Great Herring Pond and Little Herring Pond Management Plan and Diagnostic Assessment

FINAL REPORT

November 2022

for the

Town of Plymouth

Prepared by:

TMDL Solutions LLC
Centerville, MA 02632

and

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

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Town of Plymouth
Department of Marine and Environmental Affairs

Prepared By

Ed Eichner, Principal Water Scientist, TMDL Solutions
Brian Howes, Director, CSP/SMAST
Dave Schlezinger, Sr. Research Associate, CSP/SMAST

TMDL Solutions LLC
and
Coastal Systems Program
School for Marine Science and Technology
University of Massachusetts Dartmouth

Cover photo: Great Herring Pond (10/28/15)

Acknowledgements

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

The authors also specifically recognize and applaud the generosity of time and effort spent by Herring Ponds Watershed Association, specifically including Don and Geri Williams for their help in providing historical HPWA monitoring results, and the generous technical and project support provided by Kim Tower and David Gould from the Town of Plymouth, Department of Marine and Environmental Affairs.

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Executive Summary

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Great Herring Pond (GHP) and Little Herring Pond (LHP) are among the more than 400 ponds in the Town of Plymouth and two of the town's 83 Great Ponds.[1] These ponds and lakes are important recreational areas for swimming, fishing, and boating. Their natural habitats also provide important ecological and commercial services for cranberry bogs, herring runs, and nitrogen attenuation that protects downgradient estuaries. Town staff and citizens have long recognized that ponds are important community resources and in 2014, the Town Department of Marine & Environmental Affairs (DMEA) developed the Plymouth Pond and Lake Stewardship (PPALS) program with the Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) and pond associations throughout the town to integrate pond water quality with water quality management efforts. Efforts through the PPALS program have included regular summer water quality snapshots, development of a Plymouth Ponds Atlas, and data collection projects to address data gaps to support development of pond management plans. In late 2020, DMEA, CSP/SMAST, TMDL Solutions, and other GHP/LHP stakeholders, including the Herring Ponds Watershed Association, developed a strategy to address data gaps for GHP/LHP and develop a management plan based on diagnostic assessment of the ponds, including review and integration of 2021 data gap data with previous water quality sampling. This GHP/LHP Management Plan and Diagnostic Assessment provides a reasonable understanding of the GHP/LHP ecosystem and uses the collected information and its synthesis to identify and assess potential management options and develop a recommended management plan.

GHP and LHP are both community resources for the Town of Plymouth. Both ponds are classified under Massachusetts law as Great Ponds, or publicly-owned resources,[2] with surface areas of 419 acres and 81 acres, respectively. The two ponds share a watershed with streamflow from LHP flowing into GHP and then flowing out of GHP and into the Cape Cod Canal. The two ponds are located in southern Plymouth, west of Route 3 with the northern portion of GHP to the west of the Route 3 Cedarville exit. The importance of the two ponds was acknowledged in their inclusion in the 1991 designation of the Herring River Area of Critical Environmental Concern (ACEC).[3]

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[1] Eichner, E.M., B.L. Howes, and S. Horvet. 2015. Town of Plymouth Pond and Lake Atlas. Town of Plymouth, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 138 pp.

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

[3] https://www.mass.gov/service-details/herring-river-watershed-acec (accessed 3/3/02)

LHP is a very shallow pond (*i.e.*, maximum depth is 1.5 m), while GHP has a maximum depth of 15 m. Neither pond thermally stratifies, though GHP occasionally has temporary layering. Based on their temperature characteristics, both ponds would be classified as Class B warm water fisheries under Massachusetts Department of Environmental Protection (MassDEP) surface water regulation criteria.[4] GHP is classified as an impaired water due to low dissolved oxygen (DO) in the most recent EPA-approved Massachusetts Integrated List of surface waters, while LHP is assigned to Category 2 for attaining fish, other aquatic life, and wildlife use, but other uses, such as swimming or boating, have not been assessed.[5]

Project staff collected and reviewed historical data, mostly collected by the Town or HPWA, and data from 2021 refined water quality surveys to address known data gaps, including:

a. sediment core collection and incubation to measure sediment contributions to the water column readings,
b. monthly water column and stream water quality samples and streamflow measurements,
c. monthly samples of phytoplankton to determine how the population changed and whether cyanobacteria were a significant management concern,
d. surveys of rooted plants and freshwater mussels in each pond, and
e. delineation of the watersheds to both ponds and estimates of phosphorus contributions from land uses within the two watersheds.

The review of all the collected data in the Diagnostic Summary showed that LHP is nutrient-rich, but generally has acceptable water quality. Phosphorus is the key to controlling water quality in LHP and, although levels exceed the Ecoregion threshold, phytoplankton populations and biomass tend to be relatively low with cyanobacteria being only a minor portion of the overall phytoplankton population. DO readings are consistently above the MassDEP minimum and often above what they should be at atmospheric equilibrium (*i.e.*, 100% saturation). LHP has light consistently reaching the bottom and, as a result, dense growth of macrophytes over the whole pond bottom. Comparison of the 2021 macrophyte coverage to a 1970's-era coverage showed an increase in coverage, but the older survey did not provide a density assessment similar to the one completed in 2021. The 2021 macrophyte survey also noted some epiphytic growth on plants in the middle of the pond, which may be a sign of excessive phosphorus, but given that the survey was completed on only one date, it is a sign that should be monitored rather than managed at this point. Review of watershed land use, including age of houses and groundwater flow rates, showed that 128 to 178 septic systems and houses are contributing TP to LHP and water column readings balance the estimated watershed loads. Septic system wastewater is the primary source (87%) of phosphorus measured in the LHP water column. Overall, LHP seems to have relatively healthy conditions, albeit with high nutrient levels. Based on the LHP review, no management options are recommended exclusively for LHP.

Collected data from GHP showed that LHP stream inflow is the largest source of TP to GHP (47% of the overall budget), while watershed septic system wastewater from 116 to 158 houses within the GHP watershed is the second largest source (41%). Phosphorus is the key to

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[4] 314 CMR 4.00

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

controlling water quality in GHP and TP levels exceeded the Ecoregion threshold throughout the water column from May through October. Review of stream outflow readings showed that the primary source of TP concentration increases in the summer was the decrease in stream outflow and the accompanying increase in pond residence time. GHP had regular anoxia in the deepest waters (>12 m) from July through September 2021 and had anoxia from the 9 m to the bottom in August even though it mostly did not thermally stratify (June 25 profile had stratification at 8 m, but this was gone by July 14). Review of the 2021 monthly phytoplankton sampling results showed that biomass levels were generally lower than LHP, but GHP cell counts were higher in August and reached a maximum of 2,267 cells/ml in the October 14 sample. This level is only 3% of the Massachusetts Department of Public Health (MassDPH) criterion for issuing a Public Health Advisory,[6] even though the majority of the cells were cyanobacteria. MassDPH guidance also lists visual observation and toxin levels as other criteria for issuing a Public Health Advisory. Overall, GHP has impaired water quality conditions with excessive nutrient levels, regular hypoxia/anoxia less than MassDEP regulatory minima, and occasional conditions that factor cyanobacteria growth, but not at cell count levels that would prompt issuance of Public Health Advisory according to MassDPH numeric guidance.

Using the Diagnostic Summary insights of how the LHP and GHP system work, project staff evaluated management options to restore acceptable water quality in GHP. Comparing water quality conditions to water column TP mass, project staff recommend a 50 kg TP mass as a planning goal for GHP. Options to reach this goal generally need to address septic system wastewater TP. Review of wastewater management options found that if LHP watershed wastewater and its associated TP was collected and discharged outside of the LHP watershed (*i.e.*, sewering), the spring GHP water column TP mass would be reduced to approximately 66 kg without any additional reductions in the GHP watershed. In order to attain the 50 kg TP goal, an additional 60 to 70 residences in the GHP watershed would need to have their wastewater TP removed. This management strategy incorporates the anticipated increase in summer residence time, but does not include treatment of the sediments to reduce summer TP regeneration, which was estimated to be 16% of the summer TP budget. Treatment of the sediments alone to reduce summer TP inputs would be insufficient to attain the 50 kg TP goal. Project staff also reviewed use of currently permitted phosphorus reducing septic systems, but these are less efficient than sewering and would require a larger number of installations than is currently allowed under current MassDEP permitting (currently assigned to the "piloting" category) and have greater cost uncertainties associated with their installation. Project staff also reviewed an experimental in-stream Permeable Reactive Barrier (PRB) that has been tested for nutrient removal in cranberry bogs, which might be an interim step the Town could consider while planning for wastewater treatment.

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[6] https://www.mass.gov/info-details/guidelines-for-cyanobacteria-at-recreational-freshwater-locations (accessed 7/18/22)

Based on the findings in the Diagnostic Assessment and Management Option review, TMDL Solutions and CSP/SMAST staff recommend a series of long-, mid- and short-term goals for implementing an adaptive management approach for the restoration of Great Herring and Little Herring Ponds:

LONG TERM MANAGEMENT GOALS

Long term management goals to involve development of a wastewater management strategy for GHP. The diagnostic assessment shows that wastewater phosphorus is the primary source of water column TP concentrations and phosphorus control is the key for managing water quality in GHP and LHP. Reducing wastewater TP to GHP will require addressing wastewater additions to both LHP and GHP. Specific long term goals are:

- **Sewer Little Herring Pond and portion of the Great Herring Pond watershed**
    - 128 to 178 houses in the LHP watershed are currently contributing TP to LHP and GHP via stream outflow
    - 116 to 158 houses in the GHP watershed are currently contributing TP to GHP
    - Sewering and removal of wastewater phosphorus from all the houses in the LHP watershed (128 to 178 houses) and 60 to 70 houses in GHP watershed would attain the proposed GHP water column phosphorus threshold (50 kg)
    - Seek opportunities to incorporated into updated Town Comprehensive Wastewater Management Planning tasks
    - Seek separate funding opportunities through state grants to review sewering feasibility options, costs, permits
    - Should Feasibility Study prove applicable, Town and partners would move forward with planning, permitting and funding stage.
    - Form Partnerships: Buzzards Bay Coalition, AD Makepeace, Southeastern Regional Planning and Economic Development District (SRPEDD), Cape Cod Commission

INTERIM MANAGEMENT GOALS

Although watershed wastewater phosphorus reductions will address the water quality impairments in GHP, there are some **temporary interim phosphorus reduction options** that the Town should consider. These options will not individually reach the goal of removing the impairments in GHP, but they could provide some reductions in the impairments. All of these options will require monitoring to establish their efficacy and some are experimental and will likely require additional investigation to refine potential costs and regulatory hurdles. Specific interim goals to explore further are:

- In Stream Phosphorus Removal - Carters River
    - Restoration of the wetlands between LHP and GHP to slow flow and increase contact time
    - Instream Permeable Reactive Barrier. Use of iron/alum-enhanced materials within stream to bind phosphorus
- Permeable Reactive Barrier – shoreline to LHP and selected shoreline sections of GHP
    - PRBs have typically been used for distinct groundwater plumes rather than diffuse septic system plumes. May have some options for nearshore or near-leachfield installations, but feasibility and cost may be prohibitive.

- Floating Wetlands – LHP and/or GHP
    - o Floating wetlands have typically been used in highly controlled systems like stormwater basins, where inorganic phosphorus is readily available and natural system functions do not need to be addressed. P removal in these cases is typically on the order of 20% with additional issues regarding monitoring, maintenance, and management of the wetlands.
- Spot Alum Treatment - GHP
    - o Although a traditional alum treatment of the deepest portion of the pond will not adequately address the impairments in GHP because the sediments are only 12% of the summer phosphorus budget, treatment of the entire water column in the spring may remove sufficient phosphorus to prevent algal blooms. This approach would depend on an annual application and the year-to-year fluctuations in water levels/stream flow and may require special regulatory permitting.
- Evaluate direct discharge stormwater improvement options - GHP
    - o Stormwater inputs are a relatively small portion of the overall phosphorus budget to GHP, but the Town is encouraged to explore opportunities and feasibility of infiltrating of any direct discharges when updates or upgrades are considered. The Town may also consider an overall stormwater assessment of municipally owned stormwater discharges and explore infiltration and treatment options. Designs may be constrained by available land areas, but discussion of alternative designs is encouraged.

SHORT TERM MANAGEMENT GOALS

Development of long term and interim management goals will benefit from continued targeted monitoring in GHP and LHP and selection of a water quality management goal. As such, it is recommended that the Town consider the following short term goals:

- Develop and implement a Monitoring Plan that will continue through the implementation of any interim or long term strategies, as available funding allows, with the following recommendations
    - o **Deep Spot Water Quality Sampling in both GHP & LHP:**
      GHP (monthly: April – October and LHP (annual: August/September)
      GHP monthly between April and October at six depths (0.5 m, 3 m, 8 m, 9 m, 10 m, and 1 m off the bottom) and annually at LHP during August/September at two depths (0.5 m and 1 m). Each sample collection will be accompanied by dissolved oxygen and temperature profile readings (0.5 m and each meter to at least 12 m in GHP and 0.15 m, 0.5 m, and 1 m in LHP) and Secchi clarity and station depth readings. All collected samples assayed for standard PALS parameters (total phosphorus, total nitrogen, chlorophyll-a, pheophytin-a, pH, and alkalinity) plus ortho-P at the Coastal Systems Analytical Facility at SMAST using the same procedures utilized during the data collection for the Management Plan. A minimum of 10% of the total sample count will be accompanied by QA samples. Cyanobacteria sampling for parameters matching MassDPH criteria at a minimum: cell counts and toxins. Consider assays for phytoplankton speciation from sample collection through photic zone.

- **Continuous Monitoring in GHP Deep Spot (optional)**
  In GHP consider installation of continuous monitoring platforms (sondes) installed at 3 m and 10 m depths between April and October and programmed to record dissolved oxygen, temperature, depth, and chlorophyll a every 15 minutes. Sonde data will allow better understanding of temporary temperature stratification and deep anoxia in GHP, which has been indicated as a key for sediment phosphorus release.

- **Stream Flow Measurements at LHP and GHP outflows**
  Year-round monitoring of flow and water quality at Carters River/LHP outflow and GHP outflow. Monthly streamflow velocity measurements with water quality sample collection on the same date. Streamflow measurements should follow same cross-sectional measurement methods utilized during the data collection for the Management Plan. Collected samples should be assayed for following parameters: pH, Alkalinity, Chlorophyll-a, Phaeophytin, Total Pigments, Total Phosphorus, Total Nitrogen, and Ortho-Phosphate.

- **Stage-Discharge Curves at LHP and GHP outflows (optional)**
  Develop Stage-Discharge Curves at LHP and GHP outflow via installation of a stream gauge at each streamflow monitoring location. These gauges will record continuous water level recordings. These recordings will be combined with monthly streamflow measurements to evaluate whether reliable stage-discharge relationships can be developed for the two outflow locations. Continuous recordings will allow interpolation of flow rates between instantaneous readings and more complete record of outflows and nutrient export at the two locations.

- **Annual Review of Data**
  SMAST and/or TMDL Solutions to conduct annual review of data providing Technical Memorandum (draft and final) summarizing monitoring results and comparing to past monitoring, as well as recommendations for future monitoring and management activities.

- **Select a target restoration threshold of 50 kg TP mass within the GHP water column as a preliminary water quality target threshold, but avoid a TMDL designation until attainment of satisfactory water quality.**
  - GHP is listed in MassDEP's most recent Integrated List as impaired and requiring a TMDL. However, MassDEP has only created one phosphorus TMDL in southeastern Massachusetts in the last 10 years.
  - 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.

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 regional planning funds. It is further recommended that the town contact appropriate regulatory officials to explore these options. TMDL Solutions and CSP/SMAST staff are available to further assist the town with implementation, adaptive monitoring, and regulatory activities.

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I. Introduction

The Town of Plymouth has more than 400 ponds and lakes of various sizes and depths. These ponds and lakes are important recreational areas for swimming, fishing, and boating and, as such, are important components of the local and regional economy. Their natural habitats also provide other important ecological and commercial services, including use for cranberry agriculture, herring runs, and natural nitrogen attenuation that protects estuaries. Their importance has been acknowledged by an active community of pond associations and the prioritization of ponds and lakes in the activities of the Town's Department of Marine & Environmental Affairs (DMEA).

In 2014, the DMEA began work on crafting and implementing a comprehensive strategy to integrate pond and lake management into the overall water quality management strategies of the town. Working with the Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) and local pond associations, the DMEA began the Plymouth Pond and Lakes Stewardship (PPALS) program. This program began by organizing pond information (*e.g.,* areas, depths, regulatory status), past pond water quality data, standardizing procedures for current and future sampling of all ponds, and assessing the current status of 38 selected ponds through a unified PPALS snapshot water quality sampling effort during late summer 2014. A summary of these activities was included in the Town of Plymouth Pond and Lake Atlas.[7] The Atlas included a listing of all Plymouth ponds and lakes, synthesis of available past sampling data, comparison of current data to past data where possible, and assessment of the current water quality status of individual ponds. Since the completion of the Atlas in 2015, DMEA has continued to conduct PPALS summer sampling of selected ponds and worked to build consensus for the development of individual pond management plans.

Great Herring and Little Herring Ponds (GHP/LHP) were among the ponds initially prioritized for development of management plans because of a number of recent cyanobacteria blooms and public health advisories, as well as a motivated community, including the Herring Ponds Watershed Association (HPWA). HPWA has worked with DMEA on the collection of meaningful streamflow information, water quality sampling, and public education. CSP/SMAST, TMDL Solutions and DMEA have developed regular sampling protocols through the PPALS program and GHP/LHP-specific projects, including a 2016 survey of direct stormwater runoff discharges to GHP[8] and a follow-up 2020 stormwater monitoring on Eagle Hill Road.[9]

During 2020, CSP/SMAST and TMDL Solutions staff worked with the Town DMEA staff to develop a list of GHP/LHP-specific data gaps and accompanying tasks that would need to be addressed to complete a joint pond management plan, including measurement and water quality sampling of stream outflow at key points, characterization of the phytoplankton community, and assessment of the pond watersheds. These activities would be combined with historic data, including HPWA information, to develop a diagnostic assessment of the pond ecosystems,

[7] Eichner, E.M., B.L. Howes, and S. Horvet. 2015. Town of Plymouth Pond and Lake Atlas. Town of Plymouth, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 138 pp.

[8] CSP/SMAST Technical Memorandum. Great Herring Pond Stormwater Monitoring Project results. February 24, 2016. From: E. Eichner, TMDL Solutions and B. Howes, CSP/SMAST. To: K. Tower, Town of Plymouth. New Bedford, MA. 15 pp.

[9] TMDL Solutions Technical Memorandum. Eagle Hill 2019 Stormwater Monitoring Results. February 4, 2020. From: E. Eichner. To: K. Tower, Town of Plymouth. Centerville, MA. 9 pp.

which, in turn, would be used to assess management options. This document, the Great Herring and Little Herring Ponds Management Plan and Diagnostic Assessment, summarizes the results of these tasks, sets pond-specific water quality goals, and recommends a set of pond-specific strategies to restore this impaired system.

The present Management Plan is primarily composed of two sections: 1) a Diagnostic Summary of how GHP/LHP generally function based on the available historic water column data and data gap information and 2) a Management Options Summary, which reviews applicable management options, a recommended set of options, estimated costs associated with applicable options, and likely regulatory issues associated with implementation of options. It is anticipated that the Town will work through a process to review the recommendations and choose a preferred implementation strategy for restoration of GHP/LHP water quality.

II. Great Herring and Little Herring Ponds Background

Great Herring and Little Herring Ponds are both Great Ponds with surface areas of 419 acres and 81 acres, respectively.[10] The two ponds are linked by streams with an outlet stream from LHP flowing into the northern end of GHP and an outlet stream from GHP (*i.e.*, the Herring River) flowing to the Cape Cod Canal (**Figure II-1**). The Massachusetts Division of Fisheries and Wildlife (MassDFW) has available bathymetric maps for both ponds with maximum depths of 47 ft for GHP and 4 ft for LHP.[11] GHP has a public boat ramp and associated parking area at the south end (off Little Sandy Pond Road), while LHP has access through the David Alper Nature Preserve at the end of Little Herring Pond Road.

GHP and LHP are within the Herring River Area of Critical Environmental Concern (ACEC), which was designated by the state in 1991 (**Figure II-2**).[12] The ACEC was designated to protect the three public water supplies in the area, the herring run, the ponds, state-listed species (*e.g.*, the box turtle (*Terrapens carolina*) and spotted turtle (*Clemmys guttata*), and historical and cultural resources in the area. GHP, but not LHP, is listed as both a Priority Habitat of Rare Species and an Estimated Habitat of Rare Wildlife by MassDFW's Natural Heritage and Endangered Species Program (NHESP)(**Figure II-3**).

Review of US Geological Survey topographic maps show the increased development within the GHP/LHP area over the past 130 years. The earliest US Geological Survey topographic maps in 1886 show the stream connection between the ponds and the GHP outflow to the Monument River, which predated the Cape Cod Canal. This map shows there were 20 buildings along Herring Pond Road and Long Pond Road, but no other near the ponds (**Figure II-4**). The next available map is in 1921, which shows more buildings along Herring Pond Road and the first buildings along the western edge of GHP; there are no buildings around LHP. By 1940, additional buildings have been developed, a community between GHP and Island Pond has developed, and cranberry bogs have between GHP and LHP and smaller bogs along Herring Pond Road have been added to the map. The 1940 map also shows two buildings close to LHP, but none along its shoreline, and unpaved roads off Long Pond Road ending near GHP. These unpaved roads have become the current Lakewood Drive, Tamarack Road and Nightingale Road. By the next available map in 1951, the building along these roads had increased, the community

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[10] Eichner, E.M., B.L. Howes, and S. Horvet. 2015. Town of Plymouth Pond and Lake Atlas. Town of Plymouth, Massachusetts.
[11] https://www.mass.gov/info-details/massachusetts-pond-maps (accessed 3/3/02)
[12] https://www.mass.gov/service-details/herring-river-watershed-acec (accessed 3/3/02)

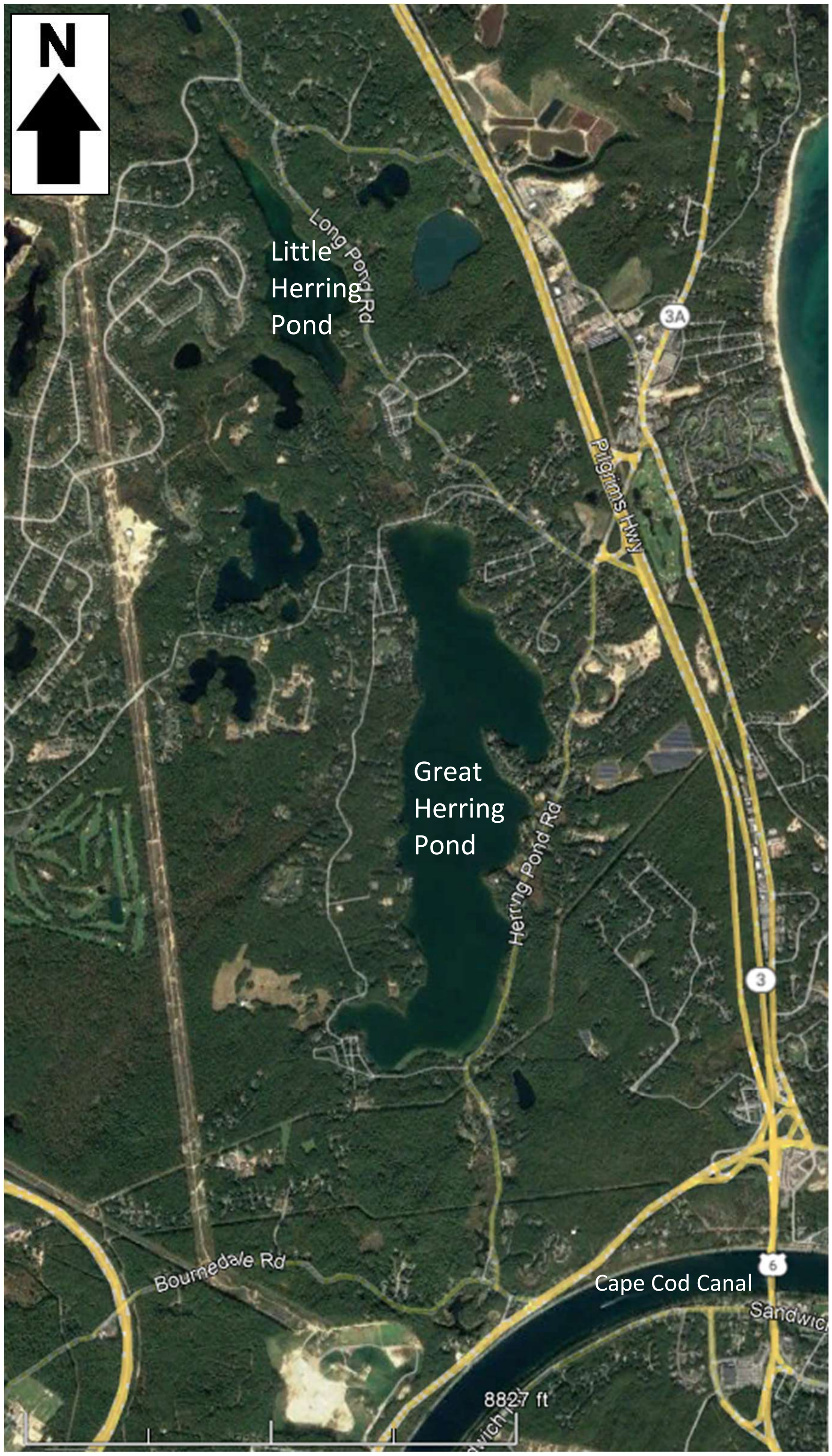

Figure II-1. Great Herring and Little Herring Ponds Locus. Great Herring and Little Herring Ponds are Great Ponds with surface areas of 419 acres and 81 acres, respectively. The ponds are linked by streams with a LHP stream flowing into GHP and a GHP outlet stream flowing into the Cape Cod Canal. Map is aerial photograph from 10/23/21 (Google Earth).

