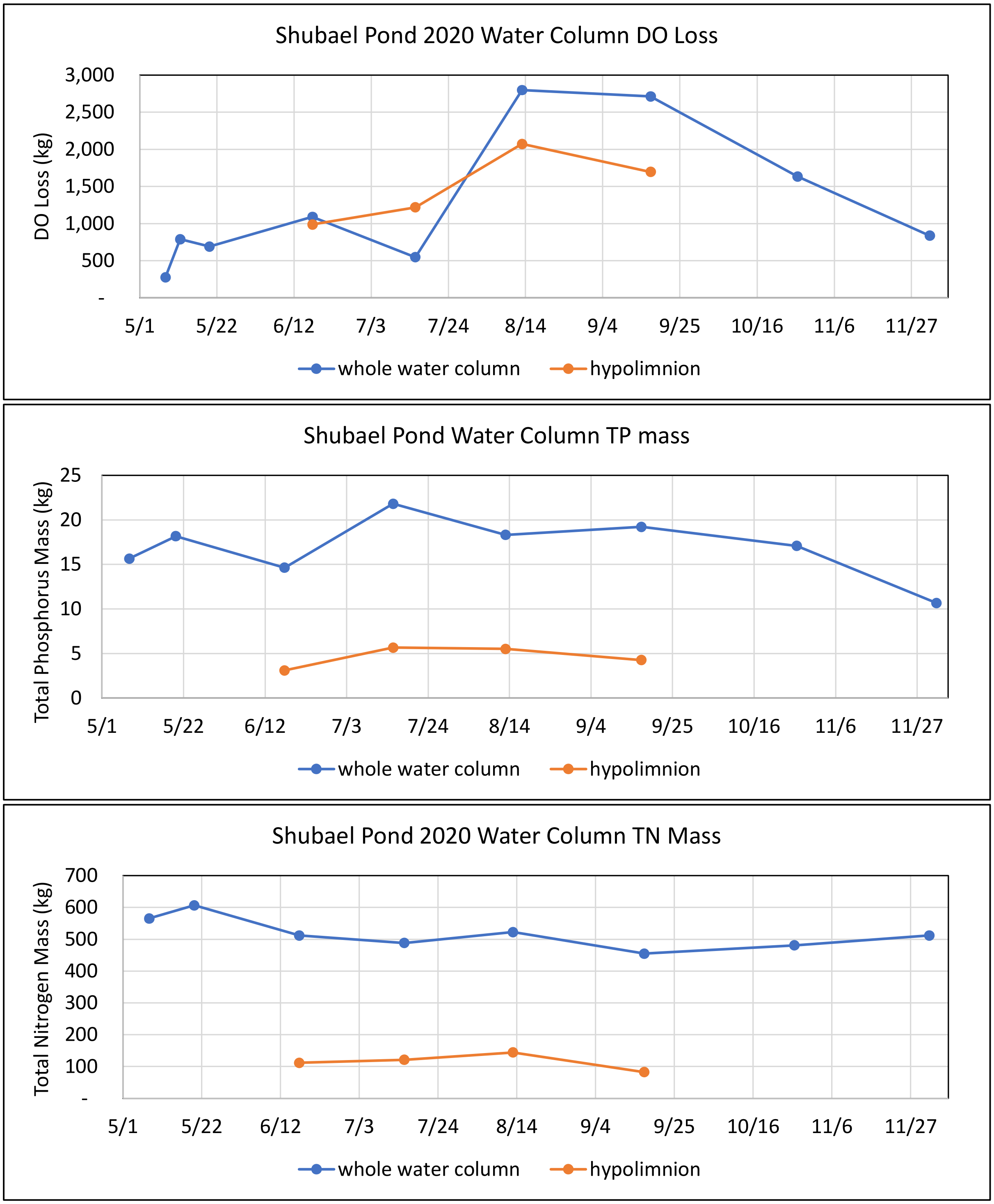

Figure IV-18. Shubael Pond 2020 Water Column DO Loss and TP and TN Mass. Water column DO loss included water column and sediment oxygen demand and photosynthesis additions. DO loss generally increased from May to August as waters warmed before slowly decreasing. The June 17 profile was the first to have a hypolimnion and hypolimnetic DO loss increased each subsequent profile before decreasing in September. Photosynthetic DO production exceeded hypolimnetic DO loss in the July 15 profile. Water column TP ranged from 10.7 kg in December to 21.8 kg in July, while hypolimnetic TP ranged from 3.1 to 5.7 kg. Average whole column TN was 518 kg with a summer decrease, while hypolimnetic TN averaged 115 kg.

The hypolimnion was first noted in the June 17 profile and DO loss in the hypolimnion increased in each subsequent profile before decreasing in the September 17 profile. It is noteworthy that DO concentrations well above atmospheric balance (*i.e.*, 100% saturation) offset DO loss due to water column and sediment oxygen demand in the June, July, and August profiles. For example, hypolimnetic DO loss in the July 15 profile was greater (1,219 kg) than the resulting overall sum of whole water column loss (547 kg) due to the DO additions from photosynthesis in shallow waters.

Review of historical water column TP and TN mass showed some indications of recent (2018 to 2020) increases, but trend analysis was again limited by lack of 2014 to 2017 data (see **Figure IV-17**). Historic 2001 to 2020 PALS Snapshot water column TP mass averaged 18.2 kg (n=14) with a maximum of 26.3 kg (September 2012), while TN averaged 508 kg (n=16) with a maximum of 776 kg (September 2008). Whole water column TP did not have a significant trend across the PALS Snapshots, but hypolimnetic TP had a statistically significant increasing trend of 0.2 kg per year (n=11, $\rho<0.03$). Hypolimnetic TN mass also had a statistically significant increasing trend (+5.1 kg/yr; n=11, $\rho<0.005$). Both of these hypolimnetic trends have relatively low annual additions (~6% of average hypolimnetic mass), but are consistent with worsening anoxia. Most TP sediment regeneration typically occurs at the onset of anoxia, but sediment TN regeneration typically only occurs after prolonged anoxia.

Review of the 2020 May to December samplings showed that the whole water column TP mass and the hypolimnetic TP mass peaked in July, while the peak TN whole water column mass occurred on May 20, prior to stratification, and the peak hypolimnetic TN mass was in the August 13 sampling (see **Figure IV-18**). Whole water column 2020 TP ranged from 10.7 kg in December to 21.8 kg in July, while hypolimnetic TP ranged from 3.1 to 5.7 kg. The July 2020 whole water column TP peak was greater than the 18.2 kg average from 2001 to 2020 PALS Snapshots, but equivalent to the 86% percentile among all the historical estimates. Whole water column 2020 TN ranged from 455 kg in September to 607 kg on May 20, while hypolimnetic TN ranged from 83 to 144 kg. Whole water column TN mass decreased from May 20 to August, when the hypolimnetic peak was measured. Average 2020 whole column TN mass (518 kg) was approximately the same as the historic 2001 to 2020 average (508 kg), while the hypolimnetic mass was greater (115 kg and 88 kg, respectively) consistent with longer periods of hypolimnetic anoxia.

IV.B.2. Phytoplankton Community

Based on the long history of high phosphorus and chlorophyll concentrations in Shubael Pond, CSP/SMAST recommended that the town include regular monthly sampling of the phytoplankton community in the 2020 data gap tasks to evaluate how the population changes and what species dominate during different portions of the spring and summer. Assessment of phytoplankton community composition along with associated measurements of chlorophyll and DO concentrations through continuously recording sensors, as well as the other 2020 data, was sought to gain a better understanding of the role the phytoplankton community plays in the water column measurements collected in Shubael Pond.

CSP/SMAST staff collected phytoplankton samples through vertical net tows on seven dates between May and December 2020. Tows were conducted through the photic zone, as determined by a Secchi reading at the lake's deepest point (S1) and central point in the pond

(S2). S2 is approximately 100 m from S1 (**Figure IV-19**). Samples were collected in brown bottles, preserved, and stored at 4°C until analysis. Laboratory results provide identification of individual phytoplankton species, cell counts (**Figure IV-20**) and biomass (**Figure IV-21**).

Phytoplankton cell counts showed that cyanophytes (*i.e,* blue-green algae or cyanobacteria[44]) were the dominant cell type on each of the sampling dates except for May, but in none of the samples did the count levels exceed the Massachusetts Department of Public Health (MassDPH) criterion for issuing a public health advisory or pond closure (*i.e.*, >70,000 cells/ml).[45] Phytoplankton levels were low during the May and June samplings (max = 301 cells/ml), but blue-greens became the predominant cell type in the June 17 samples: <2% blue-greens in the May 20 samples, but >75% in the June 17 samples. In the July 15 sampling, cell counts increased at both S1 and S2: >6,700 cells/ml at S1 and >1,600 cells/ml at S2. This increase corresponds to an increase in water column TP concentrations at both 0.5 m and 11 m (see **Figure IV-8**). The July increase at S1 was due to only one species of cyanophyte: *Microcystis aeruginosa*. Microcystis species tend to produce microcystins, which are a liver toxin, and MassDPH has established an 8 µg/L microcystins limit as a second, separate criterion for public health advisories. *Microcystis aeruginosa* are relatively small unicellular plankton that tend to form gelatinous colonies (**Figure IV-22**). Even with their small size, they were also the predominant component of the phytoplankton biomass at S1 during the July 15 sampling. It is notable, however, that the biomass and cell counts at S2, just 100 m away, had a slightly different profile with a lower cell count, still dominated by *Microcystis aeruginosa,* but a similar biomass dominated by chlorophyta (*i.e.*, green algae) composed of *Zygnema* species and *Hyalotheca* species. Green algae are not known to produce toxins.

In the remaining 2020 phytoplankton samplings (August 13, September 17, October 27, and December 2), blue-greens remained the predominant cell types, although the number species increased. Blue-greens were 95% to 100% of cell counts in the August-October samplings at both S1 and S2. On December 2, blue-greens were 98% of the cell count at S1 and 85% of the cell count at S2. *Microcystis aeruginosa* remained the predominant species in all these samplings. Blue-greens also remained the predominant component of biomass concentrations in all remaining samplings. The highest biomass level was 0.37 mg/L during the August 13 sampling at S1, 90% of which was blue-greens. This percentage of blue-greens were consistent with other impaired Cape Cod ponds (*e.g.*, Uncle Harvey's Pond in Orleans[46]), but the biomass concentration was relatively low compared to other impaired ponds (*e.g.*, Long Pond in Brewster/Harwich pre-alum treatment[47]).

Overall, the 2020 phytoplankton community sampling was consistent with impaired water quality conditions, including excessive phosphorus and diminished summer clarity. The predominance of cyanobacteria is consistent with excessive phosphorus, although none of the phytoplankton results were consistent with issuance of health advisories or pond closures.

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[44] Cyanophytes are variously referred to as blue greens, cyanobacteria, cyanophytes, blue-green algae, harmful algal blooms, etc.

[45] https://www.mass.gov/info-details/guidelines-for-cyanobacteria-at-recreational-freshwater-locations (accessed 4/7/22).

[46] Eichner, E., B. Howes, and D. Schlezinger. 2018. Uncle Harvey's Pond Management Plan and Diagnostic Assessment. Town of Orleans, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 106 pp.

[47] AECOM, Inc. 2019. Treatment Summary for Phosphorus Inactivation in Long Pond, Brewster and Harwich, Massachusetts. Willington, CT. 43 pp.

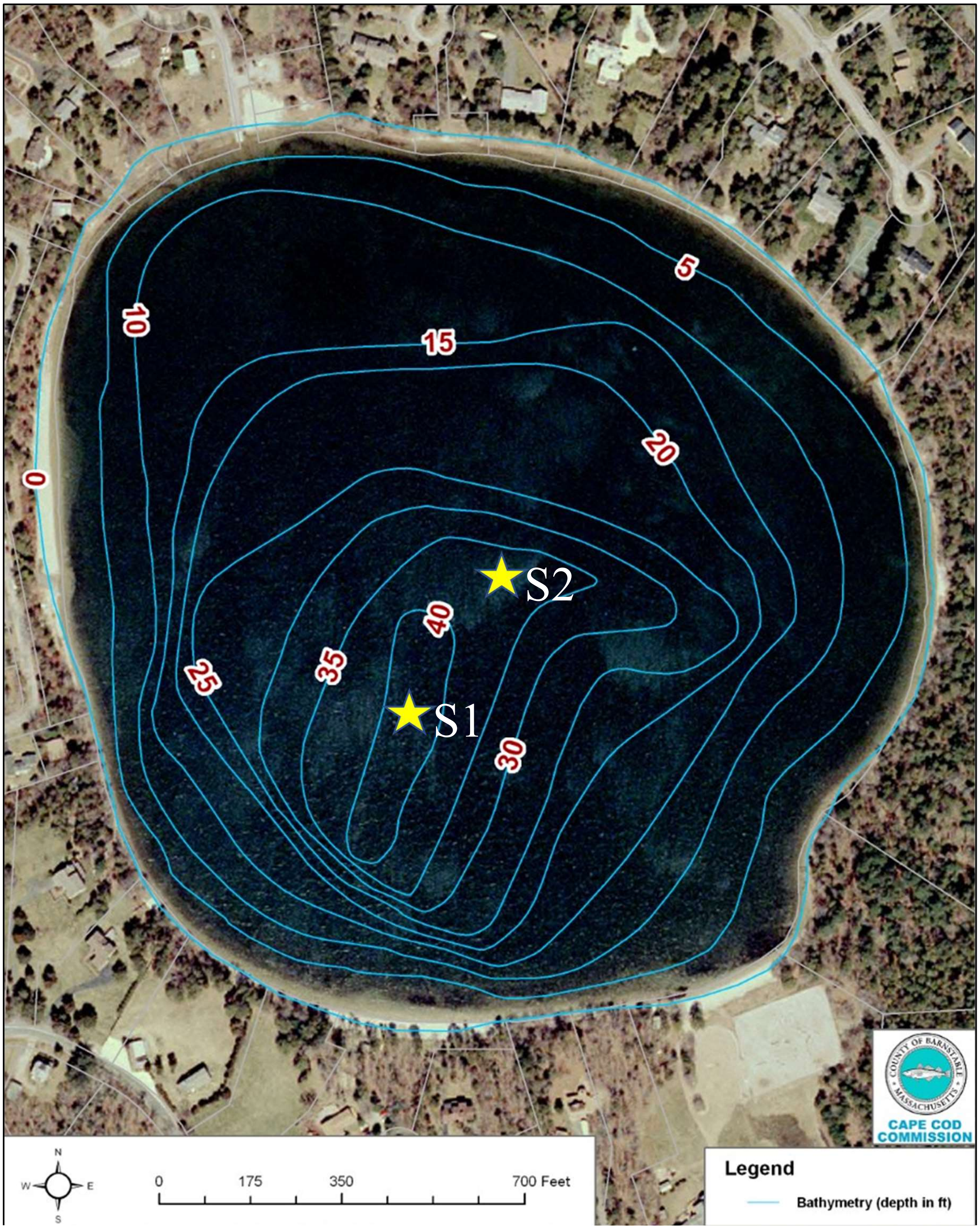


Figure IV-19. Phytoplankton Sampling Stations: Shubael Pond 2020. CSP/SMAST collected phytoplankton samples at S1 (deepest point) and S2 (pond center) on seven dates between May and December 2020: May 20, June 17, July 15, August 13, September 17, October 27, and December 2. Samples were collected through vertical net tows through the photic zone. Base map is the bathymetric map modified from Eichner (2008).

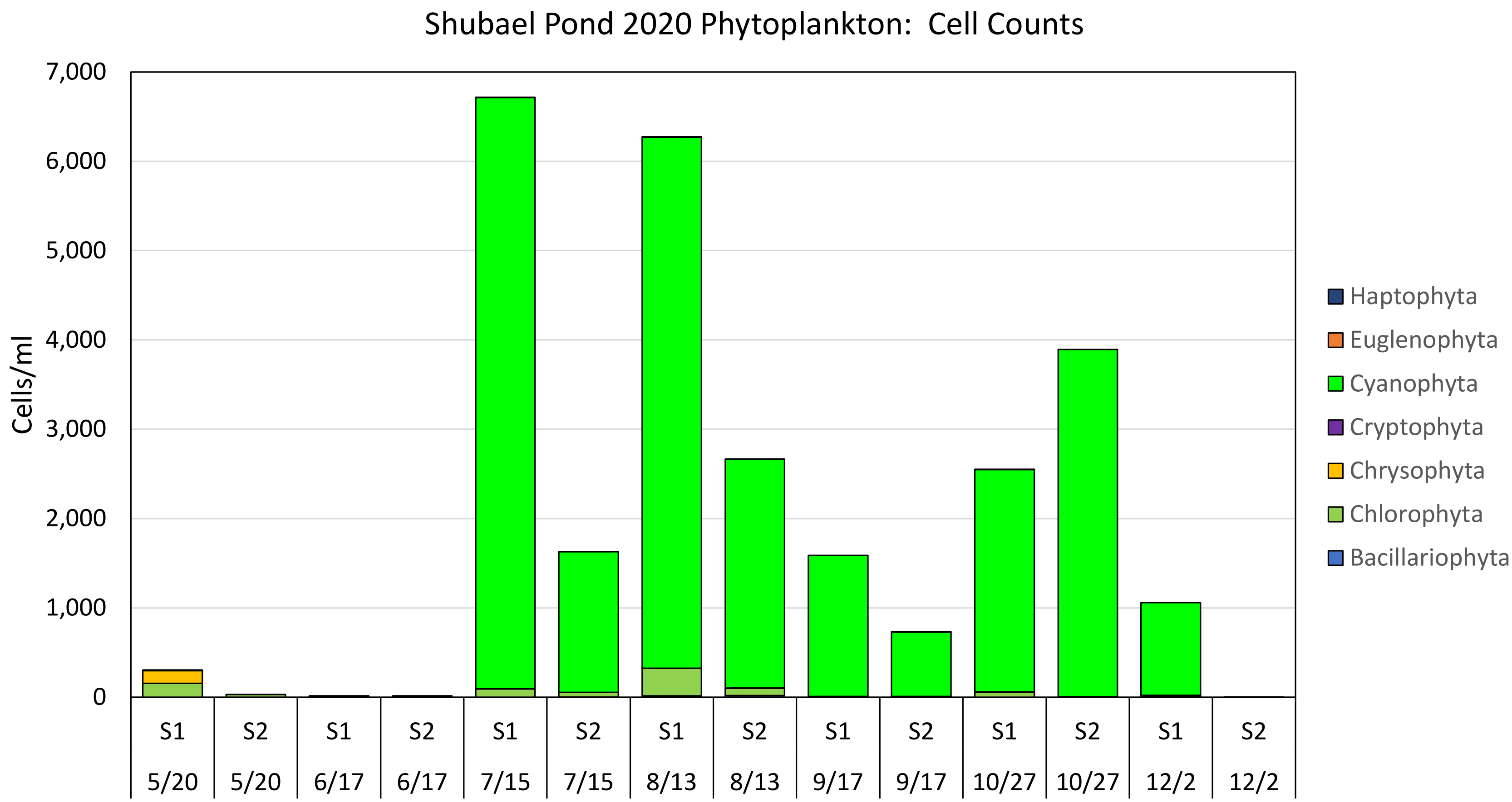


Figure IV-20. Shubael Pond 2020 Phytoplankton Cell Counts. Cell counts were low in the May and June samplings, then increased significantly in the July and August samplings and mostly decreased by >50% in the September through December samplings. The July increase at S1 was due to only one species of cyanophyte: *Microcystis aeruginosa*. Cyanophytes were >95% of the cell count in all July through October samplings and >78% in June and December samplings. Only in the May sampling were cyanophytes a small percentage (<2%) of the overall cell count. Microcystis species remained the predominant portion of the cyanophyte cell count throughout the July through December samplings. The maximum cell count was 6,715 cells/ml at the S1 station on July 15; this concentration is <10% of the MassDPH threshold (70,000 cells/ml) for recommending a public health advisory or pond closure.

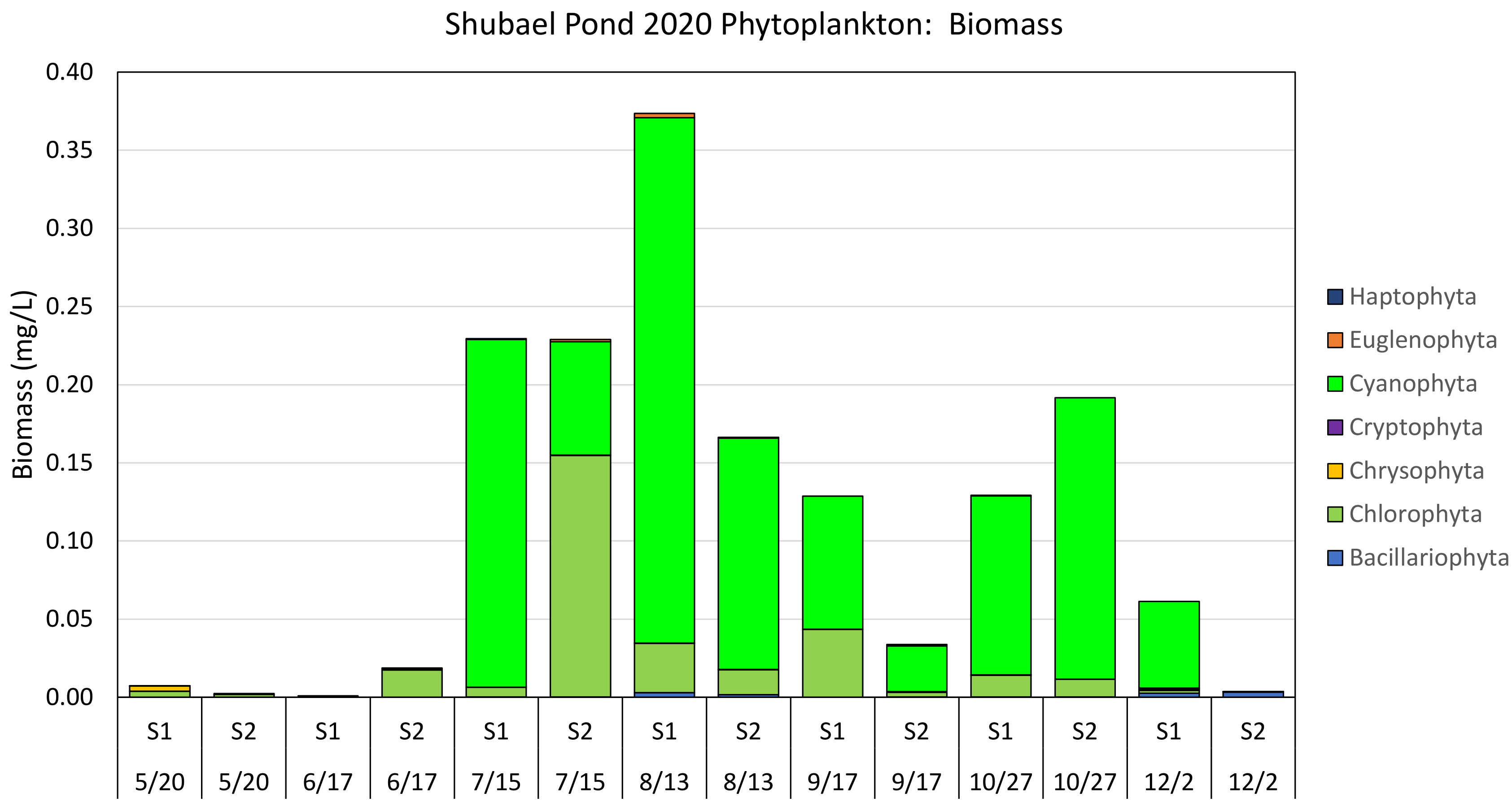


Figure IV-21. Shubael Pond 2020 Phytoplankton Biomass. Biomass concentrations mirrored cell counts with cyanophytes (blue-greens) generally becoming 80 to 90% of the biomass beginning on the July 15 sampling although there is greater difference between the S1 and S2 sampling sites. Cyanophytes were <0.2% of biomass at both S1 and S2 in the May 20 sampling, increased to 50% and 3% of the biomass at S1 and S2, respectively, during the June 17 sampling, and then 97% and 32%, respectively on July 15. The highest biomass level was 0.37 mg/L during the August 13 sampling at S1, 90% of which was blue-greens. The highest percentage of biomass by cyanophytes was 97% in the July 15 sampling at S1.

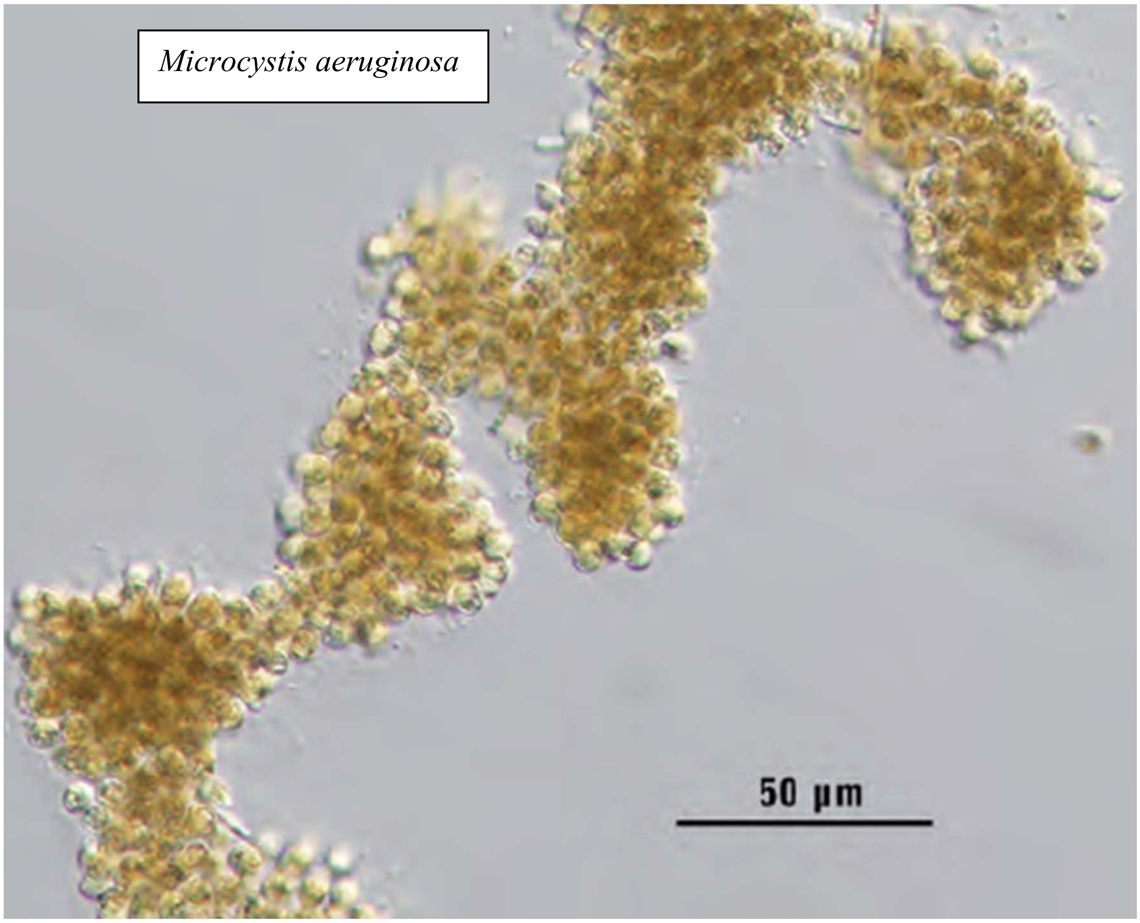


Figure IV-22. Predominant Cyanophyte in 2020 Shubael Pond Phytoplankton Samplings. *Microcystis aeruginosa* was the predominant cyanophyte/cyanobacteria in all samples from June through December and the only cyanobacteria when cell counts and biomass increased in July. Modified from Rosen, B.H., and St. Amand, A. (2015).

The Town Health Division issued a number advisories and warnings and closed the Shubael Pond twice during 2020: July 13 to August 17 (35 days) and September 26 to October 18 (22 days) (**Table IV-1**). Collectively, the pond had a pet advisory, warning, or was closed from mid-June throughout September and 110 days of the 159 days (69%) where testing occurred between May 20 and October 26. The issuance of these warnings and closures were in large part based on a portion of semi-quantitative cyanobacteria testing method that is designed to only find cyanobacteria.[48] As noted above, it was clear that cyanobacteria were the predominant phytoplankton species from July 15 through December 2, so they would always be found using this testing method. Previous reviews of data collected using this method noted significant inconsistencies with laboratory generated results.[49] The comparison of these results to the MassDPH limits would also seem to indicate additional inconsistencies; cell counts in the phytoplankton samplings were generally <10% of the MassDPH public health limit. So even though cyanobacteria was consistently found in Shubael Pond, it is clear from the phytoplankton sampling that it was at levels that were significantly less than the criteria that MassDPH considers for recommending a public health advisory.

IV.B.2 Continuous Time-Series Water Quality Monitoring

Characterization of the 2020 phytoplankton community also included the installation of two moored autonomous sensor arrays to evaluate short-term changes in key water-column parameters and their relationship to changes in the phytoplankton community. The arrays were initially installed in June, but experienced repeated sensor failures until they were corrected on August 13. The arrays were installed at the monthly water column profile sampling site and were removed December 2. The instruments recorded depth, chlorophyll-*a*, dissolved oxygen, and temperature every 15 minutes. Water quality samples were collected on 4 or 5 occasions (depending on depth) during the deployment period as part of QA/QC of sensor readings; parallel mooring and laboratory chlorophyll readings generally differed by <5%.