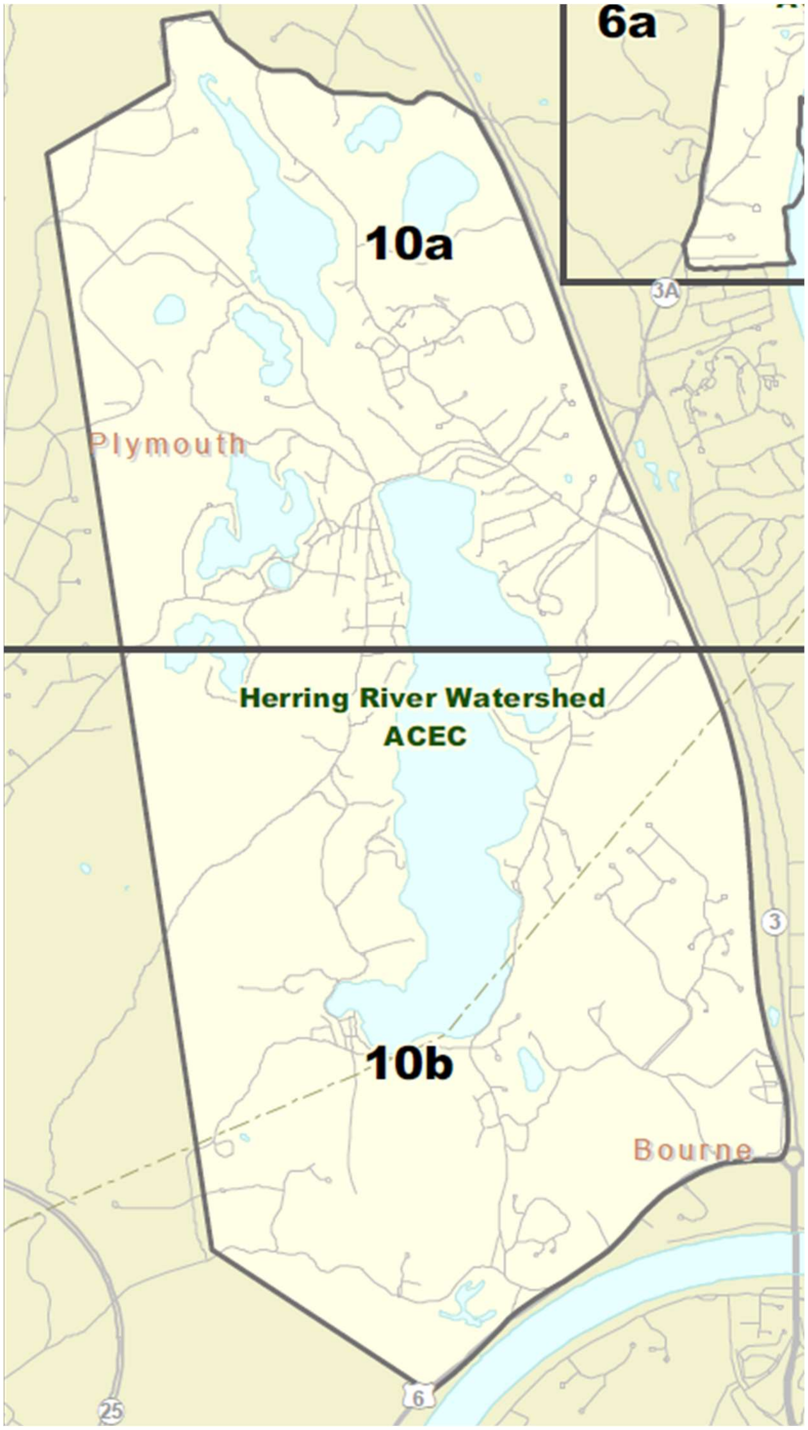

Figure II-2. Herring River Area of Critical Environmental Concern. Herring River ACEC was designated by the Massachusetts Secretary of Environmental Affairs in 1991. The ACEC included both Great Herring Pond and Little Herring Pond, as well as the Herring River to the Cape Cod Canal. The ACEC was designated to protect the three public water supplies in the area, the herring run, the ponds, state-listed species (*e.g.*, the box turtle (*Terrapens carolina*) and spotted turtle (*Clemmys guttata*), and historical and cultural resources in the area. Figure is section of map at: https://www.mass.gov/files/documents/2016/08/si/herring-river-watershed-acec-index-map.pdf

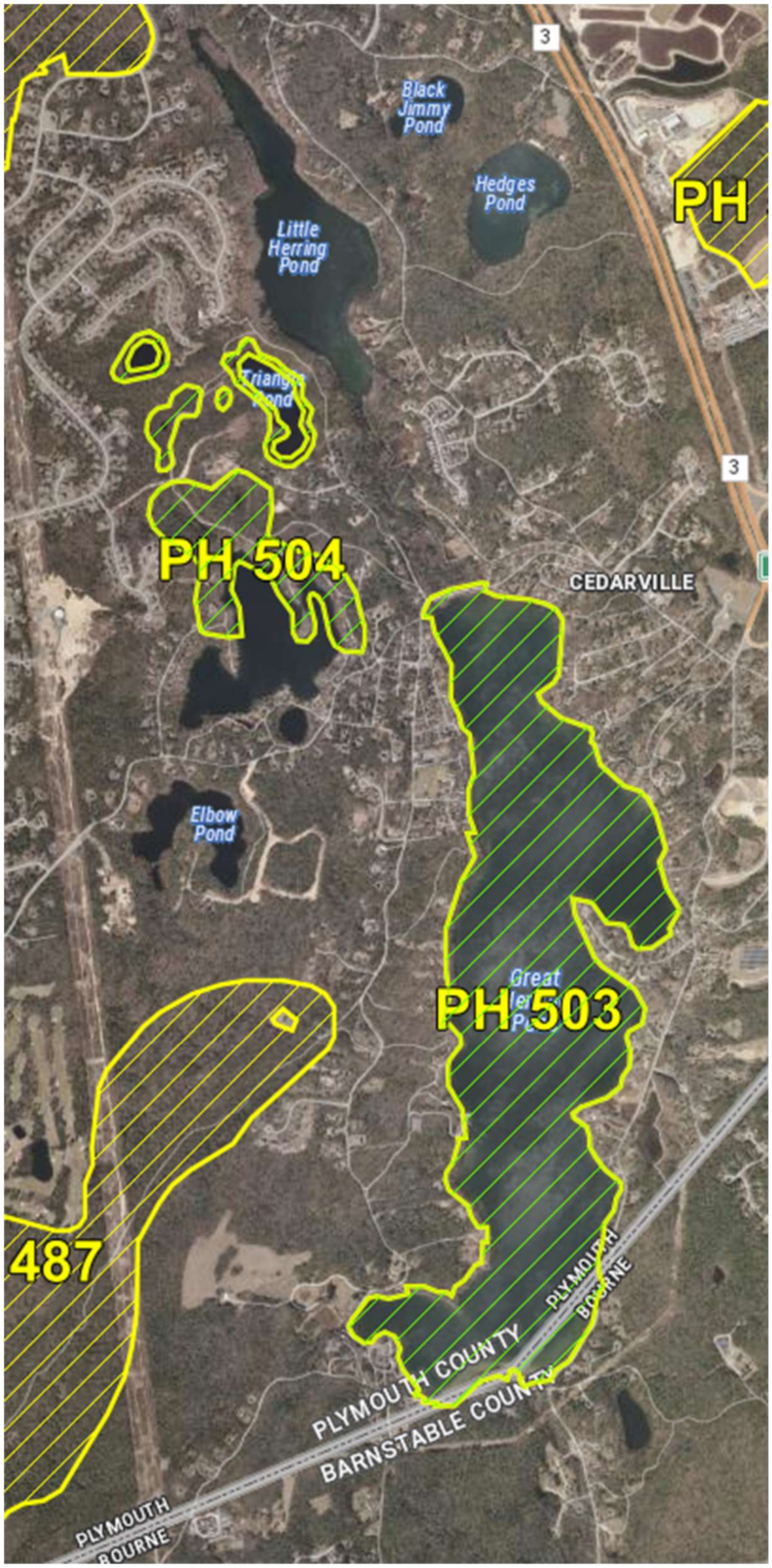

Figure II-3. Great Herring Pond NHESP Classification. GHP, but not LHP, is listed as both a Priority Habitat of Rare Species and an Estimated Habitat of Rare Wildlife by MassDFW's Natural Heritage and Endangered Species Program (NHESP).

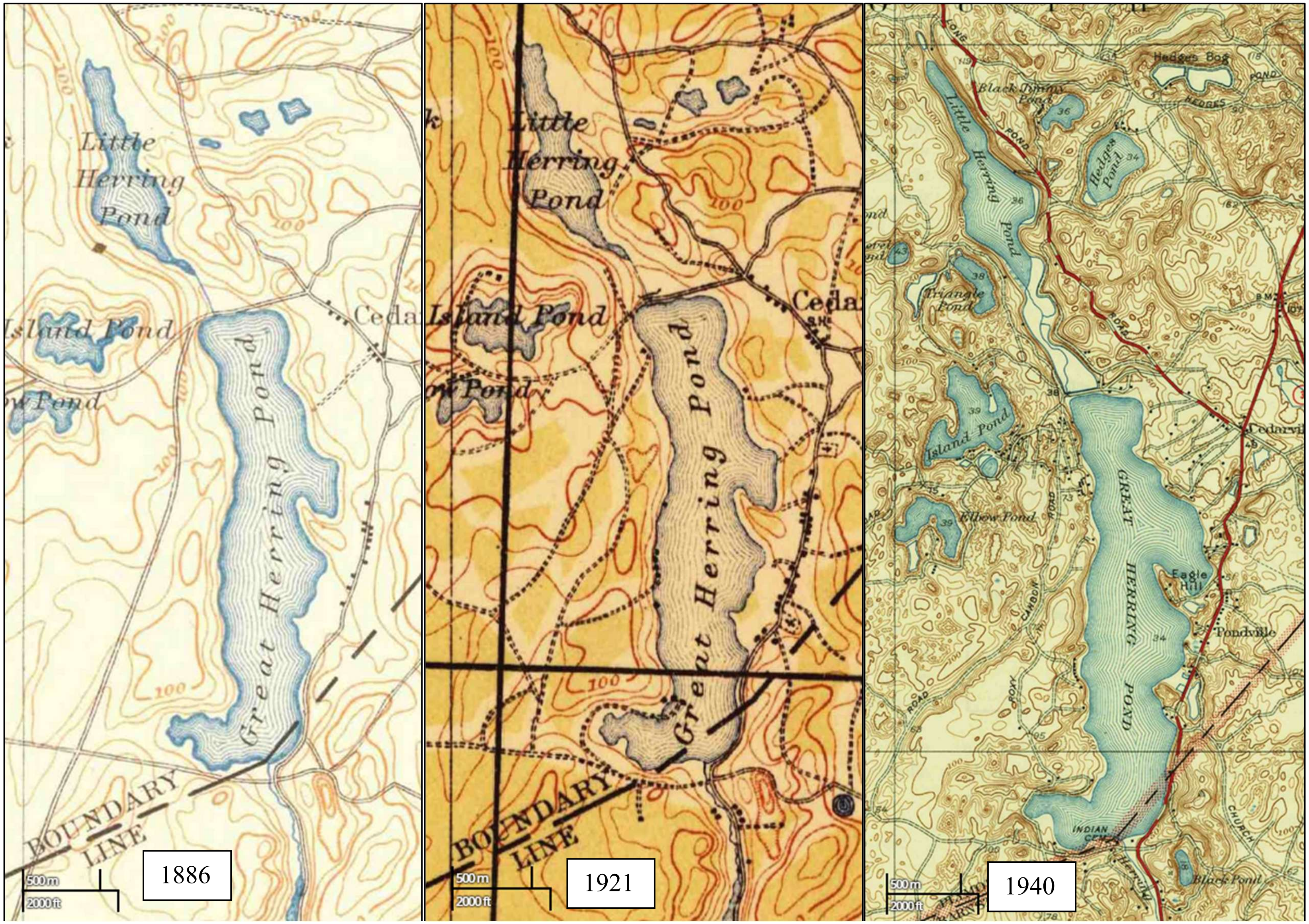

Figure II-4. GHP/LHP Historical USGS Topographic Maps: 1886, 1921, 1940. First available map in 1886 shows buildings along Herring Pond Road and Long Pond Road, as well as stream connection between LHP and GHP. 1921 map show more buildings along the roads, along with the first buildings along the western shore of GHP; no buildings are shown around LHP. By 1940, more development has occurred, including a community between Island Pond and GHP and more roads to the GHP; two building are near LHP, but there are none along its shoreline. The 1940 map also indicates a cranberry bog between the GHP and LHP and smaller bogs off Herring Pond Road.

between GHP and Island Pond had grown, including many more houses along the GHP shoreline, and the first buildings along the LHP shoreline had been built (**Figure II-5**). By the next map in 1967, the previous development trends had continued and Route 3 and its Cedarville/Herring Pond Road interchange had been constructed. Additional development was notable in the Lake Avenue area, along Carter's Bridge Road, and along and off of Cahoon Road, the southern portion of the community between GHP and Island Pond. USGS has been working on another update of the topographic map since 2012 and the current version does not have buildings included, but project staff created a map showing buildings using MassGIS coverage based on a 2016 aerial survey. This maps shows extensive increases in building counts throughout the GHP/LHP area. These increases are most pronounced around LHP, although much of the development seems to setback from the pond. Review of current development water quality impacts on the pond are discussed in the watershed section of this report.

There are a number of public water supplies in the GHP/LHP area (**Figure II-6**). These public water supplies include large municipal supplies, such as the Plymouth Water Company and the North Sagamore Water District, and a number of smaller suppliers for churches, campgrounds, and mobile homes. MassDEP permitting requires delineations of contributing areas to large supply wells, called Zone 2s. MassDEP also requires a minimum protective radius around public water supplies, which is called an Interim Wellhead Protection Area (IWPA). All of the smaller public water supplies in the GHP/LHP area have IWPA's delineated. Since some of the Zone 2 contributing area extend up to GHP, it is likely that these wells indirectly remove some water from GHP.

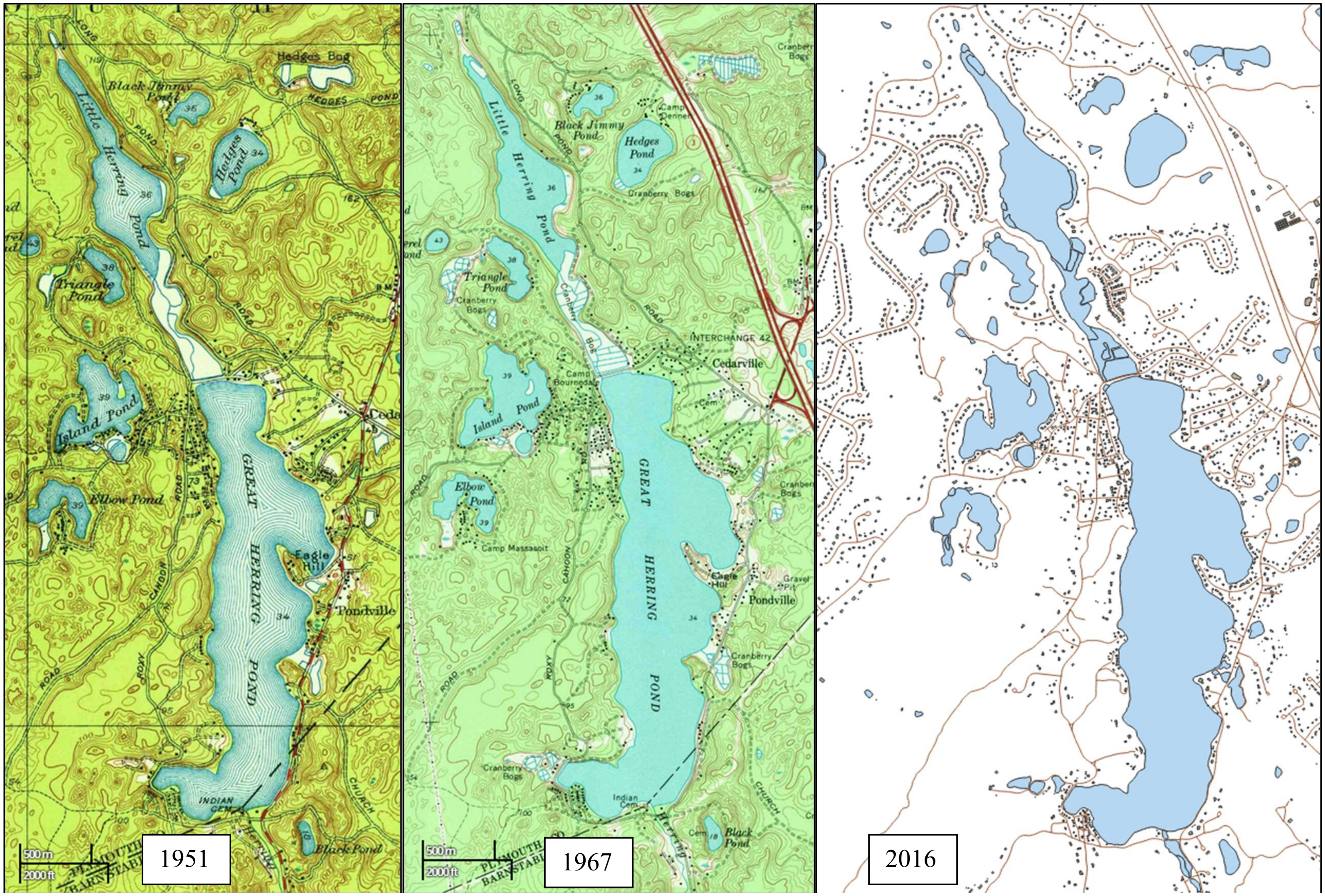

Figure II-5. GHP/LHP Historical USGS Topographic Maps (1951, 1967) and 2018 MassGIS buildings. Between 1940 and 1951, buildings began to be developed on the roads off Long Pond Road, more buildings were developed between GHP and Island Pond and near LHP, and portions of Cahoon Road were paved. Additional development had occurred by 1967, including the addition of a Route 3 interchange. USGS is still updating a current map, but MassGIS coverages based on 2016 aerial survey of buildings show greatly increased development around both ponds since 1967.

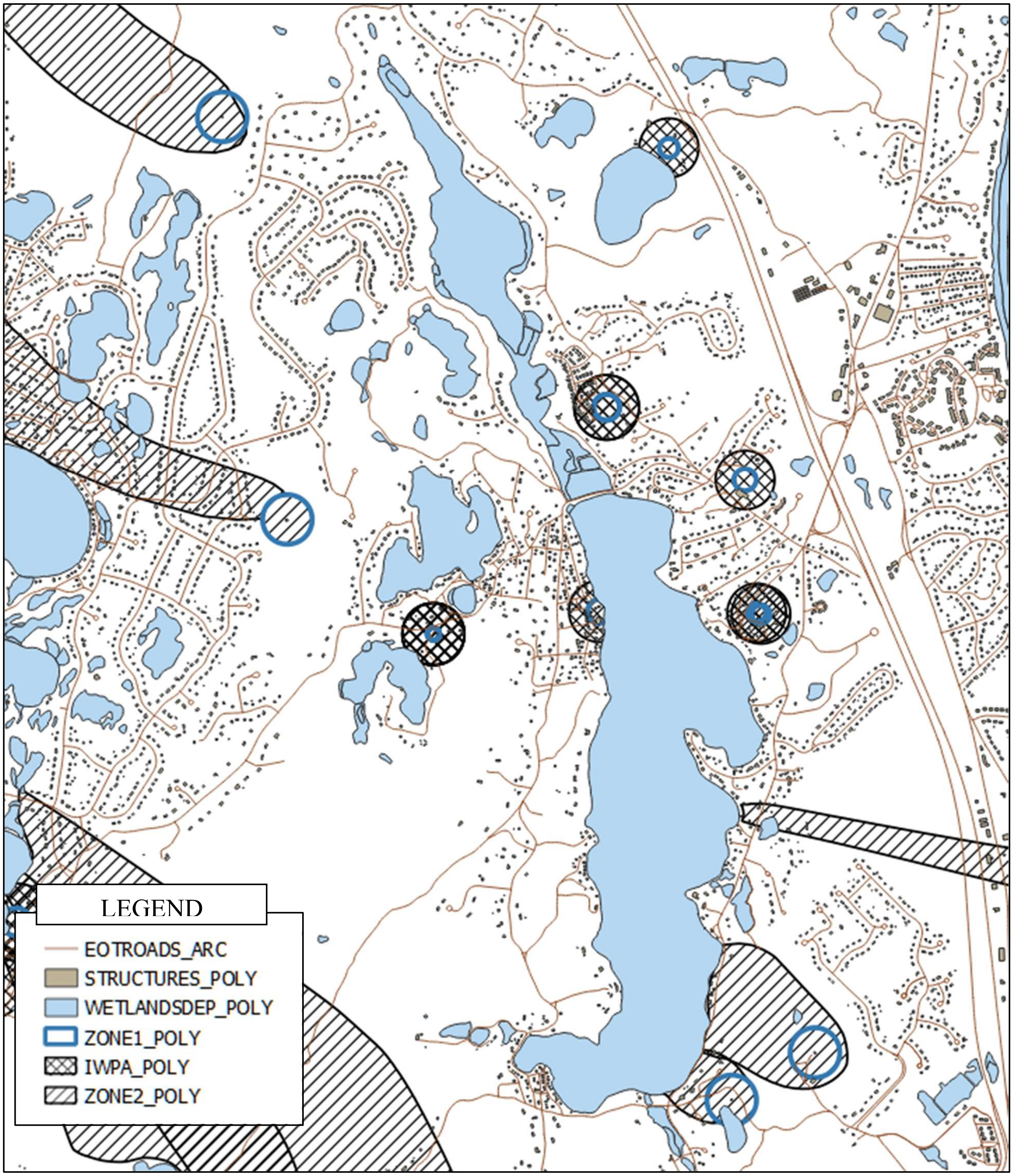

Figure II-6. Public Drinking Water Protection Areas near GHP/LHP. The GHP/LHP area includes a number of contributing areas to municipal public water supplies (Zone 2s) and wellhead protection areas (IWPAs) to smaller public supplies, such as churches and campgrounds. Since a number of the Zone 2s extend to GHP, they likely remove some water indirectly from GHP.

III. Great Herring and Little Herring Ponds Regulatory and Ecological Standards

Much of the legal basis for management of ponds and lakes in Massachusetts is based on the surface area of a given water body. GHP and LHP have surface areas greater than 10 acres, which means that they are Great Ponds under Massachusetts Law[13] 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.[14] 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."[15] Additional distinctions are made between warm and cold water fisheries.

Under these surface water regulations, GHP and LHP would be classified as Class B waters and warm water fisheries. LHP is too shallow to sustain a cold water fishery as MassDEP regulations require temperatures below 20°C throughout the year for cold water fisheries. On the other hand, GHP would appear to have sufficient depth to sustain temperature layering/stratification, but available historical monitoring data (discussed below) shows that the pond only occasionally stratifies, so it too would not be able to consistently sustain low enough temperatures for a cold water fishery. 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 GHP/LHP diagnostic assessment and water quality management planning to address state regulatory standards, we have focused on the Class B warm water regulatory standards, which means that the following numeric standards apply:

a) dissolved oxygen shall not be less than 5.0 mg/L,
b) temperature shall not exceed 83°F (28.3°C),
c) pH shall be in the range of 6.5 to 8.3 and not more than 0.5 units outside of the natural background range, and
d) *E. coli* or enterococci bacteria shall not exceed 126 or 35 colony forming units (cfu) per 100 ml, respectively for a geometric mean of all samples collected within a 90-day or smaller interval OR have more than 10% of all samples exceed 410 or 130 cfu/100 ml, respectively.

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(1)(d)6. and (6)(b) as a

[13] MGL c. 91 § 35
[14] 314 CMR 4.00
[15] 314 CMR 4.05(3)(a)

"Treated Water Supply", they shall be suitable as a source of public water supply with appropriate treatment. 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."[16]

Given that both ponds have surface areas greater than 10 acres, GHP and LHP are classified as Great Ponds under Massachusetts law. Great Ponds are publicly-owned waters of the Commonwealth. GHP is listed in the most recent EPA-approved Massachusetts Integrated List of surface waters as a category 5 surface water.[17] Category 5 is for impaired waters requiring a Total Maximum Daily Load (TMDL). Waters are classified as impaired if they do not attain Massachusetts minimum water quality standards.[18] A TMDL is a target load of a contaminant that, if attained, will adequately address the water impairments in a water body. In the most recent Integrated List, GHP is impaired due to low dissolved oxygen. LHP is assigned to Category 2 in the Integrated List: "Attaining some uses; other uses not assessed." According to the List, LHP is attaining fish, other aquatic life, and wildlife uses, but has not been assessed for: a) aesthetics, b) fish consumption, c) primary contact recreation (*e.g.*, swimming), d) secondary contact recreation (*e.g.*, boating), and e) shellfish harvesting. Though a number of ponds in the southeastern Massachusetts ecoregion have been identified as being impaired, MassDEP has approved only one phosphorus TMDLs in Massachusetts in the last 14 years and that was for White Island Pond in Plymouth.[19] Monitoring and analysis completed for the current GHP/LHP Management Plan could be used to update the classifications of the ponds on the Integrated List.