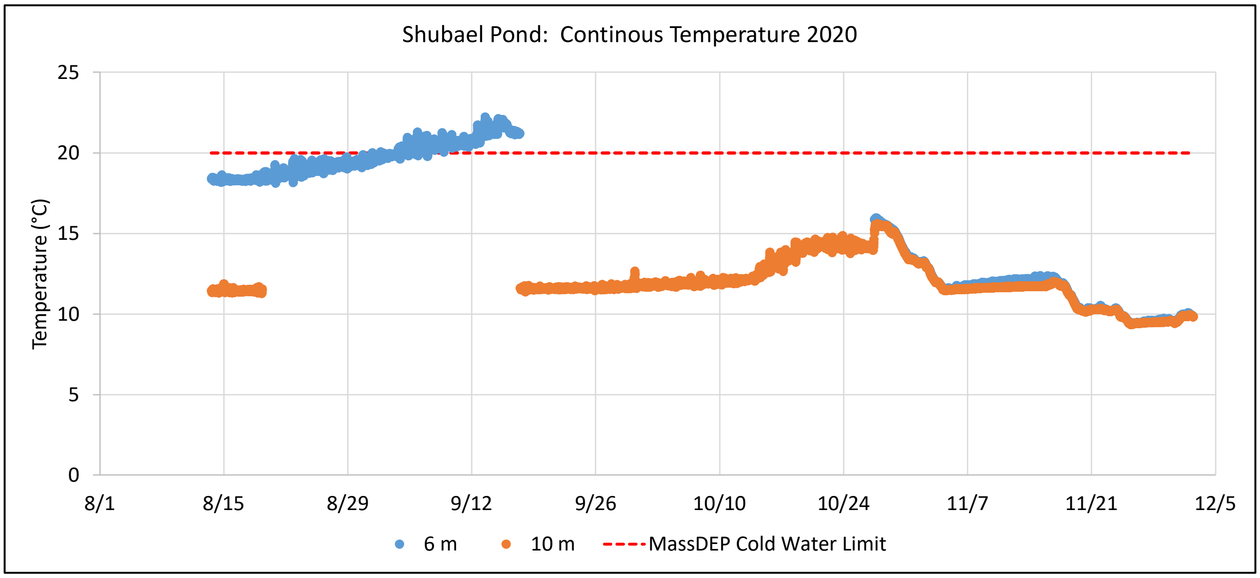
The arrays were installed at average depths of approximately 6 m and 10 m. The 6 m depth is close to the bottom of epilimnion (*i.e.*, the well-mixed, warm shallow layer during stratification), while the 10 m depth is in the middle of the hypolimnion (*i.e.*, the cold, deep layer during stratification). Each of the arrays had periods of failure where readings were not recorded, but approximately 6,800 readings were collected for the various parameters at the 6 m array and approximately 7,800 readings were collected at the 10 m array. Average depths of the two arrays based on the recordings was 6.2 m and 10.4 (**Figure IV-23**).

Temperature readings showed that the pond tended to be warmer in September 2020 than it was in August, but also that the deep waters consistently met the MassDEP criterion to be a cold water fishery (*i.e.*, temperature <20°C). August 6 m temperatures readings averaged 18.8°C (n=1,762), while September temperatures averaged 20.6°C (n=1,579) (see **Figure IV-23**). Only one August 6 m reading was greater than 20°C, but 81% of the September 6 m readings were greater than 20°C. In October, November, and December, none of the 6 m temperature reading were greater than 20°C. Deep 10 m average monthly readings were all less than 20°C and no

[48] http://lim-tex.com/wp-content/uploads/2018/05/CyanoCasting_Handbook_v18.pdf (accessed 4/7/22).

[49] TMDL Solutions Technical Memorandum. Walkers Pond: Post Management Plan Water Quality Data Review. March 4, 2020. From E. Eichner, TMDL Solutions and B. Howes, CSP/SMAST. To: C. Miller, Town of Brewster and T.N. Lewis, Horsley Witten Group, Inc. 13 pp.

Table IV-1. Town of Barnstable Health Division 2020 Shubael Pond Cyanobacteria Pet Advisories, Warnings and Closures. The Town Health Division utilized a semi-quantative cyanobacteria testing method that was designed to only find cyanobacteria without context for the rest of the phytoplankton population or how the cyanobacteria results compared to established Massachusetts Department of Public Health (MassDPH) cyanobacteria cell count thresholds. The Health Division closed the Shubael Pond twice during 2020: July 13 to August 17 (35 days) and September 26 to October 18 (22 days). Collectively, the pond had a pet advisory, warning, or was closed for 110 days of the 159 days (69%) where testing occurred between May 20 and October 26. Phytoplankton sampling results during 2020 for the current project found that all cyanobacteria cell counts were significantly lower (<10%) than the MassDPH cell count threshold. Listings were complied by A. Unruh, Barnstable DPW.	
Date	Action
5/20/2020	None
6/1/2020	None
6/15/2020	Safe
6/22/2020	Pet Advisory
6/23/2020	Pet Advisory
6/29/2020	Pet Advisory
6/30/2020	Warning
7/6/2020	Warning
7/7/2020	Warning
7/13/2020	Closed
7/20/2020	Closed
7/21/2020	Closed
7/27/2020	Closed
8/3/2020	Closed
8/4/2020	Closed
8/10/2020	Closed
8/17/2020	Closed
8/18/2020	Pet Advisory
8/24/2020	Pet Advisory
8/25/2020	Pet Advisory
8/29/2020	Pet Advisory
9/7/2020	Pet Advisory
9/14/2020	Pet Advisory
9/19/2020	Pet Advisory
9/26/2020	Closed
10/2/2020	Closed
10/3/2020	Closed
10/19/2020	Warning
10/26/2020	Pet Advisory



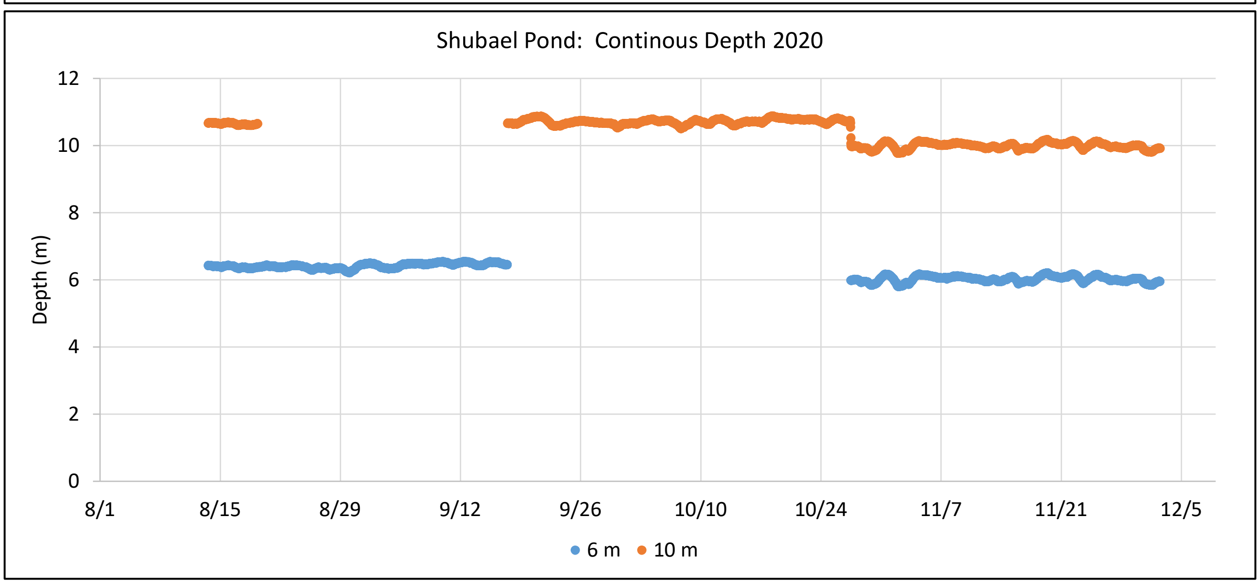


Figure IV-23. Shubael Pond 2020: Continuous Temperature and Depth Readings for Sensors at 6 m and 10 m depths. Two sensor arrays were installed in Shubael Pond on August 13 and were removed on December 2. Readings were recorded every 15 minutes. The shallow array had an average depth of 6.2 m, which is located close to the bottom of the epilimnion, while the deep array had an average depth of 10.4 m, which is located within the middle portion of the hypolimnion. All temperature readings at the deep array met the MassDEP cold-water fisheries criterion (<20°C). Shallower temperatures showed that the water column was cooler in August (average = 18.8°C) than in September (average = 20.6°C). August readings collected at the same time at both depths showed sufficient difference to confirm the temperature stratification measured in the water column profiles. Similar readings in November confirmed that stratification was no longer present and the whole water column was vertically mixed.

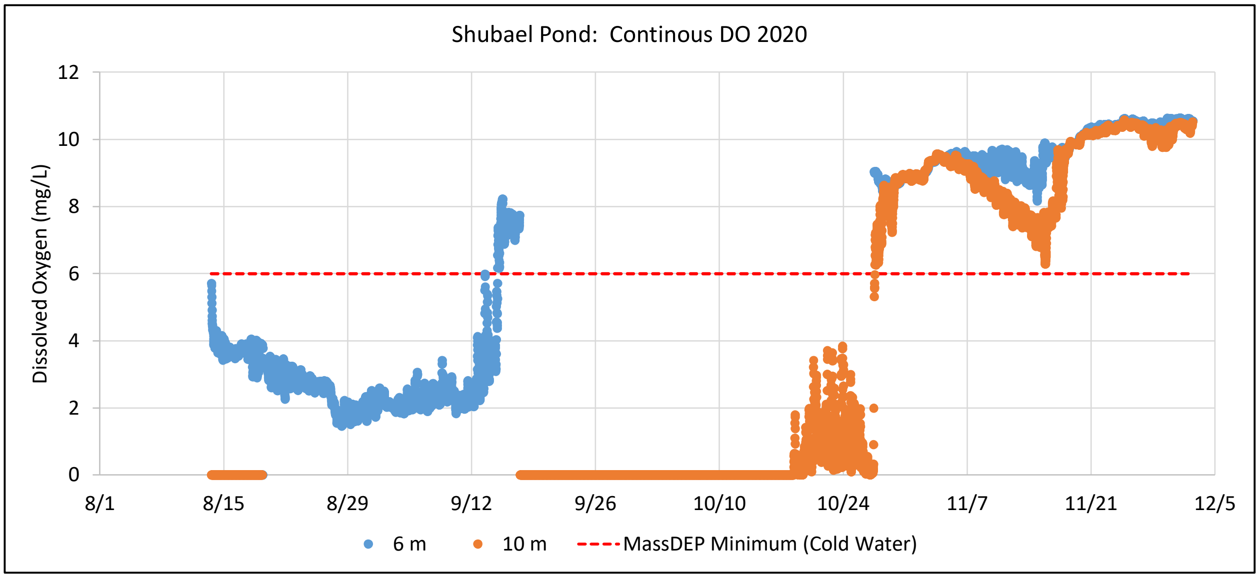
readings greater than 20°C were recorded at the 10 m array. Comparison of temperature readings at 6 m and 10 m at the same time in August consistently show significant stratification, while those from late October to early December indicate consistent readings with well-mixed water column at the two depths. Continuous readings are consistent with the monthly temperature profile readings (see **Figure IV-4**) and support the classification of Shubael Pond as a cold water fishery based on the deep hypolimnion consistently having temperatures less than 20°C.

Dissolved oxygen readings, on the other hand, show that a cold water fishery cannot be sustained because of persistent anoxia in the deep waters (**Figure IV-24**). All of the continuous August and September readings and 76% of the October DO readings at 10 m are anoxic (<1 mg/L), so cold-water fish cannot survive at this depth. Shallow, 6 m average DO readings in August and September were also less than the 6 mg/L MassDEP minimum. DO profile readings showed that acceptable DO concentrations at 10 m were not restored until the December 2 profile, when the entire pond water column was vertically mixed (see **Figure IV-4**). Average DO at 6 m was greater than 6 mg/L in October, November, and December. Continuous readings at 10 m showed that all November and December DO readings (n=3,023) were greater than 6 mg/L, which means the water column mixed shortly after the October 27 profile.

Chlorophyll a readings at 6 m show that concentrations were consistently greater than the 1.7 µg/L Ecoregion threshold, while average concentrations at 10 m are consistent with a large transfer of organic matter to the deep sediments. Average chlorophyll a readings at 6 m over the whole deployment was 3.5 µg/L with higher average concentrations in August (3.9 µg/L; n=1,766) and September (6.2 µg/L; n=1,579) and lower concentrations in October, November, and December (overall average = 2.0 µg/L; n=3,456) (see **Figure IV-24**). However, 10 m average monthly concentrations were 4X to 31X the average monthly concentrations at 6 m, indicating a large transfer of phytoplankton biomass chlorophyll to the deeper waters and deposition of nutrients in organic matter to the sediments.[50] It is not until December, when the water column is well mixed, that the 6 m and 10 m average chlorophyll concentrations are approximately the same. Average monthly chlorophyll a concentrations at 10 m are: 16 µg/L in August, 103 µg/L in September, 67 µg/L in October, 14 in November, and 3.2 µg/L in December.

Overall, the continuous readings from the sonde sensor arrays were consistent with the regular monthly water column profiles and sampling, but provided better insights into how conditions changed during 2020. Temperature readings confirmed that Shubael Pond should be considered a cold water fishery under MassDEP surface water regulations and DO readings confirmed that the deep, cold water layer is consistently impaired and anoxic for months at a time. Chlorophyll readings confirmed that large portions of the phytoplankton population and their accompanying nutrients are transferred to the deep waters and sediments especially during September.

[50] Some of the increase in 10 m chlorophyll readings is likely due to fluorescence from sediment bacteria increasing within the water column due to the anaerobic conditions in the deep, cold mixed layer of the pond, but deep chlorophyll a concentrations in the September 17 water column sampling was 69 µg/L.



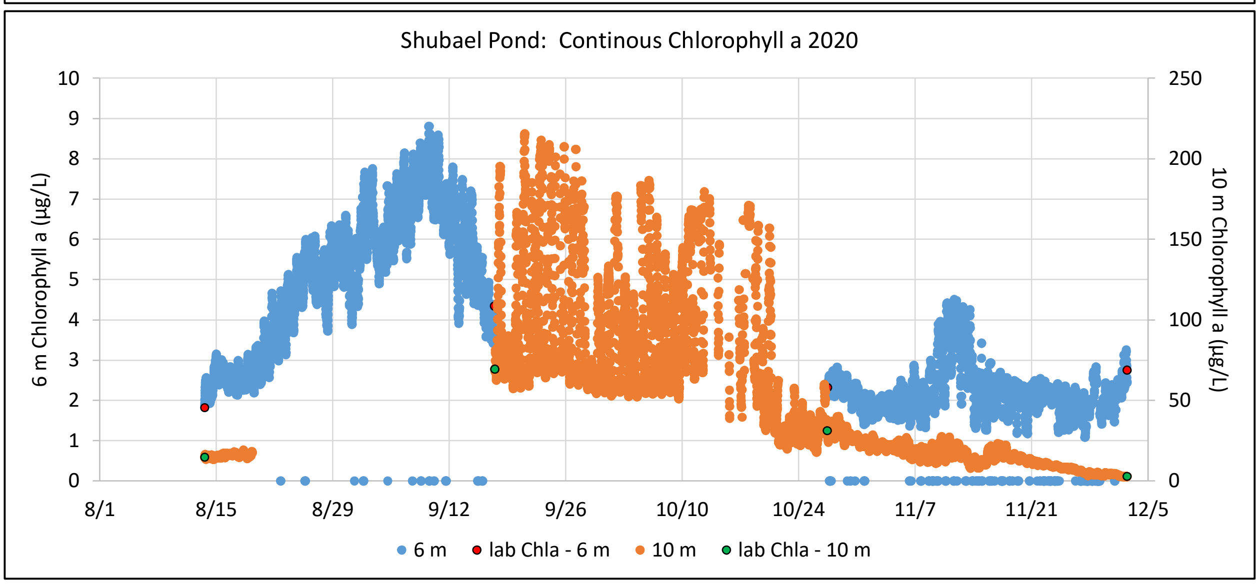


Figure IV-24. Shubael Pond 2020: Continuous Dissolved Oxygen and Chlorophyll a Readings for Sensors at 6 m and 10 m depths. Two sensor arrays were installed in Shubael Pond on August 13 and were removed on December 2. Readings were recorded every 15 minutes. The shallow 6 m array average DO readings in August and September did not meet the MassDEP limit for cold water fisheries (6 mg/L), but only 4 of 3,343 readings were anoxic. Deep 10 m DO readings were anoxic throughout August, September, and most of October (85% of readings during these months). Average DO in November and December at both 6 m and 10 m depths were greater than the MassDEP limit. Average monthly chlorophyll a readings at both 6 m and 10 m depths were greater than the Ecoregion threshold concentration of 1.7 µg/L. Deep 10 m average monthly chlorophyll concentrations were 4X to 31X the monthly averages at 6 m, which is indicative of carbon and nutrient transfer to deeper waters and the sediments. The greatest difference between monthly chlorophyll a averages at 6 m and 10 m was in October when the 6 m average decreased by 3X from the September average indicating senescence and settling of the shallow phytoplankton population as waters cooled.

IV.B.3. Rooted Plant and Freshwater Mussel Surveys

Extensive populations of freshwater mussels and macrophytes (aquatic rooted plants) have the potential to alter nutrient cycling and can complicate development of pond management strategies, especially those that involve treatment of the sediments. Bathymetric information is key for understanding the volume and depth of a pond, which are important for determining the extent and overall impact of water quality change, the relationship between the pond and its watershed, and how biota in the pond are distributed. During the initial review of available Shubael Pond water column sampling results,[51] these issues were identified as potential data gaps and were completed as tasks among the 2020/2021 data gap surveys.

CSP/SMAST staff completed rooted plant and freshwater mussel surveys on September 15, 2021 using a differential GPS mounted on a boat for positioning coupled to a survey-grade fathometer an underwater video camera.[52] The video survey recorded the bottom sediments at five frames per second. Each frame represents approximately 0.25 m^2 of pond bottom and the video record was reviewed frame-by-frame for mussel valves and plant density.

The mussel survey was completed because many of the freshwater mussel species on Cape Cod are listed by the Massachusetts Natural Heritage Program as threatened or endangered species or species of special concern, including the Tidewater Mucket (*Leptodea ochracea*) and Eastern Pondmussel (*Ligumia nasuta*).[53] Surveys completed by CSP/SMAST in other Cape Cod ponds have shown some ponds to have extensive mussel populations, while others have no mussels present.[54] Reviews of available studies suggest mussels have complex responses to nutrient enrichment with both positive and negative impacts due to high or low loads.[55] A video survey to identify whether mussels were present was recommended for Shubael Pond as a relatively low cost approach to assess whether special consideration would be needed to protect mussels as management strategies are developed.

Freshwater mussels were noted throughout the pond though generally not at depths greater than 8 m or along the northern edge of the pond (**Figure IV-25**). Lack of mussels greater than 8 m is consistent with the regular summer anoxia (see **Figure IV-3**). Other Cape Cod ponds with extensive mussels and regular anoxia typically have a ring of mussels in shallow, well-oxygenated waters (*e.g.*, Upper Mill Pond in Brewster). The lack of mussels along the northern edge and the shallower areas to the east and southeast portions of the pond seem to coincide with the high density of macrophytes (rooted plants) in these areas (**Figure IV-26**). Macrophytes and mussels seem to be competitors for bottom habitat, although they can coexist if both are at moderate densities.

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[51] Eichner, E. and B. Howes. 2021. Town of Barnstable Freshwater Ponds, 2021 Water Quality Monitoring Database: Development and Review.

[52] Bathymetry measurements were completed at the same time.

[53] https://www.mass.gov/info-details/list-of-endangered-threatened-and-special-concern-species (accessed 1/12/22)

[54] *e.g.*, Eichner, E., B. Howes, D. Schlezinger, and M. Bartlett. 2014. Mill Ponds Management Report: Walkers Pond, Upper Mill Pond, and Lower Mill Pond. Brewster, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 125 pp.

[55] Strayer, D.L. 2014. Understanding how nutrient cycles and freshwater mussels (Unionoida) affect one another. *Hydrobiologia*. 735: 277-292.

Macrophyte abundance is a complex interaction of a number of factors, including sediment characteristics, nutrient and light availability and pond depth.[56] Extensive macrophyte populations can alter nutrient cycling by favoring settling of suspended particles within colonized areas, but also can increase transfer of sediment phosphorus to aboveground plant parts, which during senescence and decay release nutrients to pond waters.[57] The plant survey was completed to provide insights into the influence of macrophytes on the overall Shubael Pond phosphorus balance and potential interactions with various water quality management actions.

High density coverage of macrophytes (>90% of the pond bottom) was noted along the northern edge, the southwestern edge, and in small pockets at the southwest and east. No benthic algae was noted. Generally, no macrophytes were noted in waters deeper than 8 m (similar to the mussel distribution). Macrophytes were noted in waters deeper than the average 2020 Secchi depth (*i.e.*, 5.1 m). Light sufficient to prompt photosynthesis can reach deeper depths than Secchi measurements.[58] Growth of macrophytes will also depend on characteristics of the bottom substrate. The somewhat patchy distribution of macrophytes around the edge of the pond is likely due to differences in substrate. It is not known whether the 2021 macrophyte distribution is different from past distributions since historical macrophyte surveys were not available.

[56] Madsen, J.D., P.A. Chambers, W.F. James, E.W. Koch, and D.F. Westlake. 2001. The interaction between water movement, sediment dynamics and submersed macrophytes . *Hydrobiologia*. 444: 71-84.
[57] Carpenter, S.R. and Lodge, D.M., 1986. Effects of submersed macrophytes on ecosystem processes. *Aquat. Bot*., 26: 341-370.
[58] Photosynthetically Active Radiation (PAR) can be ~15% of pond surface light and still allow a plant to grow.

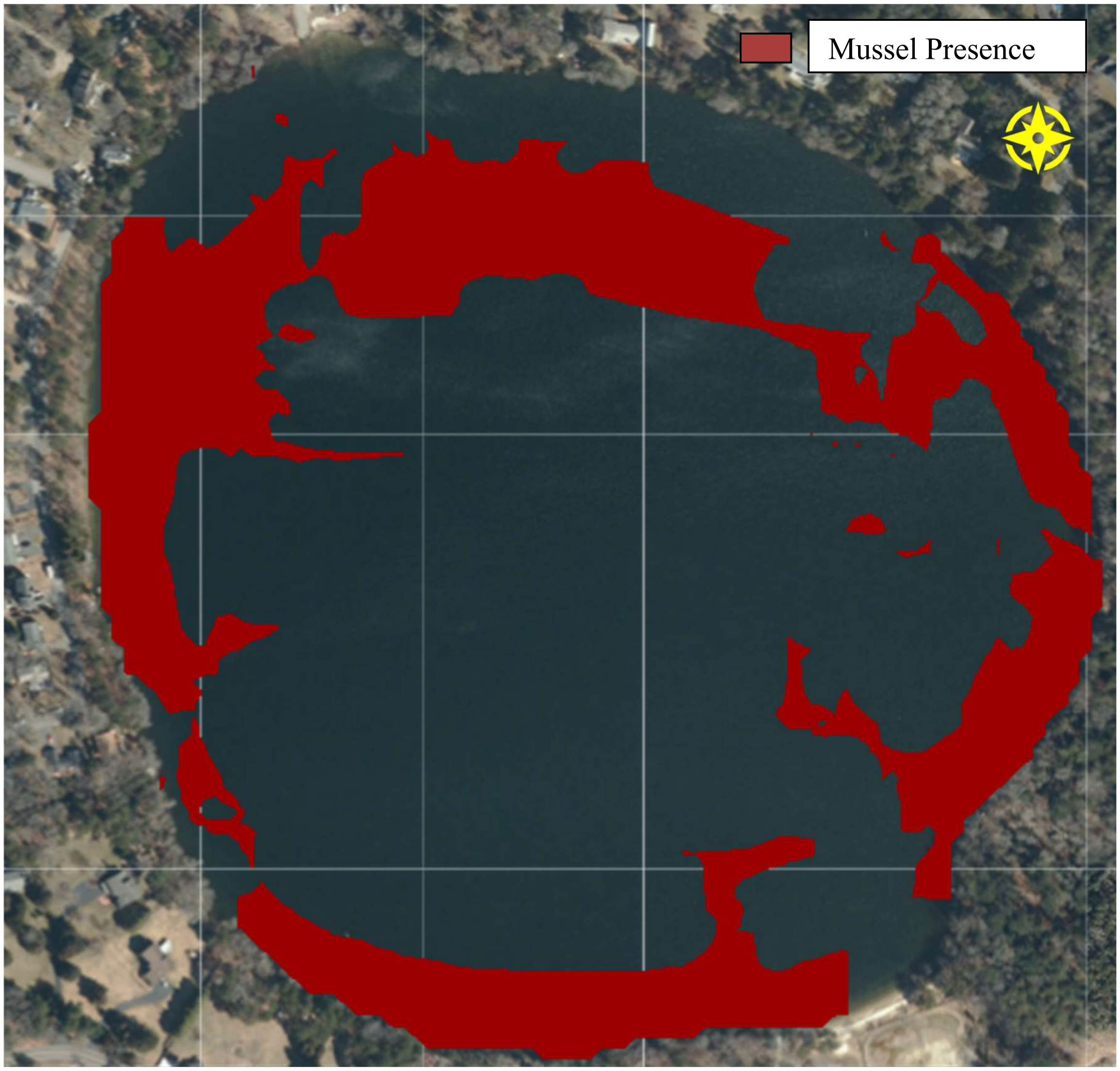

Figure IV-25. Shubael Pond 2021 Freshwater Mussel Survey. CSP/SMAST staff completed an underwater video survey on September 15, 2021, to determine the distribution freshwater mussels in Shubael Pond (the bathymetry and macrophyte surveys were completed at the same time). Cameras were synced with dGPS and recorded at five frames per second. Staff reviewed each video frame (approximately 0.25 m^2 of lake bottom) to determine a mussel distribution throughout the pond. Mussels tended to present in high density around the pond at depths less than 8 m. Mussels were not present in areas deeper than 8 m, which are areas that typically experience prolonged anoxia during the summer, and in selected shallower areas that usually corresponded to dense macrophyte coverage. It is not known whether the 2021 mussel distribution is different from past distributions or if the population is expanding or contracting since historic reviews were not available.

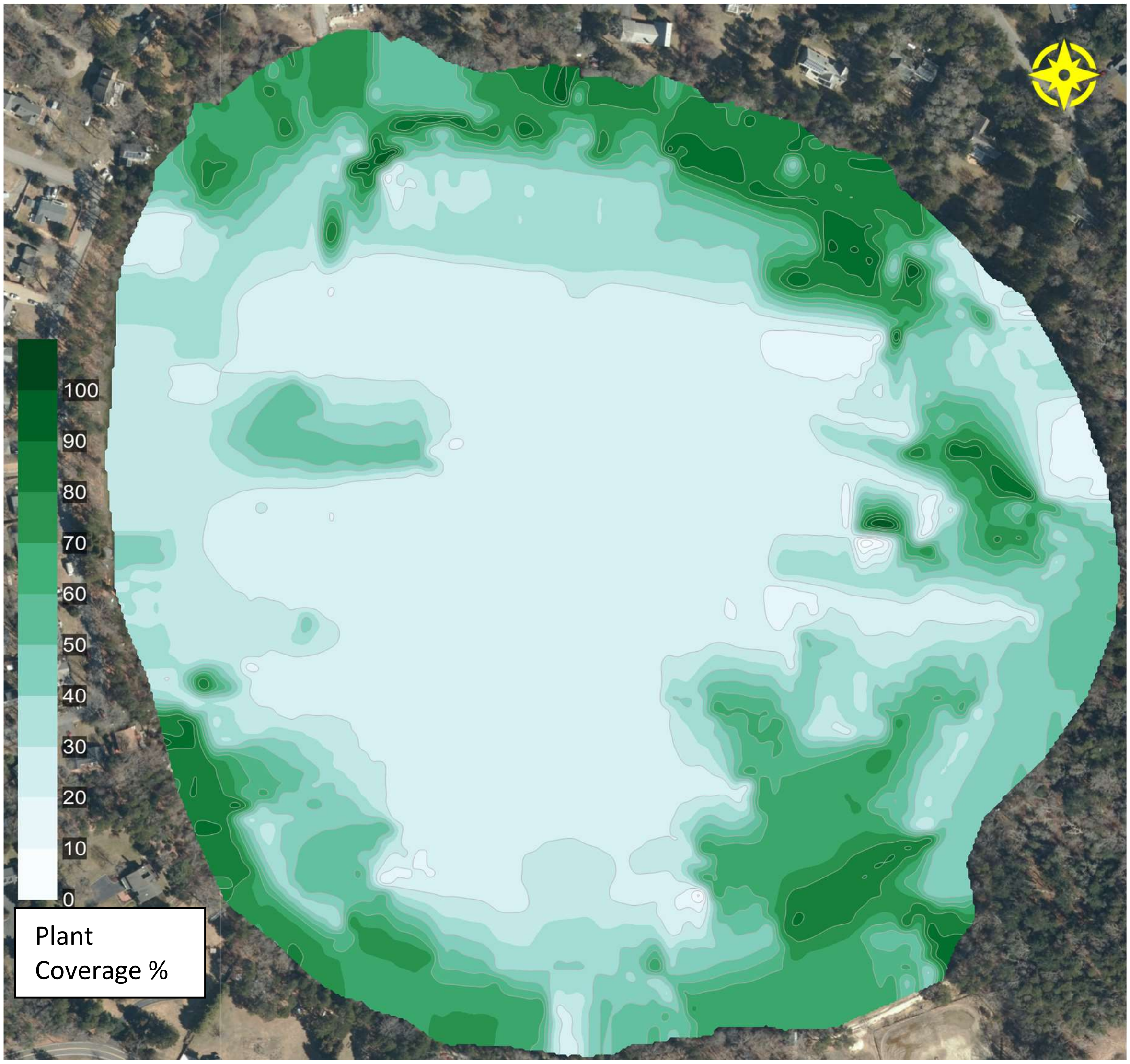

Figure IV-26. Shubael Pond 2021 Macrophyte Survey. CSP/SMAST staff completed an underwater video survey on September 15, 2021, to determine the distribution of macrophytes in Shubael Pond (the bathymetry and macrophyte surveys were completed at the same time). Cameras were synced with dGPS and recorded at five frames per second. Staff reviewed each video frame (approximately 0.25 m^2 of lake bottom) to determine the macrophyte coverage of the pond bottom (0% to 100%) in each frame. Macrophytes distribution tended to ring the pond in areas shallower than 8 m depth. High density macrophyte coverage was present along the northern and southern edges of the pond and included two very dense patches in the southeast and east (both in waters 2 to 3 m deep). The highest density areas also corresponded to areas where mussels were not present. It is not known whether the 2021 macrophyte distribution is different from past distributions or if the community is expanding or contracting since historical surveys were not available.