Advancing regulatory attention on pond management has been a challenge in the Plymouth/Cape Cod ecoregion, but a number of efforts have provided necessary guidance for the development of management strategies. Barnstable County, through the Cape Cod Commission (CCC), began a snapshot pond and lake monitoring program in 2001 in coordination with CSP/SMAST with the goal of providing reliable data for future prioritization of pond assessments, management plans, and TMDL development.[20] The CCC used initial 2001 snapshot results from over 190 ponds and lakes to develop potential ecoregion-specific nutrient thresholds.[21] This effort suggested a target TP concentration range of 7.5 to 10 µg/L for sustaining unimpaired conditions in ponds and lakes. 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 regional reference criteria at the time.[22] These ecoregion-specific thresholds are guidance targets and have not been formally adopted as regulatory standards by MassDEP or any ecoregion towns. Since Cape Cod and Plymouth are in the same ecoregion,

[16] 314 CMR 4.05(3)(b)

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

[18] 314 CMR 4

[19] USEPA TMDL tracking: https://www.epa.gov/tmdl/region-1-approved-tmdls-state#tmdl-ma (accessed 3/4/22).

[20] The Cape Cod PALS Snapshot has been completed every year between 2001 and 2021.

[21] 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.

[22] 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.

these threshold ranges provide initial guidance for assessing conditions in GHP and LHP, but may be modified as all the available data is reviewed.

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.[23] 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 Great Herring and Little Herring Ponds identified when water quality conditions were acceptable and this provided guidance on management strategies to sustain acceptable conditions.

IV. Synthesis of Historical Data for Great Herring and Little Herring Ponds

Available historic data for GHP and LHP has been collected by the HPWA and the Town through the PPALS. This data included water quality samples from over 10 pond stations, stormwater runoff stations, and the inflow and outflow streams. Some of this data is useful, but some of this data, especially older data, was collected without important secondary information, such as the depth samples were collected, temperature, dissolved oxygen, etc. The Town has recently approved a Quality Assurance Project Plan (QAPP) to standardize volunteer water column data collection and overall diagnostic assessment data collection.[24] Project staff reviewed the available data and utilized selected data in the diagnostic assessments of GHP and LHP. A summary of findings from the historical data is presented in this section.

IV.A. GHP Historical Pond Data

GHP has had samples collected utilizing a variety of field procedures and laboratory assays and at a number of sampling stations (**Figure IV-1**). Water quality samples were first collected from GHP as part of 1970s-era baseline survey of a number of Plymouth ponds.[25] It is not clear in this survey report when data was collected, but the single listed temperature reading at 1 ft depth was 18°C, which is likely early summer or late fall. Four water samples were collected, one at the midpoint in each half of the pond and one each at the pond inlet and outlet. Collected samples were assayed for total phosphorus (TP), nitrate-nitrogen (NO3-N), alkalinity, hardness, and 10 metals. It is not clear what depth the pond samples were collected from or the assay methods used. The Secchi clarity reading was 8 ft (2.4 m) and it was noted that blue-green and green phytoplankton were present throughout the pond. Submerged rooted plants were only noted along the northernmost shoreline and in the southwestern cove near Lake Avenue.

More extensive water column sampling of GHP and LHP began in 2008, but it took a few years before consistent protocols were implemented, such as always collecting dissolved oxygen and

[23] 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.

[24] Town of Plymouth Ponds and Lakes Stewardship (PALS) Program Quality Assurance Project Plan 2020-2022. 2020. Approved by MassDEP, 10/1/20. Prepared by K. Tower, Plymouth DMEA and E. Eichner, CSP/SMAST. 56 pp.

[25] Lyons-Skwarto Associates. 1970. A Base Line Survey and Modified Eutrophication Index for Forty-One Ponds in Plymouth, Massachusetts. Volumes I-V. Westwood, MA.

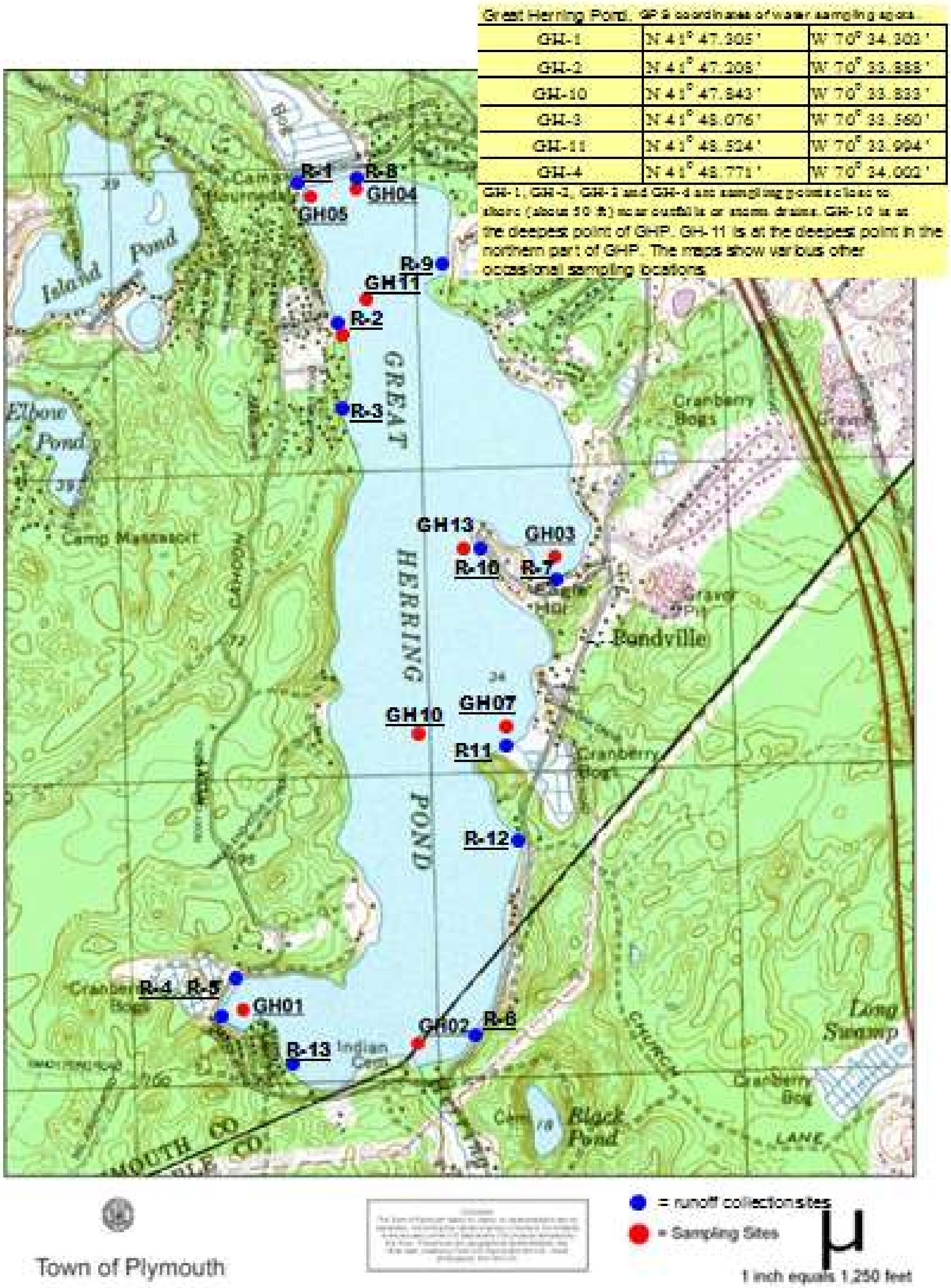

Figure IV-1. Historical GHP Sampling Stations. Water quality samples have been collected at a number of stations since 2008, although only GH1, GH2, GH3, GH4, GH10, and GH11 have been regularly sampled. GH10 is near the deepest location in the pond and has the most sampling dates. GH10 has also been sampled according to procedures in the Town Pond and Lake Sampling QAPP since 2016. Stormwater runoff and stream inflow and outflow have also been collected.

temperature readings and sampling at deeper depths. Among these earliest samplings, there are some important data. For example, the Town conducted GHP monitoring on 8/9/08,[26] 4/18/09,[27] and 6/18/11.[28] These Town efforts included water column profiles of temperature, dissolved oxygen (DO), Secchi clarity readings, some with pH profiles, phytoplankton water column sampling, and macrophyte surveys. It is not stated where in the pond readings were collected, but the shallowest deep reading among the profiles was 11 m, so the readings must have been collected near the deepest point in the pond. These temperature profile readings tended to show well mixed conditions, but the August 2008 readings showed strong stratification at 10 m depth. Most of the subsequent temperature profiles showed that temperature stratification does not occur frequently; of the 26 available historical temperature profiles collected between April and October, only three had temperature stratification (**Figure IV-2**)

Review of available historical GHP DO profiles showed, however, that deep anoxia occurs much more frequently than stratification. Ten of the 26 available historical DO profiles had anoxia and another four profiles had hypoxia with DO concentrations less than 4 mg/L (**Figure IV-3**). Since anoxia is not strongly related to temperature stratification in GHP, phosphorus release from the pond sediments driven by anoxia has the potential to mix into the rest of pond water column anytime there is sufficient wind to mix the whole water column. This setting means that a relatively large phosphorus mass deep in the pond could be rapidly mixed into the shallow water column and prompt an algal bloom. The amount of potentially available phosphorus in the sediments was measured during the data gap surveys completed for this project.

Secchi clarity readings have been collected at GHP on 32 dates between 2008 and 2019 (**Figure IV-4**). Secchi readings are an aggregate measurement of water column factors diminishing light penetration within the water column; in southeastern Massachusetts phytoplankton is usually the primary factor impacting clarity. The available dataset includes Secchi measurements collected in shallow coves where light penetrated to the bottom. After filtering all of the data to focus on light penetration at deeper sites, readings show that clarity generally decreases by 2 to 3 m from the spring to late summer, but this varies from year to year. The average April/May reading (5.2 m) is significantly higher ($\rho<0.05$, T test) than average August/September readings (2.6 m). The decrease in clarity during the summer would be consistent with larger phytoplankton populations and higher phosphorus concentrations.

Historical water quality samples have been collected at 15 stations (**see Figure IV-1**). Many of these stations have only been sampled a handful of times and, as noted, many of the samplings do not include measures of depth, temperature, and dissolved oxygen that are important for interpretation of the water quality results. Earliest samples in 2008 and 2009 were sampled for a suite of assays that do not tend to be ecologically important, such as sodium, manganese, magnesium, etc. Many of the resulting concentrations from these earlier assays were less than the assay detection limits, which is consistent with the sandy aquifer materials around GHP and LHP. Many of the samples were also inconsistent for ecologically important assays, such as

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[26] Technical Memorandum. Pond Monitoring Program: Results for August 2008. August 27, 2008. To: D. Gould and K. Michaelis, DPW Environmental Management, Town of Plymouth. From: D. Worden, Limnologist/Biologist. 7 pp.

[27] Technical Memorandum. Pond Monitoring Program: Results for April 2009. May 5, 2009. To: D. Gould and K. Michaelis, DPW Environmental Management, Town of Plymouth. From: D. Worden, Limnologist/Biologist. 4 pp.

[28] Technical Memorandum. Great Herring Pond and Little Herring Pond Monitoring Program. June 29, 2011. To: D. Gould and K. Michaelis, DPW Environmental Management, Town of Plymouth. From: D. Worden, Limnologist/Biologist. 7 pp.

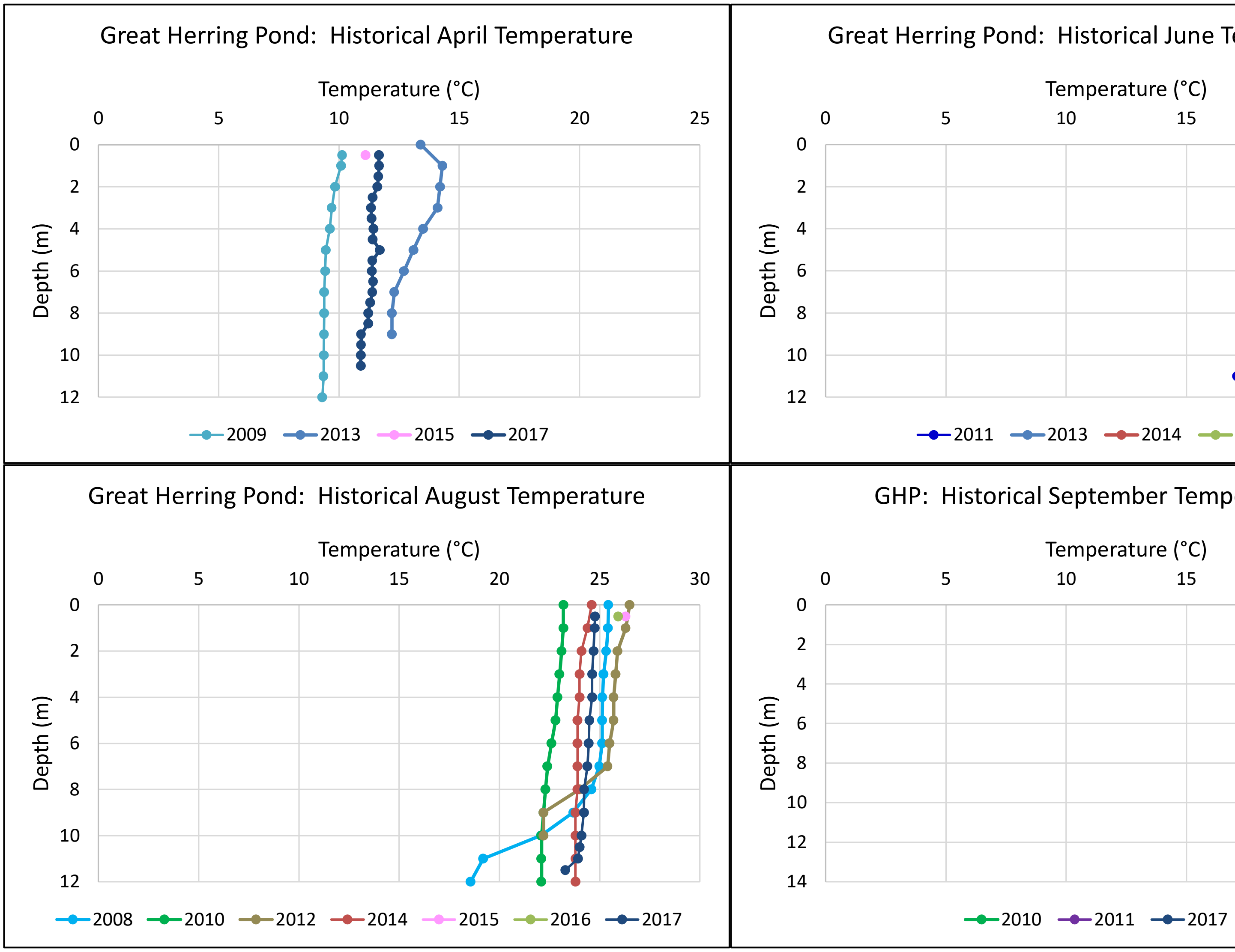

Figure IV-2. GHP Historical Temperature Profiles at Deep Basin (GH10) from Selected Months. Availab readings at station GH10 show that the pond generally has no significant stratification and little variability in m of stratification means the whole water column may mix if there is sufficient wind across the water surface historical temperature profiles, only three had temperature stratification (once in July and two in August).

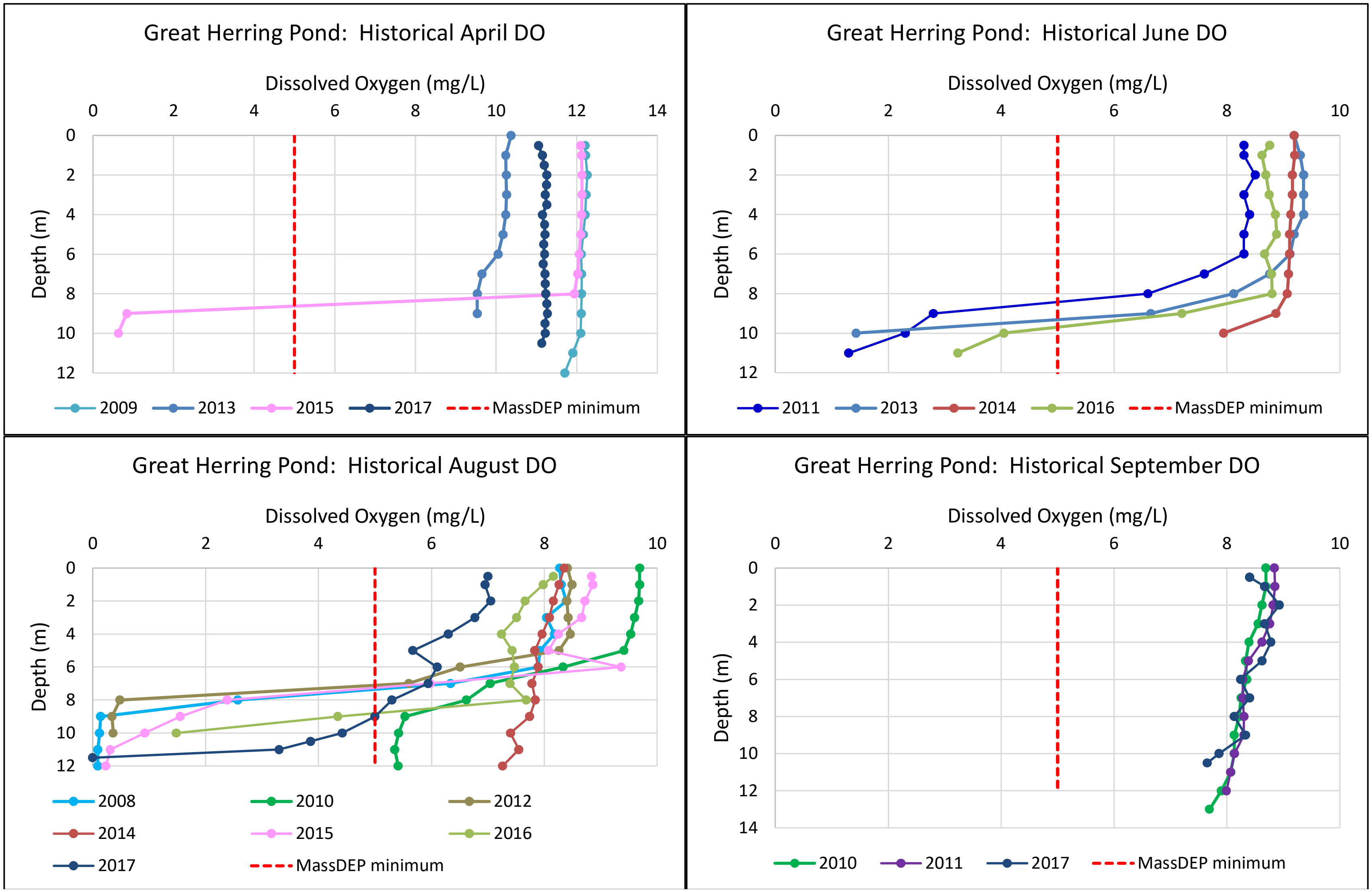

Figure IV-3. GHP Historical Dissolved Oxygen Profiles at Deep Basin from Selected Months. DO profile readings at station GH10 show variability from year to year, but almost every month has at least one profile that had deep anoxia. Of the 26 available historical DO profiles, 10 had anoxia and another four had deep DO <4 mg/L. Anoxia was not related to temperature stratification, so anoxia of sufficient duration would release phosphorus bound in the sediments and provide a source for phytoplankton blooms if mixed into the upper water column.

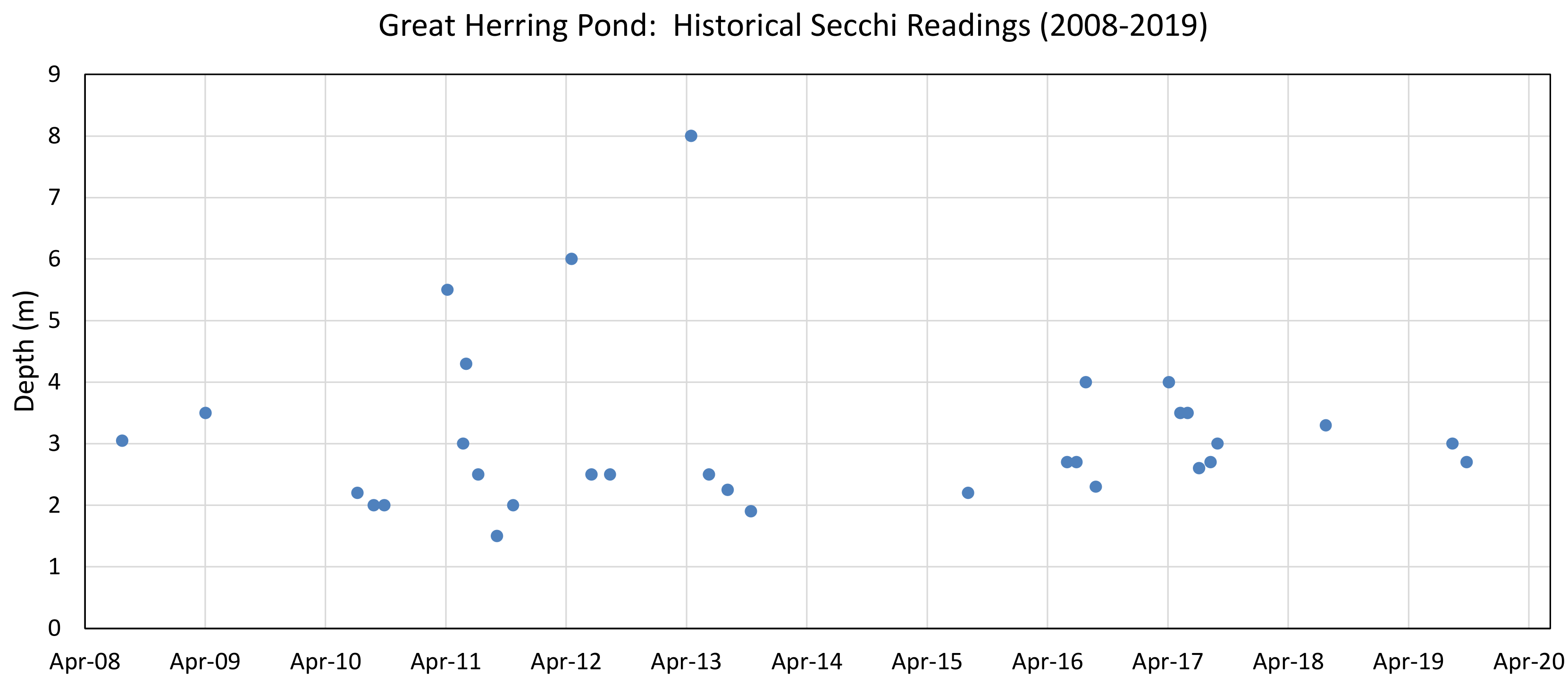

Figure IV-4. GHP Historical Secchi Readings (2008-2019). Secchi/clarity readings have been collected 32 times between 2008 and 2019 at GHP. Average readings in each month have high variability, but the average April/May Secchi/clarity reading of 5.1 m is statistically higher ($\rho<0.05$, T test) than the August/September average of 2.6 m. Seasonal loss of clarity in ponds and lakes in southeastern Massachusetts tends to be exclusively due to phytoplankton density.

including total phosphorus (TP), but not total nitrogen (TN). None of the samples were assayed for phytoplankton pigments: chlorophyll a or pheophytin a. Even with these acknowledged limitations, project staff compared average concentrations for TP, TN, pH, and N:P molar ratios and generally found no statistically significant differences between the six stations that had been regularly sampled. Review of these data found unexpectedly high variability in the nutrient concentrations even on shallow samples taken weeks apart. Some of this may be due to the variability inherent in the system, but review of the N:P ratios shows that they have some exceptionally low and high values (<5 and >100, respectively), which are largely inconsistent with monitoring in other ponds in southeastern Massachusetts. These results may be due to the methods used for TP and TN, but it is unclear without further forensic review. Average GHP concentrations of pH, alkalinity, TN, and TP were generally consistent with a nutrient enriched pond (6.98, 8.71 mg/L, 0.45 mg/L, and 41 µg/L, respectively). The average molar N:P ratio is 56, which indicates that phosphorus controls the water quality conditions.

The sampling station closest to the deepest point in GHP (GH10) has the most consistent collection of DO and temperature profiles to accompany water quality sampling (see **Figures IV-2 and IV-3**). GH10 also has samples collected at various depths within the water column, 0.5 m, 3 m, 9 m, and deep (average 10.8 m), consistent with the Town's pond and lake sampling QAPP.[29] Samples have been collected since 2009, but most of the samples collected at depths within the water column have occurred since 2016 (n=8 for most assays collected since 2016). Most of these samples are monthly samples collected in 2017 from April through September. Samples collected since 2016 have included assays conducted at the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth using the same procedures used in all PPALS Snapshot samples. Water quality sample assays have included: pH, alkalinity, chlorophyll a, pheophytin a, TN, and TP. Since most of the sampling dates with samples throughout the water column were during 2017, project staff focused on these results and the changes during the year and use them to compare to samples collected as part of the data gap surveys.

IV.B. LHP Historical Pond Data

The initial available water quality sampling of LHP was during the same 1970s-era baseline survey of a number of Plymouth ponds when GHP was also sampled.[30] LHP had more extensive sampling than GHP during this project, including monthly stream inflow and outflow readings from March through October and 12 water quality samplings: monthly in March, April, September and October and twice a month in May, June, July, and August. Water quality samples were collected at two stations within the pond and at the pond outlet; the two stations were at 1) a northern location, likely approximately 2 ft deep and 2) a mid-point location near the deepest point (6 to 8 ft deep based on Secchi readings). Sample results are reported for total phosphorus (TP), nitrate-nitrogen (NO3-N), nitrite-nitrogen (NO2-N), total Kjeldahl nitrogen (TKN), specific conductance, pH, DO, temperature, and hardness during each of the samplings and one sampling for 10 metals. The plant survey completed for this baseline survey noted dense to very dense *elodea* throughout most of the pond except for a swath from the deepest location to the outlet (**Figure IV-5**). The report is not clear what depth the samples were collected from, the assay methods used, or the dates of all samplings, but this is the most frequent sampling throughout a year until sampling completed for the current report.

[29] Town of Plymouth Ponds and Lakes Stewardship (PALS) Program Quality Assurance Project Plan 2020-2022.

[30] Lyons-Skwarto Associates. 1970.

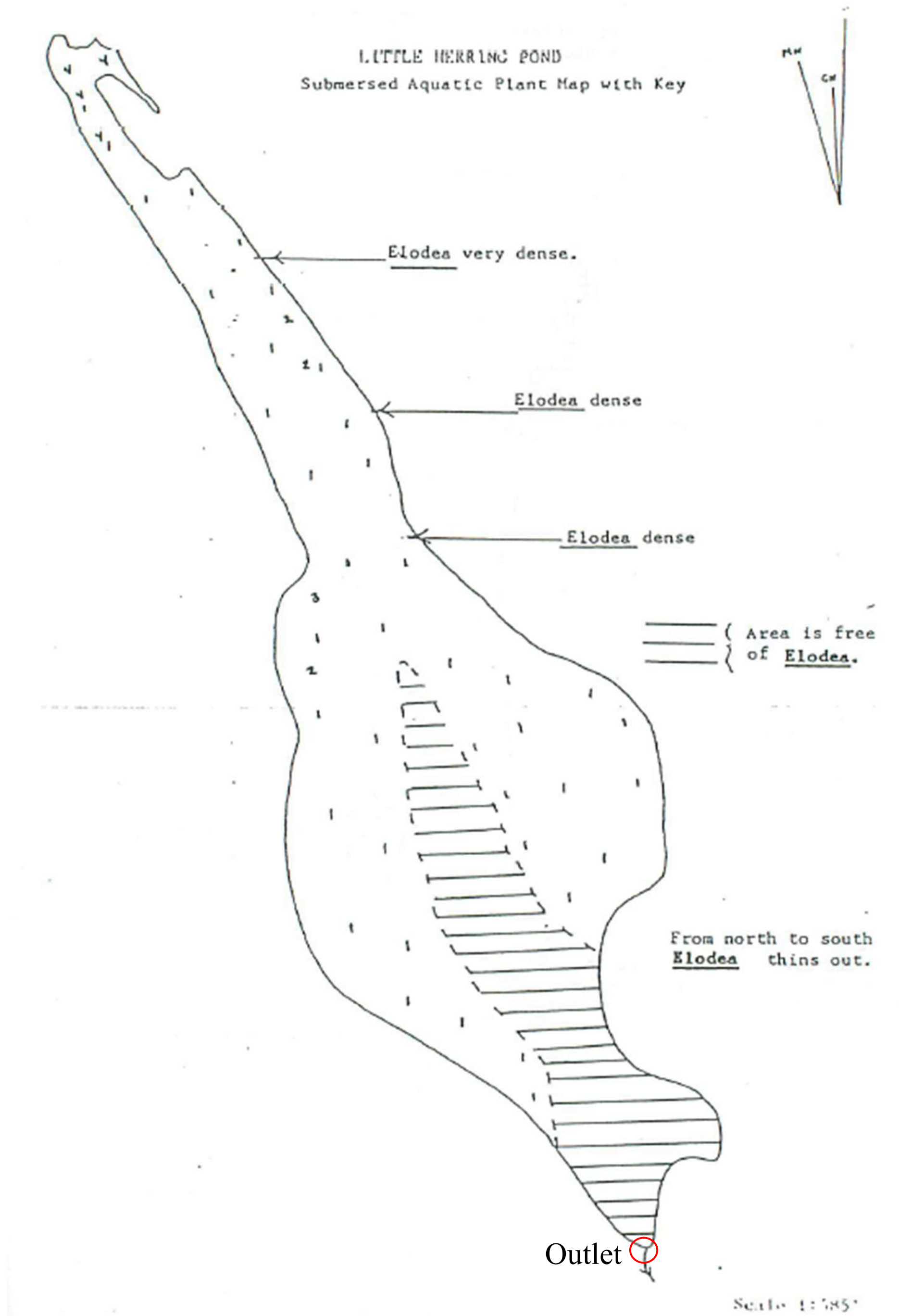

Figure IV-5. Little Herring Pond Macrophyte Survey: Late 1970's. This survey showed that most of LHP bottom was covered by dense waterweed (*elodea* spp.) except for a portion from the deepest point to the pond outlet (marked by horizontal lines).

The 1976 data has some inconsistencies, but indicates a well-oxygenated and relatively clear water column. All DO readings were above the 5 mg/L MassDEP minimum and varied between 7 and 10 mg/L. Secchi readings varied between 6 and 8 ft although the presented bathymetric data said the maximum depth of LHP was 6 ft. The clarity readings that the Secchi disk was regularly visible on the pond bottom, but this is not noted in the report. There is a table with phytoplankton cell counts which is unclear, but presented numbers are all low (<200 cells/ml) and cell counts this low would be consistent with clear water. However, average TP and TN concentrations were relatively high: 36 µg/L and 0.82 mg/L, respectively (**Figure IV-6**). Review of 1976 N:P ratios show that phosphorus generally controlled water quality conditions, but the ratio decreased from 80 to 90 in the spring to 28 to 34 from late July to mid-September. This change was due to an increase in TP concentrations, which suggests that deep DO levels became anoxic and caused sediments to regenerate TP that was bound in the sediments in the spring.

Water quality samples were collected by HPWA and the Town 35 times between 2009 and 2018. These samples generally have similar constituent concentrations for those collected in 1976, but include other key measures that were not completed in 1976, such as chlorophyll a, pheophytin, and alkalinity, but are often missing DO, temperature, and Secchi clarity readings. N:P ratios for samples with both TN and TP between 2009 and 2018 average >84, which clearly indicates that phosphorus controlled water quality conditions. Average TP and TN concentrations were relatively high and largely consistent with the 1976 averages: 35 µg/L and 0.67 mg/L, respectively.

IV.C. GHP and LHP Historical Streamflow Data

Historical streamflow measurements were extensively collected by HPWA in 2009 and 2011-2013 at the outflow from LHP, the inflow into GHP, and the outflow from GHP (**Figure IV-7**). Collection frequencies varied, but ranged from 67 to 109 readings annually at the stations in 2011-2013 with a total of 241, 259, and 342 readings available at the respective stations **(Figure IV-8)**. The density of these readings is significantly greater than the Town QAPP minimum requirements for streamflow measurements for pond diagnostic assessments.[31]

Comparison of average flows show that GHP generally loses some of its inflow. This relationship occurs in the overall dataset and the 2011 and 2012 calendar years, but not in 2013. The average outflow from LHP was 10.06 cfs (n=241). The average inflow into GHP from the stream connecting LHP and GHP was 11.17 cfs (n=259). These averages are significantly different (ρ<3E-15; T test) and likely reflect the groundwater gradients that surround the two ponds and the generalized groundwater flow toward the Cape Cod Canal. The increase in flow is approximately 0.04 cfs per 100 ft of stream between LHP and GHP.

Average flow out of GHP is 9.9 cfs (n=342). Comparison of the average GHP outflow to GHP inflow shows the GHP outflow is significant less than the GHP inflow (ρ<9E-08; T test). The average loss of flow within GHP is 1.27 cfs or 0.82 million gallons per day (MGD). Likely sources for this loss are evapotranspiration off the pond surface, return of groundwater to the surrounding aquifer, and withdrawals by irrigation wells and public water supplies in the area.

[31] Town of Plymouth Ponds and Lakes Stewardship (PALS) Program Quality Assurance Project Plan 2020-2022. 2020.

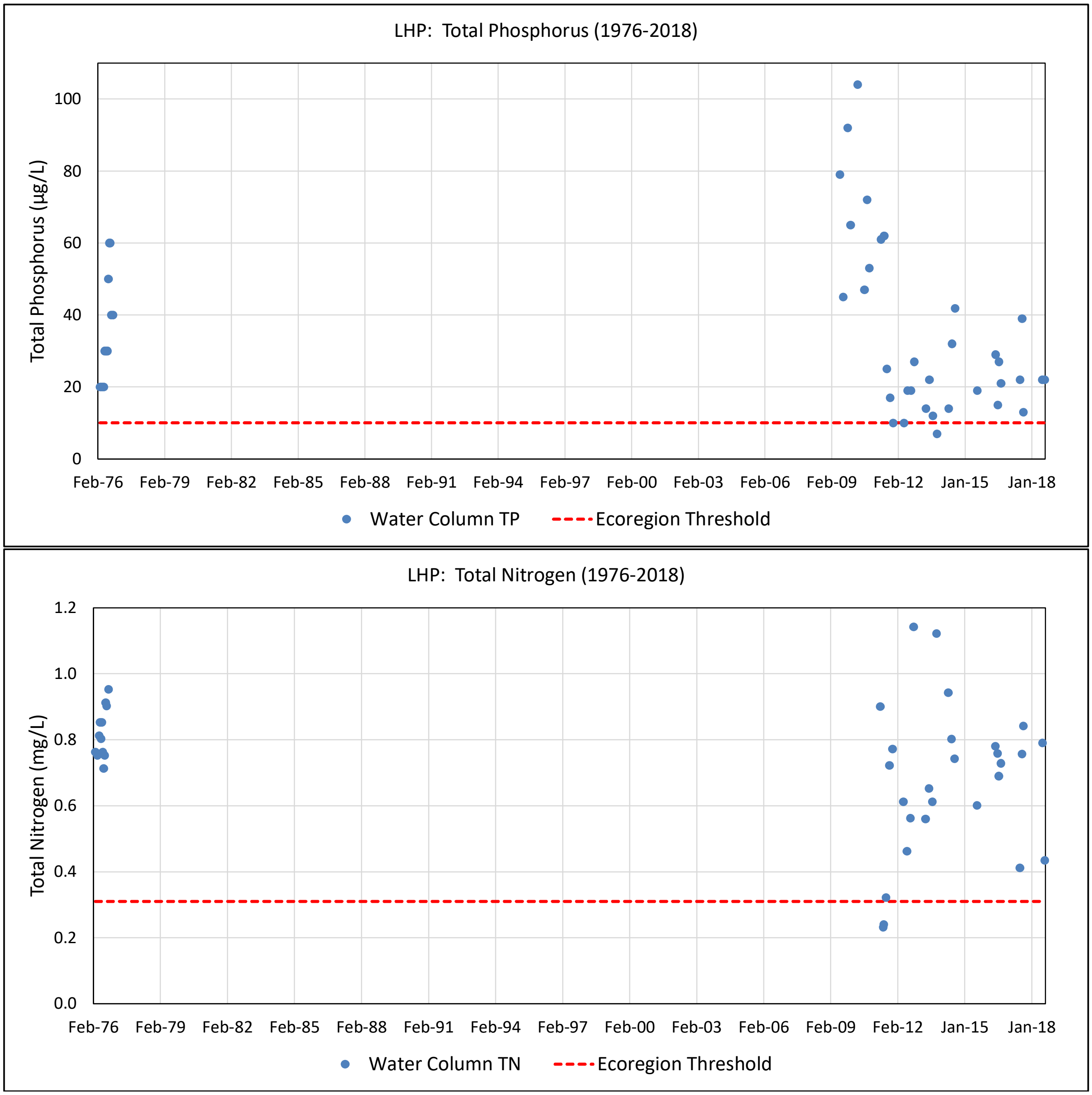

Figure IV-6. LHP: Historical Water Column Total Phosphorus and Total Nitrogen Concentrations. Available water quality sampling results show that LHP was sampled extensively in 1976 and then not again until 2009. Average concentrations in 1976 and 2009-2018 were similar for both TN and TP: 0.82 mg/L and 0.67 mg/L TN, respectively and 36 µg/L and 35 µg/L TP, respectively. Comparison of TN and TP concentrations in both 1976 and 2009-2018 show that phosphorus controlled water quality conditions in LHP and most concentrations were above regional ecoregion thresholds. It is not clear from the available report what lab methods, sampling protocols or sampling depths were used in 1976.

Figure IV-7. GHP and LHP Streamflow Monitoring Locations. HPWA measured streamflow at the outlet from Little Herring Pond (LHP_out), the inlet to Great Herring Pond (GHP_in) and the outlet from Great Herring Pond (GHP_out). CSP/SMAST collected measurements at LHP_out and GHP_out during 2021.

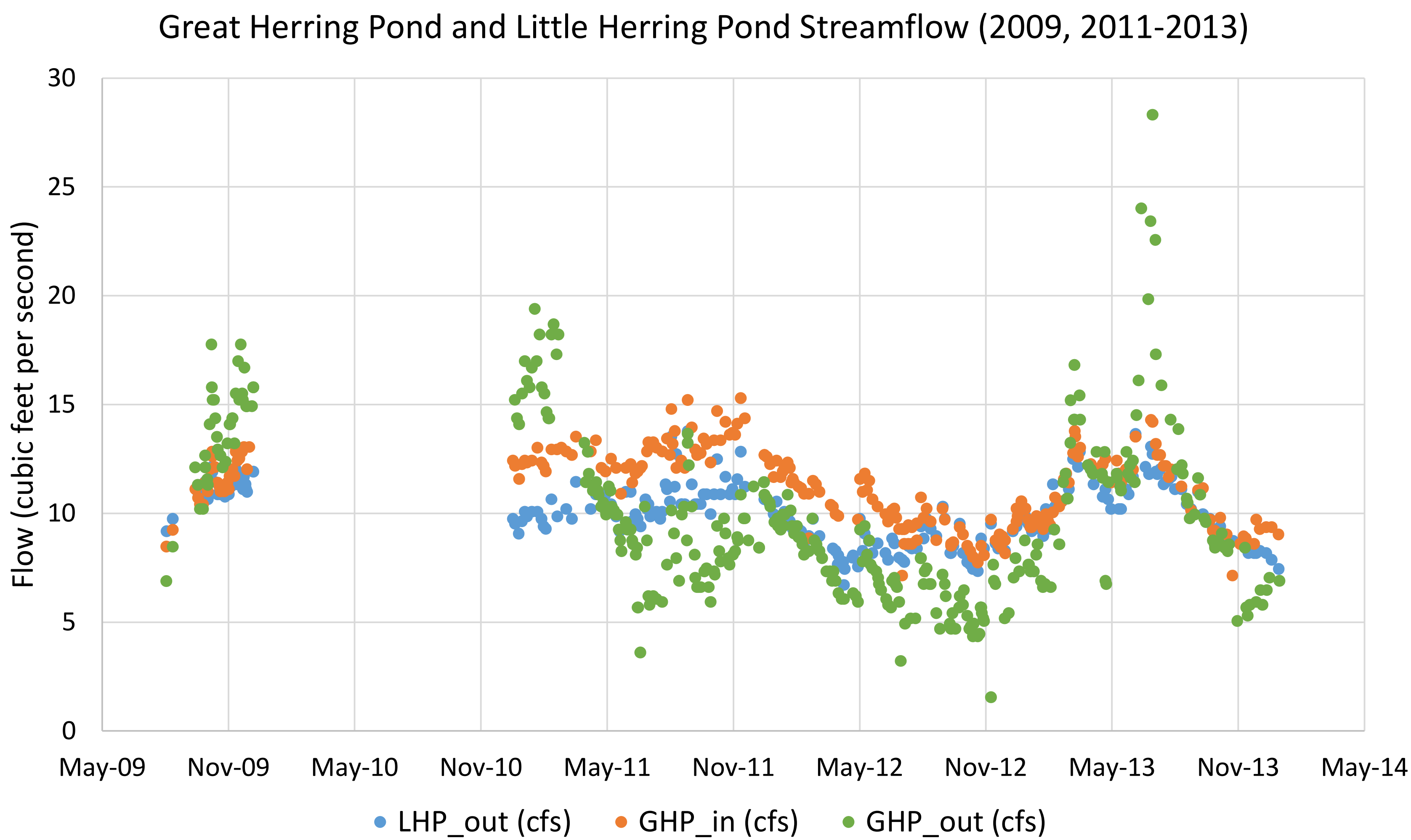

Figure IV-8. GHP and LHP Streamflow (2009, 2011-2013). Streamflow was collected by HPWA in 2009 and 2011-2013 with 67 to 109 readings each year in 2011-2013 (2009 readings were collected from August through December). Average outflow from LHP was 10.06 cfs, while average inflow to GHP was 11.17 cfs. Average outflow from GHP was 9.9 cfs, which is significantly less than the inflow (ρ<9E-08; T test). This loss of flow between GHP inflow and outflow occurred during the 2011 and 2012 calendar year readings, but not in 2013.

Review of well pumping does not suggest that it is the cause of the flow loss between GHP inflow and GHP outflow. There are a number of public water supplies and irrigation wells around GHP. The public water supplies have delineated contributing areas (*i.e.*, Zone 2's) that extend to GHP (see **Figure II-6**). These public water supply wells include those operated by the North Sagamore Water District and Plymouth Water Company. The wells most likely to have impactful withdrawals on GHP flows are the Black Pond and Church Lane wells, which are <0.3 km and <0.5 km from the pond shoreline. Pumping records for 2009-2020 provided by the North Sagamore Water District showed these wells had a combined average pumping rate of 0.34 MGD (or 0.53 cfs).[32] This pumping rate is too low to account for the flow loss within GHP.

Detailed review of annual pumping rates further suggests that there must be other factors causing the flow loss between GHP inflow and GHP outflow. Measured flow in calendar years 2011 and 2012 had the flow loss between the two stations, but 2013 did not. Annual pumping at the Black Pond well in 2013 was similar in 2012 and 2013, while 2011 was the lowest annual rate between 2009-2020 (**Figure IV-9**).[33] Review of monthly pumping rates showed that June to September pumping rates in 2013 was the highest among the three years, so higher pumping does not adequately explain the regular loss of flow measured within GHP.

A more significant loss of pond water is likely discharge of pond water to the groundwater along the eastern shoreline of GHP. Review of groundwater contours in the area show that most of the eastern shoreline of GHP is a discharge area (**Figure IV-10**).[34] Depending on water elevation of GHP, which will vary by season, pond water will flow back into the aquifer along this downgradient shoreline. Using the length of this shoreline, the approximate gradient between the two closest groundwater contours, and the hydraulic conductivity assigned by USGS to this area (227 ft/d), the rough estimate of the flow from the pond to groundwater is 1.2 cfs. This flow will vary with the fluctuation of the pond and surrounding groundwater water levels, but the match between this estimate and the measured flow loss between GHP inflow and GHP outflow suggests that this is the primary cause of flow loss.

Historical water quality samples with accompanying streamflow measurements are relatively sparse compared to flow readings. Flow readings with nitrogen and phosphorus samples were collected 12 and 14 times, respectively, at the LHP outlet and 13 and 14 times, respectively, at the GHP inlet between 2011 and 2013 (**Figure IV-11**). No comparable readings were available at the GHP outlet. Based on the available data, TN and TP exports at the LHP outlet and the GHP inlet were not significantly different. LHP TN export varied between 6.8 and 20.0 kg/d (average 11.8 kg/d), while the range at the GHP inlet 5.9 to 25.0 kg/d (average 13.9 kg/d). TP averages were 0.8 kg/d at the LHP outlet and 0.9 kg/d at the GHP inlet.

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[32] Information provided by Robert Gallo, New England Service Company (personal communication, 7/26/21).

[33] The Black Pond well is used regularly, while the Church Lane well is often not pumped for a number of months each year.

[34] Hansen, B.P. and W.W. Lapham. 1992. Geohydrology and Simulated Ground-Water Flow, Plymouth-Carver Aquifer, Southeastern Massachusetts. US Geological Survey Water-Resources Investigations Report 90-4204. Marlborough, MA. 93 pp. + 2 Plates.

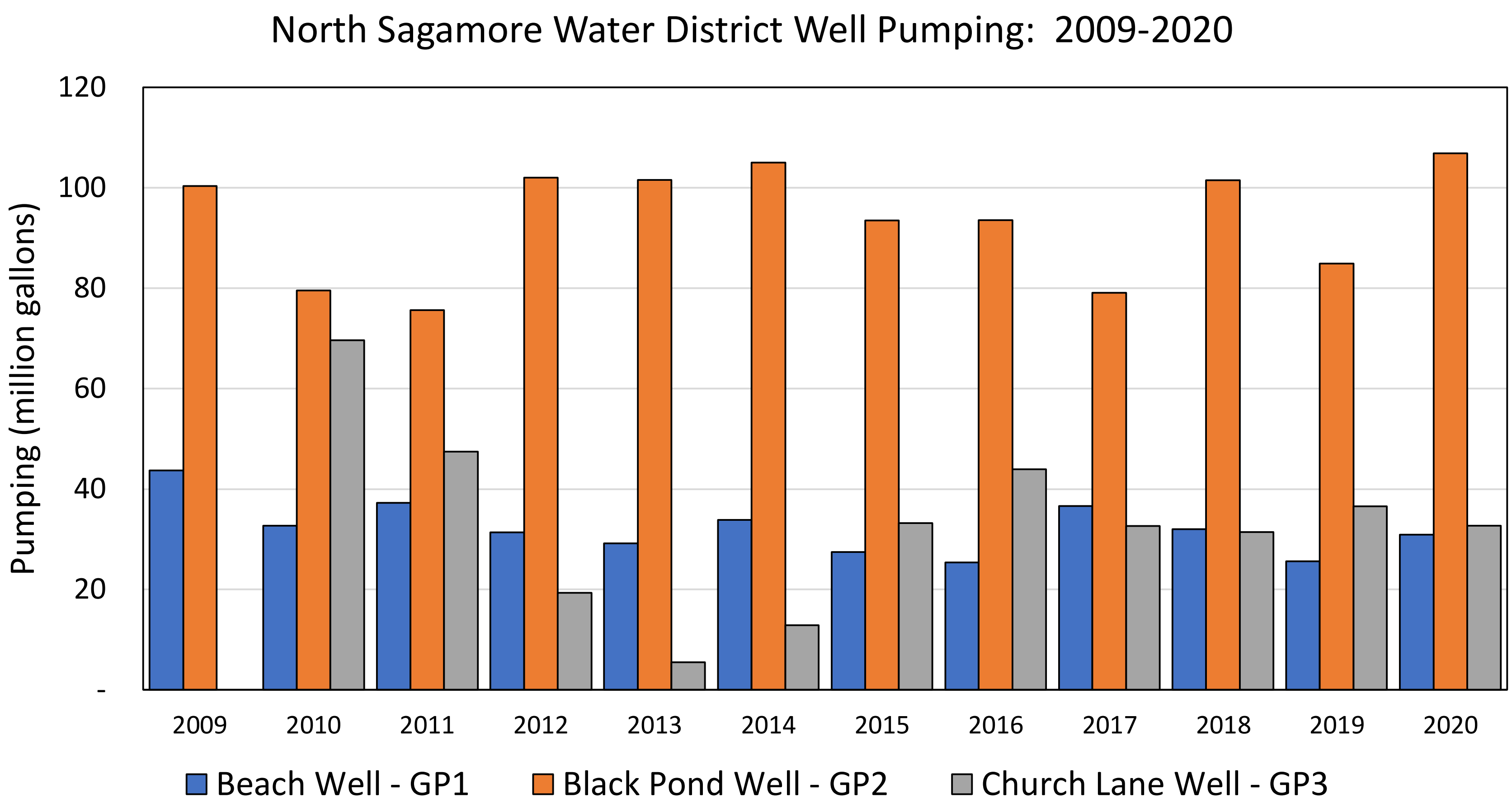

Figure IV-9. North Sagamore Water District Well Pumping: 2009-2020. The Black Pond and Church Lane wells are within 0.5 km of GHP and likely indirectly withdraw some water from GHP during pumping. Comparison of 2011-2013 pumping shows that the Black Pond well had a similar annual pumping rate in 2012 and 2013 and the combined Black Pond and Church Lane well pumping in 2011-2013 were similar.