IV.B.4 Sediment Core Collection and P Regeneration Measurements

During the initial CSP/SMAST review of historic Shubael Pond water column data,[59] it was clear that the sediment oxygen demand and resulting hypoxia was causing high bottom water nutrient concentrations during summer. However, the amount of the potential nutrient release was not clear, nor was the relationship between dissolved oxygen conditions and nutrient release. Because resolving these issues was important to developing restoration and management strategies for Shubael Pond, measurement of sediment nutrient release was identified as an important data gap that needed to be addressed during the diagnostic evaluation of Shubael Pond.

Sediment regeneration of nutrients regularly occurs in ponds and begins as organic detritus (such as phytoplankton, zooplankton, aquatic plant material or fish) settles to the bottom and is decomposed by sediment bacteria (*i.e.*, biodegradation). This bacterially-mediated decomposition of the detrital material breaks it down into its constituent chemicals, including inorganic nutrients, and consumes oxygen. Some dissolved constituents are subsequently bound with sediment materials to form solid precipitates that remain buried in the sediments, while others are released as dissolved forms to the overlying pond water.

If the sediment bacterial population consumes more oxygen than is available from the bottom waters during this process, then hypoxic/anoxic conditions occur in overlying water and redox conditions in the sediments change from oxic/aerobic conditions to anoxic/reducing conditions. During these redox transitions, chemical bonds in solid precipitates that were deposited under oxic conditions can break and the constituent chemicals can be re-released in dissolved forms into the water column. This transition and release occurs for phosphorus when DO concentrations drop to near anoxic levels in waters overlying the bottom sediments and inorganic phosphorus is released as iron:phosphorus bonds break. Once phosphorus is released from the sediments into the water column, it is available as a fertilizer for plants, including phytoplankton, macroalgae, and rooted plants.

These sediment/water column interactions can be further complicated by rooted aquatic plants/macrophytes and mussels. Extensive macrophyte populations can alter nutrient cycling by favoring settling of suspended particles within plant beds, but also can increase the transfer of otherwise buried sediment phosphorus to the above-ground plant shoots and to the water column during growth, senescence and decay.[60] Some research has also found that macrophyte beds can be net sources of phosphorus to the water column even in aerobic conditions.[61] The role of freshwater mussels on phosphorus cycling is not well studied, but the filtration of pondwater by extensive populations results in increased water clarity, deposition of organic biodeposits (feces and psuedofeces) to the sediments, and decreased water column phosphorus available to phytoplankton.[62] Determining the net phosphorus contribution from sediments back to the water column should account for the potential role of macrophytes and mussels, if their population or densities are large.

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[59] Eichner, E. and B. Howes. 2021. Town of Barnstable Freshwater Ponds, 2021 Water Quality Monitoring Database: Development and Review.

[60] Carpenter, S.R. and Lodge, D.M., 1986. Effects of submersed macrophytes on ecosystem processes. *Aquat. Bot*., 26: 341-370.

[61] Adams, M.S. and Prentki, R.T., 1982. Biology, metabolism and functions of littoral submersed weedbeds of Lake Wingra, Wisconsin, U.S.A. *Arch. Hydrobiol*. (Suppl.). 62 : 333-409.

[62] Vaughn, C. & Hakenkamp C. 2001. The functional role of burrowing bivalves in freshwater ecosystems. *Freshwater Biology*. 46(11): 1431–1446

In order to measure potential sediment nutrient regeneration within Shubael Pond, CSP/SMAST staff collected and incubated 15 intact sediment cores collected from various locations (**Figure IV-27**). These undisturbed sediment cores were collected by SCUBA divers on May 12, 2020, while the bottom waters were well oxygenated (deep DO >7 mg/L) and before strong thermal stratification was established, so that the full pool of iron-bound phosphorus in the sediments was intact. The sediment cores were incubated at *in situ* temperatures and nutrient regeneration from the sediments was measured sequentially under oxic and anoxic conditions.

During the collection of sediment cores, standard handling, incubation, and sampling procedures were followed based on the methods of Jorgensen (1977), Klump and Martens (1983), and Howes (1998). During the core incubations, water samples were withdrawn periodically and chemical constituents were assayed. Rates of sediment nutrient release were determined from linear regression of analyte concentrations through time. Cores were incubated first under sustained aerobic conditions, matching environmental conditions in Shubael Pond when dissolved oxygen in lake bottom waters is near atmospheric equilibrium (*i.e.*, as usually found in April/May or October/November). Dissolved oxygen is then removed and sediment conditions move through a redox sequence that begins with chemical phosphorus release (severing of weak chemical bonds, typically mostly with iron) and continues with phosphorus release through anaerobic bacterial remineralization alone. This latter process is the same as experienced in the Shubael Pond water column when dissolved oxygen concentrations drop to less than 1 mg/L (conditions that regularly occur in the deepest depths in summer/early fall). Deep Shubael Pond cores (>7.5 m depth) generally had a chemical release phase that lasted for 47 days under anaerobic conditions. Cores were sustained under anaerobic conditions for another 40 days (87 days total) after the chemical release phase was completed to ensure that anaerobic release rates had sufficiently stabilized. The laboratory followed standard methods for analysis as currently used by the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

Review of the sediment core incubation results showed that sediment phosphorus regeneration rates varied depending on oxygen conditions (aerobic vs. anaerobic) and the collection depth of the cores (**Figure IV-28**). Under aerobic conditions, both the shallow and deep core sediments showed P removal from the water column into the surface oxic layer of the sediments. One shallow core (SP3) showed P release under aerobic conditions, but the other six shallow cores showed P uptake by the sediments. Deep cores (>7.5 m depth) also generally showed P uptake during aerobic conditions, although three of the 7 cores had P release to the water column. In contrast, deep sediment cores under anaerobic conditions all had P release from the sediments with the rate during the chemical release phase approximately 3X to 4X the subsequent anaerobic only release phase.

Combining this information with the bathymetric surface area shows that Shubael Pond sediments are retaining phosphorus when aerobic conditions exist throughout the water column and re-releasing it to the water column during summer anaerobic conditions at rates approximately one third of winter aerobic uptake rates. During aerobic conditions, the sediments are removing 0.3 to 0.35 kg of P per day. In contrast, anaerobic chemical release which last for 47 days release 0.07 to 0.09 kg of P per day. Stable anaerobic P release after the completion of the chemical release phase is 0.03 kg of P per day.

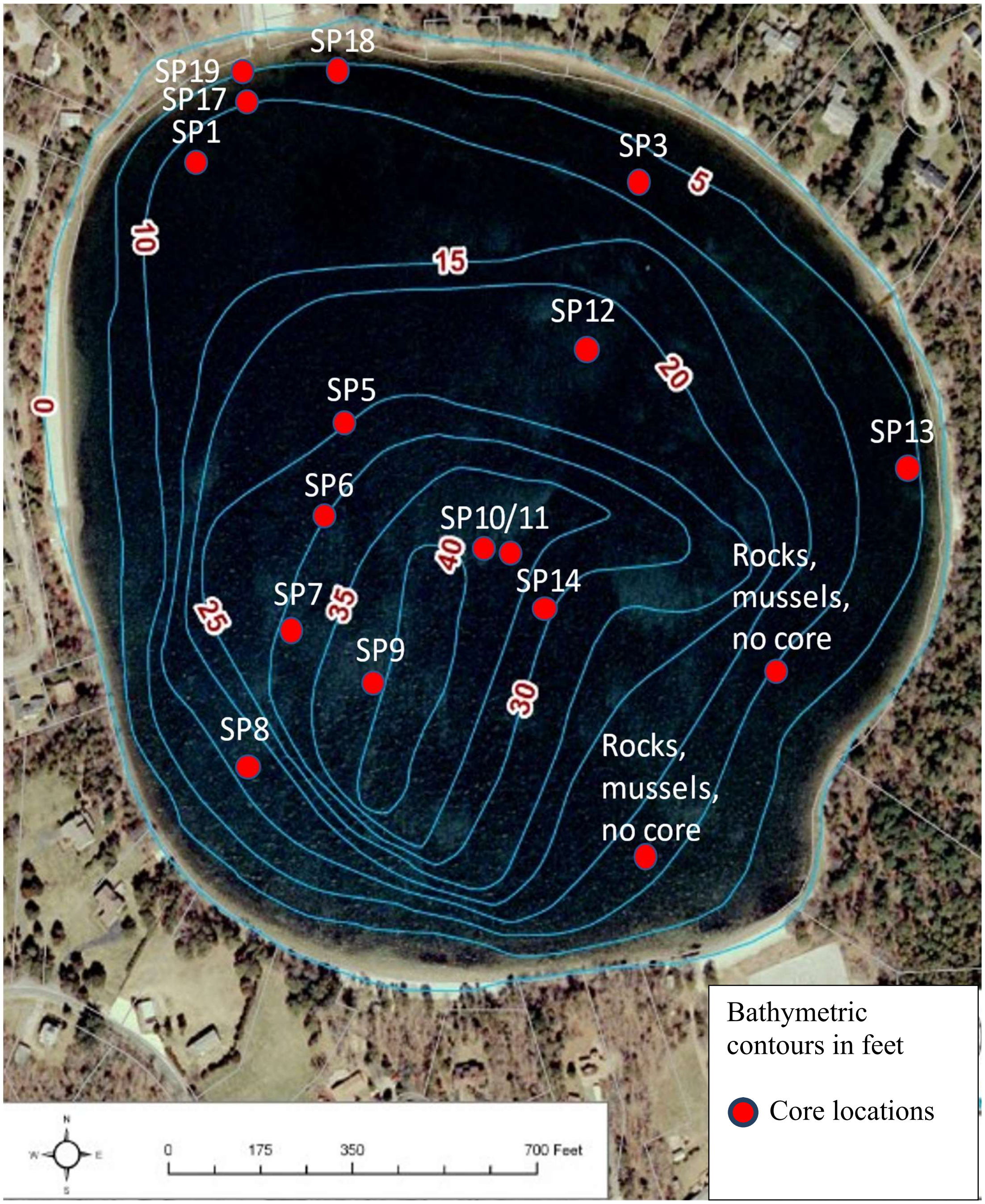

Figure IV-27. Shubael Pond 2020 Sediment Core locations. Red circles show the locations of 15 sediment cores collected in Shubael Pond on May 12, 2020. Note that core collection was not successful at two southeast locations due to rocks and extensive mussels. Base map is the bathymetric map modified from Eichner (2008).

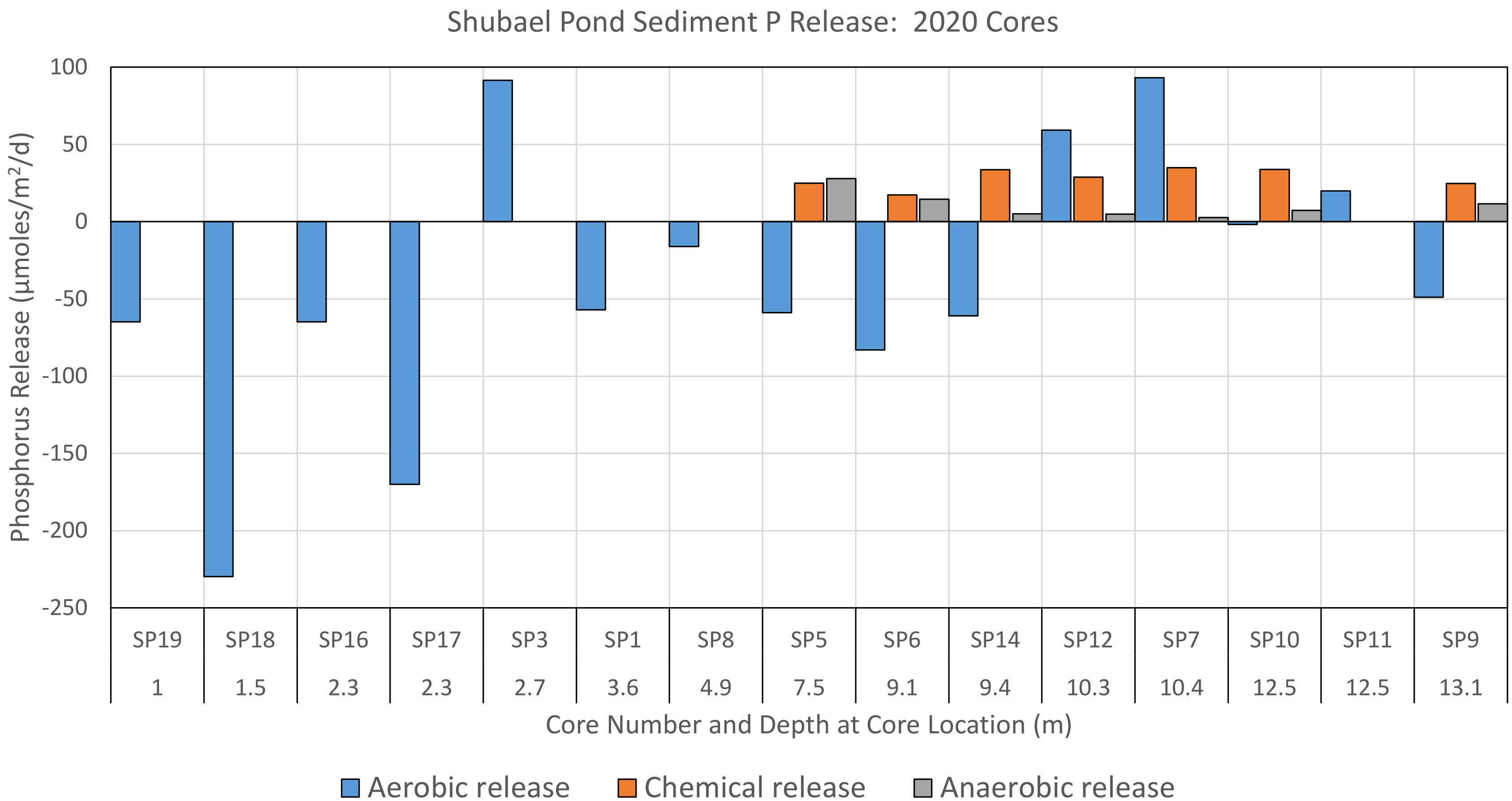

Figure IV-28. Shubael Pond Phosphorus Release from Collected 2020 Sediment Cores. Average P release measured during incubation of the cores collected at Shubael Pond on May 12, 2020 are shown. Aerobic incubation generally showed that most shallow (cores from <5 m depths) and deep sediments were generally retaining P, while anaerobic conditions caused the release of P to the water column in deep sediments (cores from >5 m depths). Anaerobic release rates were approximately one third of aerobic retention rates, so Shubael Pond sediments are generally retaining P. Chemical release rates were 3X to 4X the sustained anaerobic release only rates and were sustained for 47 days (*i.e.*, all iron:P bonds are broken). Anaerobic incubation of cores continued for another 40 days after the chemical release phase was completed to ensure that anaerobic P release though microbial remineralization had stabilized.

Using the 2020 DO profiles and sediment incubation results, sediment release for Shubael Pond can be estimated. Anaerobic conditions were first measured in the June 17 profile at 12 m (see **Figure IV-4**). Anaerobic conditions were measured at 12 m through all subsequent profiles until the 10/27 profile,[63] so these conditions were sustained at ≥12 m for approximately 150 days. Using the same approach, anaerobic conditions were sustained at 8 m, 9 m, 10 m, and 11 m for 20 days, 70 days, 84 days and 104 days, respectively. Any of these periods greater than 47 days means the sediments at that depth finished the chemical release phase and experienced steady-state anaerobic release until aerobic conditions returned. This approach results in an overall estimate of 2.3 kg P returned to the water column from the sediments. Under a worst case scenario, if anoxia persisted for 150 days over all sediments ≥8 m, the estimated TP mass added to the water column would be 4.4 kg. Since the individual profiles show an average of 4.6 kg P in the hypolimnion, the additional P measured in water column samples is likely P linked to summer organic matter settling into the hypolimnion.

Overall, the sediment core results show that the sediments have notable P reserves that can be released under sustained anaerobic conditions, but aerobic conditions are generally sustained in shallow depths (<5 m depth) and the pond sediments are collectively retaining P, mostly in the sediments in the shallow areas. Potential management of the sediment P contributions to the water column would focus on the deep sediments (>8 m depth) and would include sustaining aerobic conditions in the water column and/or chemically binding the P to remain in the sediments.

IV.B.5 Direct Stormwater Runoff Discharge to Shubael Pond

During the original discussions about water quality management of Shubael Pond, direct discharge of stormwater to the pond was identified as an issue that required additional information. After review with Town staff, three potential direct stormwater runoff discharge sites were identified: 1) the town boat ramp at the end of Willimantic Drive, 2) a pipe at the end of Shubael Pond Road, and 3) a pipe to the west of Shubael Pond Road (**Figure IV-29**).

Stormwater at the three sites had different upstream sources. The boat ramp discharges runoff that collects along the edges of Willimantic Drive. There are a series of leaching catch basins at the Willimantic Drive/Mansfield Avenue intersection, but no additional catch basins between Mansfield Avenue and the boat ramp (**Figure IV-30**). Discharge of stormwater runoff at the boat ramp generally appeared to be from flow south of Mansfield Avenue. The pipe at the end of Shubael Pond Road collects overflow stormwater generated from a series of connected catch basins along Osterville West Barnstable Road and its intersection with Race Lane, as well as portions of Race Lane that shuttle runoff to this area. Overflow from the connected catch basins flows to four leaching basins located approximated 80 m down Shubael Pond Road from the Race Lane/Osterville West Barnstable intersection (**Figure IV-31**). Once these basins fill, any overflow flows down the pipe under Shubael Pond Road. The pipe ends near Shubael Pond at a deteriorating headwall. It was noted during stormwater monitoring that there is a small, but measurable runoff from Shubael Pond Road itself that flows around the western edge of the headwall and discharges into the pond. Just to the west of the headwall, there is a partially occluded aluminum corrugated pipe that is connected to leaching catch basins at the end of Evergreen Drive. Once these catch basins fill, the runoff overflow discharges through the pipe to Shubael Pond. Flow from this pipe was not noted in any of the stormwater monitoring visits, but vegetation and shoreline sand between the pipe and the pond showed signs that flow from the pipe had occurred between visits.

[63] The 12/2 profile had aerobic conditions throughout the water column.

Figure IV-29. Direct Stormwater Runoff Discharge Locations to Shubael Pond. Stormwater discharges to Shubael Pond at three locations: A) a headwall pipe at the end of Shubael Pond Road, B) a corrugated aluminum pipe approximated 5 m to the west of the headwall and C) the boat ramp at end of Willimantic Drive. Based on monitoring during three storms, the largest source of stormwater runoff and nutrient loads is the headwall pipe, which is connected to a series of catch basins on Race Lane and Osterville West Barnstable Road (~0.5 km to the north). The corrugated aluminum pipe is connected to a series of catch basins at the eastern end of Evergreen Road. The boat ramp receives runoff from a portion of Willimantic Drive south of its intersection with Mansfield Avenue. During the two larger storms, a small amount of stormwater flowed directly from Shubael Pond Road, which is unpaved, around the headwall (yellow arrow in A) and discharged into the pond.

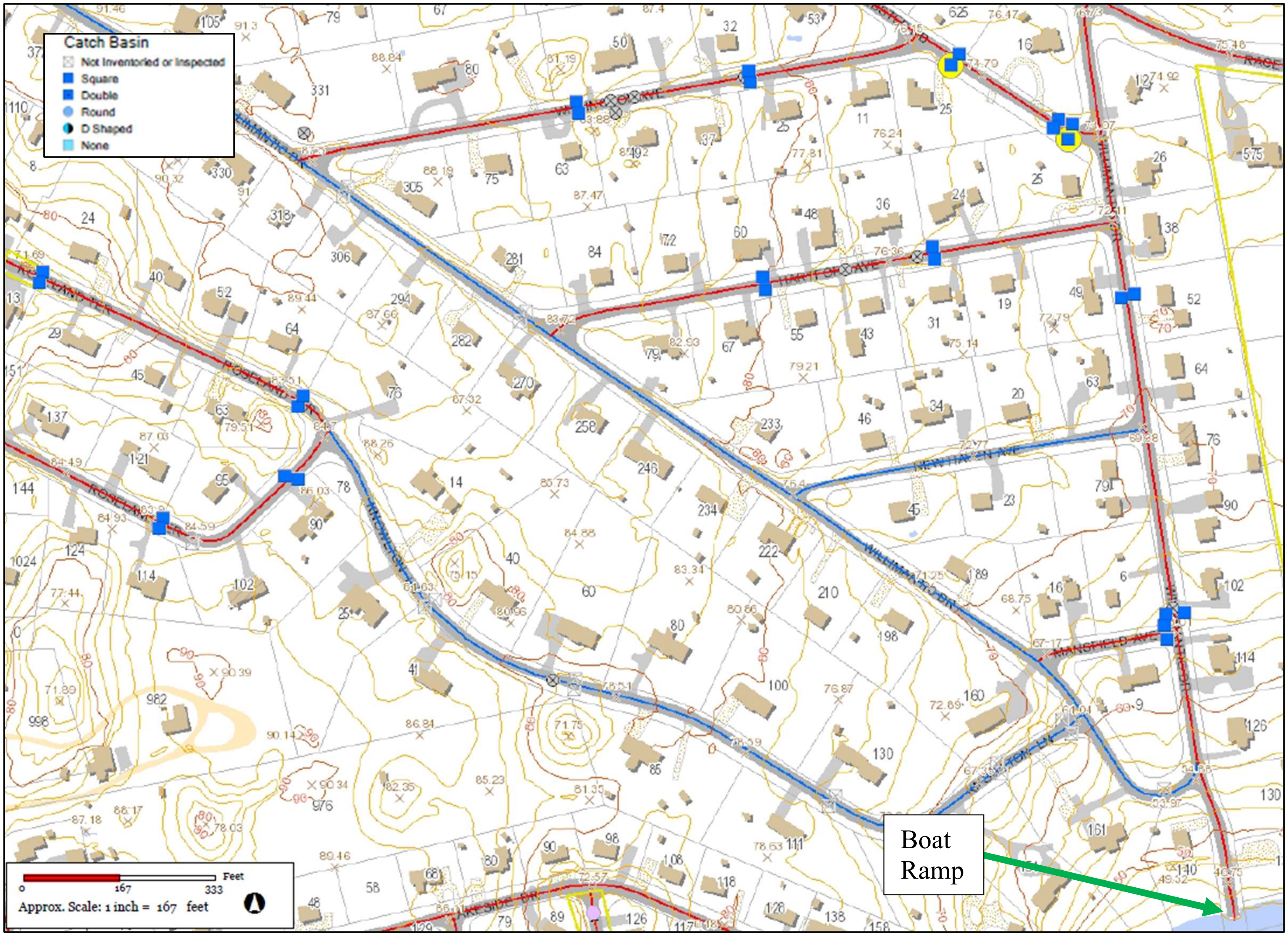

Figure IV-30. Stormwater catch basins on Willimantic Drive. At the end of Willimantic Drive is the Shubael Pond boat ramp. The nearest catch basins are at the intersection of Willimantic Drive and Mansfield Avenue. Map modified from Town of Barnstable catch basin maintenance map (printed 11/23/20).

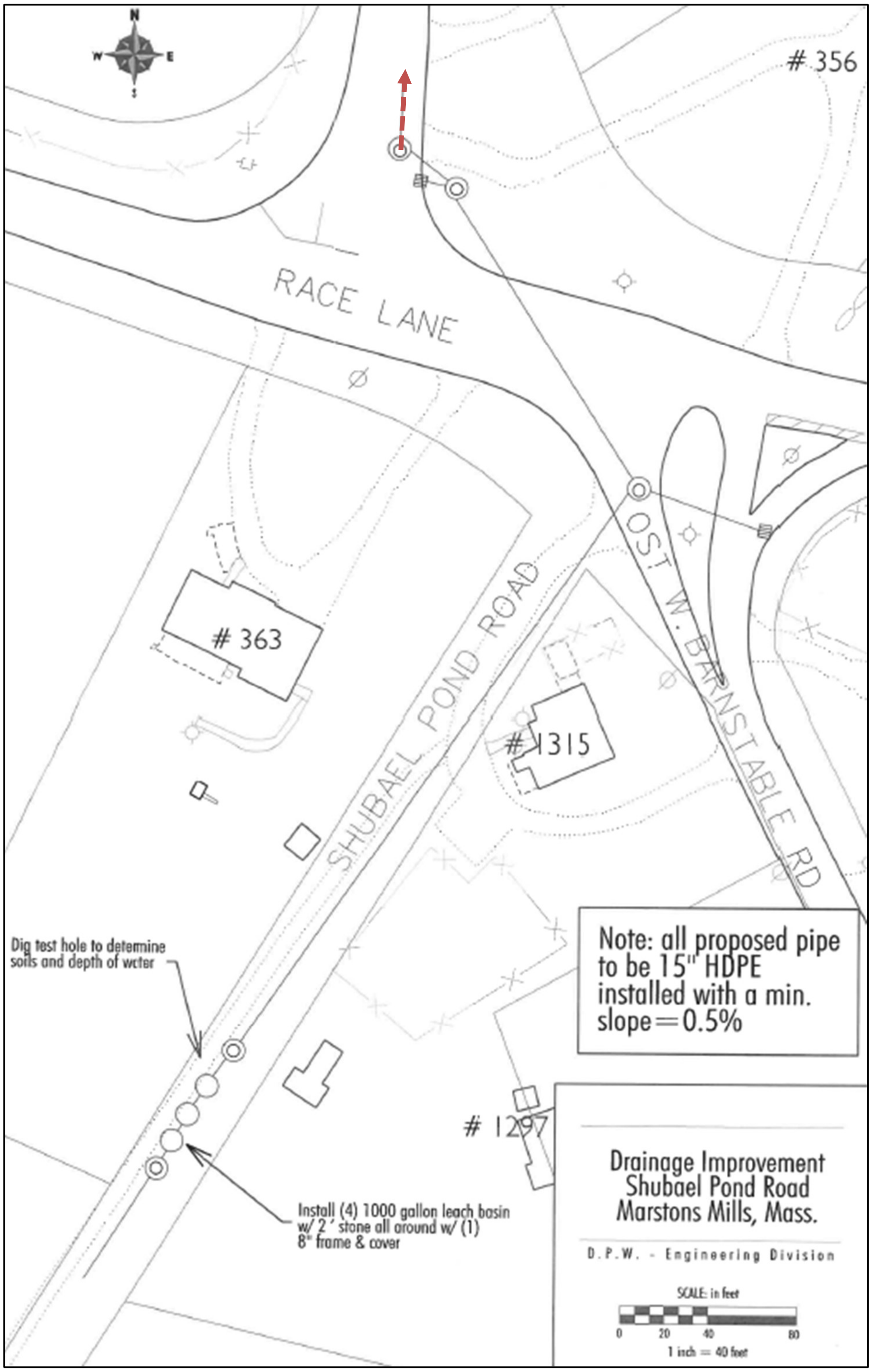

Figure IV-31. Shubael Pond Road leaching basins connected to headwall discharge. The leaching basins are part of an in-line treatment of the collected runoff from connected catch basins along Osterville West Barnstable Road that extend approximately 0.25 km north of the Race Lane intersection and portions of Race Lane flow toward the intersection. The overflow pipe from the leaching basins extends to the headwall at the end of Shubael Pond Road and discharges runoff to Shubael Pond. Modified from map provided by A. Unruh, Barnstable DPW.

It is also notable that project staff noted a partially occluded outfall pipe at the eastern arm of Willimantic Drive, closest to the boat ramp, but discussions with town staff noted this section of the road is a private way, so the connections to the pipe and its maintenance are not included in Town records.[64] No flow from this pipe was noted during stormwater monitoring, although the section of Willimantic Drive thought to be connected to the pipe regularly flooded during stormwater monitoring events (**Figure IV-32**).

Project staff visited the direct stormwater discharge sites during three storms: 11/23/20, 9/28/21, and 12/08/21. Total local precipitation on the three dates measured at Barnstable Municipal Airport was: 0.6 inches, 0.45 inches, and 0.21 inches, respectively.[65] Town DPW staff provided interim readings during selected storms from the gauge at the Barnstable Water Pollution Control Facility (WPCF). Monitoring was conducted using standard stormwater measurement techniques, including collection of first flush runoff, replicates of flow readings, and collection of runoff samples for constituent analysis. All runoff samples were assayed at the Coastal Systems Analytical Facility at SMAST for phosphorus and nitrogen components using the same assay protocols as used for the lake water samples.

Each of the three storms had different characteristics. The 11/23 storm had steady rain at 11:05 AM, intense rain at 11:15 AM, a tornado warning at 11:32 AM, and rained stopped by 2:15 PM. The 9/28 storm began at 2:53 PM with steady rain and stopped at 4:45 PM. Precipitation measured at the WPCF at 4:55 PM on 9/28 was 0.52 inches.[66] The 12/8 storm began at 12:45 PM and had the following total precipitation readings at the WPCF: 0.15 inches at 2:41 PM, 0.205 inches at 3:46 PM, and 0.252 inches at 5:57 PM.[67] The regular WPCF reading the next morning was a total of 0.346 inches in the previous 24 hours.

During each of the storms, runoff discharge to the pond began first at the boat ramp and then later at the Shubael Pond Road headwall pipe. During the 9/28 storm, which had a high precipitation rate of 0.3 inches per hour, flow out of the headwall pipe began 25 minutes after boat ramp runoff had begun discharging into the pond. However, flow at the headwall pipe continued for at least 1 hour after runoff flow had stopped at the boat ramp. During the 12/8 storm, which had a lower precipitation rate that varied between 0.08 and 0.19 inches per hour, flow at the headwall pipe began 1.5 hours after runoff began at the boat ramp. These differences in runoff timing are consistent with the upstream impervious surfaces and collection systems.

Review of the water quality data shows that the concentrations of constituents varies by location and intensity of the storm. Total phosphorus (TP) and total nitrogen (TN) concentrations were highest among the three storms in the first runoff (*i.e.*, first flush) at the boat ramp during the 11/23 storm. Second highest TP concentration was in the first flush at the boat ramp during the 9/28 storm. Second highest TN concentration was in the first flush at the headwall bypass during the 9/28 storm. As mentioned, the 10/23 and 9/28 storms were higher intensity storms than the 12/8 storm, so they would have subjected impervious surfaces to more vigorous flows. Review

[64] Personal communications, Amber Unruh, Barnstable DPW, 10/14/21
[65] https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USW00094720/detail
[66] Personal communications, Amber Unruh, Barnstable DPW, 9/28/21
[67] Personal communications, Amber Unruh, Barnstable DPW, 12/8/21

Figure IV-32. Stormwater ponding on Willimantic Drive. Willimantic Drive loops from Race Lane to Cotuit Road. At the turn toward Cotuit Road, Willimantic Drive becomes a private road and there are no catch basins in this area. Project staff identified a partially occluded pipe and headwall west of the boat ramp that may be connected to this area. This picture of ponding was taken after rain had stopped following the 9/28/21 storm.

of runoff total suspended solids (TSS) concentrations showed that the highest three concentrations were at the boat ramp during the 10/23 or 9/28 storms. Again, these findings are consistent with the stormwater systems upstream of the discharge points; the in-line leaching basins upstream of the headwall would allow settling of particles and removal of some of the portion the TP and TN concentrations in particulate forms.

Although the concentrations were high at the boat ramp, the combination of concentrations with the volume of discharge at the headwall makes the headwall the primary source of stormwater runoff nutrients to Shubael Pond. The runoff flow at the headwall site was significantly greater than the boat ramp flow during all of the storms. Peak measured flow at the headwall was at least 8X greater than the peak flow at the boat ramp and comparison of flows at similar times showed the headwall flows varied between 3X and 80X flows at the boat ramp (**Figure IV-33**). Comparison of TP and TN mass based on both the flow and the respective runoff concentrations showed that the headwall load was a minimum of 4X the boat ramp load and was a maximum of 78X the boat ramp load during corresponding portions of their runoff (**Figure IV-34**).

In order to develop an estimate of the annual nutrient loads from the stormwater discharges, staff reviewed long term precipitation records at Barnstable Municipal Airport and then applied the insights learned from direct measurements at the Shubael Pond sites. Between 1999 and 2020, annual precipitation at the Airport varied between 33.28 inches (2020) and 54.37 inches (2019) with an overall average of 44.16 inches (**Figure IV-35**).[68] There was an average of 134 dates per year with measurable precipitation between 1999 and 2020. Of these dates, an average of 29 storms per year (22% of the total) had precipitation greater than 0.5 inches and 11 storms per year were greater than 1 inch (8% of the total). Average precipitation by month only varies 1.7 inches with average monthly precipitation of 3.7 inches. However, the difference between maximum and minimum monthly totals averages 6.9 inches with the greatest variability in October (10.3 inches). Review of the records shows that daily precipitation of 0.5 inches or more represents 68% of the annual average precipitation, while storms of 1 inch or more average 37% of annual average precipitation. Trend review shows that the percentage of annual precipitation occurring on days with 1 inch or more has been increasing at a statistically significant rate (F test<0.05) prior to the drought year of 2020. Combining all this information shows that while daily precipitation of >0.5 inches occurs on 22% of the days with measured precipitation during an average year, the total precipitation from these days averages 68% of the total annual precipitation.

Using this information, staff assumed the 11/23/20 and 9/28/21 storms were representative of most of the storms at Shubael Pond, while the 12/8/21 storm is representative of small storms. The annual combined TP loading estimate from the headwall, headwall bypass and the boat ramp is 0.5 kg with 94% from the headwall site. Using this same approach for TN loading results in an annual TN load of 3.4 kg with 96% from the headwall site. Measurements from storms with greater than 1 in of rain (8% of annual storms and 37% of the annual precipitation on average) would likely increase these loads slightly due to greater volumes; TP and TN concentrations at the headwall generally were with similar ranges after the first flush.

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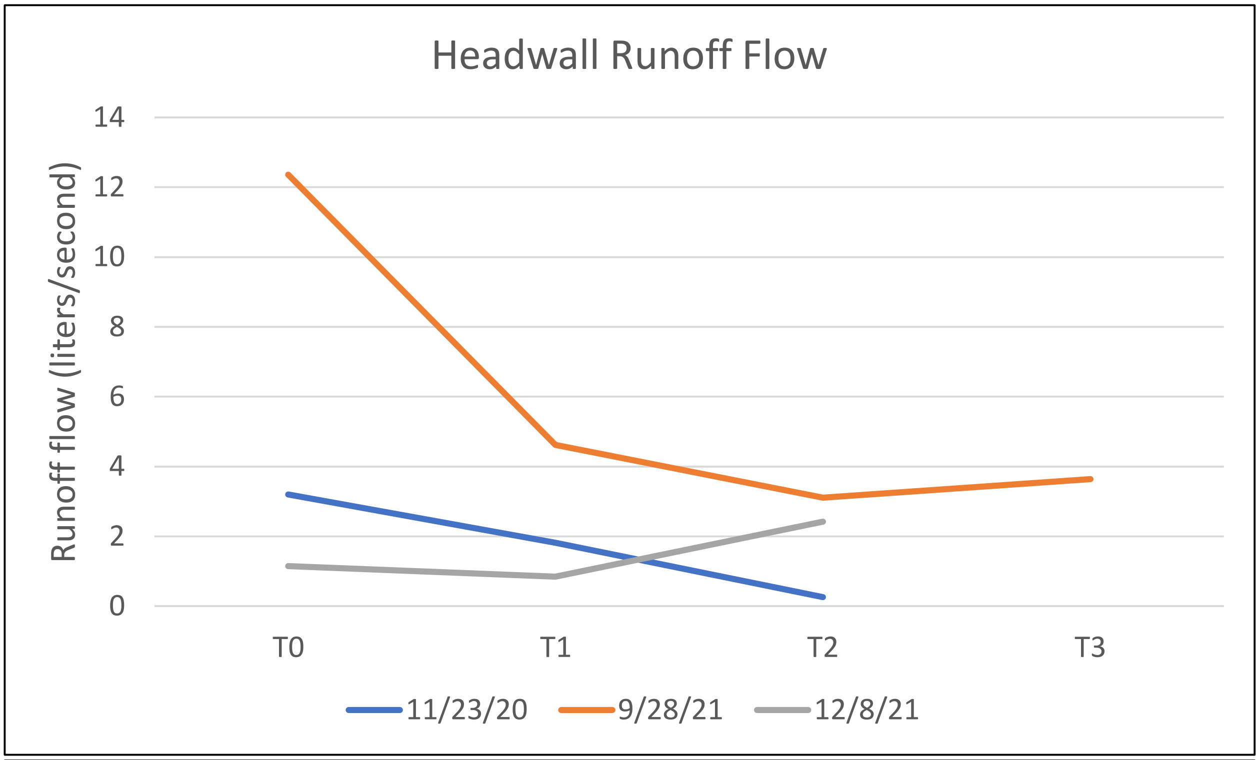
[68] https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USW00094720/detail



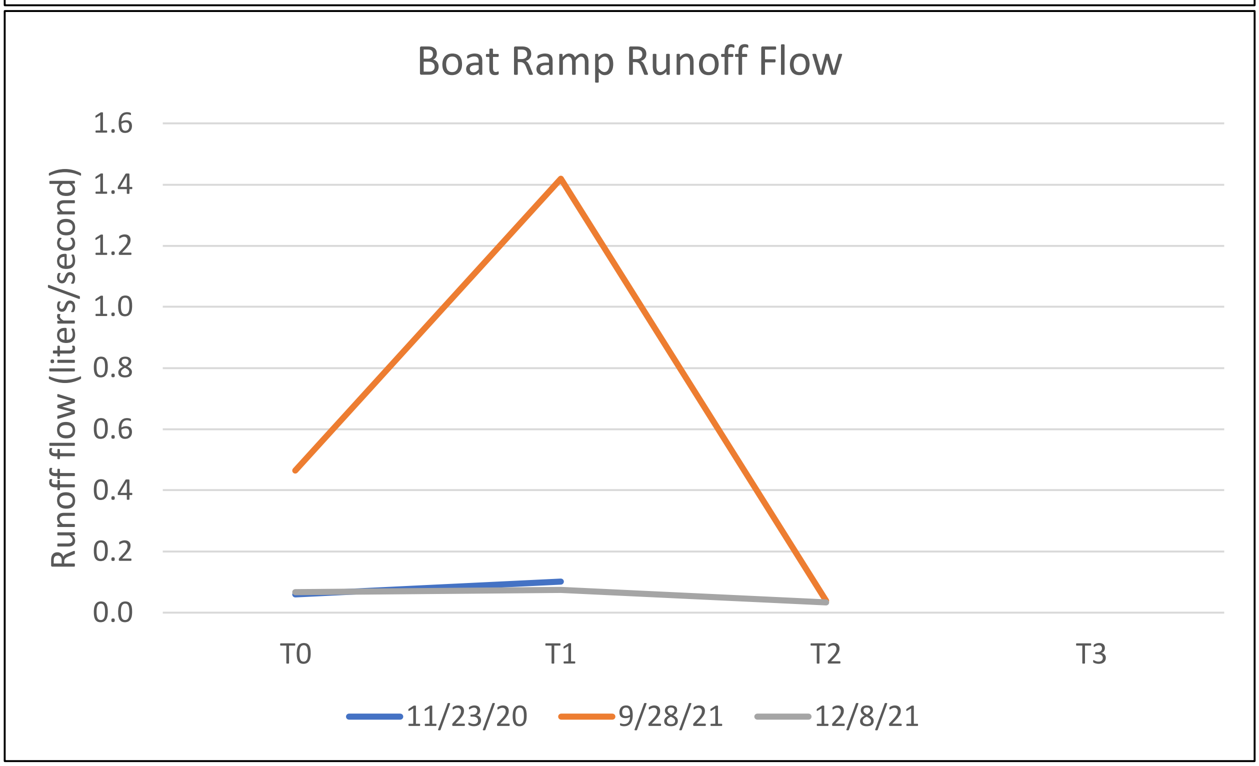


Figure IV-33. Measured Runoff Flow at Shubael Pond Road Headwall and Boat Ramp. Measured flow at the headwall was at least 8X peak flows at the boat ramp. Flows during the 9/28/21 storm were higher than either of the other storms likely due to most of the rain occurring in only 1.7 hrs. Total precipitation for the 11/23/20 storm (0.6 inches) was greater than the 9/28 storm (0.45 inches).

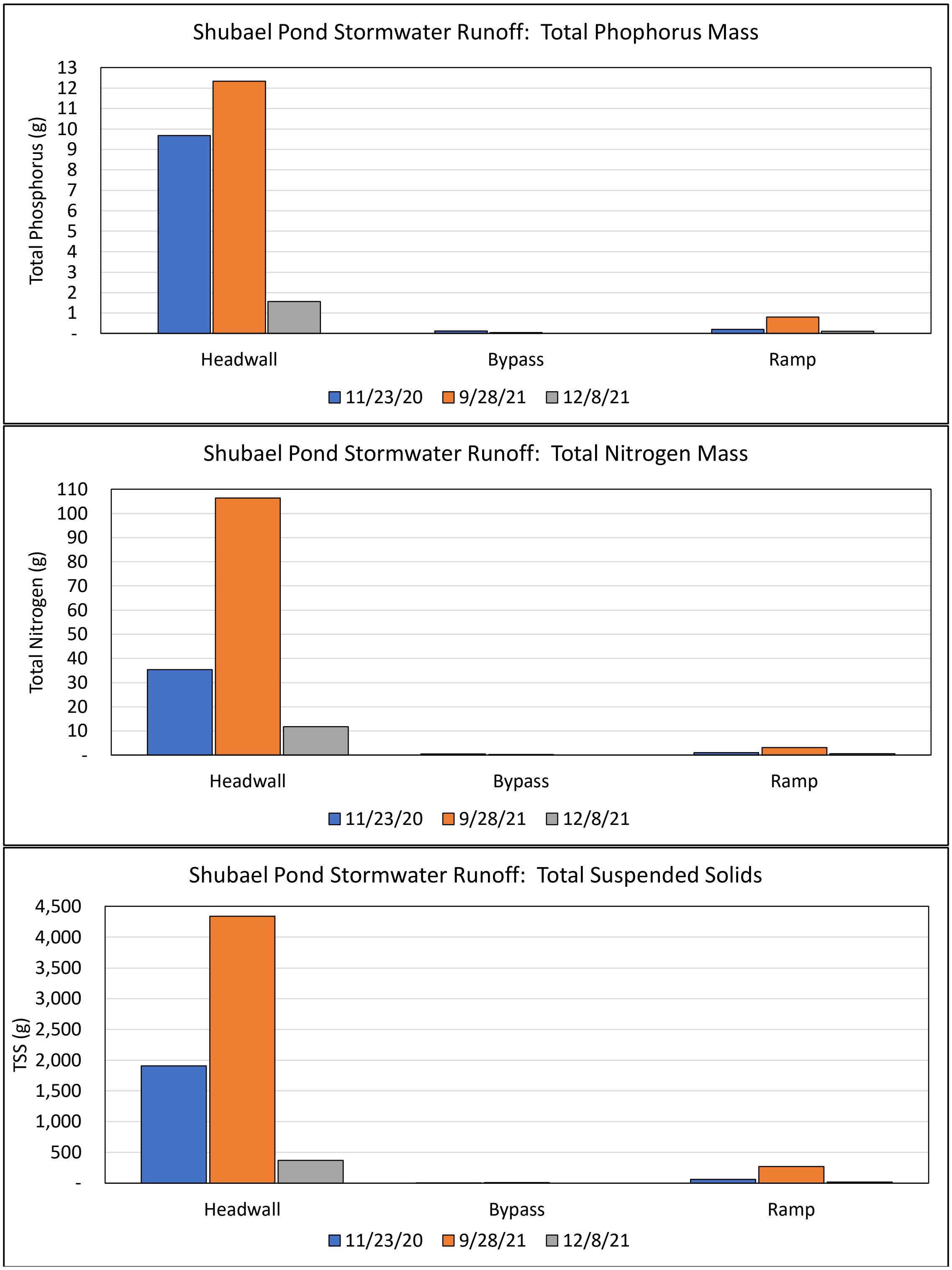


Figure IV-34. Measured Total Phosphorus, Total Nitrogen, Total Suspended Solids Mass in Runoff Flow at Shubael Pond during three storms. During all three storms, the load from the Shubael Pond Road stormwater system headwall accounted for over 91% of the TP mass, over 95% of the TN mass, and over 94% of TSS mass from direct stormwater discharge to Shubael Pond.

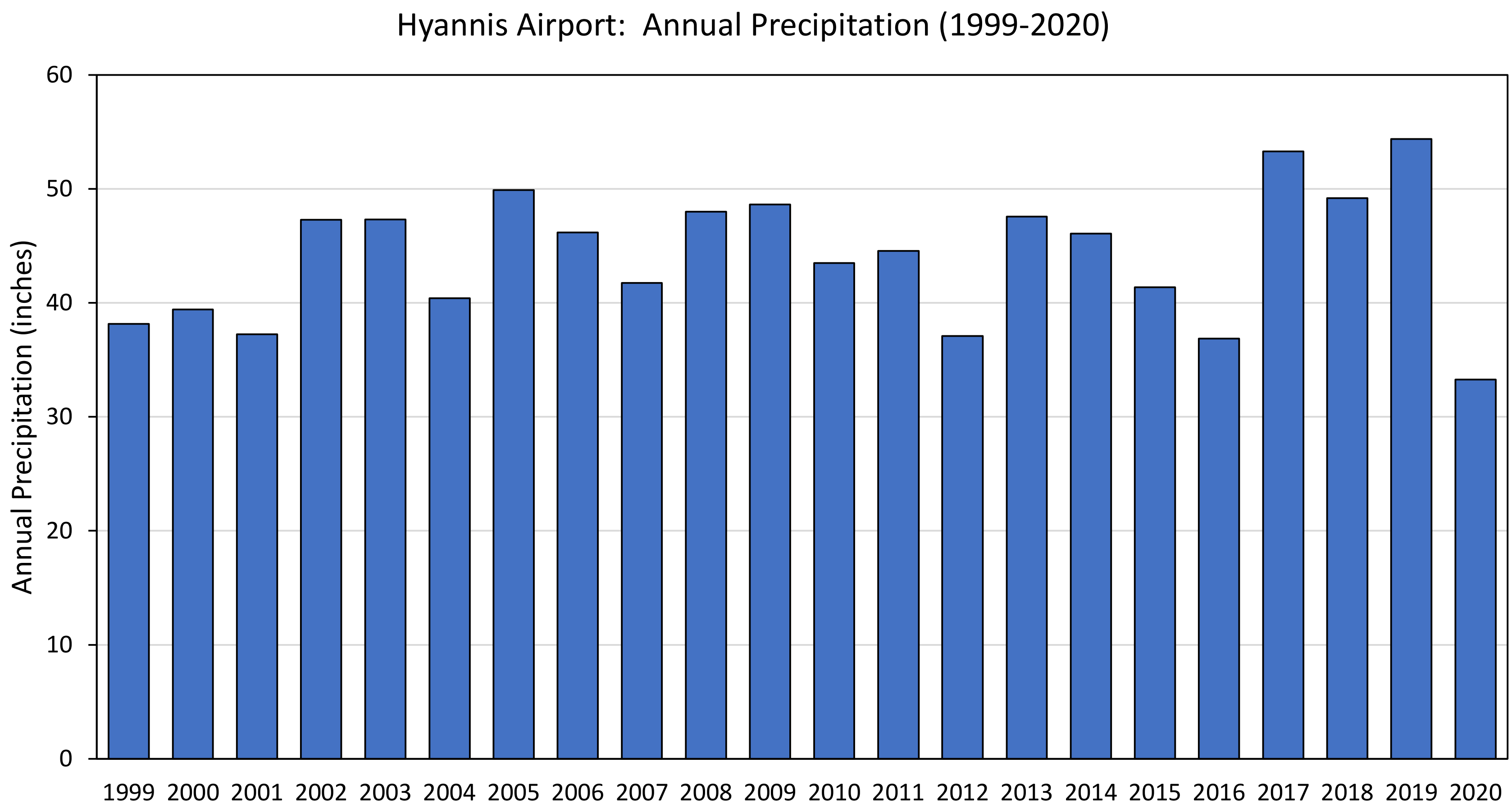


Figure IV-35. Annual Precipitation at Hyannis Airport (1999-2020). Annual precipitation at Hyannis Airport from 1999-2020 averaged 44.2 inches with the maximum annual rate in 2019 (54.4 inches) and the minimum rate in 2020 (33.3 inches). Average number of dates each year with measurable precipitation is 134 days with 29 days having 0.5 inches or more and 11 days with 1.0 inch or more.

IV.C. Shubael Pond Watershed Review and Physical Characteristics

Shubael Pond is located approximately 0.5 km south of Race Lane and 0.5 km east of Cotuit Road/Route 149. Average groundwater elevations in the area were 45 ft NGVD29.[69] United States Geological Survey (USGS) watershed delineations created for the Massachusetts Estuaries Project (MEP) as part of the Three Bays assessment[70] showed that Shubael Pond is located along the watershed divide between Three Bays and the Centerville River estuary system and the regional groundwater divide between Cape Cod Bay and Nantucket Sound (**Figure IV-36**). Flow out of Shubael Pond into groundwater is divided between the Three Bays and the Centerville River watersheds. Shubael Pond does not have any surface water inflow or outflow and, thus, is a true kettle pond with groundwater as its primary inflow and outflow pathway.

More recently USGS has been involved in a study of innovative/alternative nitrogen-reducing septic systems within the Shubael Pond watershed.[71] As part of this study, which has not been published, provisional data has been collected that explored groundwater discharge into the pond. This data has suggested a different "hinge" line dividing Shubael Pond outflow between Three Bays and the Centerville River watersheds than indicated by the USGS regional groundwater modeling. Movement of this line would also alter the watershed delineation to Shubael Pond. In order to provide some potential insights into the movement of this line on pond water quality characterization and pond management strategies, project staff developed a preliminary estimate of a revised watershed based on the regional groundwater sheds and the estimated hinge line location (**Figure IV-37**). It is anticipated that this will be altered as the USGS reviews all of the groundwater data they are collecting.

IV.C.1. Shubael Pond Water Budget

A water budget for a pond accounts for all water entering and leaving a pond. Ensuring that the volumes of water entering a pond balances with the amount leaving provides an understanding of the relative importance of each water pathway and, in turn, how these pathways impact ecosystem functions, including water quality. Since nutrients also enter and exit with each of the water flows, the relative magnitude of each pathway also provides guidance for development and prioritization of management strategies.

The primary water input source to kettle ponds on Cape Cod is typically groundwater discharge from their watershed. Additional water input sources to consider would be imported drinking water recharged through septic systems, direct stormwater runoff outfalls, and precipitation on the pond surface. Water movement out of these groundwater-fed ponds is typically through pond water returning to the groundwater aquifer along the downgradient side of the pond and evapotranspiration off the surface of the pond, but if a surface water outflow (*i.e.*, stream or herring run) is present, this usually becomes the primary exit pathway for water out of the pond.

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

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

[71] https://www.usgs.gov/centers/new-england-water-science-center/science/assessment-hydrologic-conditions-three-bays (accessed 1/10/22).

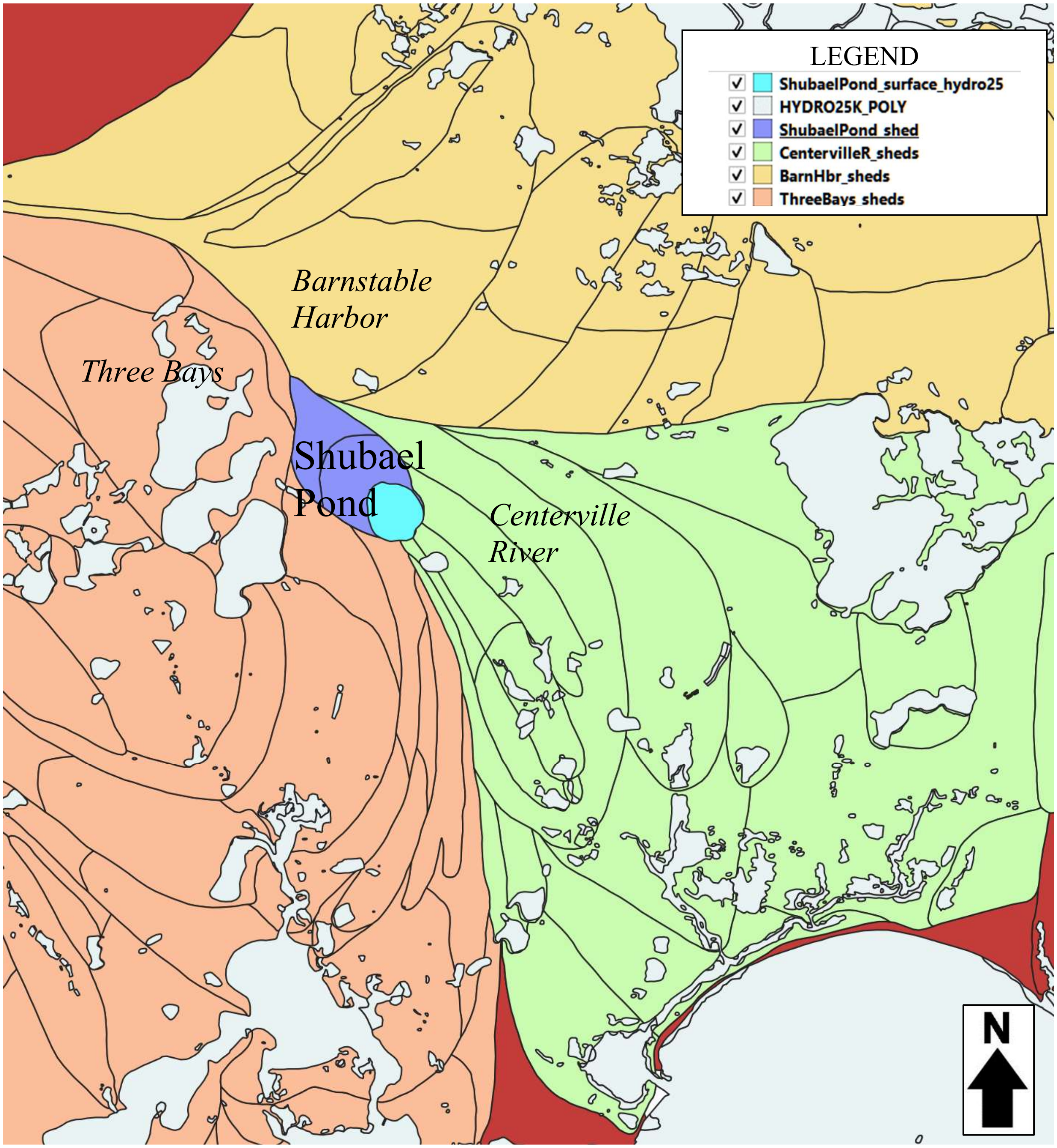


Figure IV-36. Shubael Pond Watershed. Watersheds to Barnstable Harbor, Three Bays, and Centerville River were delineated by the US Geological Survey as part of the Massachusetts Estuaries Project and the development of a regional groundwater model (Walter and Whealan, 2005). The watershed to Shubael Pond is shared between the Three Bays and Centerville River systems and is adjacent to the regional groundwater divide between Cape Cod Bay and Vineyard Sound.