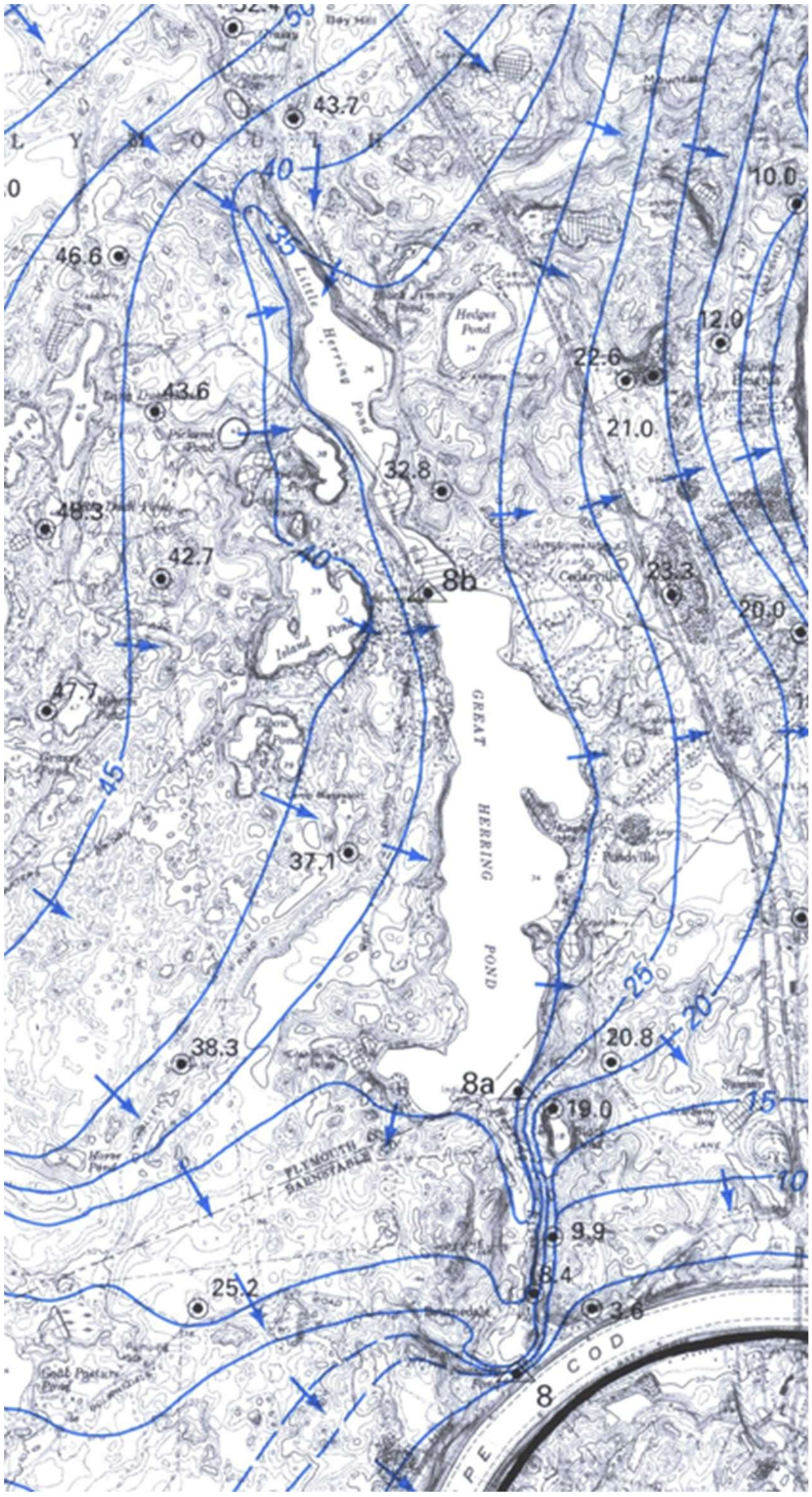

Figure IV-10. Historical Groundwater Contours in LHP/GHP area. Groundwater contours in the area of LHP and GHP derived by the USGS based on 1984 measurements (Hansen and Lapham, 1992) show groundwater flow into both LHP and GHP from the west. Based on the contours, GHP has flow of pond water into the aquifer system along all of its eastern shoreline. The amount of this outflow would vary depending on the difference between the elevation of the pond surface and the groundwater to the east.

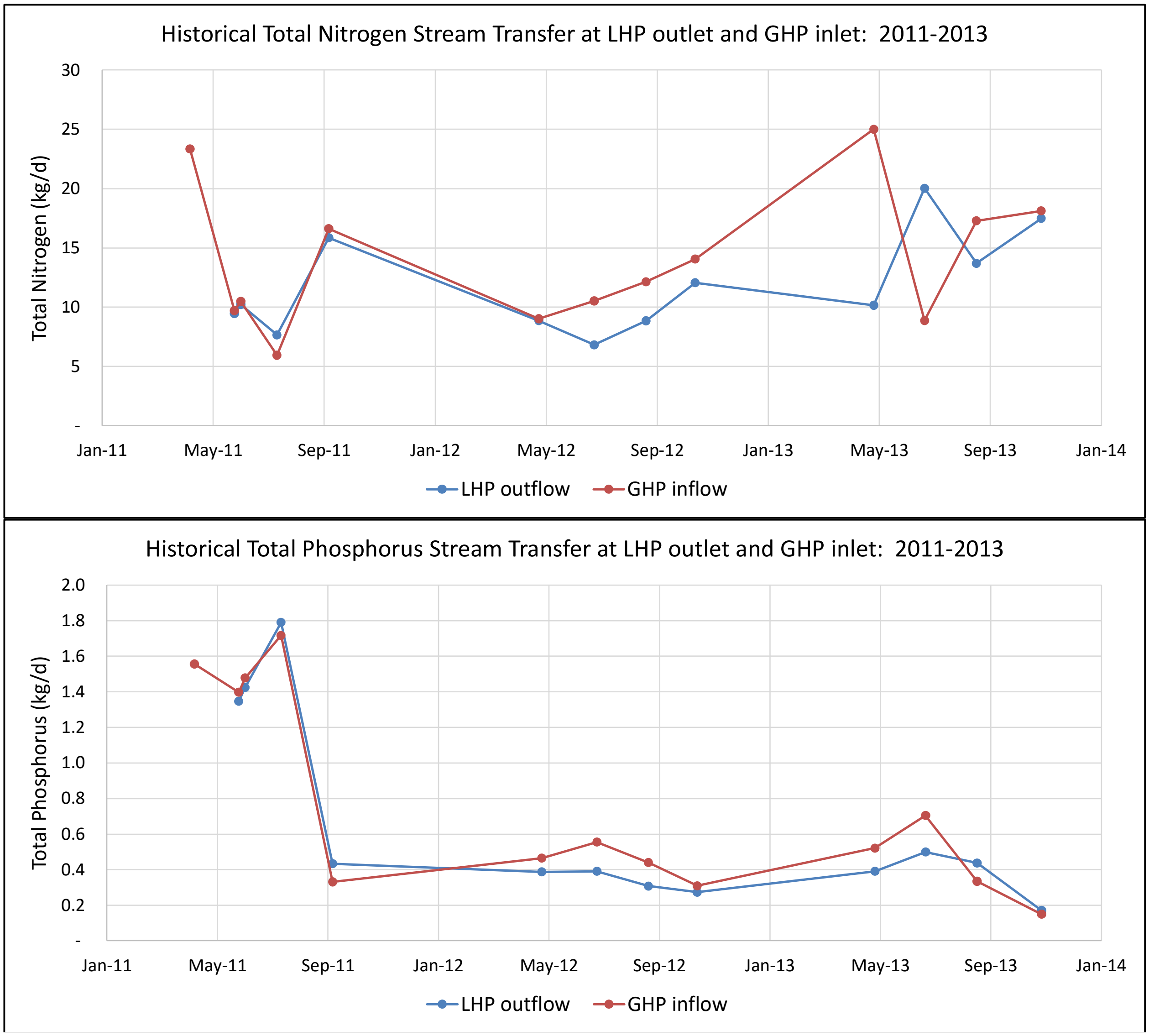

Figure IV-11. Historical Stream Nutrient Transfer out of LHP and into GHP: 2011-2013. Nitrogen and phosphorus water quality samples were collected 12-14 times with complementary flow readings between 2011 and 2013 at the outlet of LHP and the inlet to GHP (~900 m of stream length between them). Historical water quality samples with complementary streamflow readings are comparatively sparse compared to streamflow readings. There were no statistical differences between the N or P average mass transfers at the two locations. Average N transfer was 11.8 kg/d at LHP_out and 13.9 kg/d at GHP_in, while average P transfer was 0.8 kg/d at LHP_out and 0.9 kg/d at GHP_in.

IV.D. GHP and LHP Historical Stormwater Data

In 2015, CSP/SMAST and TMDL Solutions completed stormwater runoff sampling around GHP at the request of the Town.[35] This project identified 13 discharge sites around the pond, many of which had been previously had collection of water quality samples by HPWA. No historical stormwater sampling of LHP was identified and no LHP stormwater outfall location were identified on historical maps. Project staff collected water quality samples and flow readings at 6 of the 13 sites around GHP during three 2015 storms: October 28, December 14/15, and December 17. Precipitation during the sampling periods for these three storms were 0.62 inches, 1.3 inches, and 0.32 inches, respectively. Among the storms and runoff sites, TP concentrations ranged from 0.07 to 0.54 mg/L, TN concentrations ranged from 0.63 to 5.15 mg/L, and total suspended solids (TSS) ranged from 14 to 1324 mg/L. Combining the step-wise stormwater flow readings during each of the storms with the water quality results, indicated the following: a) sites R7 and R10 generally had the highest flows and contaminant loads, while sites R4 and R8 generally have the highest contaminant concentrations (see **Figure IV-1** for site locations), b) large storms (>1 inch) generally have much more significant impacts than smaller storms, although readings show that storms during periods of regular precipitation have less impact than storms during predominantly drier periods, and c) initial runoff will have higher contaminant concentrations, but contaminant loads later in storms can be larger than the initial loads. Project staff reviewed precipitation at Plymouth Airport and used the range of storms and associated concentration data to estimate the following annual stormwater runoff contaminant loads to GHP from all 13 sites: TP, 5.6 kg; TN, 45 kg; and TSS, 1,800 kg.

The two sites with the highest contaminant loads in the 2015 sampling (R7 and R10) are located on Eagle Hill Road. Town updated the stormwater systems connected to these outfalls and asked TMDL Solutions to complete similar measurements of water quality and stormwater runoff to compare to the 2015 results.[36] This project was supposed to be completed in 2018, but was complicated by high pond level/groundwater level elevations keeping the sites submerged. R10 eventually emerged in late 2019, while R7 remained submerged throughout 2018 and 2019. Project staff completed monitoring of 2019 storms at R10 on August 28, October 2, and October 16 using the same sampling and water quality assays used in 2015. Among the 2019 storms, TP concentrations ranged from 0.15 to 0.74 mg/L, TN concentrations ranged from 0.62 to 3.26 mg/L, and TSS ranged from 4.4 to 48.3 mg/L. The contaminant concentrations were generally similar between the 2015 and 2019 storm sets at R10, but the greater flows in 2015 resulted in much larger contaminant loads. The 2019 monitoring also showed that storms of 0.11 inches produced runoff, which was lower than the 0.2 inches determined from the 2015 monitoring. The TP, TN, and TSS loads in the 2019 storms reinforced the lessons from the 2015 sampling that stormwater runoff loads will vary by the characteristics of the storms, not just the total precipitation.

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[35] CSP/SMAST Technical Memorandum. February 24, 2016. Great Herring Pond Stormwater Monitoring Project Results. From: E. Eichner, TMDL Solutions and B. Howes, CSP/SMAST. To: K. Tower, Town of Plymouth. 15 pp.

[36] TMDL Solutions Technical Memorandum. February 4, 2020. Eagle Hill 2019 Stormwater Monitoring Results. From: E. Eichner. To: K. Tower, Town of Plymouth. 9 pp.

V. Great Herring and Little Herring Ponds Diagnostic Review

Great Herring Pond (GHP) and Little Herring Pond (LHP) are located within the same setting, but historic data shows that they have had varying monitoring and different characteristics. In order to develop diagnostic assessments of both ponds, project staff developed a monitoring strategy to address key data gaps identified from the review of the historical data. The 2021 data gap survey results were combined with the historical data to provide a reasonable understanding of how the GHP and LHP ecosystems function and the key factors that control water quality conditions. This diagnostic assessment then forms the basis for development of management strategies to address identified impairments.

V.A. 2021 Water Column Data Review

V.A.1. Little Herring Pond

Water quality measurements were collected 10 times between April and October 2021 in LHP. Measurements were collected over the deepest spot in the pond and included temperature and dissolved oxygen (DO) profiles, Secchi clarity readings, and collection of water quality samples at three depths: 0.15 m, 0.5 m, and 1 m. Water samples were collected using the same procedures specified in the Town pond monitoring QAPP and samples were assayed at the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth using the same procedures used in all PALS Snapshot samples. Samples were analyzed for: pH, alkalinity, ortho-phosphorus, total phosphorus (TP), total nitrogen (TN), chlorophyll a, and phaeophytin.

Temperature and DO profiles showed that the LHP 2021 water column was well mixed with no substantial differences in readings at the three depths (**Figure V-1**). Temperature readings were 13 to 14.5°C in April and increased to a maximum of 25.8°C in August before decreasing in September and October. DO concentrations were highest in late April with a maximum concentration of 13.73 mg/L on April 28 at 1 m depth. DO concentrations did not show any indication of sediment oxygen demand decreasing water column concentrations. DO concentrations throughout the summer were greater than the MassDEP minimum for warm water fisheries (5 mg/L).[37] However, DO saturation levels were extremely high in late April (>125%) and August-October (>110%). DO saturation levels significantly above atmospheric equilibrium (*i.e.*, >100%) are indicative of large phytoplankton populations. Secchi readings were consistently clear enough to always seen the disk on the bottom (station depth averaged 1.40 m).

Water quality laboratory results show a consistently high nutrient setting. All TP concentrations were higher than the Ecoregion threshold (10 µg/L).[38] TP concentrations did not vary significantly with depth and were generally between 20 and 25 µg/L except for higher concentrations in the June 16 sampling (**Figure V-2**). The increase in the June 16 sampling was likely due to the notable warming of the pond sediments from May to June (*i.e.*, warmer sediments would prompt quicker bacterial degradation of organic material deposited during the winter). All TN concentrations were also higher than the TN Ecoregion threshold (0.31 mg/L) and averaged 0.69 mg/L. Comparison of TN and TP concentrations show that phosphorus is the key nutrient for determining water quality conditions in LHP.

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[37] 314 CMR 4.05(3)

[38] Ecoregion thresholds are generally associated with acceptable pond and lake water quality and were determined based on monitoring from over 191 ponds (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.).

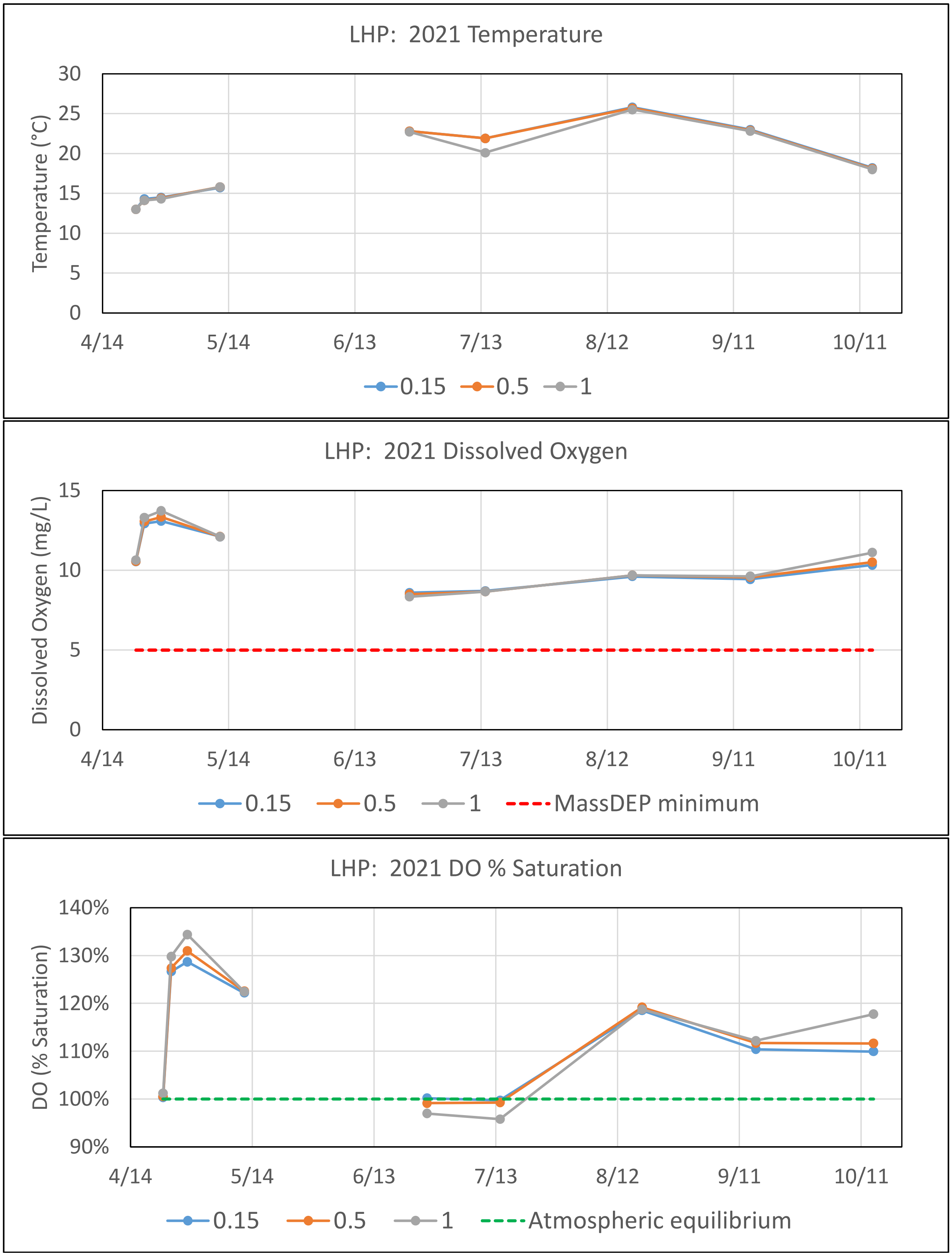

Figure V-1. 2021 LHP Water Column Temperature, Dissolved Oxygen, and DO % saturation. Readings were collected over the deepest point (average depth of 1.4 m). Temperature and DO readings were generally consistent throughout the water column, indicative of well-mixed conditions. All DO readings were above the MassDEP minimum, but % saturation levels were very high and indicative of a large phytoplankton population or extensive submerged, rooted plants.

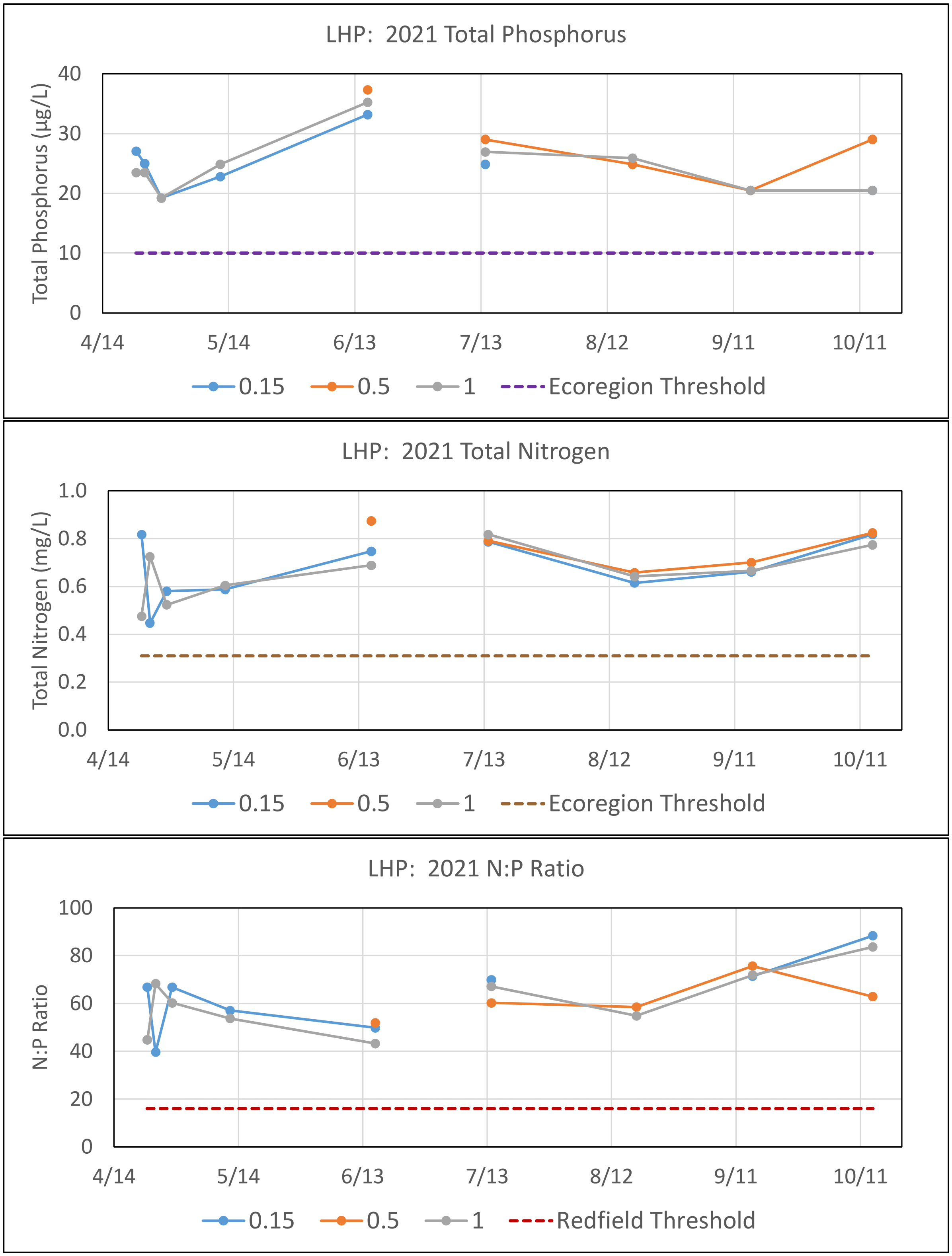

Figure V-2. 2021 LHP Water Column Total Phosphorus, Total Nitrogen, and N:P Ratio. Readings were collected over the deepest point (average depth of 1.4 m). TP and TN concentrations were similar at all depths; no indication of significant sediment regeneration. All TP and TN concentrations were above their respective Ecoregion thresholds. N:P ratio showed that phosphorus is the key nutrient for determining LHP water quality and ecosystem conditions.

Review of 2021 LHP phytoplankton chlorophyll pigments show that the phytoplankton population was relatively acceptable in April and May, but had concentrations more than 10X the Ecoregion threshold in August (**Figure V-3**). Chlorophyll a is the primary pigment for photosynthesis and is used as a proxy for measurements of the phytoplankton population in pond water samples. LHP chlorophyll a concentrations in 2021 were slightly above the 1.7 µg/L Ecoregion threshold concentration in April, May, and mid-June (average = 2.0 µg/L), but then increased to 6-7 µg/L in July and then ~25 µg/L in August before decreasing to 7-9 µg/L in September and October. Review of pheophytin concentrations show they were low in April and May, indicative of a relatively stable phytoplankton population, but increased sharply in June corresponding to the large increase in TP concentration (see **Figure V-2**). Since pheophytin a is a primary product of chlorophyll degradation, the increase in June without an accompanying chlorophyll a increase suggests that the phytoplankton population was cycling/growing rapidly. By July, the chlorophyll a concentration increased and the pheophytin concentration decreased suggesting phytoplankton population was growing and retaining TP in the water column. August concentrations show that the phytoplankton was still growing without extensive senescence and rerelease of nutrients. September pheophytin concentrations increased notably while chlorophyll decreased suggesting that the phytoplankton species that created the August peak were dying faster than they were producing new plants. Overall, the chlorophyll concentrations suggest the April/May conditions in the LHP were largely unimpaired, but June conditions prompted chlorophyll increases that continued through August. If other measures show that April/May conditions were unimpaired, the characteristics of LHP may be more tolerant of higher TP concentrations than other ponds in the region.

Conclusive comparison of 2021 data to past historical data is limited by some of the uncertainties associated with past sampling procedures (*e.g.*, only surface samples) and laboratory assays discussed above. However, most of the 2021 TP concentrations were within the range of monthly historical readings (**Figure V-4**). The exception was May 2021 readings, which were much higher than past readings. It should be noted that May 1976 readings more closely matched 2021 readings. It should also be noted that August 1976 TP concentrations were higher than the historical range or the 2021 data. Again, this may be due to assay procedures rather than fluctuations in the system.

V.A.2. Great Herring Pond

Water quality measurements were collected 8 times between April and October 2021 in GHP. Measurements were collected over the deepest spot in the pond and included temperature and dissolved oxygen (DO) profiles, Secchi clarity readings, and collection of water quality samples. Water quality samples were collected at nine depths: 0.5 m, 1 m, 2 m, 3 m, 8 m, 9 m, 10 m, 11 m, and 12 m. Water samples were collected using the same procedures specified in the Town pond monitoring QAPP and samples were assayed at the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth using the same procedures used in all PALS Snapshot samples. Samples were analyzed for: pH, alkalinity, ortho-phosphorus, total phosphorus (TP), total nitrogen (TN), chlorophyll a, and phaeophytin.

Temperature and DO profiles showed that the GHP 2021 water column was generally well mixed, but had strong stratification at substantially different depths on two dates: June 25 and July 14 (**Figure V-5**). In April and May, differences between the shallowest and deepest

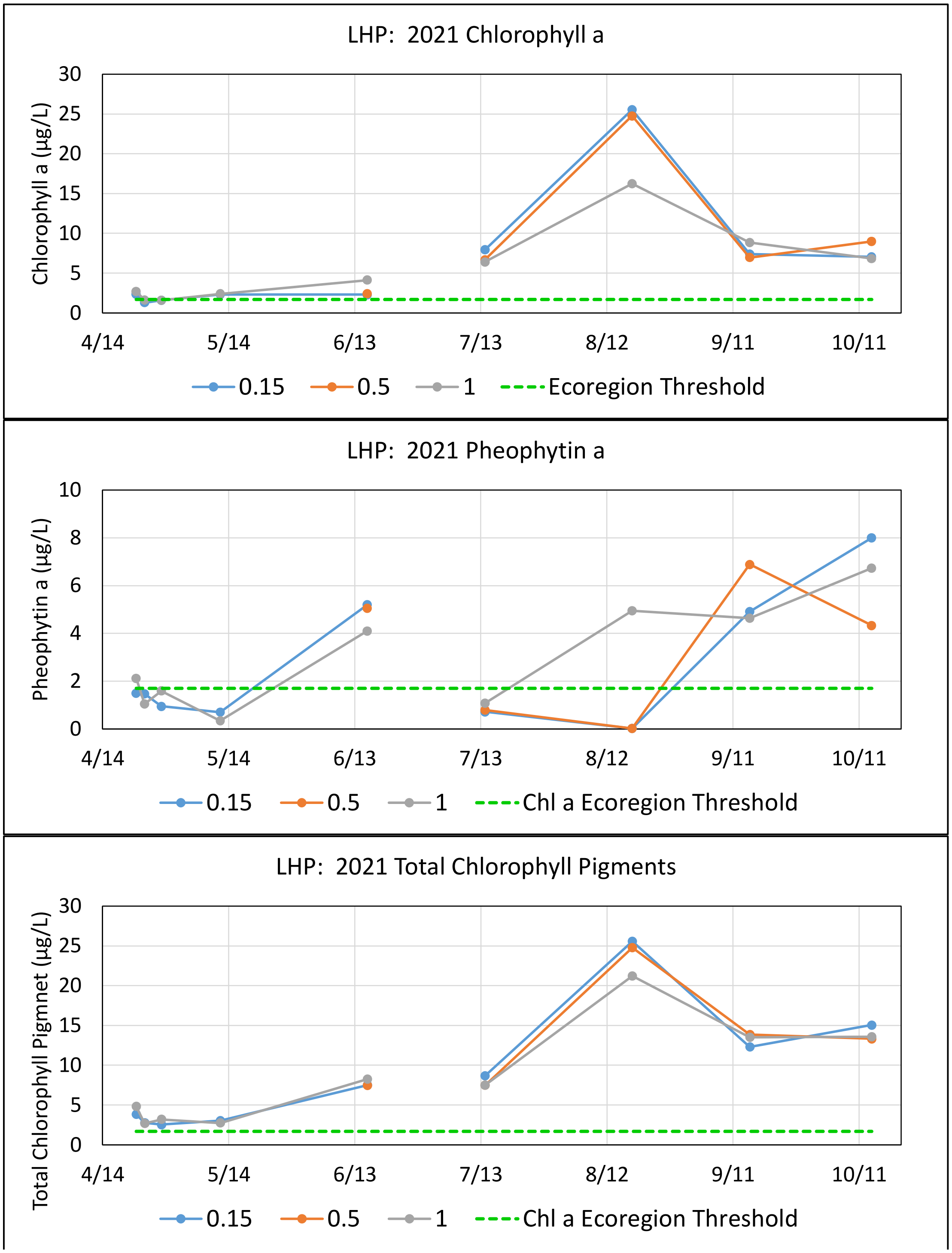

Figure V-3. 2021 LHP Water Column Chlorophyll Pigments. Readings were collected over the deepest point (average depth of 1.4 m). LHP chlorophyll a concentrations were slightly above the 1.7 µg/L Ecoregion threshold concentration in April, May, and mid-June (average = 2.0 µg/L), but then increased to 6-7 µg/L in July and then ~25 µg/L in August before decreasing to 7-9 µg/L in September and October. The increase in pheophytin a concentrations in June show that the phytoplankton population responded to the June TP increase, mostly by cycling plant nutrients. In July, the population shifted to produce more plants with less cycling (decrease in pheophytin concentrations) and this was sustained through August. In September, these plants began to senescence and chlorophyll a concentrations decreased and pheophytin concentration increased.

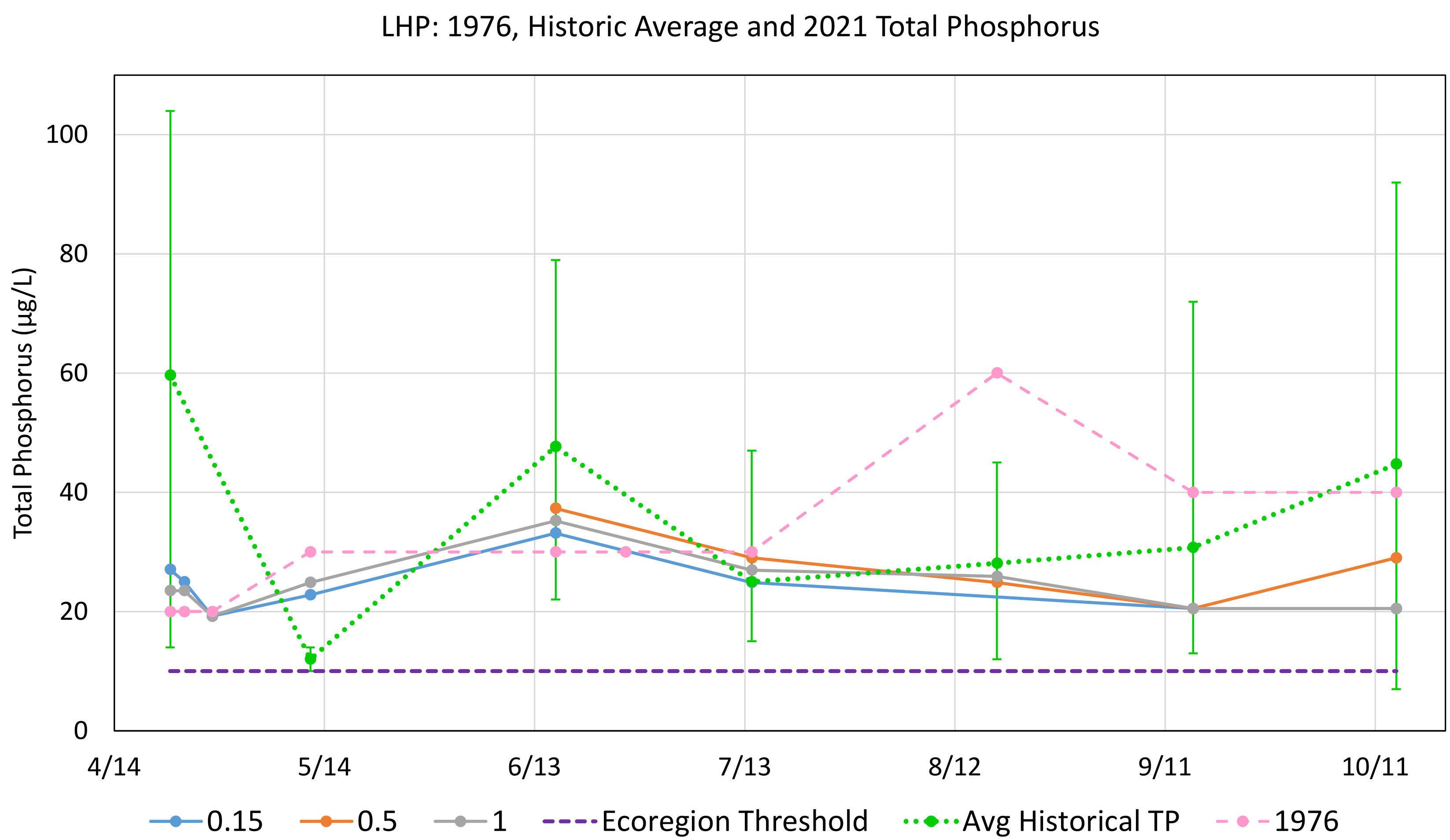

Figure V-4. Comparison of LHP 2021 TP Concentration to Historical Averages and 1976 readings. In general, 2021 LHP TP concentrations were within ranges of historical data (error bars are maximum and minimum monthly concentrations). The exception is May 2021 concentrations, which were higher than the two available historical May readings. The 1976 May TP concentrations more closely approximated 2021 readings, but the laboratory methods and sampling procedures in 1976 are unknown. It is also notable that the August 1976 TP concentrations were higher than the historic range and 2021 readings.

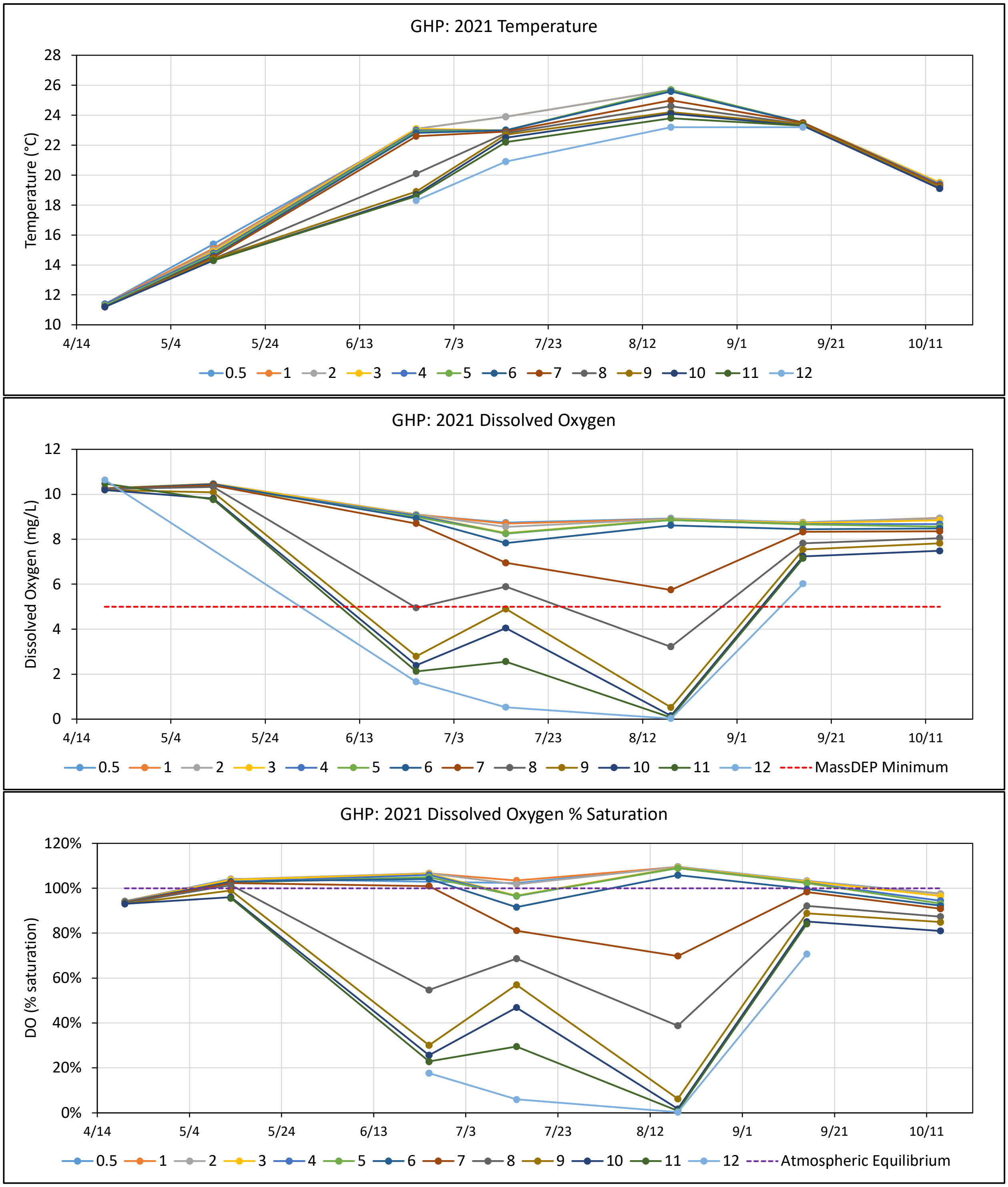

Figure V-5. GHP Temperature, Dissolved Oxygen, and DO % Saturation 2021 Profiles. Profiles were collected in GHP on 8 dates in 2021. Temperature readings generally showed a well-mixed water column except for stratification at 8 m on June 25 and 12.6 m on July 14. DO readings showed hypoxia deeper than 8 m that generally persisted until the September 15 profile. Anoxia developed and persisted in deeper waters from July 14 through August 18. Shallow DO % saturation levels were well above atmospheric equilibrium (105% to 110%) in June through August profile indicative of significant phytoplankton populations.

temperature readings were less than 1.1°C, which means the entire water column can mix given sufficient wind across the surface of the pond. In the June 25 profile, temperature differences within the profile had increased and were sufficient to induce stratification (or thermal layering) at 8 m depth. This stratification means that if sufficient wind occurred the upper 7 m of the water column would mix, but the waters 8 m and deeper would be isolated from the mixing. Typically, when stratification initially occurs, sediment oxygen demand begins to cause significant decreases in DO concentrations in the deeper, isolated layer. The June 25 profile matches this expectation with depressed DO concentrations throughout the lower layer; all concentrations from 8 m and deeper were less than the MassDEP minimum of 5 mg/L (see **Figure V-5**).

Ponds as deep as GHP usually maintain thermal stratification throughout the summer once it is established; the upper layer warms as the summer progresses and the lower layer maintains the temperature established at the initiation of stratification. However, in 2021 the thermal stratification in GHP had largely been eliminated by the July 14 profile (19 days later) with some remnant stratification at 12.6 m (1 m above the bottom) (see **Figure V-5**). The three remaining monthly 2021 profiles in August, September, and October showed that GHP had sufficient wind across the surface to prevent thermal stratification and cause continued mixing of the whole water column. This pattern of only occasional temporary stratification is consistent with historical temperature profiles (see **Figure IV-2**).

However, even with regular replenishment of water column DO from atmospheric contact and water column mixing, the deep DO concentrations decreased further after the initial hypoxia in the June profile. In the July 14 profile, anoxia occurred at 12 m and deeper with DO concentrations at 9 m and deeper less than the MassDEP minimum (see **Figure V-5**). In the August 18 profile, anoxia occurred in a greater proportion of the water column (9 m and deeper) with 8 m also below the MassDEP minimum. By the September 15 profile, the anoxia was limited to 12.5 m and deeper and it was not present in the October 14 profile. The early summer deep hypoxia and late summer deep anoxia is also consistent with historical DO profiles (see **Figure IV-3**).

Further review of the 2021 DO concentrations also show that shallow levels were often well above atmospheric equilibrium (*i.e.*, 100% saturation). DO saturation levels in the April 20 profile were less than 100% throughout the water column, likely due initial warming of the sediments, while in the May 13 profile DO saturation levels in the upper 3 m were all 104% (see **Figure V-5**). This higher saturation level is generally within atmospheric equilibrium variability, but the June 25 profile had DO saturation levels of 104% to 107% in the upper 6 m suggesting that significant phytoplankton growth was occurring in both May and June. July 14 DO readings returned to near equilibrium, but the August DO saturation levels in the upper 6 m varied between 106% and 110%. In the September 15 profile, saturation levels in the upper 5 m decreased to 102% to 103% and were 97% to 98% in the upper 3 m in the October 14 profile. DO saturation levels regularly above 105% are typically associated with extensive phytoplankton growth.

GHP Secchi readings in 2021 were generally consistent with historical readings. The April 20 Secchi reading was 7.2 m, which is slightly less than the maximum of the three April historical readings (8 m on 4/30/13)(**Figure V-6**). Most of the other 2021 Secchi readings are within the range of 2010-2019 historical readings except for the July 2021 reading, which had the highest Secchi reading measured in July.

TP concentrations in GHP during 2021 were generally greater than the regional Ecoregion threshold of 10 µg/L (**Figure V-7**). April 20 samples throughout the water column had TP concentrations close to 10 µg/L, but generally each subsequent sampling had higher concentrations indicative of increased additions of TP. Shallow TP concentrations (0.5 m-3 m) all had similar increases and concentrations through the July 14 sampling, when they were between 20 and 22 µg/L. Subsequent sampling at 0.5 m and 3 m remained within this range, but 1 m and 2 m TP concentrations were much higher in some of the remaining 2021 samplings (maximum of 34 µg/L at 1 m on August 18 and maximum of 35 µg/L at 2 m on September 15). These higher, shallow TP concentration were likely due to difference in the distribution of phytoplankton; some phytoplankton have the ability to control their buoyancy to seek optimal light conditions. Deep TP concentrations (8 m-12 m) increased initially in the May 13 sampling, but tended to be in the same range (20 to 30 µg/L) in most of the samplings except for the higher concentrations in the deepest (12 m) samples and the 10 m-12 m samples on August 18. TP concentrations in the 12 m samples increased to 86 µg/L in the July 14 sampling and 129 µg/L in the August 18 sampling before decreasing to 27 µg/L in the September 15 sampling. The August 18 TP concentrations at 10 m and 11 m were 58 µg/L and 60 µg/L, respectively. These increases in deep TP concentrations were consistent with the prolonged anoxia measured at 12 m in July and August (see **Figure V-5**). Anoxia was also measured at 9 m through 11 m on August 18.

TN concentrations in GHP during 2021 were generally slightly greater than the regional Ecoregion threshold of 0.31 mg/L, but mostly fluctuated around the threshold for most of summer. Deep TN concentrations were higher than shallow readings and April through June shallow readings were highly variable (**Figure V-8**). Shallow (0.5-3 m) TN concentrations were between 0.4 and 0.45 mg/L in April 20 samples, then fluctuated across a wider range in the May and June samplings, then returned to a smaller range (0.33 to 0.36 mg/L) in the July. Each subsequent sampling had a small range with TN concentrations closer to the Ecoregion threshold. Deep (8-12 m) TN concentrations were generally greater than shallow concentrations, but only the 12 m samples in the July and August samplings, when deep anoxia was measured, were notably greater than the monthly sampling ranges of the other deep samples. Comparison of annual TN averages at all depths did not show any significant differences.

Comparison of 2021 TN and TP concentrations showed that phosphorus controls water quality conditions in GHP. April N:P ratios throughout the water column had values well above the Redfield threshold (*i.e.*, 16) indicating that more nitrogen was available than phosphorus for phytoplankton growth (**Figure V-9**). In each subsequent 2021 sampling through August, the N:P ratios decreased at all depths mostly due to the relative increase in TP concentrations, but generally remained well above the threshold and, therefore, showing phosphorus control of water quality conditions. As would be expected based on the anoxia-driven increase in deep TP concentrations, the 12 m ratios decreased the most and the August 12 m sample had a ratio lower than the Redfield threshold. This decrease in the N:P ratio is often measured in ponds with extensive deep TP sediment release due to anoxia.

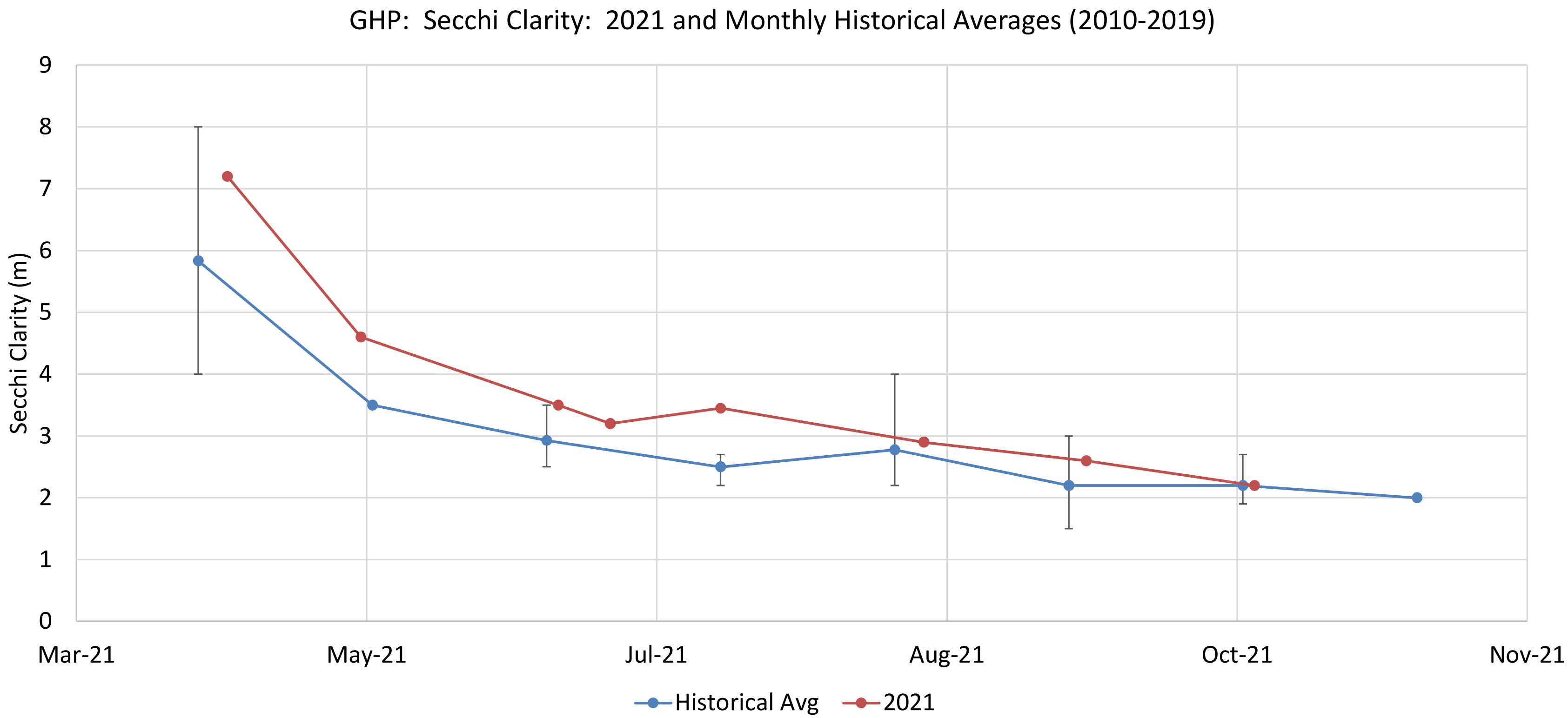

Figure V-6. GHP Secchi Clarity: 2021 and Monthly Historical Averages (2010-2019). GHP Secchi readings decreased throughout 2021 and were generally consistent with historical readings. Among the 2021 readings, only July 14 was outside of the range of previous July Secchi readings (July 14 reading was 3.4 m, while the maximum of the four historical July readings was 2.7 m). .The April 20 Secchi reading was 7.2 m, which is slightly less than the maximum of the three April historical readings (8 m on 4/30/13). A total of 26 historical Secchi readings have been collected over the deepest point in GHP.

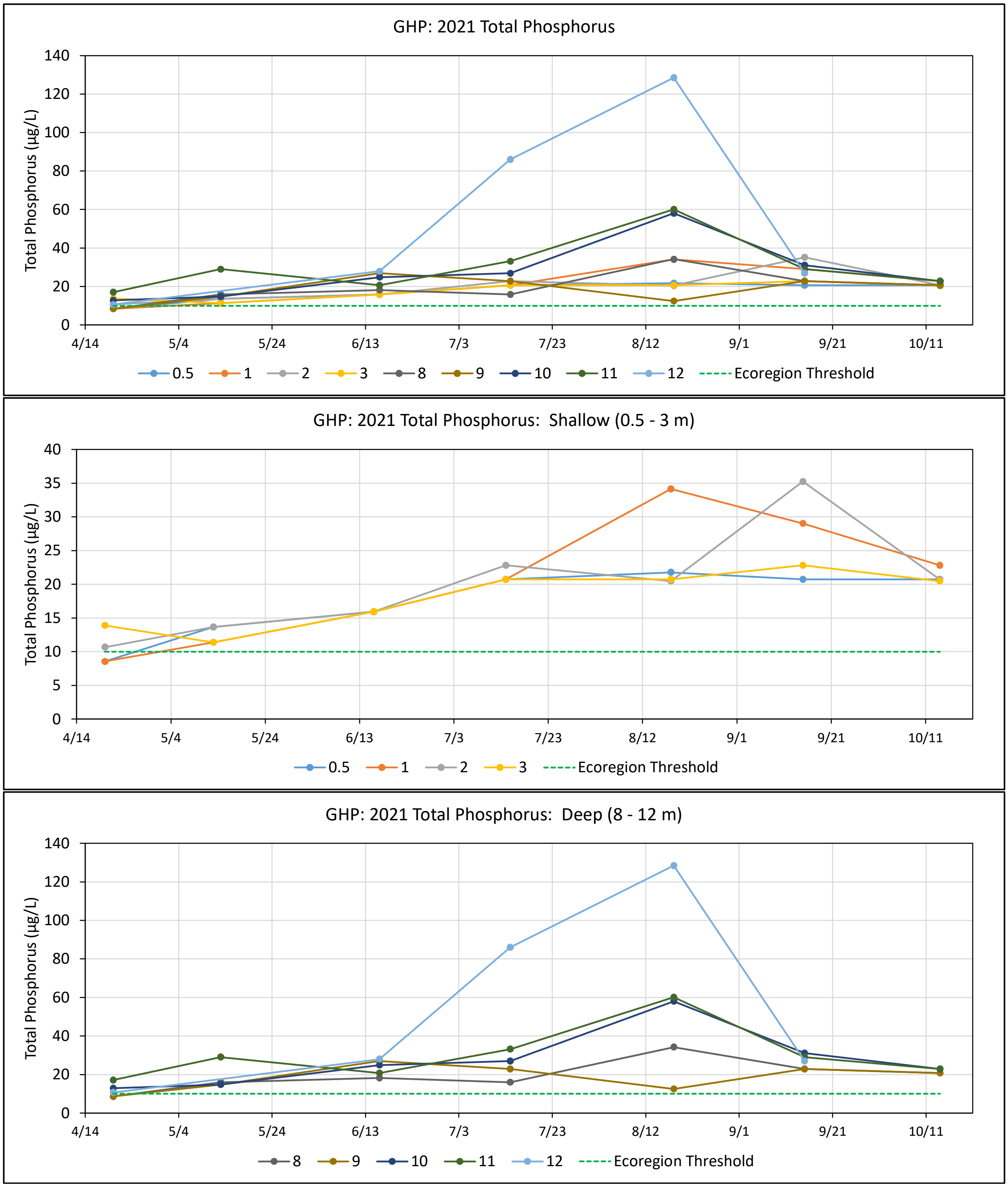

Figure V-7. GHP 2021 Water Column Total Phosphorus. GHP 2021 TP concentrations at all depths were generally greater than the regional Ecoregion threshold of 10 µg/L except for some of the April 20 samples. Shallow TP concentrations increased between April and July, when they were between 20 and 22 µg/L. Subsequent sampling at 0.5 m and 3 m remained within this range, fluctuations were measured in 1 m and 2 m samples. Deep TP concentrations increased in the May 13 sampling, but then tended to fluctuate between 20 to 30 µg/L except for the 12 m samples, which increased in July and August, and higher concentrations in the 10 m-12 m samples on August 18.