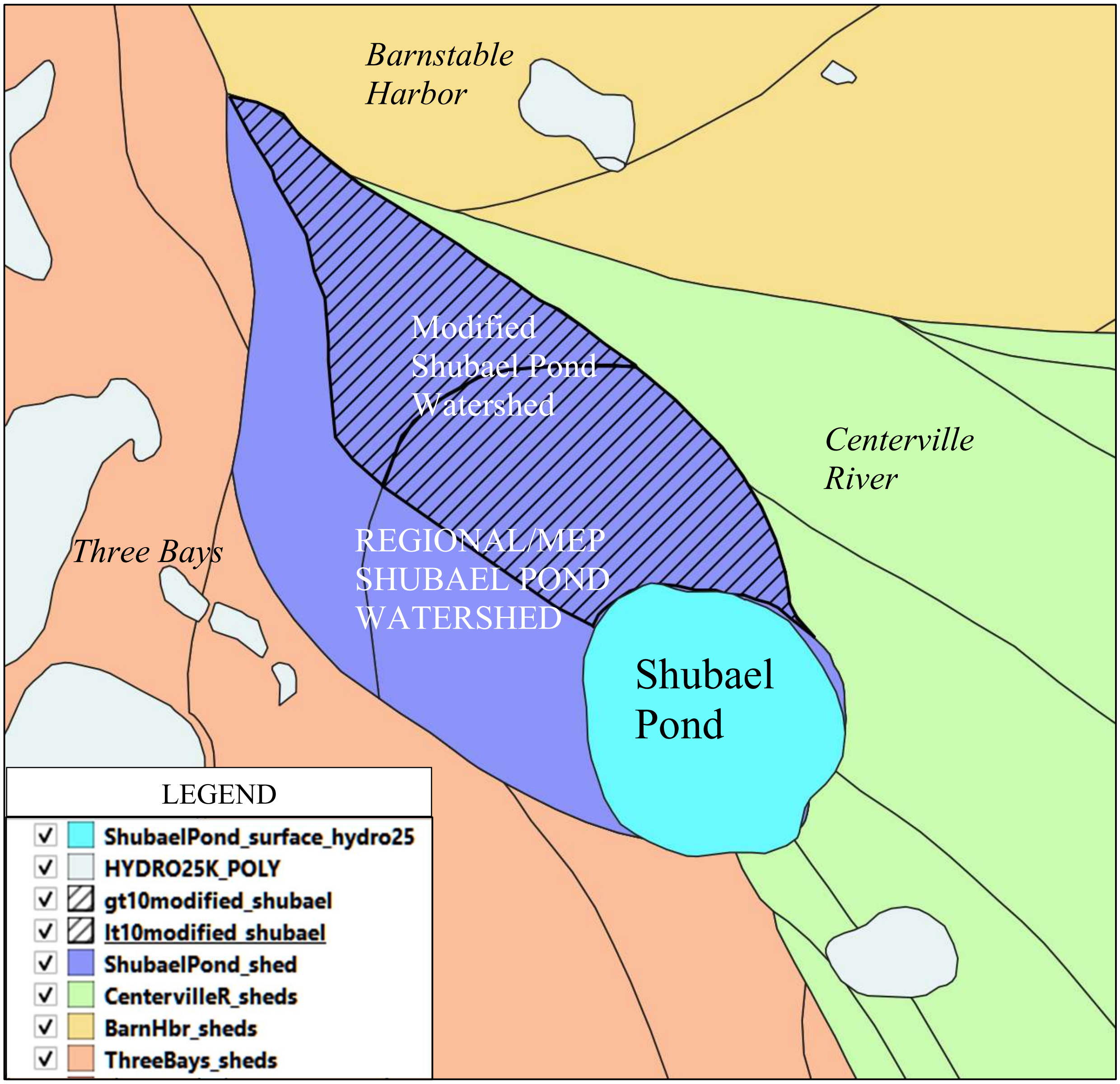


Figure IV-37. Modified Shubael Pond Watershed. USGS is presently conducting a study of innovative/alternative nitrogen-reducing septic systems within neighborhood to the west of Shubael Pond (*i.e.*, circumscribed by Lakeside Drive). The study has included groundwater elevations and used a variety of groundwater discharge methods. Provisional data, which is not available for public review, suggest that the northern portion of Lakeside Drive is the hinge line for the portion of the watershed flowing to the Three Bays estuary, rather than the southern portion of the drive that was suggested by USGS regional groundwater modeling. In order to evaluate the potential impact on pond management, project staff developed a modified Shubael Pond watershed using the provisional data. The net result is a smaller watershed to Shubael Pond (crosshatching above) than the watershed used in MEP assessments of Three Bays and Centerville River (purple fill area including crosshatched area). It is anticipated that this will be refined as the USGS considers all of the groundwater data they are collecting.

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Shubael Pond has four input pathways of water and two outputs of pond water. It has no inflow or outflow streams. The water budget balancing these inputs and outputs for Shubael Pond is represented in the following equation:

$$\text{groundwater}_{in} + \text{surface precipitation} + \text{imported wastewater} + \text{stormwater} = \text{groundwater}_{out} + \text{surface evapotranspiration}$$

Among these pathways, only surface precipitation can be directly measured simply. Groundwater_{in} is usually estimated based on recharge within the pond watershed,[72] while surface evaporation is generally estimated by calculation based upon temperature, humidity, wind and other factors and previous regional measurements. Imported wastewater is generally based on measured water use at individual watershed parcels. Groundwater_{out} is usually estimated by difference.

IV.C.1.a Groundwater flow and Precipitation

Groundwater flows into ponds on Cape Cod along an upgradient shoreline margin and then pond water flows back into the groundwater aquifer along the downgradient shoreline margin as the groundwater follows a path to the downgradient ocean or estuary shoreline. The water level of a pond is typically an exposed portion of groundwater system that has filled a depression in the land surface. The pond surface is approximately at the same elevation as the surrounding groundwater.

Watersheds to freshwater ponds in this setting are defined by upgradient groundwater flowpaths. As mentioned, streams can serve to collect groundwater, but they can also serve as rapid drains, especially on the downgradient sides of ponds, to redirect groundwater flow to different flowpaths. Downgradient streams tend to function as “release valves” because water flowing out through a stream has less resistance than pond water returning to the groundwater system. Groundwater levels fluctuate with precipitation. Levels are determined by how much precipitation is not utilized by plants or evaporated back to the atmosphere; the remainder infiltrates through the sandy soils to recharge the groundwater system. Recharge is the portion of precipitation that slowly percolates down to the top of the saturated soils (*i.e.*, the water table). Recharge will vary seasonally with greater recharge occurring during the winter and less occurring during the summer. Precipitation on pond surfaces is also subject to evapotranspiration, which returns water to the atmosphere.

As mentioned, the watershed to Shubael Pond was delineated by the USGS as part of the Massachusetts Estuaries Project (MEP) assessments of Three Bays[73] and Centerville River[74] (see **Figure IV-36**). This delineation was based on results of a regional groundwater model[75] that included a recharge rate of 27.25 inches per year. Annual groundwater discharge to Shubael Pond based on MEP watershed area and a 27.25 in/yr recharge rate is 733,116 m3/yr, while the

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[72] Recent USGS data collection in the area has used more quantifiable methods of groundwater inputs, but this data is not available at the time this is being written.

[73] Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2006). Three Bays MEP report.

[74] Howes B., H.E. Ruthven, J. S. Ramsey, R. Samimy, D. Schlezinger, J. Wood, E. Eichner. 2006. Centerville River MEP Report.

[75] Walter, D.A. and A.T. Whealan. 2005. U.S. Geological Survey Scientific Investigations Report 2004-5181.

annual groundwater discharge to Shubael Pond from the modified watershed is 319,614 m3/yr based on the same recharge rate.

Precipitation on the surface of the pond is another component of the water budget. Daily precipitation is collected in Barnstable at the Hyannis Airport. Average annual precipitation at this site between 1999 and 2020 was 44.2 inches per year, but varied widely in during the period that impacted water quality readings: 2019 and 2020 precipitation totals were 54.4 inches and 33.3 inches, respectively.[76] The 2019 annual precipitation was the highest amount between 1999 and 2020, while 2020 was the lowest (see **Figure IV-35**). The long-term average is approximately the same as the 45 inches per year used in the USGS regional groundwater modeling effort, which suggest that the estimated recharge rate used in the regional modeling would be reasonable during average conditions.

Higher precipitation would tend to decrease water column nutrient concentrations, while lower precipitation would tend to increase nutrient concentrations. But the relationship is somewhat more complex because higher precipitation tends to raise groundwater levels and may increase flow rates (*i.e.*, adding more watershed nutrients) depending on the relative pond level. Review of 2020 monthly total precipitation showed that July, August, and September (*i.e.*, the primary management period) had monthly precipitation totals that were less than the 10th percentile for the respective months (**Figure IV-35**). Review of the 2019 and 2020 annual precipitation totals show that the precipitation on the surface of the Shubael Pond could vary approximately 24% on either side of average conditions. Evapotranspiration off the surface of Shubael Pond was assumed to equal the difference between average precipitation and the annual recharge rate (27.25 inches per year). Based on these assumptions, 97,721 m3/yr was estimated to be returned to the atmosphere from the lake surface under average conditions.

IV.C.1.b Shubael Pond Water Budget Summary

The overall annual water budget for Shubael Pond is shown in **Table IV-2**. Groundwater was the predominant water pathway in and out of the lake based on the USGS MEP watershed, accounting for 69% of the inflow and 91% of the outflow under average conditions. Given the volume of the pond, water has an average residence time in the lake of 1.04 year or 380 days. Variation in the pond surface precipitation would vary the residence time over a small range from 0.99 year to 1.11 year. This water budget also includes imported wastewater recharged from septic systems within the watershed[77] and stormwater inputs based on measurements collected in 2020 and 2021.

A larger variation in the residence time would occur based on a change in the watershed area to reflect the provisional findings from the USGS denitrifying septic system project (see **Figure IV-37**). This change in the watershed delineation would decrease the groundwater recharge to the pond and the amount of imported wastewater, but the pond surface precipitation and stormwater inputs would not change. Based on average conditions, this modified watershed would result in a water residence time of 1.79 years or 654 days (see **Table IV-2**). Because the watershed volume is a smaller proportion of the water budget in this scenario, variation in the pond surface precipitation has a bigger impact and a wider range: 1.64 year to 2.00 year.

[76] https://www.ncdc.noaa.gov/cdo-web/datasets/GHCND/stations/GHCND:USW00094720/detail

[77] Wastewater flows are based on town database used in CWMP.

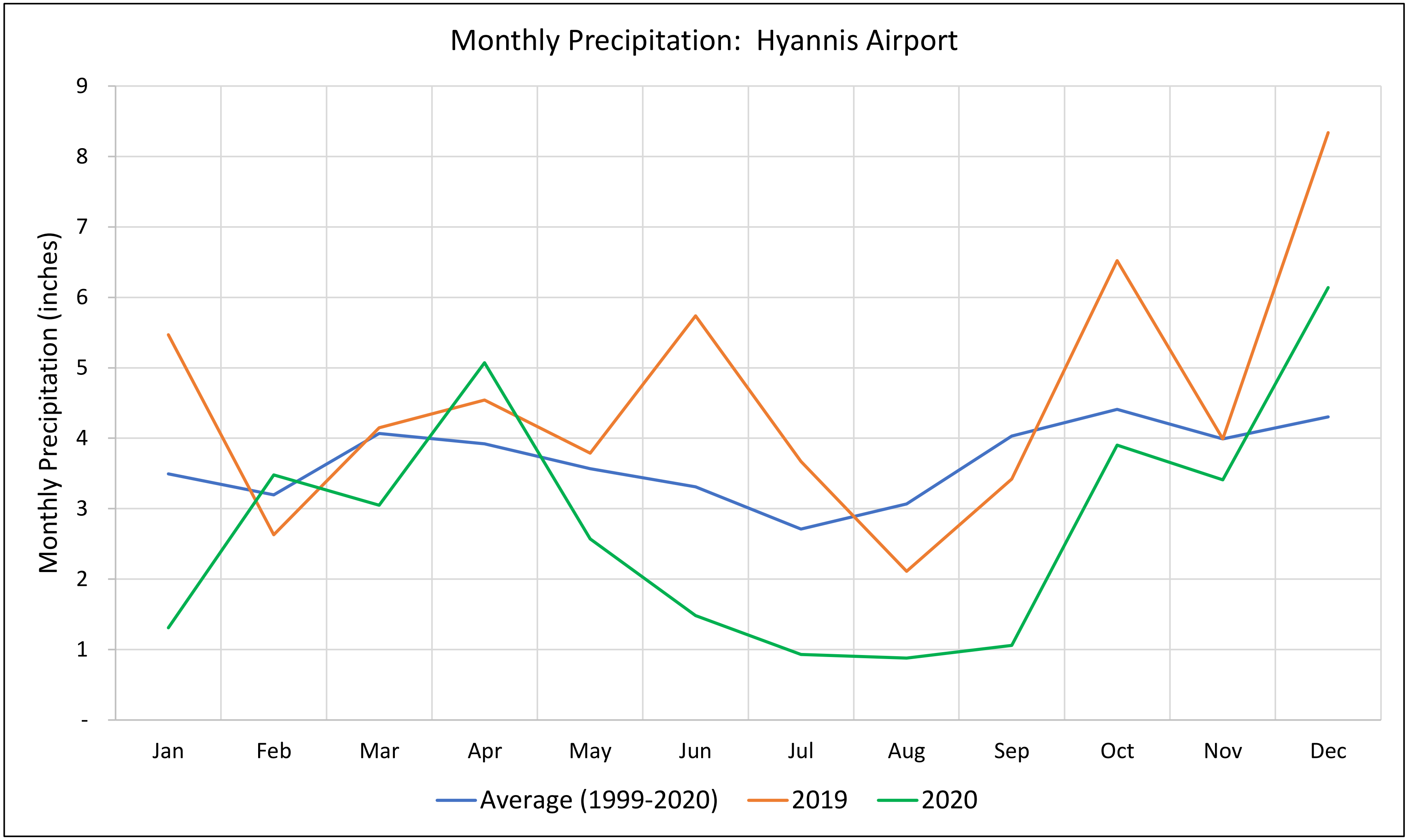

Figure IV-38. Monthly Precipitation at Hyannis Airport (1999-2020). Among annual precipitation totals at Hyannis Airport between 1999 and 2020, 2019 had the maximum annual total and 2020 had the minimum annual total. The 2019 monthly precipitation totals generally were 1 to 2 inches greater than monthly averages throughout the year, while the bulk of the 2020 reduction was due to monthly totals 2 to 3 inches below monthly averages in June, July, August and September.

Table IV-2. Shubael Pond Water Budget. The water budget was based on annual water flows, but variations in flows that will alter the residence time on a seasonal basis as well. The water budget accounts for flows of water into and out of the pond. Two water budget scenarios are presented: 1) watershed delineation based on USGS regional groundwater modeling and 2) watershed based on estimated change in watershed based on USGS provisional data. The provisional data version significantly reduces the watershed area and will require additional review when USGS allows public discussion of their data. Change in the watershed area also changes the number of houses adding imported water via recharge through their septic systems, but does not change the amount of precipitation on the pond surface or the stormwater additions. Review of precipitation data shows the pond surface precipitation varies approximately 24% around the average. This variation has a small impact on the pond water residence time in the regional groundwater version of the water budget (7%), but a larger impact in the provisional data version (12%). Stormwater inputs are annual estimates based on water volumes measured during this project. Annual average residence time of Shubael Pond based on these flows and the measured pond volume is 1.04 year based on the groundwater watershed from the regional model and 1.79 year based on the provisional data watershed.

Regional USGS Groundwater Model: MEP (Average conditions)			
IN		**OUT**	
Source	**m3/yr**	**Sink**	**m3/yr**
Groundwater	733,116	Groundwater	957,797
Pond Surface Precipitation	254,692	Pond Evapotranspiration	97,721
Wastewater (imported water)	65,507		
Stormwater	2,069		
TOTAL	1,055,518	TOTAL	1,055,518
Provisional USGS: Denitrifying Septic System Project (Average conditions)			
IN		**OUT**	
Source	**m3/yr**	**Sink**	**m3/yr**
Groundwater	319,614	Groundwater	514,901
Pond Surface Precipitation	254,692	Pond Evapotranspiration	97,721
Wastewater (imported water)	36,114		
Stormwater	2,069		
TOTAL	612,622	TOTAL	612,622

IV.C.2. Shubael Pond Phosphorus Budget

Phosphorus enters Shubael Pond through various pathways. As noted above, CSP/SMAST staff measured the phosphorus content of the pond water column, sediments, and stormwater runoff. Also as noted above, phosphorus control is the key for determining water quality in Shubael Pond. Pond water column phosphorus is an aggregation of all phosphorus sources reaching the lake from its watershed and precipitation, as well as the net inputs and outputs from sediment regeneration and deposition. A phosphorus budget accounts for all the sources and sinks of phosphorus in order to provide guidance for which management strategies will best control phosphorus levels in Shubael Pond.

External phosphorus loads to Shubael Pond vary depend on the pathway of entry. Phosphorus travels very slowly (*e.g.*, 0.01-0.02 ft/d[78]) within the upgradient aquifer relative to groundwater flow (*e.g.*, 1 ft/d[79]). This is slow rate of travel is different than nitrogen, which is also a key nutrient, but not the one that controls water quality conditions in the pond. Nitrogen (as nitrate) tends to travel at the same rate as the groundwater, so nitrogen from throughout the watershed can will impact the nitrogen concentrations in Shubael Pond. Since phosphorus movement in the aquifer is relatively slower, management of phosphorus inputs to ponds generally focusses on watershed properties within 250 to 300 ft of the pond shoreline except where there are direct surface water inputs from streams, pipes, or stormwater runoff. Shoreline properties generally have phosphorus impacts on pond water quality within typical wastewater management planning horizons (*i.e.*, 20 to 30 years) whereas the impact from direct surface water inflows is immediate.

Septic system TP plumes move very slowly in sandy aquifer systems as phosphorus binds to iron coating sand particles; as these binding sites are gradually used up the phosphorus travels toward the pond. Studies of phosphorus movement in septic system plumes have shown that phosphorus movement is dependent on a number of factors, including groundwater flow rates and hydraulic conductivity, but 20 to 30 years to travel 300 ft is a reasonable planning estimate.[80] Each time a septic system leaching structure is replaced, a new TP binding site path must be utilized before there is breakthrough of wastewater TP to the pond. Given that most leachfields are replaced within a 20 to 30 year period, management of septic system TP additions focusses on leachfields within 300 ft.

The steady-state watershed nitrogen load to Shubael Pond was previously estimated in the Three Bays MEP assessment as 2,231 kg N/yr[81] and a recently completed and refined 2019 update found a nearly identical loading rate (2,160 kg N/yr).[82] These loads were based on approved MEP practices albeit with different site-specific data collected 14 years apart. MEP practices focus on obtaining parcel-specific information for each parcel in the watershed, including water use, building footprint areas, and road surface areas, and combining these with MEP nitrogen loading factors (**Table IV-3**).[83] Comparison of these watershed loads to the estimates of water column nitrogen mass indicate attenuation rates of 64% to 84% with an average of 77% based on

[78] Robertson, W.D. 2008. Irreversible Phosphorus Sorption in Septic System Plumes? *Ground Water*. 46(1): 51-60.

[79] 1 ft/d is typically used as a Cape Cod planning rate. Site-specific rates vary depending on aquifer materials and nearby waters.

[80] Robertson, W.D. 2008. Irreversible Phosphorus Sorption in Septic System Plumes? *Ground Water*. 46(1): 51-60.

[81] Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner (2006). Three Bays MEP report.

[82] CSP/SMAST Technical Memorandum. December 5, 2019. MEP Scenarios: Town of Barnstable Wastewater Plan and Land Use Updates.

[83] MEP nitrogen loading factors were reviewed and approved by MassDEP

Table IV-3. Phosphorus and Nitrogen Loading Factors for Shubael Pond Watershed Estimates. Listed below are factors used in the development of the watershed phosphorus and nitrogen loading estimates for Shubael Pond. Nitrogen loading factors are the same as those utilized in Massachusetts Estuaries Project assessments in Barnstable. Listed sources are the primary basis, but most have been confirmed by other sources and/or modified to better reflect Shubael Pond conditions in Barnstable. No lawn P load is listed due to state regulations restricting P in turf fertilizers.

Factor	Value	Units	Source
Phosphorus			
Wastewater P load	1	lb P/septic system	MEDEP, 1989
P retardation factor	25 to 37	Groundwater velocity/solute velocity	Robertson, 2008
Road, Roof and Driveway surface P load	0.61 to 1.52 + measured runoff	kg/ha/yr	Waschbusch, *et al.*, 1999 modified by P leaching + measured stormwater runoff summarized in this report
Atmospheric P deposition on pond surface	5 to 8	mg/m2/yr	Reinfelder, *et al.*, 2004.
Nitrogen			
Wastewater flow	Measured water use	Adjusted for consumptive use	Town water supply records
Wastewater N coefficient	23.63	mg/L	MEP (MassDEP-approved)
Road surface N load	1.5	mg/L	MEP (MassDEP-approved)
Road surface direct runoff N load	0.75 mg/L + Measured	kg/yr	MEP (MassDEP-approved) + measured stormwater runoff summarized in this report
Atmospheric N deposition on pond surface	1.09	mg/L	MEP; MassDEP-approved
Common Factors			
Watershed Recharge Rate	27.25	in/yr	Walter and Whealan, 2005
Precipitation Rate	44.8	in/yr	Walter and Whealan, 2005
Building Area	Measured	ft2	Town GIS
Road Area	Measured	ft2	Town GIS
Driveway Area	Measured	ft2	Town GIS

August/September (PALS) samplings over the 2001 to 2019 timeframe. Average water column TN mass over the 2020 sampling for this project (May to December) averaged 518 kg, which would be a 76% nitrogen attenuation rate. Both the MEP and the 2021 update assigned a 50% nitrogen attenuation rate to Shubael Pond.

Both the MEP and the 2021 update of watershed nitrogen load to Shubael Pond were based on the MEP USGS watershed (see **Figure IV-36**). The modified provisional watershed (see **Figure IV-37**) includes a smaller area and fewer houses. As such, it increases the pond residence time from 1.0 year to 1.8 year. The estimated unattenuated nitrogen load based on the provisional watershed is 1,332 kg/yr. Based on the measured water column TN mass, the nitrogen attenuation rate required is 78%. The relatively similar attenuation rates regardless of the watershed area used reflects that the watershed development upgradient of Shubael Pond is relatively homogenous, so even a portion of the watershed has similar areal loading. The smaller watershed and nitrogen loading balances the increase in residence time resulting in a similar attenuation rate when the modified provisional watershed is considered. Further refinement of these relationships will likely occur when all the provisional USGS data is available for public review.

In order to complete a similar review of phosphorus loading to Shubael Pond, staff had to go through the same land use analysis steps, but with a focus on phosphorus inputs to the pond instead of nitrogen. In order to develop estimates of watershed phosphorus inputs, staff began by reviewing the likely travel time for phosphorus in groundwater on the upgradient side of the lake. Review of groundwater contours in the Shubael Pond area based on historical and provisional USGS data, suggest a groundwater travel time range of 0.86 to 0.95 ft/d on the upgradient side of the lake. Measurements of phosphorus movement in septic system plumes in sandy soils have estimated it is slowed by factors of 25 to 37 compared to the groundwater flow rate.[84] Using these endpoints with the groundwater travel time resulted in estimated phosphorus movement of 0.03 to 0.04 ft/d on the upgradient, watershed side of Shubael Pond. Project staff then reviewed the watershed boundaries and parcels on both the upgradient and downgradient shorelines to assess their potential phosphorus loads. Downgradient properties were reviewed for potential direct/overland discharges or stormwater inputs (such as those from Shubael Pond Road). The refined parcel review included reviewing Town Board of Health (BOH) records for the location and age of each septic system leachfield/leaching pit compared to phosphorus travel times.[85] This review included Town Assessor records to determine the age of each house or building and determining road and building areas based on a review of aerial photographs. Lawn areas were not delineated because of phosphorus limits on turf fertilizers in Massachusetts.[86]

Staff initially identified 47 parcels that were completely or partially within the Shubael Pond MEP watershed and had phosphorus travel times with the potential to reach the pond (**Figure IV-39**). Among these parcels, 19 were in the smaller watershed delineated based on USGS provisional data and 28 were in the remaining portion of the MEP watershed. Land within the areas of these parcels included parcels without septic systems (*e.g.*, the boat landing parking lot) and road rights of way. All of the parcels within the watershed and with the potential to

[84] Robertson, W.D. 2008. Irreversible Phosphorus Sorption in Septic System Plumes? *Ground Water*. 46(1): 51-60.

[85] Completed by Town DPW staff

[86] 330 CMR 31.00

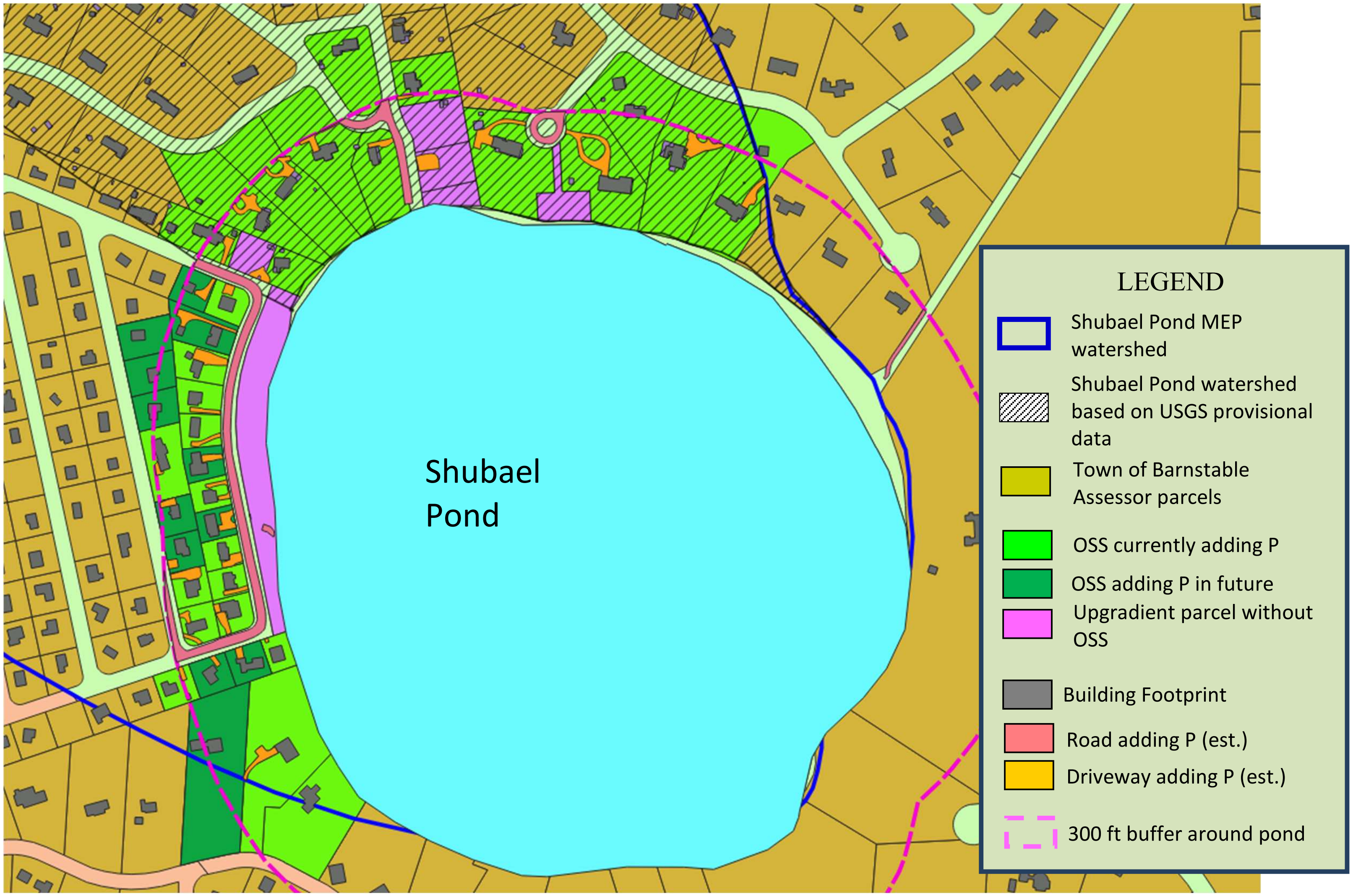

Figure IV-39. Shubael Pond Watershed Parcels Reviewed for Phosphorus Loading Budget. Project staff developed phosphorus loads from land uses within the MEP Shubael Pond watershed and a watershed based on USGS provisional data, which is a subset of the MEP watershed. These loads were developed looking at the age of on-site septic systems (OSS) and houses to gauge whether they were old enough for their phosphorus to have reached the pond. Parcels shaded bright green have OSS currently contributing phosphorus to the pond, while those shaded dark green will in the future. Staff also developed loads based on road and driveway areas (based on Town GIS coverages).

contribute wastewater phosphorus are classified by the Town Assessor as single family residences (SFRs): 13 within the small watershed and 27 within the remaining portion of the MEP watershed. Among the SFRs in the smaller watershed, the average year of construction is 1956, while in the remainder of the MEP watershed it is 1972. Based on the review of available BOH septic system records, the average age of septic system leaching structures in the smaller watershed is 42 years old, while those in the remainder of the MEP watershed are 21 years old.

Once the land use information was adequately developed, staff used phosphorus loading factors based on Cape Cod-specific, Shubael Pond-specific, and literature values to develop phosphorus loads from each source. Previous Cape Cod pond P budgets have used a septic system loading rate of 1.0 lb P/yr developed by the Maine Department of Environmental Protection for use in sandy soils (see **Table IV-3**). These reviews have confirmed that this is a reasonable factor. Review of published phosphorus loading factors have shown that annual *per capita* phosphorus loads range from 1.1 to 1.8 pounds, while sandy soil retention factors range between 0.5 and 0.9. Combining these factors together results in an annual *per capita* wastewater P load to a pond in sandy soil of between 0.11 and 0.9 lb. If one uses the Barnstable average annual occupancy during the 2010 Census (2.3 people per house),[87] the *per capita* range results in an average individual septic system P load range of 0.3 to 2.1 lbs, which has an approximate mid-point of 1 lb (0.454 kg) P per septic system per year.

Using the age of the septic systems and the distance of the leaching structures (*e.g.*, leachfields, leaching pits), staff then reviewed which of the systems were old enough to have had wastewater P discharge reaching Shubael Pond. This review found that all 13 of the SFRs adjacent to the pond within the watershed based on provisional USGS data are currently adding wastewater P to Shubael Pond, while 14 of 27 SFRs in the remainder of the MEP watershed could be adding wastewater P. Based on the travel times and septic system P loads, the overall wastewater P load to Shubael Pond from the MEP watershed was estimated to be 12.3 kg/yr, while the P load from the watershed based on provisional USGS data was estimated to be 5.9 kg/yr.

Staff also determined the road, roof, and driveway areas within 300 feet of the pond and within the two watershed configurations. All of these areas were determined based on Town GIS coverages.[88] Potential for P loads from roof runoff was determined by reviewing the age of the houses. Based on this review, all the properties in the overall MEP watershed (including all of those in the watershed based on provisional USGS data) except one were adding runoff P to the pond. Driveway and roof P loads were determined based on the GIS areas and the loading rates listed in **Table IV-3**. Loads were adjusted for P retention in the vadose zone and P leaching to the groundwater assuming that these loads are discharged to land surface. Road areas other than those directly measured (*e.g.*, the boat ramp) were treated similarly. Total impervious P loads, including the measured stormwater P loads (see section IV.B.5), to Shubael Pond from the MEP watershed was estimated to be 0.9 kg/yr, while the load from the watershed based on provisional USGS data was estimated to be 0.6 kg/yr.

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[87] https://www.census.gov/quickfacts/fact/table/barnstabletowncitymassachusetts/HSG010219#HSG010219 (Final 2020 data is not available while this is being written; accessed January 18, 2022).

[88] Town GIS coverages from J. Benoit, GIS Director

Another source of P loading to surface waters is direct atmospheric deposition to the pond surface, through both precipitation and dry deposition. The most extensive local dataset of chemical constituents in precipitation is from a station in Truro at the Cape Cod National Seashore. These results, which were collected through the National Atmospheric Deposition Program, include many factors, but did not regularly include P and samples that did include P generally had detection limits too high for accurate measurements.[89] However, the primary airflow over Cape Cod during the summer is from the southeast, which is air that was last over land in New Jersey. The New Jersey Department of Environmental Protection maintained phosphorus measurements through the New Jersey Atmospheric Deposition Network from 1999 through 2003.[90] Although data is not available to assess whether loads were modified in the passage of the air over the Atlantic Ocean, P deposition across all 10 sites in the New Jersey monitoring network was relatively consistent, varying between 5 and 8 $mg/m^2/yr$. Review of other available northeastern datasets suggests that these rates are reasonable.[91] Application of these factors to Shubael Pond resulted in an estimated range of atmospheric P loads of 1.1 to 1.8 kg/yr.

Calculation of the annual watershed P budget includes the sum of all the inputs from wastewater, roof runoff, road and driveway runoff, and atmospheric deposition to the pond surface. Using the best estimates of these loading components, the total annual external P input into the lake each year is 14.3 kg based on the MEP watershed and 7.6 kg for the watershed based on USGS provisional data (**Figure IV-40**). The primary source of watershed P load to Shubael Pond from either watershed is wastewater from septic systems: 86% of the MEP watershed load and 77% of the load from the watershed based on USGS provisional data. Adjusting these masses to the reflect the respective water residence times of the pond results in an estimated water column P mass of 14.9 kg for the MEP watershed and 13.7 kg for the watershed based on USGS provisional data. Both of these estimates closely approximate water column TP mass based on water quality sampling data given the potential variation in time of travel, precipitation, etc. Water column data in early spring or winter (*i.e.*, without significant contributions of sediment regeneration) are somewhat limited, but the average water column TP mass based on five 2020 estimates from May and December was 14.6 kg.

Review of the 2020 sediment incubation data estimated that another 2.3 kg TP was added to the water column during the summer from the sediments (see section IV.B.4). This evaluation was based on reviewing the sediment core incubation data and the length of time sediments at each depth were exposed to anoxic conditions between June and November. Review of 2020 water quality data between June and October showed that the amount of TP in the water column varied between 14.6 kg and 21.8 kg and averaged 18.1 kg (n=5). Adding 2.3 kg to the watershed TP loads estimated for the MEP watershed and the watershed based on USGS provisional data equal 17.2 kg and 17.8 kg, respectively. Based on these comparisons, the modeled estimated loads are in a reasonable balance with the measured water column TP mass.

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[89] Gay, F.B. and C.S. Melching. 1995. Relation of Precipitation Quality to Storm Type, and Deposition of Dissolved Chemical Constituents from Precipitation in Massachusetts, 1983-85. U.S. Geological Survey, Water Resources Investigation Report 94-4224. Marlborough, MA. 87 pp.

[90] Reinfelder, J.R., L.A. Totten, and S.J. Eisenreich. 2004. The New Jersey Atmospheric Deposition Network. Final Report to the NJDEP. Rutgers University, New Brunswick, NJ. 174 pp.

[91] Vet, R. *et al*. 2014. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. *Atmospheric Environment*. 93 (2014): 3-100.

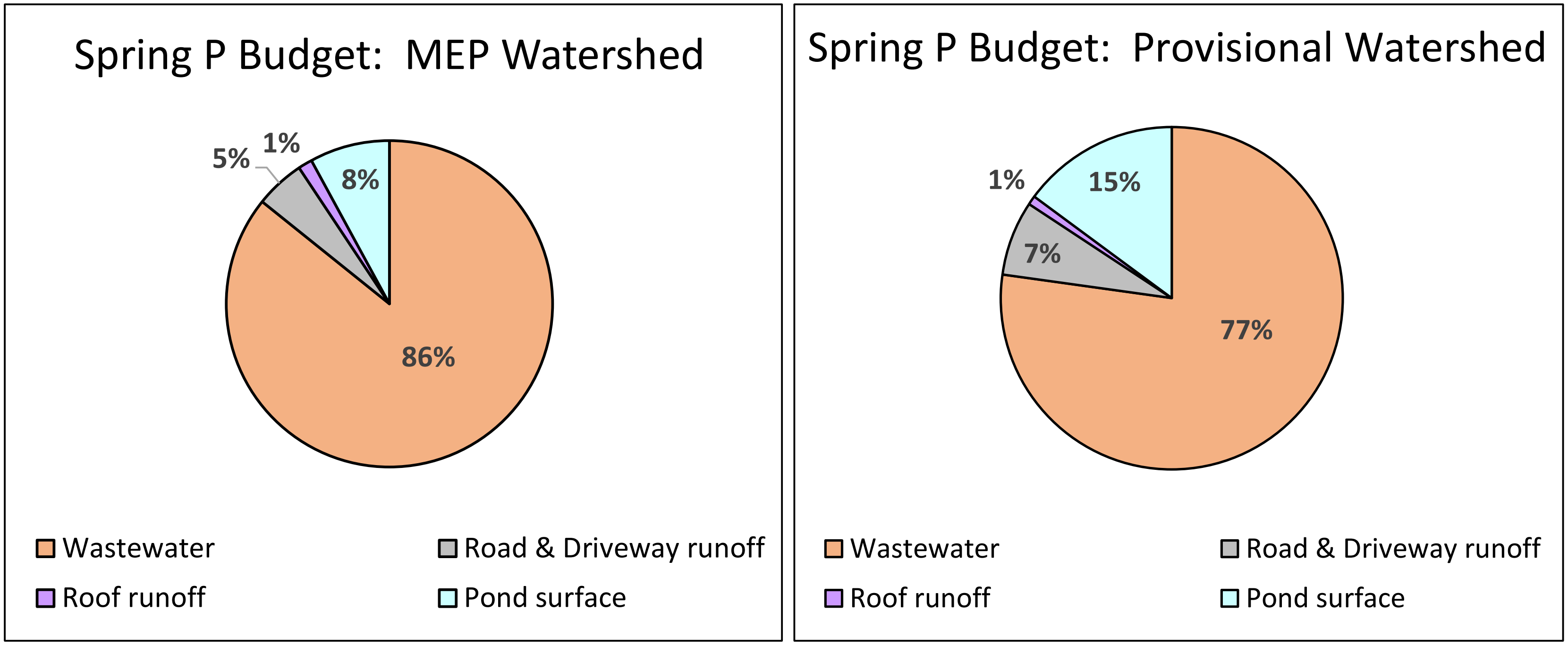


Figure IV-40. Comparison of Spring Watershed Phosphorus Sources to Shubael Pond. Watershed TP loads to Shubael Pond were determined from watershed/groundwater inputs from: septic systems/wastewater, stormwater runoff from nearby roofs and roads (roads were based on measurements collected at the Shubael Pond Road overflow), and direct deposition on the pond surface through precipitation and dry fall. Loading factors were based on review of literature values, as well as Shubael Pond and Barnstable-specific factors. Key factors, such as travel time of P in groundwater and age of houses vs. age of septic system leachfields were also determined and reviewed to assess the variability of loading estimates. Spring loading estimates for the MEP watershed and the watershed based on USGS provisional data were comparable to the average TP water column mass based on available May and December measurements: MEP watershed mass was 14.3 kg/yr, while the watershed based on USGS provisional data was 7.6 kg/yr. Adjusting both for the respective residence time of water in the pond resulted in similar water column mass estimates: 14.9 kg and 13.7 kg, respectively. In both watershed estimates, wastewater P from septic systems is the predominant source of watershed P to Shubael Pond.

Overall, the watershed P loading estimates show good agreement with measured water column TP in April, which is consistent with summer additions being largely from sediment regeneration. Sediment interactions with the water column show both uptake and release of TP depending on the depths of aerobic and anaerobic conditions. Sediment P additions are more prominent in the summer (*e.g.*, in 2020, the peak water column TP mass was in the July 15 profile). The average summer TP budget based the review of the MEP watershed, the watershed based on the USGS provisional data, and sediment core incubation results has a reasonable balance with the water column measurements (**Figure IV-41**). TP loads from septic systems are the primary source of P to the Shubael Pond water column and, thus, are the key for managing water quality in the pond.

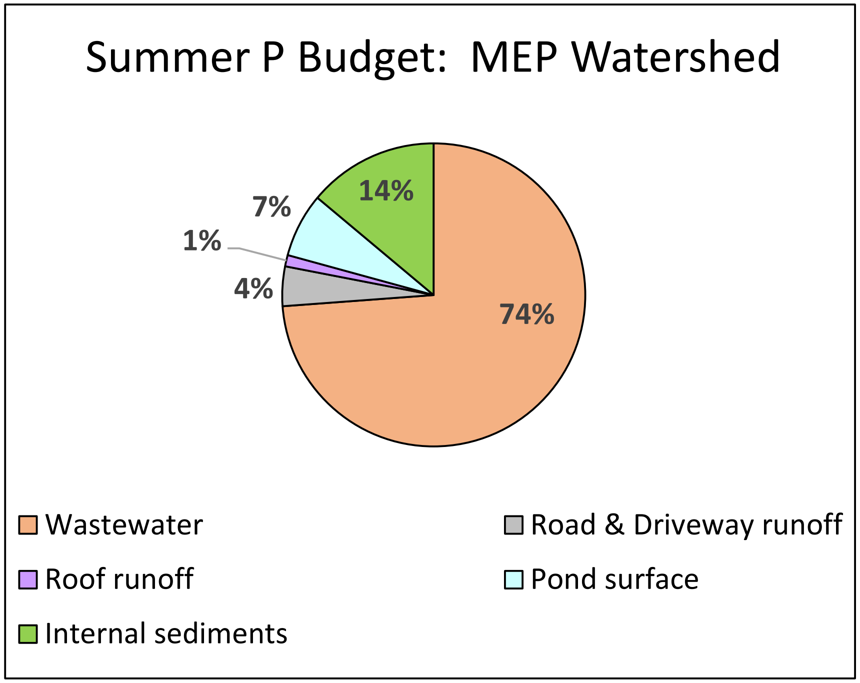
IV.D. Shubael Pond Diagnostic Summary

Shubael Pond is a 56-acre Great Pond located in the village of Marstons Mills in the Town of Barnstable. The pond is located approximately 450 m south of Race Lane and approximately 470 m east of Route 149/Cotuit Road. The pond has been sampled 13 times during the August/September PALS Snapshot, but had not been sampled throughout the summer until the 2020 sampling completed in support of this management plan. Sampling during 2020/2021 was completed by School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) staff and included water quality samples and profiles collected 10 times during 2020. CSP/SMAST staff also completed a number of 2020 pond-specific data gap surveys to provide additional context for water column measurements and a more refined basis for development water quality management strategies. Surveys included measurement of sediment nutrient regeneration, continuous measurement of water column conditions, stormwater discharge measurements, and review of the watershed and development of phosphorus and water budgets. Review of all the collected data, both historic and 2020/2021 data gap surveys results, supports the following key conclusions:

- The 2021 bathymetric survey found that Shubael Pond has a maximum depth of 13 m and a total volume of 1,098,269 cubic meters.

- A previously completed watershed delineation by the US Geological Survey (USGS) as part of the Massachusetts Estuaries Project (MEP) assessment of Three Bays showed that the watershed to the pond is 262 acres. However, a current USGS project has collected unpublished provisional groundwater data in the Shubael Pond area that suggests that the watershed area should be reduced and the delineation reoriented. Project staff used this recent information to delineate a smaller 114 acre provisional watershed. Staff used both the MEP and the smaller watershed to consider the water quality data collected in the pond.

- The water budget for the lake showed that groundwater discharge is the primary source of incoming water regardless of the selected watershed (69% for the MEP watershed, 52% for the watershed based on USGS provisional data). Water flowing out of the pond also primarily flows back into the groundwater system (91% for the MEP watershed, 84% for the watershed based on USGS provisional data). Based on the MEP watershed, the average residence time of water in the pond is approximately 1.0 year compared to 1.8 years based on the watershed based on USGS provisional data.



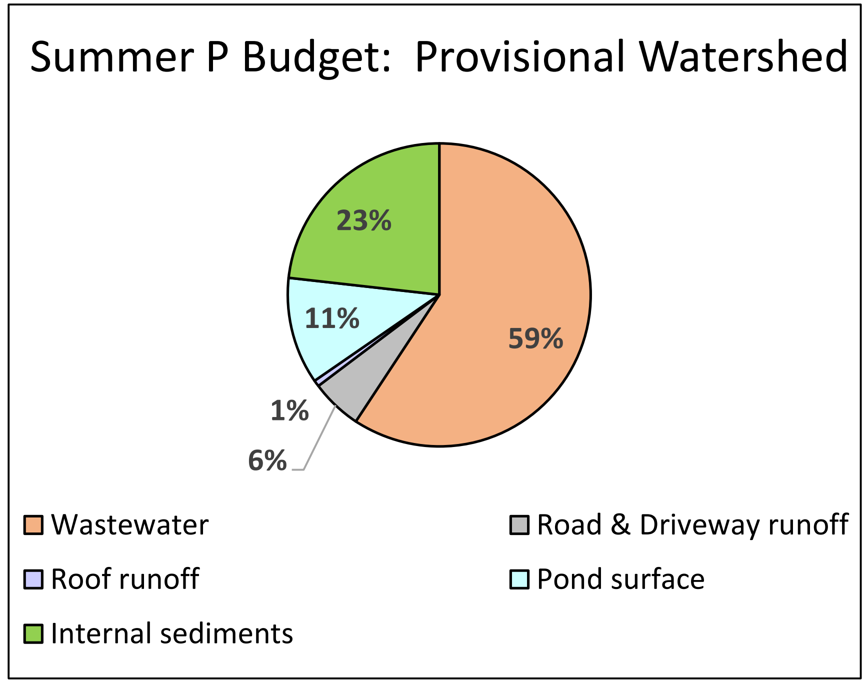


Figure IV-41. Comparison of Overall Summer Phosphorus Sources to Shubael Pond. During the summer, sediments in Shubael Pond create anoxic conditions that cause the release of accumulated P from pond sediments to the water column. Based on the review of sediment core incubation and persistence of water column anoxia, the sediments added 2.3 kg of P to the water column in 2020. Average estimated summer water column TP with the 2.3 kg of regenerated P was 17.2 kg based on the MEP watershed loading and 17.8 kg for the watershed based on USGS provisional data. Average estimated water column TP mass between June and October based on profile samples was 18.2 kg. These water column mass estimates are in reasonable agreement with the Shubael Pond measurements. Collectively, these readings show that the primary source of water column TP in Shubael Pond in summer is P from septic systems near the pond, same as it is during the spring. Summer sediment additions to the water column account for 14% to 23% of the overall P budget depending on which watershed is considered. These comparisons show that septic systems are the primary Shubael Pond P source in both the MEP watershed and the watershed based on USGS provisional data.

- Review of temperature profiles showed that the pond typically has temperatures cold enough to support a cold water fishery throughout the year, but the deep cold waters are impaired by anoxia and hypoxia throughout the summer. During 2020 measurements from May through December, anoxia was first measured at 12 m in June and then at progressively shallower depths in each subsequent monthly profile through September (9/17 profile had anoxia at 8 m depth). The late October profile (10/27) had anoxia at 11 m. During 2020, thermal layering (*i.e.*, stratification) was also first measured in June and persisted through September. Continuous DO readings at 6 m showed that DO concentrations were less than the MassDEP regulatory dissolved oxygen minimum (6 mg/L) in between profile readings (*i.e.*, from mid-August until mid-September). PALS Snapshot data from 2001 through 2020 had average August/September conditions that failed to meet MassDEP regulatory dissolved oxygen minimum (6 mg/L) from 7 m to the bottom.

- Comparison of total phosphorus (TP) and total nitrogen (TN) concentrations throughout the year showed that TP controls water and habitat quality conditions in the pond and, therefore, its control should be the primary focus for water quality management. Deep TP and TN concentrations in 2020 increased by more than 2X during the summer. Average shallow TP concentration during 2020 was 13.5 µg/L (>10 µg/L TP Ecoregion threshold), while the average 2020 deep TP concentration was twice as high, 26.6 µg/L. PALS Snapshot data from August/September 2001 to 2020 showed regular impacts of summer sediment regeneration with a gradient of increasing TP concentrations with increasing depth. Shallow TP samples from the PAL dataset showed a statistically significant increasing trend from 2001 to 2020.

- Water quality measures complementary to nutrient concentrations also showed impaired conditions due to the impacts of high TP levels. More than 80% of shallow chlorophyll a concentrations in the PALS dataset from August/September 2001 to 2020 exceeded the ecoregion threshold (1.7 µg/L). Pigment concentrations (chlorophyll + phaeophytin) showed high deep concentrations consistent with transfer of dead and senescent phytoplankton and their accompanying nutrients to the sediments. Secchi clarity readings in 2020 decreased from an average of 6.8 m in May/June to a minimum of 2.6 m in August. Continuous readings of dissolved oxygen at 10 m depth were anoxic until mid-October. A 2020 survey showed that mussels were extensive to approximately 8 m (the shallowest depth of regular anoxia), but were generally absent in deeper waters. This is a pattern seen in other Cape Cod ponds with mussels and regular anoxia.

- Review of the phosphorus sources to the Shubael Pond found that watershed septic systems were the predominant source of phosphorus measured in the water column. Review of the MEP watershed and the watershed based on USGS provisional data found that septic system phosphorus was 86% and 77% of the respective phosphorus mass reaching the pond excluding summer sediment regeneration additions. This review included estimates for driveway and roof runoff, precipitation on the pond surface, direct stormwater runoff based on site-specific measurements. Review of septic system ages and distance to the pond shoreline showed that 13 single family residences (SFRs) are contributing phosphorus to the pond from the watershed based on USGS provisional data and another 14 SFRs (27 total) were contributing to the pond based on the MEP watershed. An additional 13 SFRs in the MEP watershed were close enough to the pond that they will eventually contribute phosphorus to the pond once the septic system phosphorus plumes complete the travel time from the leaching structure (*e.g.*, leachfield) to the pond.

- Review of sediment core measurements compared to water column measurements showed that summer sediment contributions to the water column reduced the septic system share, but watershed septic systems remained the predominant source of phosphorus to the pond throughout the summer. During the summer, watershed septic systems contributed 74% of the phosphorus in the water column on average when the MEP watershed was considered and 59% of the phosphorus load based on the watershed based on USGS provisional data.

- The good match between estimated phosphorus sources and measured phosphorus in the water column provides a reliable basis for predicting water quality changes under different phosphorus reductions and for developing management strategies for pond restoration.

V. Shubael Pond Water Quality Management Goals and Options

Shubael Pond is impaired based on comparison of water quality monitoring results to both ecological and regulatory measures, as noted in the Diagnostic Summary above. Impairments occur throughout the water column and impact a variety of habitats and pond uses. Review of available water quality data clearly identifies phosphorus control as the primary path to improving water and habitat quality throughout Shubael Pond. Identified impairments in Shubael Pond include:

a) regular deep water dissolved oxygen concentrations less than the Massachusetts regulatory minimum,
b) degradation and complete loss of the deep cold water fishery habitat due to hypoxia and anoxia,
c) shallow water phosphorus and chlorophyll concentrations greater than Cape Cod Ecoregion thresholds,
d) enhanced sediment phosphorus regeneration with bottom water anoxia during the summer,
e) freshwater mussel habitat impaired by bottom anoxia, and
f) loss of water clarity during the summer (>4 m in 2020).

Review completed through the Diagnostic Summary showed that wastewater phosphorus from the lake watershed is the largest source of phosphorus to Shubael Pond during both the spring and summer. Wastewater phosphorus from septic systems in the Shubael Pond watershed is 86% or 77% of the phosphorus entering the pond during the spring depending on whether the MEP watershed or the watershed based on provisional USGS data is used, respectively. Summer sediment P release reduces these percentages of the overall P budget (to 74% and 59%, respectively), but wastewater phosphorus remains the primary source of P to Shubael Pond. These analyses show that reducing wastewater phosphorus is a key component to removing the Shubael Pond impairments, but also show that defining the watershed areas where the wastewater comes from and the likely timing and cost of wastewater solutions will also require some consideration. Temporary management steps may also need to be considered if implementation of wastewater solutions require five or more years to complete.

Management actions to restore water quality generally have two components: 1) identification of target water quality conditions in the pond that need to be attained to remove impairments and 2) implementation of management actions to attain the water quality targets. As discussed above, MassDEP surface water regulations generally rely on descriptive standards for evaluating water quality, although there are a limited set of numeric standards for four factors: dissolved oxygen, temperature, pH, and indicator bacteria.[92] These regulations work in tandem with the TMDL provisions of the federal Clean Water Act, which requires the Commonwealth to identify impaired waters (*i.e.*, water bodies failing to attain state water quality standards) and develop water body-specific targets to restore them to acceptable conditions. Since Shubael Pond is on MassDEP's most recent list of waters without any impairments or a completed assessment, the Town has the opportunity to define the TMDL and set the management goals that will attain the TMDL.

Since this is a draft management plan, project staff reviewed potential options that apply to the impairments in Shubael Pond, but will help select a final strategy following feedback on the draft. Final recommended options will be developed and incorporated into a final plan through

[92] 314 CMR 4.00 (CMR = Code of Massachusetts Regulations)

public discussions and with input from appropriate stakeholders before implementation schedules are discussed.

The following potential management options are based on the consideration of the data and pond ecosystem characterization discussed in the Diagnostic Summary and puts forward the most applicable management options that will restore appropriate water quality conditions in Shubael Pond and allow the Town to attain regulatory compliance.

V.A. Shubael Pond TMDL and Water Quality Goals

As documented above, Shubael Pond has impaired conditions throughout its water column, although the nature of the impairments differs with depth. Shallow waters lose significant clarity during the summer and have average total phosphorus and chlorophyll a concentrations above Ecoregion thresholds, but maintain acceptable dissolved oxygen concentrations. Deep waters are anoxic at the bottom and this anoxia rises to shallower depths as the summer progresses. In addition, waters 7 m and deeper have average dissolved oxygen concentrations less than the MassDEP regulatory minimum threshold of 6 mg/L. These deep waters have temperatures cold enough that they meet MassDEP criterion for cold water fisheries, but the summer hypoxia and anoxia essentially eliminate this in-pond habitat. Trend analysis of shallow TP concentrations show that they are steeply increasing (+0.62 µg/L/yr) between 2001 and 2020. These increasing TP concentrations are likely due to increasing summer sediment regeneration and breakthrough of existing watershed septic system plumes.

Low dissolved oxygen concentrations in ponds and lakes are generally due to excessive plant/phytoplankton growth caused by nutrient additions. Bacterial decay of excessive plant growth prompts sediment oxygen demand greater than the combined DO additions from atmospheric resupply by water column mixing and photosynthetic DO production. In ponds that thermally stratify in summer (like Shubael Pond), the deep, cold layer is isolated from atmospheric oxygen resupply and photosynthesis is reduced by reduced light penetration, so the impacts of sediment oxygen demand are exacerbated. Effectively reducing excess nutrients addresses the low dissolved oxygen conditions by reducing organic matter deposition to sediments and sediment oxygen demand while also increasing water clarity.

Setting nutrient TMDL targets for restoration of pond impairments is generally based on establishing a set of water quality and ecosystem conditions from available data in the pond of interest and/or by comparing that pond to similar types of water bodies in similar settings. The largest set of Cape Cod TMDLs are those based on the Massachusetts Estuaries Project (MEP) assessments of estuarine waters and the MEP assessment process provides some insights into what MassDEP and USEPA consider acceptable TMDL development for freshwater ponds in Massachusetts. The MEP technical team utilized a multiple parameter approach for the assessment of each waterbody that included measurement and review of a) historic and current eelgrass coverage (eelgrass functions as a keystone species in Cape Cod estuaries), b) benthic animal communities (invertebrates living in estuaries provide the primary food source for most of the secondary consumers[93]), c) water quality conditions, including nitrogen concentrations (nitrogen is the generally the nutrient controlling water quality conditions in estuaries), dissolved oxygen, and chlorophyll (*e.g.,* phytoplankton biomass), and d) macroalgal accumulations that impair benthic habitat. For regulatory purposes, the MEP team generally selected a monitoring location (or locations) within each estuary where attaining a selected nitrogen concentration

[93] Fish and birds

should restore water conditions throughout the system based on a review of all the collected system data and modeling and this was incorporated into the resulting nitrogen TMDLs. It was recognized that this relatively straightforward approach would require confirmatory direct assessments of key ecological components (eelgrass and benthic communities), but this approach provided a short-hand regulatory goal that could be used by towns and regulators for nitrogen management planning and assessing progress toward restoring water and habitat quality.

Development of freshwater pond TMDLs in Massachusetts has been limited with only one completed within the Cape Cod Ecoregion over the past 10 years and none completed on Cape Cod. During the development of the Cape Cod PALS program, the initial 2001 PALS Snapshot data were reviewed with a USEPA nutrient criteria method to determine that an appropriate total phosphorus concentration for Cape Cod ponds was between 7.5 to 10 µg/L.[94,95] It was recognized at the time of this Ecoregion threshold that selection of this criteria would also require consideration of other measures such as dissolved oxygen and chlorophyll concentrations, the physical characteristics and setting of each individual pond, and the role of sediment nutrient regeneration. Subsequent review of individual Cape Cod ponds has shown that some ponds may be more sensitive to phosphorus additions and become impaired at TP concentrations lower than this initial range.

Review of 2001-2020 shallow TP concentrations in Shubael Pond showed that late summer TP concentrations were initially below the Ecoregion threshold, but have risen well above the threshold in recent years. Initial PALS Snapshot data in August/September 2001-2003 were generally less than 5 µg/L, but recent data (2018-2020) averaged >15 µg/L. In addition, average TP concentrations at each regularly sampled deeper depth increment (*i.e.*, 3 m, 9 m, etc.) are well above the Ecoregion threshold and rise to >4X the threshold at the deepest depth (11 m), consistent with deep water summer sediment regeneration and anoxia. The TP concentrations collected throughout 2020, the only year with summer-long sampling, showed that shallow TP concentrations rose from 10.2 µg/L, or the Ecoregion threshold, in May to 16.3 µg/L in July and August. This pattern shows high TP concentrations are regularly available to the phytoplankton population throughout the summer making the pond susceptible to algal blooms in response to a large, rapid TP input from existing sources, such as a large storm with associated runoff or larger sediment regeneration input due enhanced anoxia from prolonged quiescent conditions with cloudy days.

In order to review potential management strategies, CSP/SMAST staff selected 11 kg TP as an appropriate initial water column mass target for achieving restoration and as a potential phosphorus TMDL for Shubael Pond. This goal was selected to ensure acceptable TP, chlorophyll and DO concentrations throughout the year and was largely informed by review of May and December 2020 sampling results in Shubael Pond and past PALS Snapshots with acceptable conditions. This mass is roughly equivalent to 10 µg/L TP throughout the water column, so it is a higher concentration than shallow concentrations measured in 2001-2003 (avg = 4.6 µg/L TP). Since most of the historical data is late summer PALS Snapshot data, the 2020 data is the only basis for evaluating unimpaired conditions in spring or the majority of the summer. Among the 2020 data, December 7 sampling was the only TP water column estimate

94 Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas.

95 10 µg/L was also a reasonable TP criterion based on Ecoregion data gathered by USEPA (limited data was available on Cape Cod prior to PALS sampling snapshots)

that was less than 11 kg. Given the limits on available data, the 11 kg TP threshold could be modified as additional water quality data is collected, but is the best available at this time.