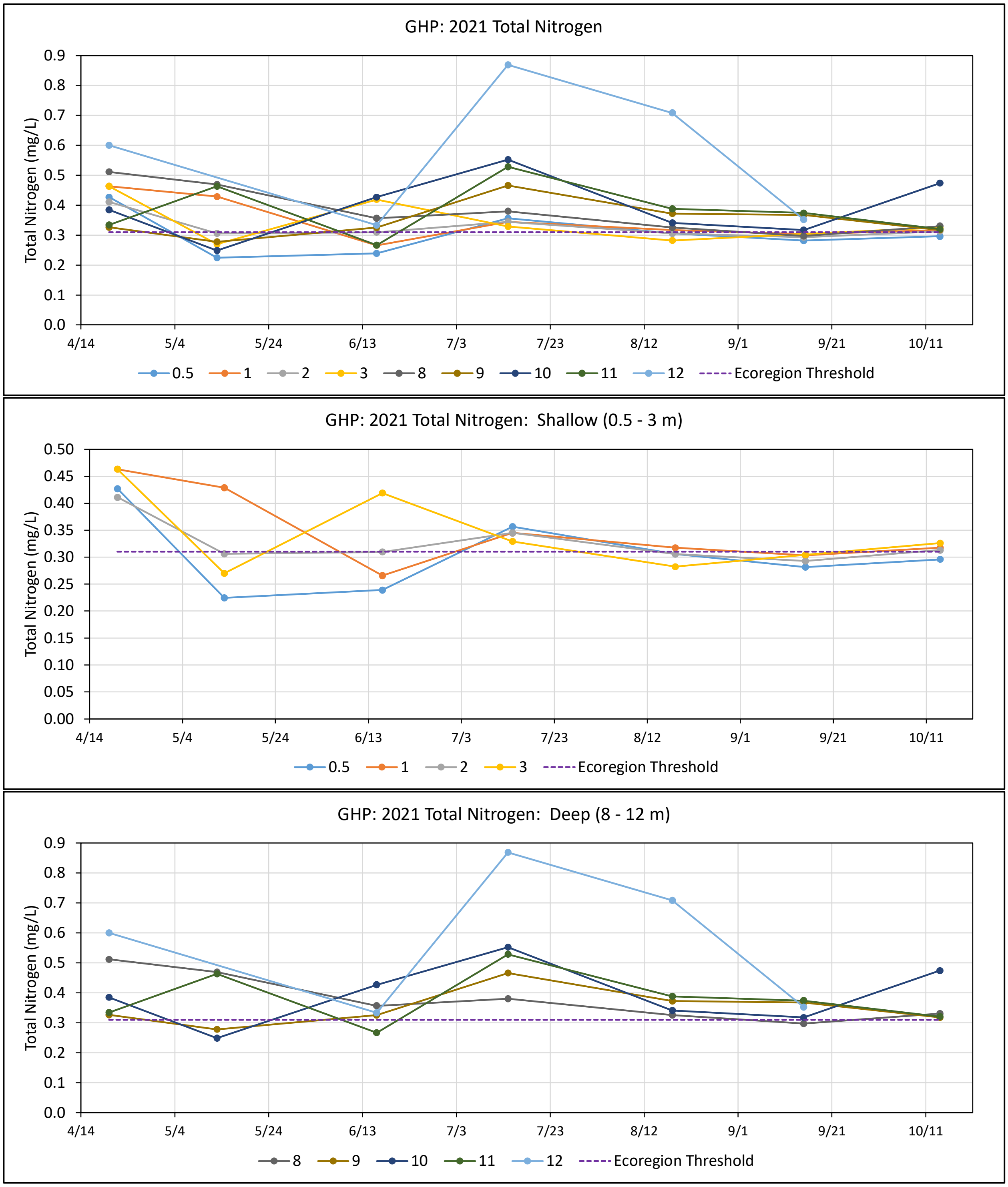

Figure V-8. GHP 2021 Water Column Total Nitrogen. April 2021 shallow GHP TN concentrations were between 0.4 and 0.45 mg/L (>0.31 mg/L the regional Ecoregion threshold), then fluctuated across a wider range in the May and June samplings, then returned to a smaller range (0.33 to 0.36 mg/L) in the July before fluctuating around the Ecoregion threshold in August, September, and October samplings. Deep TN concentrations were generally greater, but only the 12 m samples in the July and August samplings, when deep anoxia was measured, were greater than the monthly sampling ranges of the other deep samples. Comparison of annual TN averages at all depths did not show any significant differences.

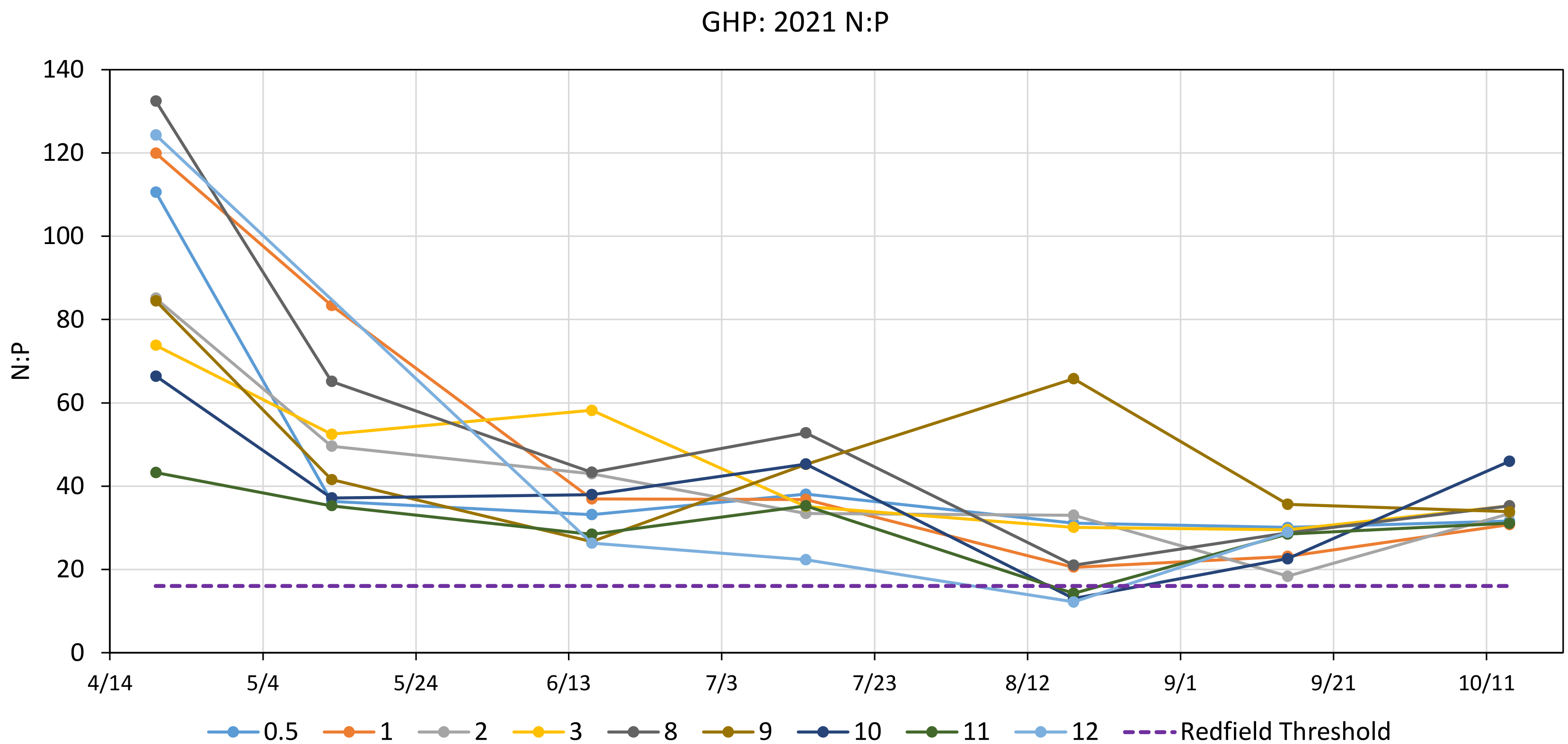

Figure V-9. GHP 2021 Water Column N:P Ratios. Comparison of 2021 TN and TP concentrations showed that phosphorus controls water quality conditions in GHP. The initial 2021 April sampling showed high N:P ratios throughout the water column with ratios 3X to 8X the Redfield threshold of 16. Ratios generally decreased in each subsequent sampling due to relatively higher TP inputs before increasing again in the October sampling. The relatively higher TP inputs would be consistent with the mid-summer deep anoxia adding TP to the water column and the lack of thermal stratification mixing the TP inputs throughout the water column.

Review of the 2021 GHP phytoplankton pigments (chlorophyll a and pheophytin a) show the increasing growth of the phytoplankton population throughout the sampling period (**Figure V-10**). The increase in chlorophyll throughout the summer matched the decrease in clarity and the increase in TP (see **Figures V-6 and V-7,** respectively). Chlorophyll a is the primary photosynthetic pigment used by most phytoplankton, while pheophytin a is a secondary photosynthetic pigment and among the primary breakdown products of chlorophyll a. GHP chlorophyll concentrations throughout the water column were generally less than the Ecoregion threshold of 1.7 µg/L in the April 20 sampling, but gradually increased in the May 13 and June 16 sampling and then more than doubled in the July 14 sampling. The July 14 sampling showed highest chlorophyll a concentrations at 3 m and 12 m (19.7 µg/L and 20.2 µg/L). Having similar concentrations at these two depths show the impact of the water column mixing that occurred between the June 25 and July 14 profiles; June 25 had strong stratification at 8 m, but by July 14 the strong stratification only occurred at 12.6 m. Pheophytin concentrations mostly increased in deeper waters (8-12 m), as would be expected as senescing phytoplankton settle toward the sediments, but this pattern is also complex because the frequent mixing of the water column would tend to regularly change depth to the bottom for settling phytoplankton particles. Deep pheophytin concentrations varied mostly between 6 and 14 µg/L with a peak of 24.7 µg/L at 12 m on July 14. Between July and October, shallow pheophytin a concentrations mostly varied between 0.5 and 6 µg/L. Combined chlorophyll pigments (chlorophyll a + pheophytin a) showed that after June 16, concentrations consistent with impaired conditions existed throughout the GHP water column during all subsequent monthly readings.

As would be expected, 2021 pH and alkalinity levels in GHP were low with significantly higher levels in the shallow waters due to the influence of phytoplankton (**Figure V-11**). 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. Ponds and lakes in the Ecoregion that includes Plymouth typically have naturally low pH and ALK.

As mentioned in Section III, 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 the Ecoregion geology 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). Sampling data from 193 ponds and lakes in the Cape Cod portion of the Ecoregion in 2001 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] Ponds in the Ecoregion with higher pH readings typically have higher nutrient levels, since photosynthesis consumes hydrogen ions and higher nutrient levels prompt more phytoplankton photosynthesis. GHP pH readings only exceeded the MassDEP minimum in August and October, when surface water conditions were most impaired.

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[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.

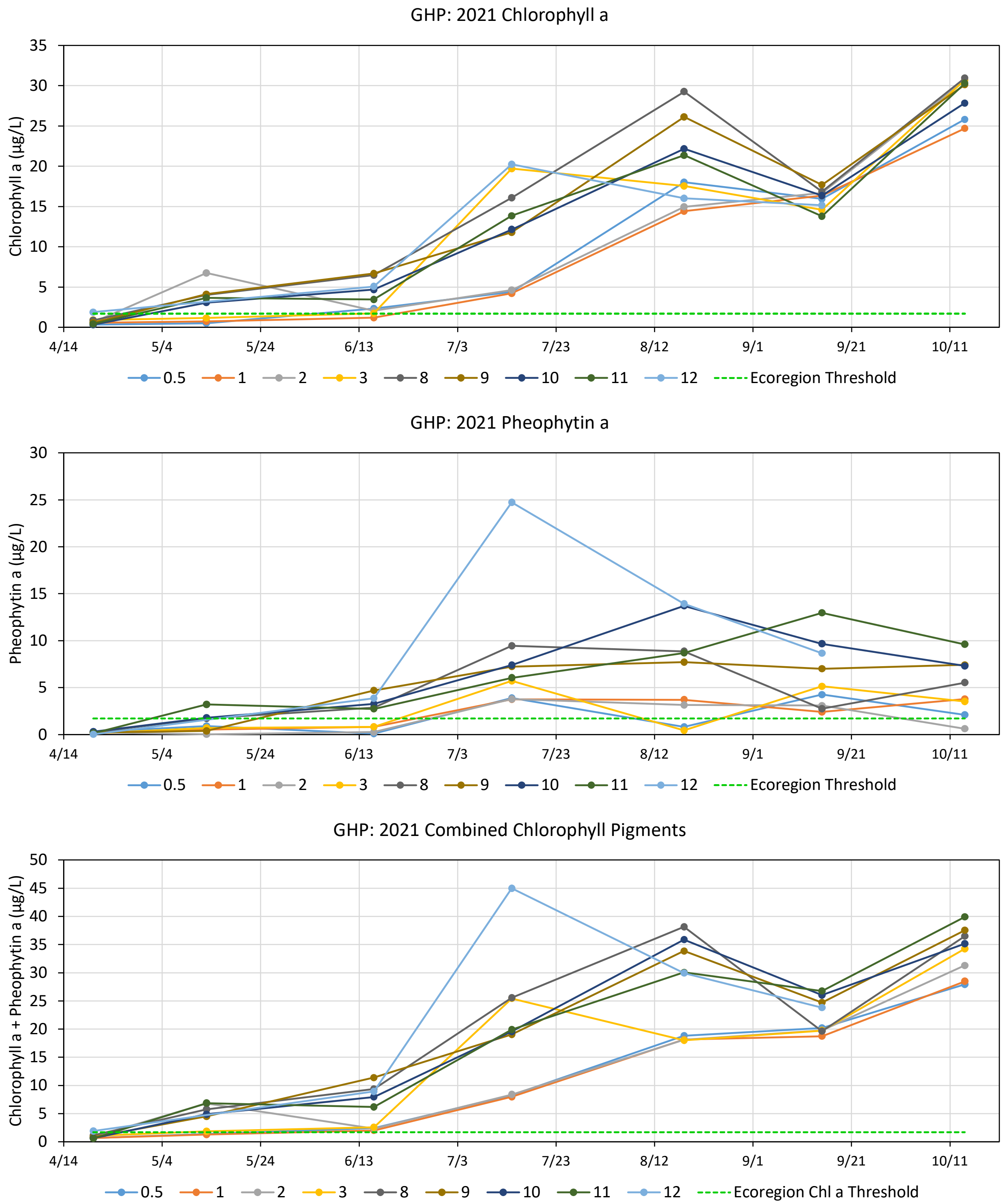


Figure V-10. GHP 2021 Water Column Chlorophyll Pigments. Review of the 2021 chlorophyll a and pheophytin a show the increasing growth of the phytoplankton population throughout the sampling period. April GHP chlorophyll concentrations at all depths were generally less than the Ecoregion threshold of 1.7 µg/L, but increased in each subsequent sampling and began to shift into the deeper depths as the water column mixed and phytoplankton senesced at settled. Pheophytin concentrations mostly increased in deeper waters (8-12 m), but also had a complex pattern because of the regular water column mixing. Combined chlorophyll pigments (chlorophyll a + pheophytin a) showed that after June 16, impaired conditions existed throughout the GHP water column during all subsequent monthly readings.

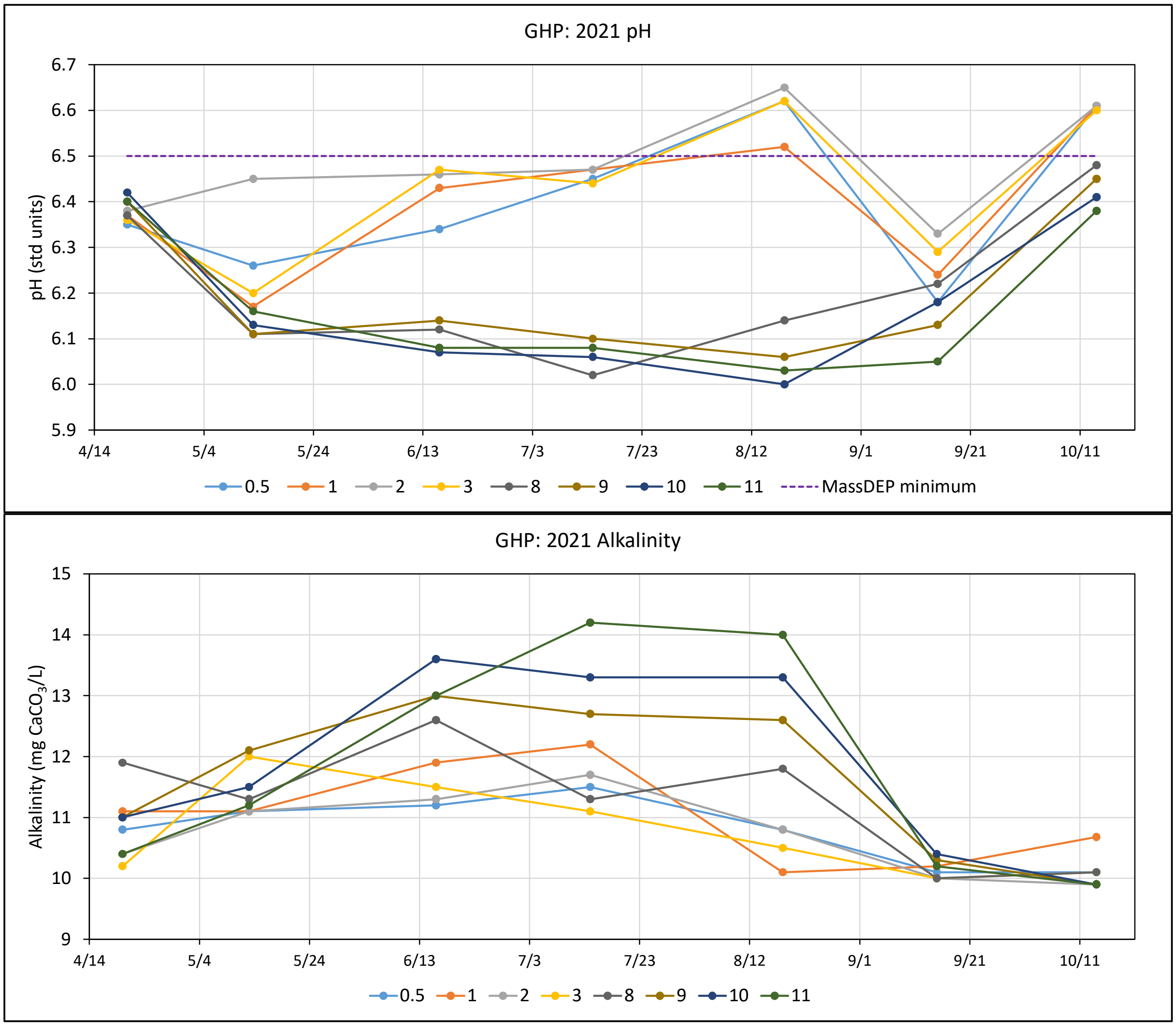


Figure V-11. GHP 2021 Water Column pH and Alkalinity. Shallow pH levels increased with increasing phytoplankton from May through August (see chlorophyll concentrations) and remained greater than deep levels throughout most of the year. pH levels were naturally low due to the surrounding sandy geology and were consistent with other ponds in the Ecoregion that includes Plymouth, Cape Cod, Nantucket, and Martha's Vineyard. Shallow alkalinity levels generally varied between 11 and 12 mg $CaCO_3$/L between April and July and then decreased to between 10 and 11 mg $CaCO_3$/L between August and October. Higher deep alkalinity levels were consistent with carbonate additions associated with phytoplankton settling within the water column.

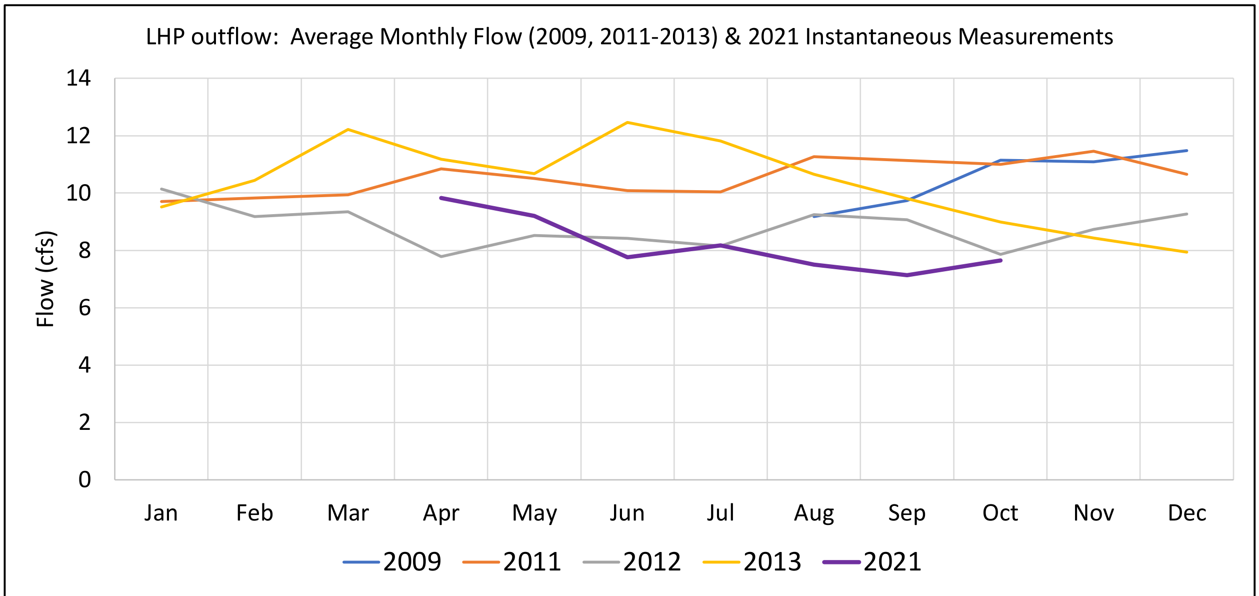
Alkalinity levels in GHP varied over a limited range during 2021. Shallow alkalinity levels mostly varied between 10 and 12 mg $CaCO_3$/L with higher concentrations between April and July than August through October (see **Figure V-11**). Deep alkalinity levels were generally higher than shallow levels from July through August, likely related to the carbonates associated with settling phytoplankton.

V.B. Stream Water Quality and Flow

In order to complement the water column readings and provide a check on the historical nutrient transfer rates (see **Figure IV-11**), CSP/SMAST staff collected monthly water quality samples and instantaneous flow readings between April and October at the outflow from LHP and GHP (see **Figure IV-7** for locations). LHP 2021 outflow readings varied between 0.20 and 0.28 cubic meters per second (*i.e.*, 7.1 and 9.8 cfs), while GHP outflow varied between 0.11 and 0.26 m^3/s (*i.e.*, 4.0 and 9.4 cfs). Instantaneous flow readings in 2021 at the GHP outflow were generally consistent with monthly averages developed from more frequent readings (*i.e.,* generally >20 readings per month) in 2011-2013 and a portion of 2009 (**Figure V-12**), but the August 18, 2021 reading (0.11 m^3/s) was the lowest August reading among all the datasets. Similarly, 2021 LHP instantaneous flows in June, August, and September were the lowest recorded readings. The lower flow readings in 2021 are not surprising given that June, July, and August groundwater levels were the lowest among the years when streamflow readings were collected (**Figure V-13**).

Even with the lower flows in 2021, nitrogen and phosphorus export from LHP and GHP were generally consistent with historical nitrogen and phosphorus export readings from 2011-2013. Historical nutrient export readings were more limited than flow readings with 12 readings for LHP export and 13 readings for GHP export. LHP 2021 TN export was generally in the same range as historical readings with an average of 12.1 kg/d (n=7), but GHP 2021 TN export tended to be lower than past readings (7.7 kg/d, n=7) (**Figure V-14**). GHP 2021 TP export was also lower than past readings until September and October, when TP export was greater than historical readings during those months (**Figure V-15**). LHP 2021 TP export was generally slightly greater than 2012 and 2013 TP export, but was much less than 2011 TP export. Average 2021 TP export from LHP and GHP was 0.44 kg/d and 0.36 kg/d, respectively.

Review of the all the available data showed that the rate of TP and TN export is not closely related to flow. Comparison of export rates, which include flow, and flow measurements showed no significant relationship. The high TP export from both ponds during 2011 suggest that higher groundwater conditions may mobilize near shore TP transport, but the lack of high TP exports during 2013, when early summer flow rates were highest among those measured suggest a more complex relationship between export, groundwater levels, and streamflow. Differences in export are likely related to differences in the residence times of both ponds. The average 2021 TP export from the two ponds were not significantly different, while the average TN export from GHP was significantly lower than the export from LHP (<0.05, T test). The average historical TN export from the two ponds was not significantly different.