V.B. Potential Management Options: Watershed and In-Pond Controls

Water quality management options for ponds and lakes typically are divided among those that address watershed phosphorus inputs and those that address in-pond inputs and/or characteristics. Options include treatments to prevent phosphorus additions and/or treatments to remove phosphorus once it is in the pond. Consideration of each pond's individual details help to select the best options for its characteristics. As noted for Shubael Pond, the watershed septic system loads are the primary phosphorus source and the source most responsible for its water and habitat quality impairments. As a result, phosphorus will be the primary focus of management strategies, but staff also reviewed other strategies to help stakeholders understand other options and their potential to address water and habitat quality impairments in Shubael Pond.

The review of management options in **Table V-1** incorporated the results from the Shubael Pond Diagnostic Summary above and, based on the lake-specific characteristics, this review found that watershed wastewater P reduction is the primary applicable option for water and habitat quality management in Shubael Pond. This option has a number of issues to resolve including: 1) the type of wastewater technology (*e.g.*, sewering or somewhat experimental phosphorus reducing septic systems), 2) the area where wastewater should be treated based on the watershed delineation differences, and 3) the likely timing for addressing this issue. The details of the options for managing wastewater P reductions are discussed below.

On the question of timing, other management options may provide inadequate reduction to restore the system, but implementation could slow the decline in water and habitat quality conditions if planning for wastewater solutions is going to take a number of years. Most of these actions are in-lake management techniques that will address the 14 to 23% of the summer water column P load. The other one is a stormwater treatment option that will address 4 to 7% of the summer water column P load. These options could also be combined with wastewater reduction options if only partial wastewater action is pursued. Each of these partial, temporary options are discussed below. Partial applicable options are:

a) In-pond P control: Hypolimnetic Aeration (addition of air/oxygen) to create sufficient bottom water oxygen concentrations to favor chemical binding of sediment P within surficial sediments and reduce sediment P regeneration and directly sustain acceptable DO concentrations, system would need to be run forever,
b) In-pond P control: Dredging of sediments to remove sediment P regeneration source from the lake,
c) In-pond P control: Phosphorus Inactivation/Alum Treatment (addition of aluminum salt mix) to permanently bind available P within the sediments, reducing regeneration to the water column, and
d) Enhanced stormwater treatment (additions to Shubael Pond Road stormwater system).

Table V-1 also includes a review of a number of additional lake management techniques that are not applicable. These are techniques that do not address the water quality problems in Shubael Pond, have no track record in Massachusetts or Cape Cod, and/or are experimental due to few or no field studies evaluating: a) their efficiency of lowering P levels, b) their ecosystem impacts, c) their general lack of use under New England and Massachusetts conditions, and/or d) regulatory hurdles to be overcome for their implementation.

Table V-1a. **WATERSHED PHOSPHORUS LOADING CONTROLS: Address watershed sources of phosphorus entering the pond, typically: a) septic system phosphorus discharges from properties adjacent the pond, b) road runoff from stormwater, and c) excess fertilizers from lawn or turf applications. Other additions can occur from pond-specific sources, such as streams, connections to other ponds or ditches/pipe connections to areas outside of the watershed. Since phosphorus is typically bound to iron rich, sandy aquifer soils on Cape Cod, phosphorus movement through groundwater tends to be very slow (estimated 20-30 yrs to travel 300 ft), so watershed controls in these settings typically focus on sources within 300 ft of the pond shoreline or a stream discharging to the pond.**					
OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Wastewater P reductions	• Sewering • Alternative Septic Systems • Septic Leachfield Setbacks • Septic Leachfield Replacement or Movement • PRBs (Iron)	• Addresses watershed wastewater P source • Can be implemented with a range of costs to homeowners and at time of property transfer • Can control other wastewater contaminants	• May have high individual property cost and/or community cost • May involve lag time for implementation and for benefits to be realized due to groundwater flow rates • May not solve all WQ impairments • PRBs will involve shoreline habitat disruptions	• Brewster BOH septic leachfield setback regulation • Some Town preliminary sewer plans include properties around ponds	Applicable: wastewater is largest P source in overall lake P budget under spring (77% to 86%) and summer (59% to 74%) conditions
Fertilizer P reductions	• Restrict P in lawn fertilizers (done under Mass law) • Restrict lawn areas • Require natural buffers near pond with limited paths/use of non-fertilized landscaping	• Relatively straightforward • Can be simple as adjusting landscaping • Requires no infrastructure funding	• Changing the landscaping paradigm can be difficult • May involve lag time for benefits to be realized due to groundwater flow • May not solve all water quality impairments	• State P fertilizer regulations (330 CMR 31): use of P only for turf establishment; 10-20 ft setback	Applicable, but already implemented: state regs limit P for residential uses
Stormwater P reductions	• Remove or infiltrate direct discharge • Recharge outside of watershed, 300 ft buffer • Runoff treatment using BMPs	• Rerouting discharge or infiltration usually relatively straightforward • Removes P source • DPWs usually have stormwater repair funding on hand • Removes other contaminants *e.g.*, Bacteria, TSS, metals	• Does not solve all water quality impairments	• Not specifically done for ponds in the past, but is now being discussed in many MA municipalities	Applicable: Direct discharges are only 4 to 7% of the overall load; Shubael Pond Rd system is the largest source and could be retrofitted to create further reductions

Table V-1b. IN-LAKE PHYSICAL CONTROLS: Address phosphorus or plant growth by changing water or sediment conditions within the pond. These types of *in situ* treatments typically move large volumes of pond water (adding or subtracting) to change concentrations, removing sediments to create greater volume and remove the sediment P source or physical removal/limitation for plant growth. Some of these techniques are difficult to implement in Cape Cod settings due to hydrogeology.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Enhanced Circulation (shallow ponds), Destratification (deeper ponds)	• Use of water or air to keep water column vertically well mixed • typically used in shallow ponds with weak stratification	• Uses mixing of atmospheric source of oxygen to address sediment oxygen demand • Additional oxygen reduces sediment P release • Prevents oxygen stratification • May disturb blue-green growth	• May spread high nutrients and oxygen demand to rest of water column with improper design • Will destroy cold water habitat in Shubael Pond; may not be permittable • Variable success • Needs power	• Santuit Pond, Mashpee & Skinequit Pond, Harwich (Solar Bees) • Flax Pond, Harwich (Living Machine)	<u>Not Applicable</u>: disrupting stratification would eliminate cold water fishery
Dilution, Decreased residence time	• Add water to pond	• Increased flushing • Can add treatment additives	• Need to find source outside of watershed • May create undesirable ecosystem impacts on plankton	• Mostly a hard geology/stream fed solution; need water source	<u>Not applicable</u>
Drawdown	• Lower water level increases water column atmospheric mixing • Oxidation of exposed sediments	• May provide rooted plant control • May reduce nutrient availability • Opportunity for shoreline cleaning	• Negative impact on desirable species (can affect fish spawning areas) • Difficult or impossible in sandy aquifer settings	• Mostly a hard geology/stream fed solution (limited dewatering at Ashumet Pond was very difficult)	<u>Not applicable</u>

Table V-1b (continued). IN-LAKE PHYSICAL CONTROLS: Address phosphorus by changing water or sediment conditions within the pond. These types of *in situ* treatments typically move large volumes of pond water (adding or subtracting) or remove sediments to create greater volume and remove the P source. Some of these techniques are difficult to implement in Cape Cod settings due to the sandy aquifer conditions.

OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Dredging of sediments	• Removal of P with sediments • Wet or dry excavation • Hydraulic dredging (all require dewatering area and disposal site)	• Reset/renovation of ecosystem through removal of accumulated nutrients • Increases water depth • Reduces sediment oxygen demand • Reduces sediment nutrient regeneration	• Disturbs benthic community • Dry excavation (draining pond) removes fish population • Downstream impacts of dewatering area • Disposal of sediments • Duration of benefits may be short in ponds with large watershed inputs • Typically expensive	• Usually reviewed but not implemented due to high cost • Current discussion for Mill Pond, Barnstable in order to deepen filled basin (not P control)	<u>Applicable</u>: but sediments are only 14% to 23% of summer water column P; would not attain P restoration target without other management activities; would have number of issues to resolve if pursued (*e.g.*, add'l sediment characterization, selection of dewatering/disposal areas, etc.)
Dyes and surface covers to restrict plant growth	• Create light limitation to restrict phytoplankton or rooted plant growth through physical means (surface cover) or light absorption (dyes)	• Opaque surface covers may be removed or reset • Dyes may produce some control of rooted plants depending on concentration	• May exacerbate anoxia (limits plant oxygen production) • Dye may not adequately address surface phytoplankton	• Mystic Lake, Barnstable (benthic barriers use part of strategy to control hydrilla)	<u>Not applicable</u>; does not address P additions and may increase available P in the pond via plant die off
Mechanical removal of plants	• Pumping and filtering of water • Suction dredging • Surface skimming • Contained growth vessels • Harvesters	• Growth approaches utilize natural plant growth followed by harvest to reduce nutrients and biomass	• Need dewatering for many options • Plant growth/regrowth monitoring required • Impact on other biota may be a concern • Can spread coverage depending on impacted species	• Mystic Lake, Barnstable (hand pulling, suction dredging as part of hydrilla strategy) • Walkers Pond, Brewster (use of harvester) • Mill Pond Falmouth	<u>Not applicable</u> (primary P source are watershed sources)

Table V-1b (continued). IN-LAKE PHYSICAL CONTROLS: Address phosphorus by changing water or sediment conditions within the pond. These types of *in situ* treatments typically move large volumes of pond water (adding or subtracting) or remove sediments to create greater volume and remove the P source. Some of these techniques are difficult to implement in Cape Cod settings due to the sandy aquifer conditions.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Selective Withdrawal	• Remove deep, near-sediment water • Generally done for deep thermally stratified ponds	• Removes impaired waters and highest nutrient waters • May address low oxygen/sediment demand	• Treatment and disposal of water required • May mix high nutrients into upper water column (and prompt blooms) • May increase suspension of sediments, increase turbidity • Balance between withdrawal and replenishment may be difficult to achieve (drawdown/warming)	• None	Applicable: but significant challenges because of lack of use in unconfined aquifers (like Cape Cod); decrease in water residence may increase watershed inputs
Sonication	• Use of low level sound waves to disrupt phytoplankton cells	• Harms blue green phytoplankton (causes leakage of cells that control buoyancy) • Usually coupled with aeration or circulation	• Non-target impacts not well characterized • Mostly lab applications, limited field applications data • May release blue green toxins into water	• none (no scientific studies)	Not applicable (experimental); would likely have significant regulatory hurdles; phytoplankton levels generally low

Table V-1c. IN-LAKE CHEMICAL CONTROLS: Address phosphorus or low oxygen by addition of chemical(s) that alter water conditions to either provide oxygen and/or bind phosphorus. These types of *in situ* treatments typically require some sort of delivery system into the pond water column and generally include pond water quality management techniques that have been used most frequently.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Aeration (non-stratified shallow ponds)	• Addition of air or oxygen to address sediment oxygen demand (SOD) and to lower P release	• Prevents low bottom water DO • Additional oxygen reduces sediment P release • Restores natural levels, so should have no negative ecosystem impacts	• May require structure and equipment on pond shore • Poor design of aerator may resuspend sediments and increase P availability • Needs power	• Lovell's Pond, Barnstable • Mill Pond, Falmouth	Not Applicable: Hypolimnetic aeration applicable
Hypolimnetic aeration or oxygenation (applies to ponds with well-defined stratification)	• Add air or oxygen to address deep layer hypoxia while maintaining thermal layering/ stratification • Some alternatives remove water, treat, then return	• Higher oxygen concentrations keep phosphorus in sediments • Higher oxygen keeps other compounds in sediments • Higher oxygen in lower layer provides more diverse cold water habitat and supports cold water fishery	• Potential to disrupt stratification/degrade cold water fishery • Potential to mix nutrient rich bottom waters into upper layers • Could result in super-saturation, which may harm sustainable fish population • Likely to require use every year with long-term maintenance of aeration system	• none	Applicable: But will only address a maximum of 14% to 23% of summer water column P
Algaecides	• Add herbicide to kill phytoplankton • Can be applied in targeted area (use of booms/curtains) • Types include: copper, peroxides, synthetic organics	• Removal of phytoplankton from water column will improve clarity • Dying, settling phytoplankton may transfer large portion of nutrients to sediments	• Restricted use of water during summer • Potential impact on non-target species and accumulation concerns for copper/ organics • Increased oxygen demand from settling phytoplankton; greater release of sediment nutrients • May have to be used each year or multiple times during summer season • Synthetic organics may have daughter compounds with persistent toxicity	• none	Not applicable; does not address P additions and may increase available P in the pond

Table V-1c (continued). IN-LAKE CHEMICAL CONTROLS: Address phosphorus or low oxygen by addition of chemical that alter water conditions to either provide oxygen and/or bind phosphorus. These types of *in situ* treatments typically require some sort of delivery system into the pond water column and generally include pond water quality management techniques that have been used most frequently.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Phosphorus inactivation	• Addition of aluminum, iron, calcium or other salts or lanthanum clay to bind phosphorus and remove its biological availability to phytoplankton (choice depends on pond water chemical characteristics) • Bound P complexes settle to sediments • Can be added as liquid or powder • Can be applied in targeted area (use of booms/ curtains or careful application)	• Can reduce water column P concentrations and phytoplankton population • Can minimize future sediment P regeneration • Single application can be effective for 10-20 years • Removal of phytoplankton from water column will improve clarity • Can minimize regeneration of other sediment constituents • Variety of application approaches both in timing, dosing, areal distribution, and depth • Can reduce sediment oxygen demand and low water column DO • No maintenance • Significant experience on Cape Cod for permitting and use	• Persistent anoxia may reduce P binding for some additions (*e.g.*, Fe) • pH must be carefully monitored during aluminum application; mix of alum salts addresses potential low pH toxicity during application • Cape Cod ponds already have low pH; potential toxicity for fish and invertebrates, related to low pH • Possible resuspension of floc in shallow areas in areas with high use • May need to be repeated in 10 to 20 years if not paired with watershed P source reduction	Alum applications: • Hamblin Pond, Barnstable: 1995, 2015 • Long Pond, Harwich/Brewster: 2007 • Mystic Lake, Barnstable: 2010 • Lovers Lake, Chatham: 2010 • Stillwater Pond, Chatham: 2010 • Ashumet Pond, Mashpee/Falmouth : 2011 • Herring Pond, Eastham: 2012 • Great Pond, Eastham: 2013 • Lovell's Pond, Barnstable: 2014 • Cliff Pond, Brewster: 2016 • Uncle Harvey's Pond, Orleans, 2021	Alum application: applicable: but will only address a maximum of 14% to 23% of summer water column P; may have mussel permitting issues Iron application: not applicable: sufficient iron generally exists, low DO negates use Calcium application: not applicable: generally used in waters where pH ≥ 8 Lanthanum application: not applicable: concerns about biotoxicity, bioaccumulation, especially in low pH settings

Table V-1c (continued). IN-LAKE CHEMICAL CONTROLS: Address phosphorus or low oxygen by addition of chemical that alter water conditions to either provide oxygen and/or bind phosphorus. These types of *in situ* treatments typically require some sort of delivery system into the pond water column and generally include pond water quality management techniques that have been used most frequently.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Sediment oxidation (generally regarded as experimental in region)	• Addition of oxidants, binders, and pH adjustors to oxidize sediments • Binding of phosphorus is enhanced • Denitrification may be stimulated	• May reduce phosphorus sediment regeneration • May decrease sediment oxygen demand	• Potential impacts on benthic biota • Duration of impacts not well characterized • Increased N:P ratio may increase sensitivity to watershed inputs • Duration unknown	• none	Not applicable; town may consider if it chooses to evaluate experimental options in other ponds; would only address a maximum of 14% to 23% of summer water column P
Settling agents (akin to P binding, but primarily targets the water column)	• Creation of a floc through the application of lime, alum, or polymers, usually as a liquid or slurry • Floc strips particles, including algae, from the water column • Floc settles to bottom of pond	• Cleaning of water column removes algae and accompanying nutrients and transfers them to sediments • May reduce nutrient recycling depending on dose	• Potential impacts on benthic biota, zooplankton, other aquatic fauna • May require multiple or regular treatments • Adds to sediment accumulation • Potential resuspension of floc in shallow ponds	• none	Not applicable; has not been completed in any ecoregion ponds (experimental); would likely have permitting issues because of mussels and use over most of pond area; would likely need to be done annually because not addressing P source
Selective nutrient addition	• Add nutrients to change relative ratios to favor different components of plankton community • Favor settling and grazing to transport nutrients to sediments and avoid HABs	• May reduce algal levels where control of limiting nutrient not feasible • May promote non-nuisance forms of algae • May rebalance productivity of system without increasing algae component	• May increase algae in water column • May require frequent additions to maintain nutrient balances • May be incompatible with water quality in downstream waters	• none	Not applicable; has not been completed in any ecoregion ponds (experimental); pond already has sufficient N will not substantially address sediment oxygen demand or nutrient regeneration; may create non-blue green algal blooms

Table V-1d. IN-LAKE BIOLOGICAL CONTROLS: Address phosphorus by altering the composition or relationships between the plants and animals in the pond, typically through shifting nutrients from plants/algae to other organisms (e.g., fish or zooplankton). Usually requires accompanying in-lake chemical controls to enhance oxygen levels. Generally have not been used on Cape Cod.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Enhanced grazing	• Manipulation of relationships between algae/ phytoplankton, zooplankton, and fish to favor reduced algae level • Addition of herbivorous fish • Manipulation to favor herbivorous zooplankton (typically by manipulating fish population)	• May increase water clarity by reducing cell sizes or density of algae • May produce more fish • Uses natural processes	• May involve introduction of non-native or exotic species • Effects may not be tunable • Effects may not be lasting and require regular updates • May create conditions favoring less desirable algal species • Not an ecosystem restoration, a change to a different ecosystem.	• none	Generally not applicable, application would require: • more extensive characterization of food web (including resident fish, mussels, zooplankton, etc.) • May drive more nutrients to sediments and create larger P regeneration pool Given its lack of use in Cape Cod ecosystems, should be considered experimental and would likely have significant regulatory hurdles
Bottom-feeding fish removal	• Remove agitation, resuspension, and reworking of sediments by bottom-fish	• May reduce turbidity and nutrient conversion by these fish • May shift more of the pond biomass indirectly to other fish	• May be difficult to achieve complete removal of this population • Effects may not be tunable • May be a favored species for other biota and/or humans	• none	Not applicable, bottom fish are not cause of Shubael Pond impairments

Table V-1d. **IN-LAKE BIOLOGICAL CONTROLS: Address phosphorus by altering the composition or relationships between the plants and animals in the pond, typically through shifting nutrients to other organisms (e.g., fish or zooplankton). Usually requires accompanying in-lake chemical controls to enhance oxygen levels. Generally have not been used on Cape Cod.**					
OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Microbial competition	• Addition of microbes, often with oxygenation, can shift nutrient pool and limit algal growth • Tends to control N more than P since N can be denitrified and removed from the system	• May shift nutrient use from algae to microbes; leaving less nutrients for algal blooms • Uses natural processes • May decrease organic sediments	• Limited scientific evaluation • Without oxygenation, may still favor blue green algae • Unknown impacts on rest of ecosystem species, nutrient, energy cycles • Time between applications unclear • Bacterial mix unclear • Most pond sediments already have diverse natural microbial populations	• none	Not applicable; better potential choice for sediment-dominant P budgets; may create system susceptible to smaller increments of P additions Given its lack of use in Cape Cod ecosystems and lack of peer reviewed studies should be considered experimental and would likely have significant regulatory hurdles
Pathogen addition	• Addition of microbes that will kill algae • May involve fungi, bacteria, or viruses	• May cause lakewide reduction in algal biomass • Depending on competition, impacts may be sustained through number of pond years • May be tailored to address specific algae	• Limited scientific evaluation • May cause release of cytotoxins • May cause sediment nutrient additions and increased sediment oxygen demand • May favor growth of resistant nuisance forms of algae • Unknown impacts on rest of ecosystem species • Time between applications unclear	• none	Not applicable Given its lack of use in Cape Cod ecosystems and lack of peer reviewed studies should be considered experimental and would likely have significant regulatory hurdles

Table V-1d. IN-LAKE BIOLOGICAL CONTROLS: Address phosphorus by altering the composition or relationships between the plants and animals in the pond, typically through shifting nutrients to other organisms (e.g., fish or zooplankton). Usually requires accompanying in-lake chemical controls to enhance oxygen levels. Generally have not been used on Cape Cod.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Shubael Pond
Competitive addition of plants	• Addition/ encouragement of rooted plants to competitively reduce availability of nutrients to phytoplankton/algae through additional growth • Addition of plant pods, floating islands, etc., for removable addition • Plants may create light limiting conditions for algal growth	• May shift nutrient use from phytoplankton/ algae to rooted plants and reduce algal biomass • Uses natural processes • May provide prolonged control	• May add additional nutrients to overloaded ponds • May lead to excessive growth of rooted plants • May add additional organic matter to sediments and increase oxygen demand and phosphorus availability	• none, although natural competition in some Cape Cod ponds may offer some examples of impacts	Not applicable; implementation has significant potential downsides and would likely reduce open area of pond available for use; uncertain impact on extensive existing population
Barley straw addition	• Addition of barley straw might release toxins that can set off a series of chemical reactions which limit algal growth • Straw might release humic substances that can bind phosphorus	• Relatively inexpensive materials and application • Reduction in algal population is more gradual than with algaecides, limiting oxygen demand and the release of cell contents	• Some indication favors selected algal species • May add additional organic matter to sediments increasing oxygen demand and water column P availability • Impact on non-target species is largely unknown • Will require regular additions and maintenance	• May have been used in some Harwich ponds, but no documentation or monitoring • Testing for County Extension Service showed no definitive effect	Not applicable; likely would cause increased sediment oxygen demand and greater P release; generally regarded as unregistered herbicide and cannot be officially permitted or applied by licensed applicator in MA

V.C. Applicable Management Options

V.C.1. Watershed Phosphorus Management

Septic system wastewater effluent is the primary source of watershed phosphorus inputs to Shubael Pond during both the spring and the summer, even when sediment regeneration of P is at its maximum (see **Figures IV-40 and IV-41**). In the USGS MEP watershed, wastewater P from existing sources alone exceeds the 11 kg P remediation target and the septic systems in the subset watershed based on USGS provisional data match the 11 kg P target after accounting for the associated change in pond residence time. Other watershed P sources are either uncontrolled (*i.e.*, atmospheric deposition) or a much smaller portion of the annual P load to the Shubael Pond water column (*e.g.*, road, driveway, and roof runoff combined are ~6% of the April MEP/USGS watershed P load). Potential strategies to address the septic system P load need to address: 1) the differing watersheds and their loads, 2) reliability of technology, and 3) potential timeframes for reducing the septic P loads.

Portions of the Shubael Pond watershed are already planned for sewering during Phase 3 of the current Town Comprehensive Wastewater Plan (CWMP) (**Figure V-1**). Phase 3 properties would be sewered 21 to 30 years from the start of the CWMP implementation. As noted in **Figure V-1**, the Phase 3 sewering would connect all the properties within the Shubael Pond MEP/USGS watershed currently adding septic system P loads to the pond, as well as those projected to add additional P to the pond in the future, except for five properties along Evergreen Drive and Reid Lane. These five properties all are currently adding septic system P to Shubael Pond and are also within the watershed based on the provisional USGS information. Removal of the wastewater P by sewering the properties in the planned Phase 3 area would reduce the overall P loading to Shubael Pond below the 11 kg P target based on the MEP/USGS watershed and the provisional watershed under average August sediment loads (**Figure V-2**). The 11 kg target would also be attained for both watershed configurations when maximum estimated sediment loads occur, although the load for the provisional watershed and maximum sediment loads would be at the 11 kg TP limit.

Connection of these watershed properties to a town sewer system is currently projected to occur 21 to 30 years from now. Based on the age of the septic systems in the MEP/USGS watershed, another 13 septic system would begin adding wastewater TP to the pond before that time. If sewering occurred in five years, approximately 5 additional septic systems would be adding wastewater TP to the pond. All of the septic systems in the provisional watershed are currently adding wastewater TP to the pond and no future additions are projected within the next 21 years.

Although the provisional watershed analysis suggests that wastewater additions should be at steady-state, available TP concentrations have a statistically significant increasing trend (see **Figure IV-7**). This finding suggests that septic system TP has not leveled off and that some conservatism should be applied if the Town considers adjusting the boundaries of the sewered area upgradient of the pond. The trend data also suggests that existing impairments in the pond will worsen if sewering does not occur for 21 to 30 years. If this timeline cannot be adjusted alternative, interim wastewater P reduction strategies should be considered, such as phosphorus-reducing septic systems.

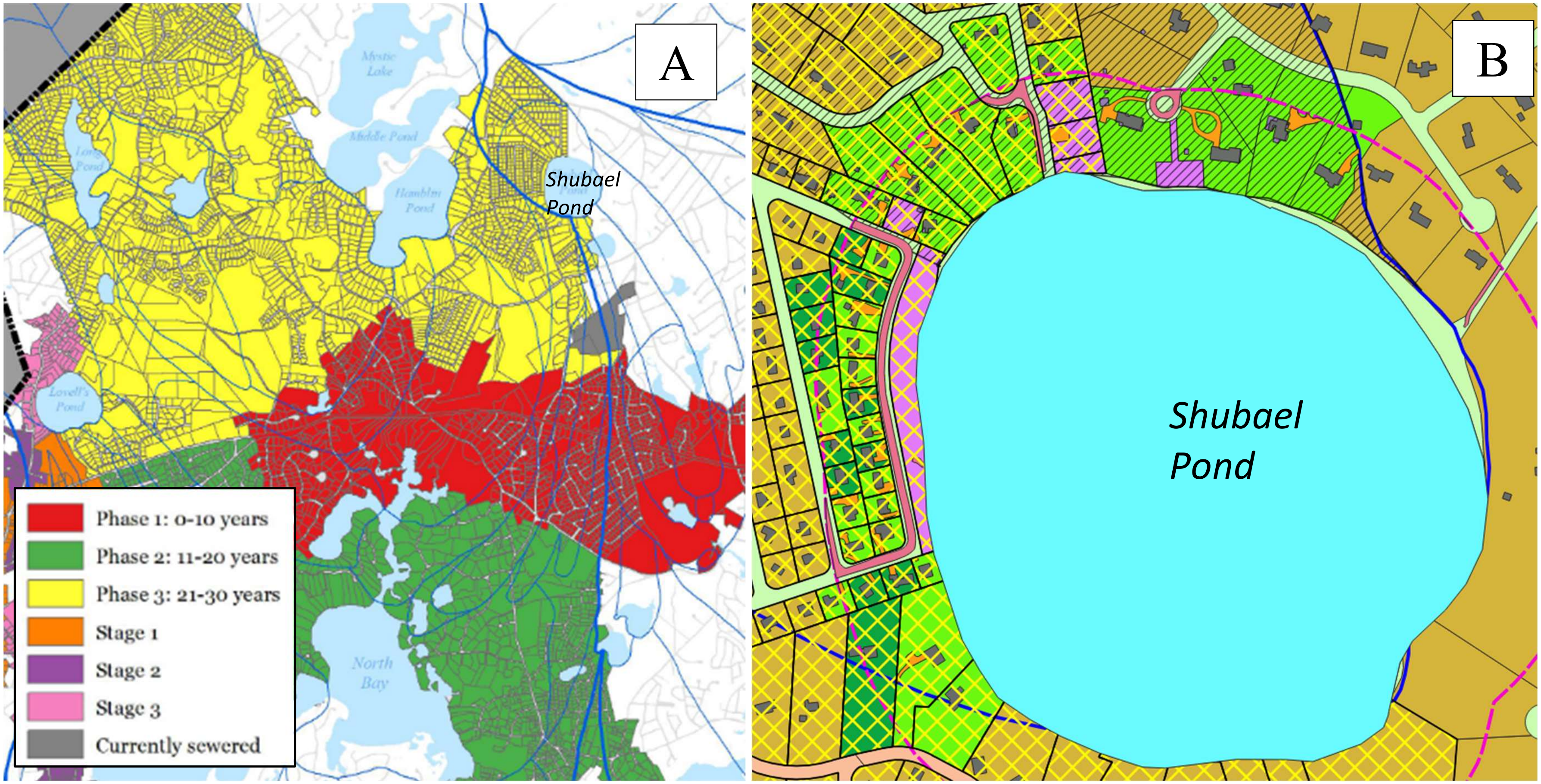


Figure V-1. 2020 Barnstable CWMP Sewer Areas and Phasing in Shubael Pond Area. Barnstable Comprehensive Wastewater Management Plan (CWMP) includes three 10 year phases of sewering throughout the Town. A portion of the Shubael Pond watershed is included in Phase 3 sewering, which is 21-30 years from the start of the CWMP. Panel A shows regional phasing of areas near Shubael Pond, while Panel B shows Phase 3 area (yellow cross-hatching) overlaid on parcels currently contributing P to the pond. Note that 5 parcels within the combined MEP/provisional watersheds are not included in the planned sewer area; parcels on Evergreen Drive and Reid Lane. Panel A is modified from Figure 5-1 in Town CWMP/SEIR (2020), while Panel B is modified from Figure IV-36 in this report.

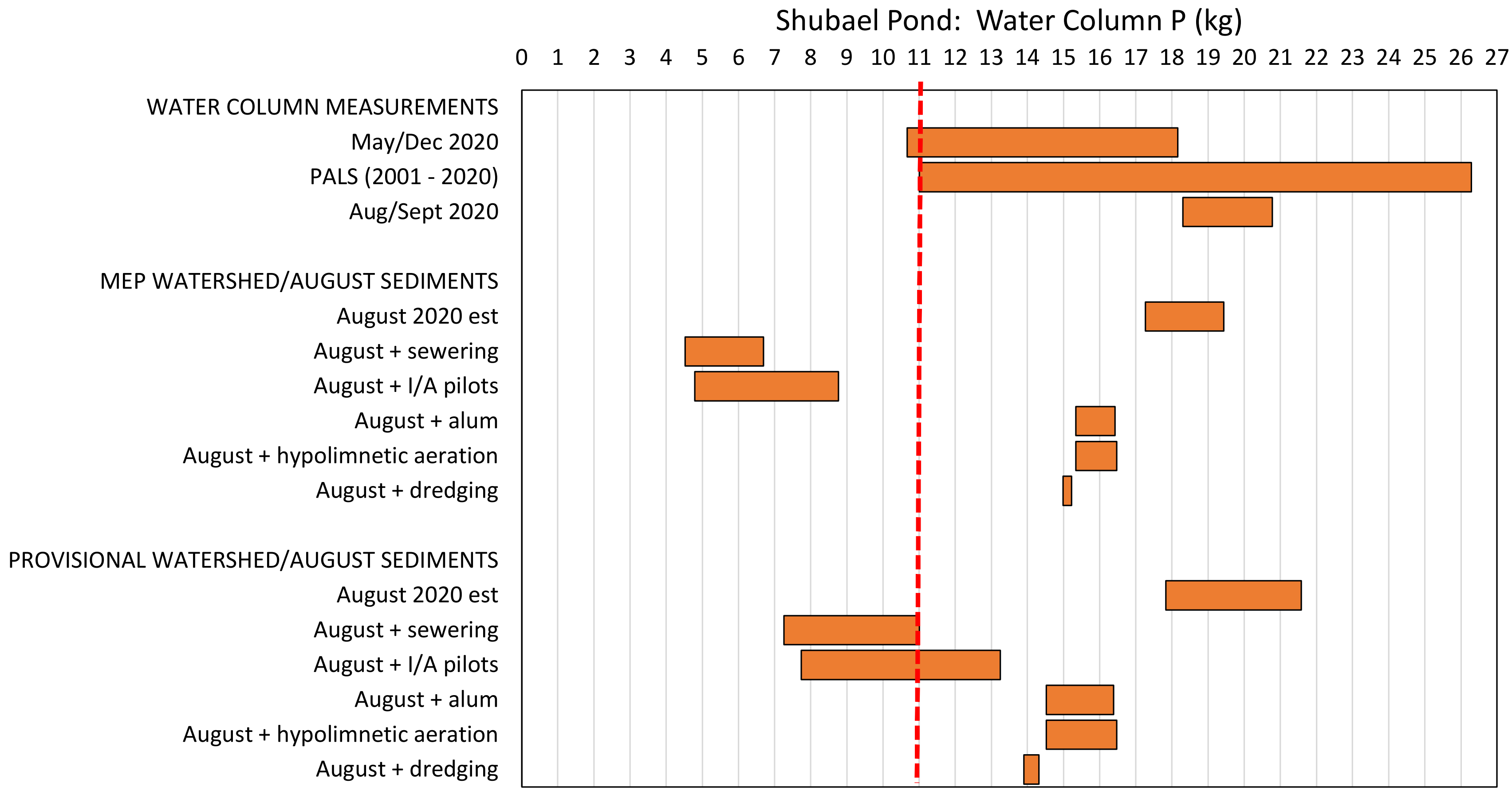


Figure V-2. Shubael Pond: Comparison of Selected Phosphorus Management Options to Attain TP Water Column Threshold. Project staff compared the potential performance ranges for applicable phosphorus management options to the recommended 11 kg TP water column threshold mass (red dashed line). The only options that attain the TP threshold mass are those that address watershed wastewater TP reductions (*i.e.*, sewering or innovative/alternative phosphorus-reducing septic systems). This outcome occurs because wastewater inputs are 77% to 86% of the water column TP inputs depending on whether the watershed delineation is based on the provisional USGS data or is the MEP/USGS delineation. In-pond treatments to reduce summer sediment TP regeneration are insufficient on their own to achieve the TP threshold. Combination approaches may be possible, but will need to include a component that at least partially address watershed wastewater TP inputs.

There are currently no phosphorus removal technologies for innovative/alternative (I/A) septic systems approved for general use in Massachusetts.[96] There are three phosphorus removal technologies that are approved for piloting use (*i.e.*, no more than 15 installations with monitoring to field test their performance): a) PhosRID Phosphorus Removal System, b) Waterloo EC-P for Phosphorus Reduction, and c) NORWECO Phos-4-Fade Phosphorus Removal. MassDEP piloting approval "is intended to provide field-testing and technical demonstration to determine if the technology can or cannot function effectively."[97]

The PhosRID Phosphorus Removal System uses a reductive iron dissolution (RID) media anaerobic upflow filter to reduce total phosphorous to less than 1 mg/L and consists of two treatment units: the initial unit with RID media and a second unit, which operates as an oxygenation filter. The media is consumed and is estimated to require replacement every 5 years. The Waterloo EC-P for Phosphorus Reduction submerges iron plates in a septic tank or treated effluent tank; the plates are connected to low-voltage control panel with the objective of creating iron-P precipitates and system effluent of less than or equal to 1 mg/L TP. The Norweco Phos-4-Fade is an upflow tank added between the septic tank and leaching structure with built-in filter media designed to produce an effluent with a TP concentration of 0.3 mg/L or less. The media is consumed and is estimated to require replacement every 2 to 5 years.

All three of the on-site phosphorus removal pilot systems will reduce the wastewater phosphorus sufficiently to attain the 11 kg TP threshold for Shubael Pond without any additional P reductions when average in-pond sediment loads are considered for both the MEP/USGS watershed and the provision watershed (see **Figure IV-2**). However, none of the pilot systems will attain the TP threshold on their own for the provisional watershed when maximum sediment loads are considered. Pilot systems with the MEP/USGS watershed attain the threshold when maximum sediment loads are considered.

Extensive use of any of these piloting technologies would require some regulatory and, likely, financial coordination. As noted above, MassDEP limits the installation of septic systems or components with piloting approval to no more than 15 installation and requires significant water quality monitoring to document the performance of the systems. Since these are somewhat experimental systems, there should likely be some discussions about contingencies if the systems fail to perform as intended. Discussions should also include whether a single technology would be used (one technology would be easier to standardize and streamline monitoring, as well as maintenance and replacement of media), but there are 13 properties in the provisional watershed and use on all of the properties would approach the 15 unit MassDEP limit for any one of the technologies.

Since these systems are somewhat experimental, costs for the maintenance and monitoring of these systems are not well established. In order to provide some idea of potential costs, project staff reviewed a 2010 proposal to the Town of Mashpee that estimated that the individual PhosRID system costs were $8,364 per unit with an annual operation and maintenance cost of

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[96] MassDEP Title 5 Innovative/Alternative Technology Approval Letters website (accessed 6/10/21). http://www.mass.gov/eea/agencies/massdep/water/wastewater/title-5-innovative-alternative-technology-approvals.html.

[97] *Ibid*.

\$574.[98] Applying inflation adjustments and assuming a 20 year annual cost life cycle, these costs applied to the 13 properties currently estimated to be contributing wastewater phosphorus to the Pond from the watershed based on the provisional USGS data would result in a current estimated cost of approximately \$332,000. Combining this with the estimated cost for the 14 properties currently estimated to be adding septic system P to the pond from the remaining MEP portion of the watershed would result in a combined 20 year life cycle cost of approximately \$689,000 with additional cost if it was applied to the other systems that are not yet adding wastewater P to the pond.

Reductions in other watershed inputs would be insufficient on their own to achieve the 11 kg TP threshold. Roof runoff, road and driveway runoff, and direct precipitation on the pond surface collectively add 2 kg/yr TP. Direct precipitation is 1.1 kg of the total and cannot be reduced by local management activities. Road and driveway runoff is estimated to be 0.7 kg, of which 0.5 kg is estimated from direct runoff measurements into the pond during this project, and 94% of the 0.5 kg is from the Shubael Pond Road runoff system. Roof runoff is the remaining 0.2 kg/yr. Reductions of some of these could be accomplished, but would have to be linked to other, more significant TP reductions to be able to at the 11 kg TP restoration threshold. Eliminating these loads combined with the provisional watershed septic loads treated with P-reducing septic systems would not meet the 11 kg TP threshold and maximum sediment loads.

Among the impervious surface runoff sources, direct runoff is the only one that could be significantly reduced and that could be done by improving the existing systems that are already in place. The Shubael Pond Road stormwater system already includes a series of in-line leaching catch basins, so that the discharge at the headwall represents overflow from those catch basins. Adding additional in-line catch basins or another type of interim discharge would reduce the direct discharge flow and TP load to the pond. The Willimantic Drive boat ramp is only a small portion of the direct runoff discharge to the pond, but its flow could be reduced further by the addition of catch basins along the road and closer to the pond. These types of changes may be something the Town could consider if updates are made to the stormwater systems.

In summary, implementation of sewering and piloting phosphorus-reducing septic systems within the Shubael Pond watershed will remove sufficient phosphorus to attain the TP water column threshold in most cases. Sewering is proposed as part of the CWMP, but the current schedule does not include implementation until a minimum of 20 years from now. Somewhat experimental phosphorus-reducing septic systems could also meet the threshold except in the case of maximum internal sediment regeneration, but would require regular maintenance and substantial costs. Strategies to reduce other sources of phosphorus, such as stormwater runoff, will not produce significant enough changes to meet the TP threshold, but could be complementary best practices as there are other environmental advantages.

V.C.2. In-Pond P Management

Staff reviewed the range of likely reductions associated with applicable in-pond sediment P management and all of them were insufficient on their own to attain the TP remediation target without complementary reductions in watershed septic system TP additions. Staff reviewed the

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[98] Lombardo Associates, Inc. 2010. Town of Mashpee, Popponesset Bay, & Waquoit Bay East Watersheds. Nitrex Technology Scenario Plan. Submitted to Town of Mashpee. Newton, MA.

potential impact of in-pond actions (*i.e.*, alum treatment, hypolimnetic aeration, and sediment dredging) on both average and maximum summer sediment TP additions (2.3 kg and 4.4 kg, respectively) (see **Figure IV-2**). These approaches resulted in a range of predicted water column TP masses from 13.9 kg to 16.5 kg under average sediment regeneration and 14.1 to 19.0 kg under maximum sediment regeneration. It is not surprising that none of these approaches achieved the 11 kg remediation threshold given that they only address the sediment TP load and this was only 14% to 23% of the overall load.

However, each of these actions could be combined with limited watershed wastewater reductions in order to the achieve the 11 kg threshold. If the wastewater load is reduced by 40 to 45% in either of the watershed delineations, the 11 kg threshold can be achieved provided it is combined with a technique that reduces the sediment TP regeneration by 33% to 95%. Preliminary planning costs based on a 20 year lifecycle for the three techniques are: $21,000 to $29,000 for two alum treatment (12.1 acres), $150,000 for a hypolimnetic aeration system, and $965,000 to $1.9 million for dredging of the pond. Additional costs would be incurred for permitting and associated monitoring. Two alum treatments are assumed based on conservative longevity of 10 years each before sediment regeneration returns to current conditions; this longevity assumes no P reduction management activities in the watershed. Dredging will likely have a slightly longer longevity, but its longevity will also be limited if no accompanying watershed P reduction actions occur. Sediment treatment performance is usually optimal in pond systems where sediment regeneration is the primary source of water column TP, which is not the case in Shubael Pond. More extensive reviews of these options can be completed if the Town chooses to pursue any of these options alone or in combination.

VI. Summary and Recommended Plan

Shubael Pond is a Great Pond under Massachusetts law. Review of historic and 2020 water quality data showed that the pond has impaired water and habitat quality based on both state regulatory standards and guidance developed from reviewing ponds and lakes in the Cape Cod Ecoregion.

Temperature and DO profiles have been collected 25 times at Shubael Pond, including 16 Pond and Lake Stewardship (PALS) August/September snapshots between 2001 and 2020 and 9 sampling runs completed throughout the year in 2020 to support this Management Plan. Temperature readings show regular, strong stratification existing in the PALS snapshots with a warm, well-mixed upper layer and a cold deep layer isolated from atmospheric mixing. The 2020 readings show this stratification began to weakly develop in May, was strongly in place by June and persisted through September. The deep layer consistently meets MassDEP temperature criterion for a cold water fishery, but every completed PALS profile had anoxia (DO<1 mg/L) in the deepest waters and occasionally had anoxia throughout the cold layer. Once temperature stratification was established in June 2020, anoxia was found in the deepest waters and was measured in increasing portions of the cold layer throughout the summer. In the September 2020 profile, the whole cold layer was anoxic and anoxia was even measured within the transition zone between the cold and warm layers. This type of impairment is well below the MassDEP minimum DO concentration of 6 mg/L and would not allow a cold water fishery to be sustained throughout the year.

Nutrient concentrations show impairments throughout the water column. Total phosphorus (TP) concentrations in the Spring 2020 prior to stratification are generally at or slightly greater than the Ecoregion threshold of 10 µg/L. Once stratification is established, sediment regeneration of TP is prompted by deep anoxia and TP concentrations increase throughout the water column. In September 2020, shallow TP concentrations were greater than 14 µg/L and deep concentrations greater than 40 µg/L were measured. With nutrient concentrations relatively high, chlorophyll a concentrations, which reflect phytoplankton growth, also increased with shallow concentrations regularly above the 1.7 µg/L Ecoregion threshold. Trend analysis of shallow PALS TP concentrations between 2001 and 2020 show that they have been increasing approximately 0.6 µg/L per year. Comparison of nitrogen and phosphorus concentrations show that phosphorus management is the key to developing acceptable long-term water and habitat quality conditions. Review of periods when acceptable water quality conditions existed resulted in project staff recommending that total water column TP mass be limited to 11 kg; meeting this goal should result in restoration of pond ecological health and elimination of the documented impairments.

Data gap information collected during 2020 showed how these water quality impairments occur and established the sources of the TP and total nitrogen (TN) measured in the water column. Data gap surveys completed in 2020 included: a) watershed delineation and watershed land use analysis, b) measurements of direct stormwater discharge to the pond, c) collection of sediment cores and incubation of the cores to measure conditions that cause TP and TN regeneration, and d) collection of phytoplankton samples to understand how the population changes due to nutrient availability.

The comparison of watershed and summer sediment nutrient inputs showed that septic system wastewater was the primary source of phosphorus to the Shubael Pond water column. Data gap reviews showed that there is a pond watershed that was delineated by the US Geological Survey (USGS) as part of the Massachusetts Estuaries Project (MEP), but there is also new provisional USGS data in the area near the pond, that is not yet publicly available, that suggests that the pond watershed is potentially smaller than the USGS/MEP watershed. Review of land use and septic systems (*e.g.*, their age, distance to the pond, and likely P travel time to the pond) shows that septic system TP is the primary source of water column phosphorus for either watershed delineation (77 to 86%). However, the watershed differences are important for the residence time of water in the pond and the area that should be selected for potential future management of watershed phosphorus sources. Summer sediment sources of TP vary depending on the depth and longevity of bottom water anoxia, but review of water column and sediment core data show that even during maximum regeneration, septic system TP remains the largest current source of water column phosphorus (59 to 74% during the summer). Sediment regeneration is estimated to be 14% to 23% of the average summer water column TP depending on the watershed delineation considered. Stormwater runoff and direct precipitation on the pond surface are the other sources of water column TP with direct precipitation varying between 7 and 15% and stormwater runoff varying between 4 and 7% depending on the watershed and season.

Since septic system phosphorus additions are the largest source of TP to the Shubael Pond water column, review of management options focused on ways to eliminate or reduce wastewater TP additions. Sewering most of the parcels in the USGS/MEP watershed is currently planned by the Town in Phase 3 of the CWMP, which is targeted for 21 to 30 years from now. Planned sewering will leave 5 parcels unsewered that are currently contributing wastewater P to the pond in both versions of the watershed. If the planned sewering is implemented, cumulative TP loads from all sources in either watershed version plus average sediment contributions will result in a total P load be less than the recommended target maximum of 11 kg TP except for a scenario where maximum summer sediment contributions are combined with TP loads from the provisional version of the watershed. Although planned sewering can achieve the TP restoration goals for Shubael Pond, the current schedule for the implementation of the sewering would lead to 21 to 30 years of worsening water quality in Shubael Pond.

Project staff also reviewed the impact of reducing wastewater TP additions by installing phosphorus-reducing septic system throughout both versions of the watersheds. There are currently three types of these septic systems and they are currently under “piloting” review by the Massachusetts Department of Environmental Protection (MassDEP). Their current piloting approvals state they reduce TP effluent concentrations to 0.3 mg/L or 1 mg/L. Their current MassDEP status means they are somewhat experimental and only 15 of each type of system can be installed throughout Massachusetts along with extensive required performance monitoring. Installation of these systems on the 27 parcels currently contributing wastewater TP to Shubael Pond in the USGS/MEP watershed or the 13 parcels currently contributing wastewater TP to the pond from the provisional watershed would reduce the overall TP additions from all sources in either case to less than the recommended 11 kg TP threshold except for a scenario with the following characteristics: provisional watershed, 1 mg/L TP effluent systems, and maximum estimated summer sediment loads. Preliminary cost estimates associated with the installation of one of the types of phosphorus-reducing septic systems in the provisional watershed and the USGS/MEP watershed are $332,000 and $689,000, respectively.

Although wastewater reductions are necessary to meet the 11 kg TP restoration threshold goal, project staff also reviewed potential TP reductions from applicable approaches to reduce sediment TP regeneration. These approaches included an alum treatment, hypolimnetic aeration (aeration of only the cold, deep layer), and sediment dredging. These approaches resulted in a range of predicted water column TP masses from 13.9 kg to 16.5 kg under average sediment regeneration and 14.1 to 19.0 kg under maximum sediment regeneration. It is not surprising that none of these approaches alone achieved the 11 kg remediation threshold given that they only address the sediment TP load, which was only 14% to 23% of the overall load. Although in-pond sediment regeneration approaches are insufficient on their own to meet the 11 kg TP restoration threshold, there are likely options that could achieve the threshold when combined with more limited sewering than currently planned or installation of a number of phosphorus-reducing septic systems on key properties.

One additional insight gained from the review of Shubael Pond water quality is that the pond is removing an average of 76% or 78% of its watershed nitrogen based on the 2020 water quality monitoring and depending on which watershed delineation is considered. Incorporation of this insight into watershed nitrogen loading estimates for Three Bays and Centerville River could lead to changes in sewering strategies in the Town CWMP. Both the Three Bays MEP study[99] and 2021 MEP nitrogen loading update[100] assigned a 50% nitrogen attenuation rate to Shubael Pond.

Based on these findings, CSP/SMAST staff recommends the following steps for implementation of an adaptive management approach for the restoration of Shubael Pond:

1. **Develop and implement a water column phosphorus reduction strategy for the Shubael Pond.**
    - Septic system wastewater phosphorus additions to the pond are the primary source of water column TP concentrations and phosphorus control is the key for managing water quality in Shubael Pond.
    - The current Town CWMP includes sewering in the Shubael Pond watershed that will attain restoration of the pond water quality, but the implementation of the sewering is not planned for Phase 3 of the CWMP (*i.e.*, 21 to 30 years from now). Changes to the planned sewering schedule or an alternative wastewater treatment strategy are required to achieve acceptable water quality in Shubael Pond in the near-term.
    - If the sewering schedule cannot be accelerated then interim actions to slow the decline in water and habitat quality should be considered. This will require discussions with the Town DPW as to feasibility, but the concept would be to take

99 Howes B., S. W. Kelley, J. S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner. 2006. Three Bays MEP Report.

100 CSP/SMAST Technical Memorandum. December 5, 2019. MEP Scenarios: Town of Barnstable Wastewater Plan and Land Use Updates.

actions to keep impaired pond conditions stable and not allow them to worsen further until the Phase 3 sewering is completed.

- Key to defining acceptable water quality is reviewing the watershed delineation to the pond. The USGS/MEP watershed is included in the CWMP, but recent provisional data from USGS suggests the watershed is smaller.
- Reductions in phosphorus loads from other sources are insufficient to achieve the necessary restoration of pond water quality, but there may be other strategies that combine more limited wastewater TP reductions with reductions from other sources that achieve the restoration goal.

2. Develop and implement an adaptive management monitoring program.

- Monitoring in 2020 completed for this project was the first complete summer of water quality monitoring for Shubael Pond. Implementation of a water column phosphorus reduction strategy should be accompanied by regular monitoring to assess its performance. This data should be collected for two to three summers and management strategies should be revisited if acceptable water quality is not achieved. Details of the monitoring should include sampling of at a minimum of PALS depths (0.5 m, 3 m, 9 m, and 1 m off the bottom) monthly over the deepest point in the pond between June and September with accompanying DO and temperature profiles and Secchi clarity readings. If monitoring after 2 to 3 years shows acceptable water quality, monitoring can be reduced to a spring (April/May) sampling and a PALS sampling in August/September.

3. Select a target restoration threshold of 11 kg TP mass within the water column as a preliminary water quality target threshold, but avoid a TMDL designation until attainment of satisfactory water quality.

- Shubael Pond is currently not listed as an impaired water for nutrients on MassDEP's most recent Integrated List, but the review of data in this report show that it fails to attain MassDEP minimum criterion for dissolved oxygen and has other impairments related to excessive phosphorus loading. Under the Clean Water Act, impaired waters are required to have a TMDL for the contaminant causing the impairment.
- It is recommended that the Town avoid submitting information on a TMDL until after implementation of a P reduction strategy and subsequent adaptive management monitoring to document improvement and attainment of water quality goals. It is possible that MassDEP (or another party) may cause the Town to expedite a TMDL listing. If this occurs, the information in this Plan should be sufficient to meet the data requirements for a phosphorus TMDL submittal. If the Town develops and pursues an acceptable strategy, management of the pond would remain predominantly within local purview until the Town is ready to state that water quality impairments have been addressed.

Funding for the implementation of the recommended management plan will require further discussions. Potential funding sources for pond restoration/management activities typically include:

a) Town Budget,
b) directed funds from the state legislative budget,
c) Massachusetts Department of Environmental Protection (MassDEP) pass-through funding from EPA [*i.e.*, Section 319, 604b, or 104b(3) grants],
d) Massachusetts Department of Conservation Recreation (MassDCR) grants,
e) Massachusetts Coastal Zone Management (MassCZM) grants, and
f) Barnstable County funds.

VII. References

Adams, M.S. and Prentki, R.T., 1982. Biology, metabolism and functions of littoral submersed weedbeds of Lake Wingra, Wisconsin, U.S.A. *Arch. Hydrobiol. (Suppl.)*. 62: 333-409.

AECOM, Inc. 2019. Treatment Summary for Phosphorus Inactivation in Long Pond, Brewster and Harwich, Massachusetts. Willington, CT. 43 pp.

Bingchang Tan, Hu He, Jiao Gu, Kuanyi Li. 2018. Eutrophic water or fertile sediment: which is more important for the growth of invasive aquatic macrophyte Myriophyllum aquaticum? *Knowl. Manag. Aqua*t. *Ecosyst*. 419(3)

Carpenter, S.R. and Lodge, D.M. 1986. Effects of submersed macrophytes on ecosystem processes. *Aquat. Bot.* 26: 341-370.

CSP/SMAST Technical Memorandum. December 5, 2019. MEP Scenarios: Town of Barnstable Wastewater Plan and Land Use Updates. To: G. Beaudoin, Town Engineer, Barnstable Department of Public Works. From: B. Howes, E. Eichner, and J. Ramsey. 36 pp.

Eichner, E. 2008. Barnstable Ponds: Current Status, Available Data, and Recommendations for Future Activities. School of Marine Science and Technology, University of Massachusetts Dartmouth and Cape Cod Commission. New Bedford and Barnstable, MA.

Eichner, E., B. Howes, and D. Schlezinger. 2018. Uncle Harvey's Pond Management Plan and Diagnostic Assessment. Town of Orleans, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 106 pp.

Eichner, E., B. Howes, and D. Schlezinger. 2021. Savery Pond Management Plan and Diagnostic Assessment. Town of Plymouth, Massachusetts. TMDL Solutions LLC, Centerville, MA and Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth, New Bedford, MA. 101 pp.

Eichner, E. and B. Howes. 2021. Town of Barnstable Freshwater Ponds, 2021 Water Quality Monitoring Database: Development and Review. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 106 pp.

Eichner, E., B. Howes, D. Schlezinger, and M. Bartlett. 2014. Mill Ponds Management Report: Walkers Pond, Upper Mill Pond, and Lower Mill Pond. Brewster, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 125 pp.

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

Frimpter, M.H. and F.B. Gay. 1979. Chemical Quality of Ground Water on Cape Cod, Massachusetts. US Geological Survey, Water-Resources Investigations 79-65. Boston, MA. 20 pp. + 2 plates.

Gay, F.B. and C.S. Melching. 1995. Relation of Precipitation Quality to Storm Type, and Deposition of Dissolved Chemical Constituents from Precipitation in Massachusetts, 1983-85. U.S. Geological Survey, Water Resources Investigation Report 94-4224. Marlborough, MA. 87 pp.

Howes B., H.E. Ruthven, J. S. Ramsey, R. Samimy, D. Schlezinger, J. Wood, E. Eichner. 2006. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Centerville River

System, Barnstable, Massachusetts. Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 172 pp.

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

Living Lakes, Inc. 1992. Living Lakes Program, Final Report, Shubael Pond. Greenbelt, MD. 42 pp.

Lombardo Associates, Inc. 2010. Town of Mashpee, Popponesset Bay, & Waquoit Bay East Watersheds. Nitrex Technology Scenario Plan. Submitted to Town of Mashpee. Newton, MA.

Lu Y, Zhou Y, Nakai S, Hosomi M, Zhang H, Kronzucker HJ, Shi W. 2014. Stimulation of nitrogen removal in the rhizosphere of aquatic duckweed by root exudate components. *Planta*. 239(3): 591-603.

Madsen, J.D., P.A. Chambers, W.F. James, E.W. Koch, and D.F. Westlake. 2001. The interaction between water movement, sediment dynamics and submersed macrophytes. *Hydrobiologia*. 444: 71-84.

Maine Department of Environmental Protection. 1989. Phosphorus Control in Lake Watersheds: A Technical Guide to Evaluating New Development.

Massachusetts Department of Environmental Protection. December 2019. Massachusetts Year 2016 Integrated List of Waters. Final Listing. Massachusetts Division of Watershed Management, Watershed Planning Program. CN: 470.1. Worcester, MA. 375 pp.

Massachusetts Division of Fisheries and Game. 1948. Fisheries Report – Lakes of Plymouth, Berkshire and Barnstable Counties.

Reinfelder, J.R., L.A. Totten, and S.J. Eisenreich. 2004. The New Jersey Atmospheric Deposition Network. Final Report to the NJDEP. Rutgers University, New Brunswick, NJ. 174 pp.

Robertson, W.D. 2008. Irreversible Phosphorus Sorption in Septic System Plumes? *Ground Water*. 46(1): 51-60.

Rosen, B.H., and St. Amand, A. 2015. Field and laboratory guide to freshwater cyanobacteria harmful algal blooms for Native American and Alaska Native Communities: U.S. Geological Survey Open-File Report 2015–1164, 44 p., http://dx.doi.org/10.3133/ofr20151164.

Strayer, D.L. 2014. Understanding how nutrient cycles and freshwater mussels (*Unionoida*) affect one another. *Hydrobiologia*. 735: 277-292.

TMDL Solutions Technical Memorandum. Walkers Pond: Post Management Plan Water Quality Data Review. March 4, 2020. From E. Eichner, TMDL Solutions and B. Howes, CSP/SMAST. To: C. Miller, Town of Brewster and T.N. Lewis, Horsley Witten Group, Inc. 13 pp.

U.S. Environmental Protection Agency. 2000. Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs. First Edition. EPA-822-B00-001. US Environmental Protection Agency, Office of Water, Office of Science and Technology. Washington, DC.

U.S. Environmental Protection Agency. 2001. Ambient Water Quality Criteria Recommendations. Information Supporting the Development of State and Tribal Nutrient Criteria for Lakes and Reservoirs in

Nutrient Ecoregion XIV. EPA 822-B-01-011. US Environmental Protection Agency, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division. Washington, DC.

Vaughn, C.C. and C.C. Hakenkamp. 2001. The functional role of burrowing bivalves in freshwater ecosystems. *Freshwater Biology*. 46: 1431-1446.

Vet, R., R.S. Artz, S. Carou, M. Shawa, C. Ro, W. Aas, A. Baker, V.C. Bowersox, F. Dentener, C. Galy-Lacaux, A. Hou, J.J. Pienaar, R. Gillett, M.C. Forti, S. Gromov, H. Hara, T. Khodzherm, N.M. Mahowald, S. Nickovic, P.S.P. Rao, and N.W. Reid. 2014. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. *Atmospheric Environment*. 93(2014): 3-100.

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