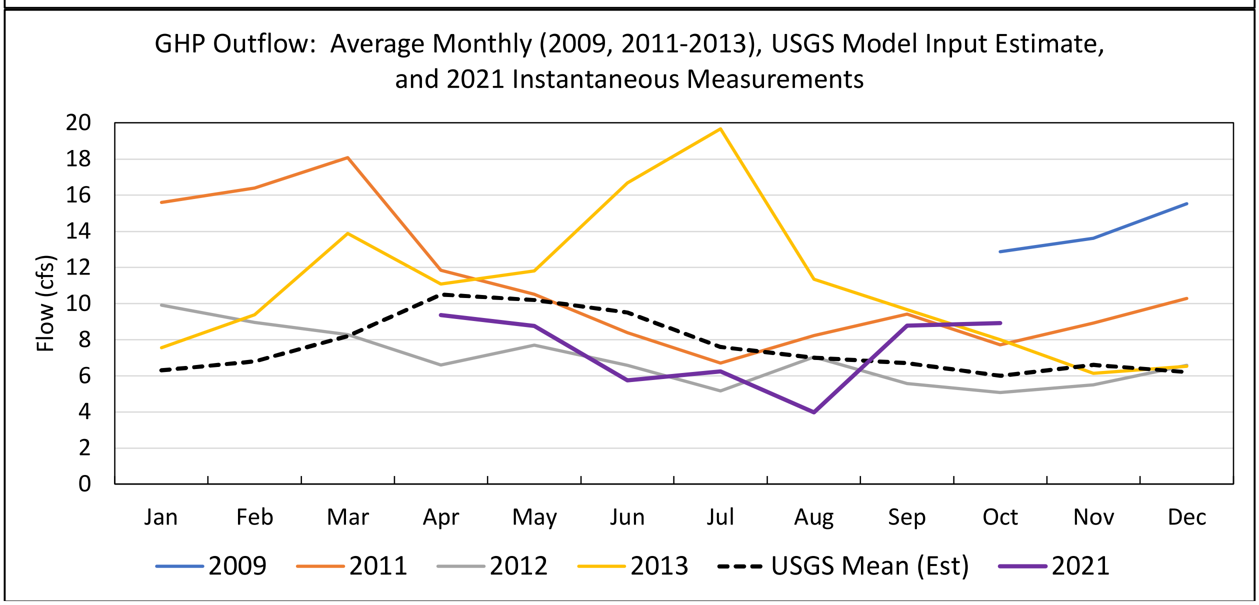


Figure V-12. Average Monthly Historical Outflows from LHP and GHP and 2021 Instantaneous Measurements. As part of the 2021 data gap monitoring, project staff collected instantaneous streamflow measurements at the LHP and GHP outflows. These readings were generally consistent with available historical flow readings collected in 2009 and 2011-2013 albeit closer to minimum readings in the historical data. The LHP outflow June, August, and September 2021 instantaneous readings and the GHP August 2021 instantaneous reading were the lowest recorded at those locations among the available data. Review of groundwater levels showed that at the June, July, and August 2021 groundwater levels were the lowest among the years when streamflow readings were collected.

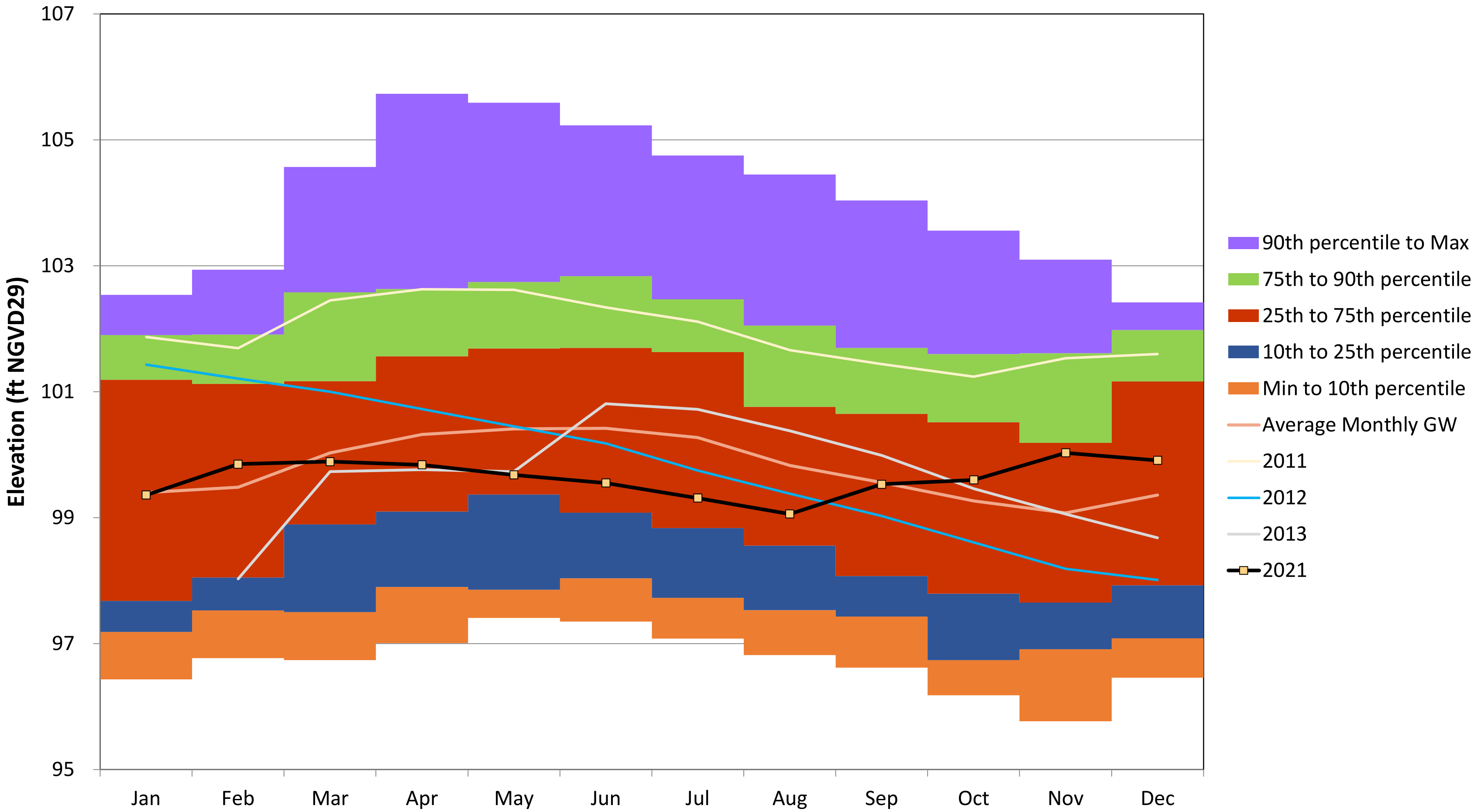


Figure V-13. Plymouth Groundwater Levels: Average, 2011-2013, 2021. Groundwater elevations have generally been collected monthly at PWW-494 since 1985, which is the longest water level dataset closest to LHP and GHP. Given the characteristics of the aquifer system were LHP and GHP are located, streamflow readings will fluctuate depending on the elevation of the groundwater. During 2011 when regular historical streamflow readings were initiated, groundwater levels were generally in the 75th to 90th percentile of the available readings, while groundwater levels in 2012 and 2013 were generally closer to average. Summer groundwater levels in 2021 were the lowest among the available periods when streamflow readings have been collected.

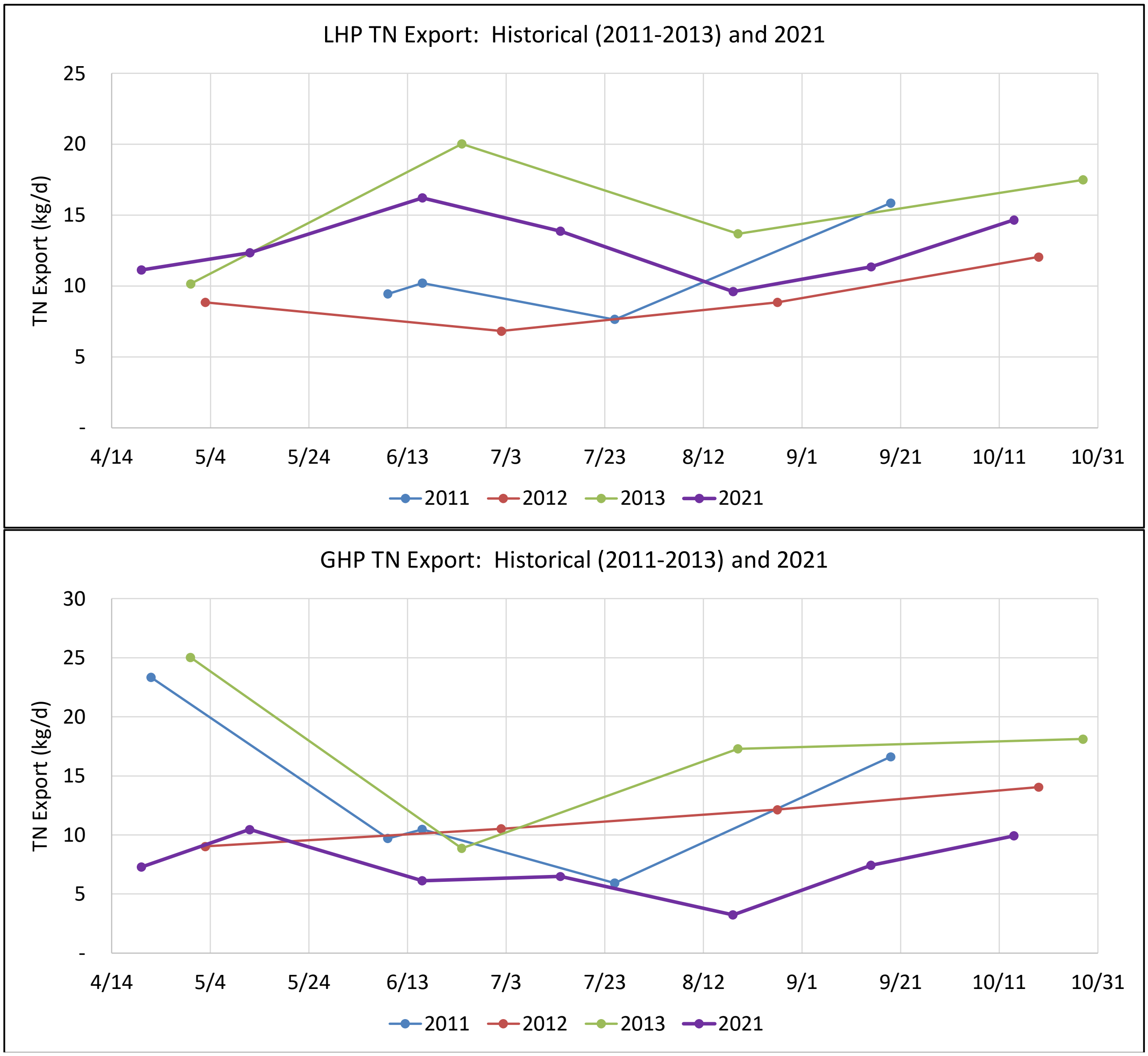


Figure V-14. Historical (2011-2013) and 2021 TN Export from LHP and GHP. 2021 TN export from LHP was within the same range of available historical export (2011-2013), while 2021 TN export from GHP tended to be lower than available historical readings. 2021 LHP TN export averaged of 12.1 kg/d (n=7), while 2021 GHP TN export averaged 7.7 kg/d (n=7). Average historical TN export from LHP and GHP were 11.8 kg/d and 13.9 kg/d, respectively.

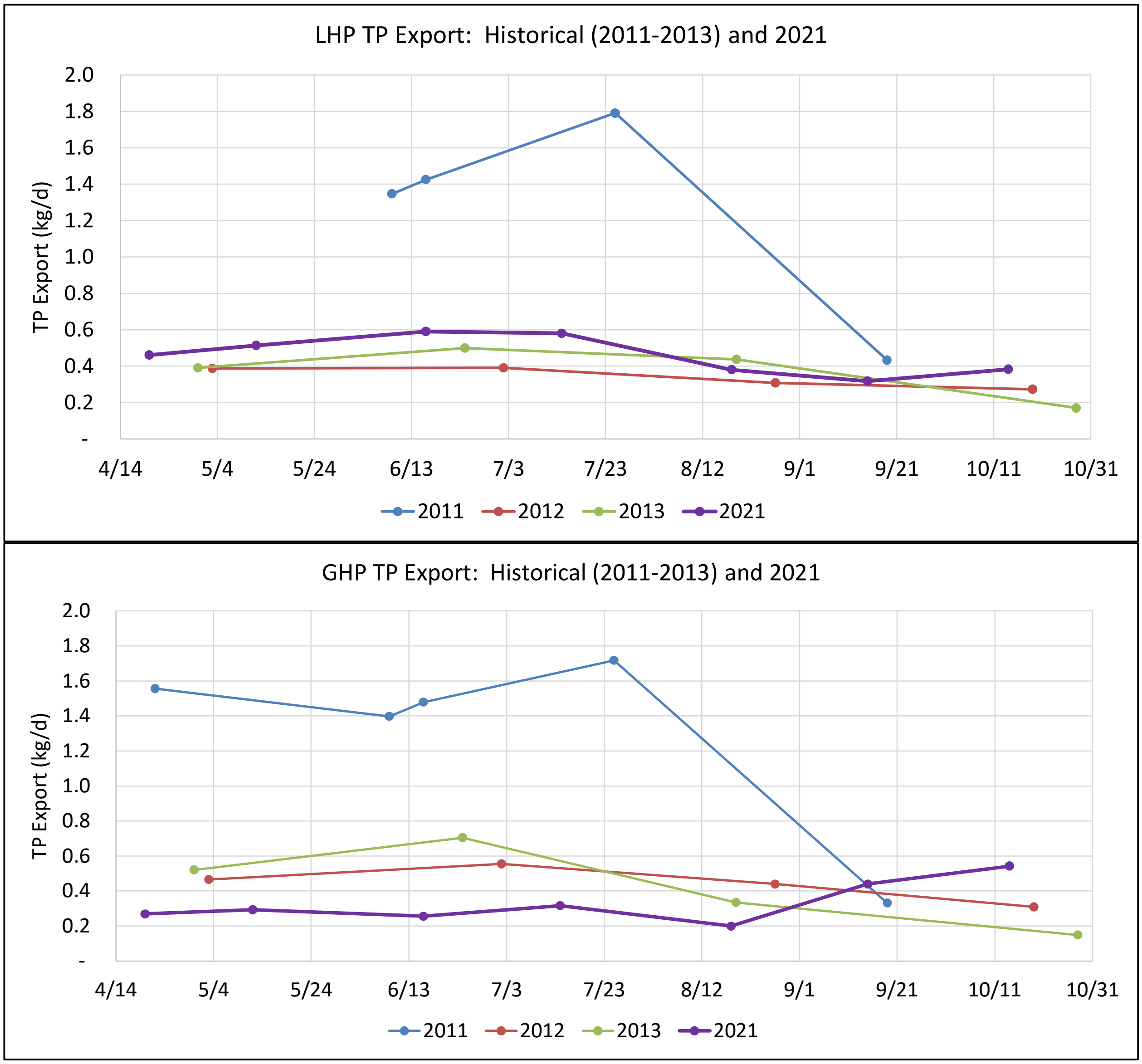


Figure V-15. Historical (2011-2013) and 2021 TP Export from LHP and GHP. 2021 TP export from LHP was slightly higher than 2012 and 2013 export readings, but much lower than 2011 readings. GHP export was lower than all past readings until September and October when TP export was greater than all historical readings for those months. Average 2021 TP export from LHP and GHP was 0.44 kg/d and 0.36 kg/d, respectively. Average historical TP export from LHP and GHP were 0.78 kg/d and 0.93 kg/d, respectively.

V.C. Bathymetry and Water Column Nutrient and DO Mass

CSP/SMAST staff completed bathymetric surveys of GHP on October 20-22, 2021 and LHP on September 30, 2021. Surveys were completed 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 ponds, which is a significant data density increase over previous bathymetric mapping. This data collection determined that the total volume of LHP is 322,568 cubic meters with a maximum depth of 1.5 m (**Figure V-16**), while GHP has a total volume of 10,526,019 cubic meters with a maximum depth of 15 m (**Figure IV-17**). As noted in **Figure V-13**, groundwater levels at the time of the bathymetry surveys approximated average conditions, so the volumes should also approximate average conditions.

Combining the volume of the pond with available water quality data provides additional insights into the availability of nutrients and dissolved oxygen mass within the water column, as well as a measured check on the phosphorus budget. As previously noted, LHP has relatively high TP concentrations (see **Figure V-2**) and DO concentrations typically higher than atmospheric equilibrium (see **Figure V-1**). However, because the volume of LHP is relatively small, the average monthly TP mass in the water column was also relatively small (8 kg) with a range of 6.2 kg to 11.2 kg over the nine 2021 samplings (**Figure IV-18**). Average monthly TN mass was 220 kg with a range of 177 kg to 260 kg. Water column DO mass is a balance between DO additions from phytoplankton photosynthesis, DO loss from sediment demand, and atmospheric mixing venting excess water column DO or providing DO when sediment demand is excessive. On six of the nine 2021 dates, LHP had DO in excess of atmospheric equilibrium (monthly average +358 kg in the water column). The other three were approximately in balance with the atmosphere.

Relative to its size, GHP had similar TP mass, lower TN, and much lower DO. GHP had a DO deficit in most of its water column profiles with near surface waters having DO mass in excess of atmospheric equilibrium, but deep waters having significant DO losses. Of the seven DO profiles, all but one had less DO throughout the water column than would be projected at atmospheric equilibrium (**Figure IV-19**). GHP 2021 TP mass increased from April through August before decreasing in September and October likely due to sediment inputs caused by the deep low DO. The GHP 2021 water column TP mass averaged 207 kg with much lower water column mass in April (116 kg) and May (142 kg) and much higher mass in August (279 kg) and September (265 kg). The average 2021 TP mass per volume in both GHP and LHP was the same (0.02 kg TP/1000 m^3), but the LHP mass was relatively stable while GHP increased from the spring to late summer. GHP water column TN mass was relatively stable except for the April profile; the 2021 average was 3,659 kg, while the April mass was 4,773 kg. The average TN mass per volume in GHP was approximately half of the LHP rate: GHP 0.35 kg TN/1000 m^3 and LHP 0.63 kg TN/1000 m^3. These relationships are discussed further in the watershed and nutrient budget discussions.

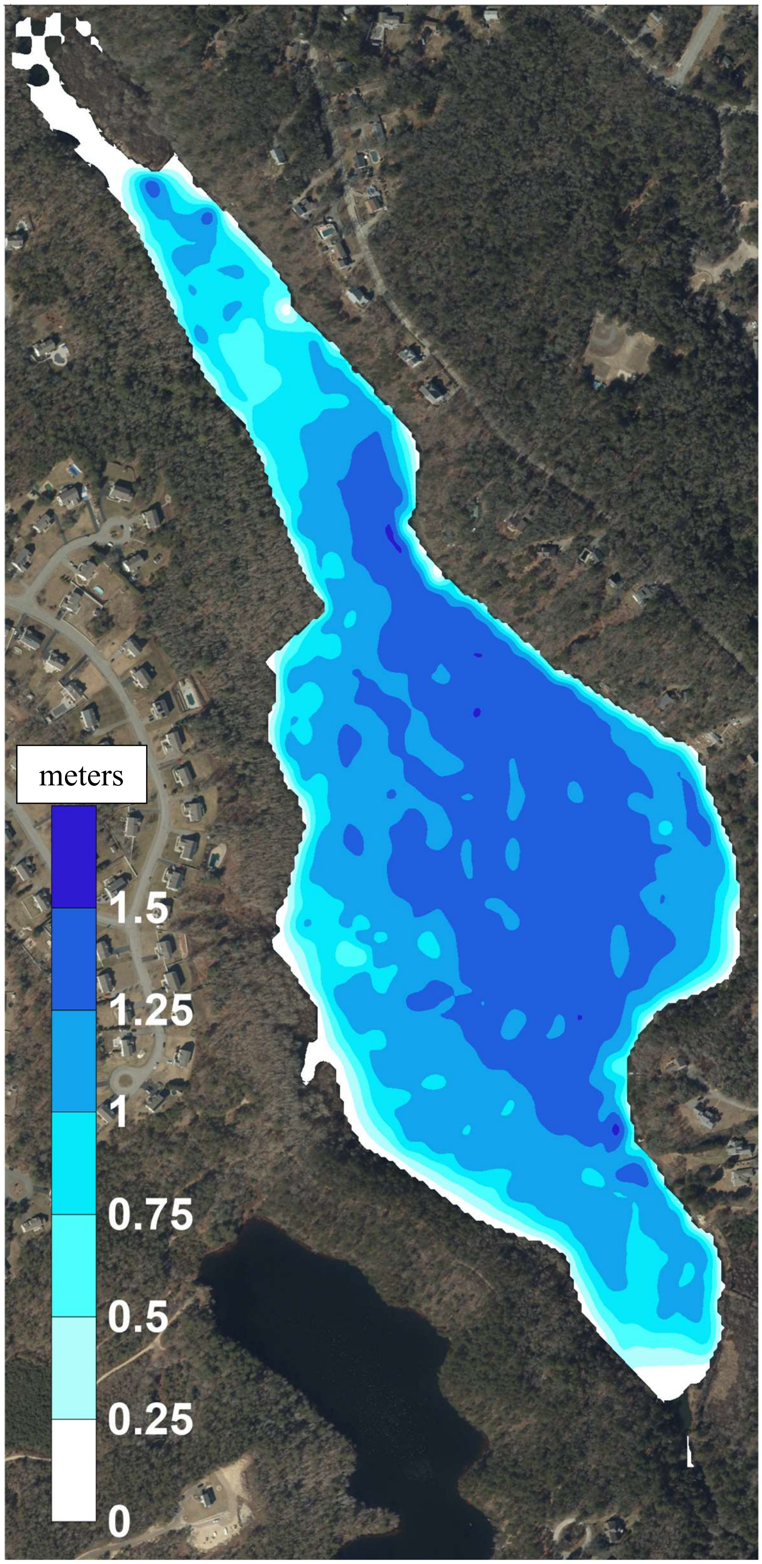


Figure V-16. Little Herring Pond 2021 Bathymetry. CSP/SMAST staff completed a bathymetry survey on September 30, 2021 using a boat with a differential GPS for positioning coupled to a survey-grade fathometer and submerged video camera. Data collection resulted in more than 300,000 depth points and synthesis of this data determined the total volume of Little Herring Pond is 322,568 cubic meters with a maximum depth of 1.5 m. Figure shows depth contours in meters.

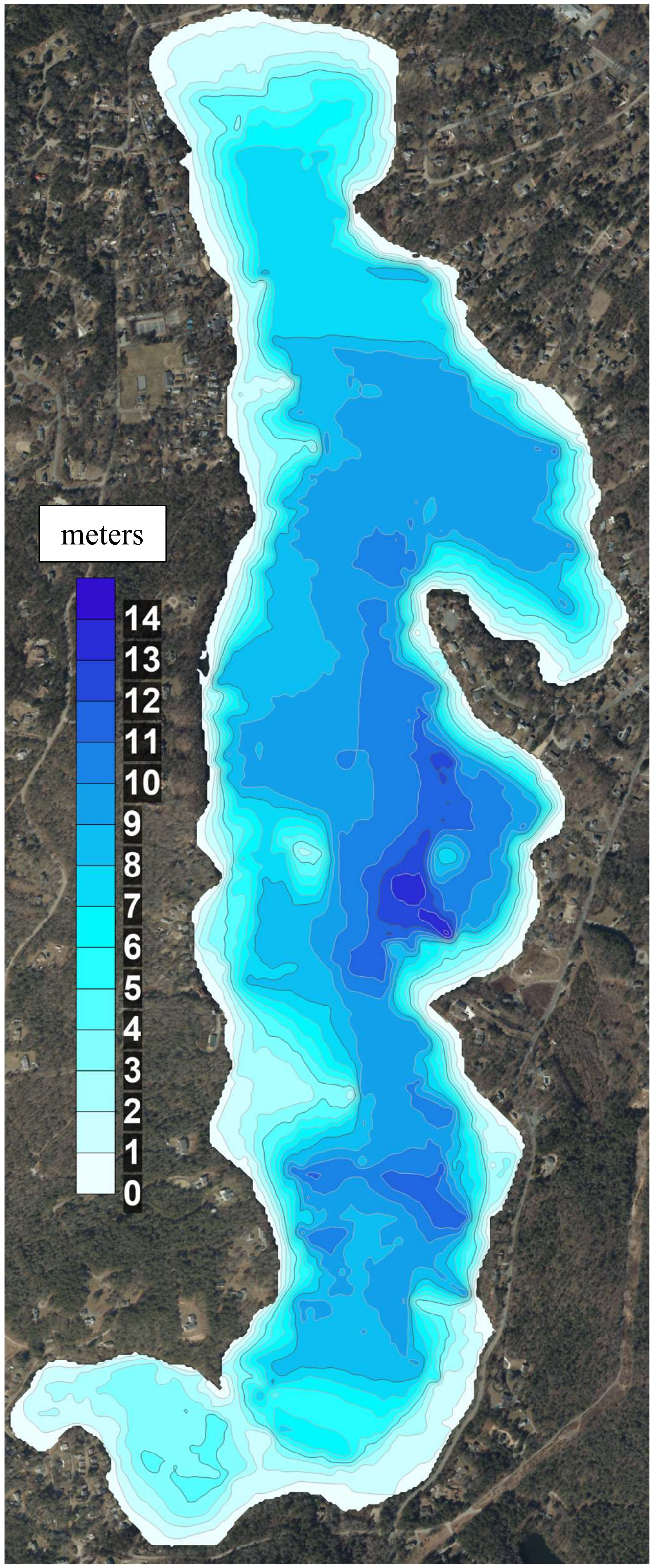


Figure V-17. Great Herring Pond 2021 Bathymetry. CSP/SMAST staff completed a bathymetry survey on October 20-22, 2021 using a boat with a differential GPS for positioning coupled to a survey-grade fathometer and submerged video camera. Data collection resulted in more than 1.4 million depth points and synthesis of this data determined the total volume of Great Herring Pond is 10,526,019 cubic meters with a maximum depth of 15 m. Figure shows depth contours in meters.

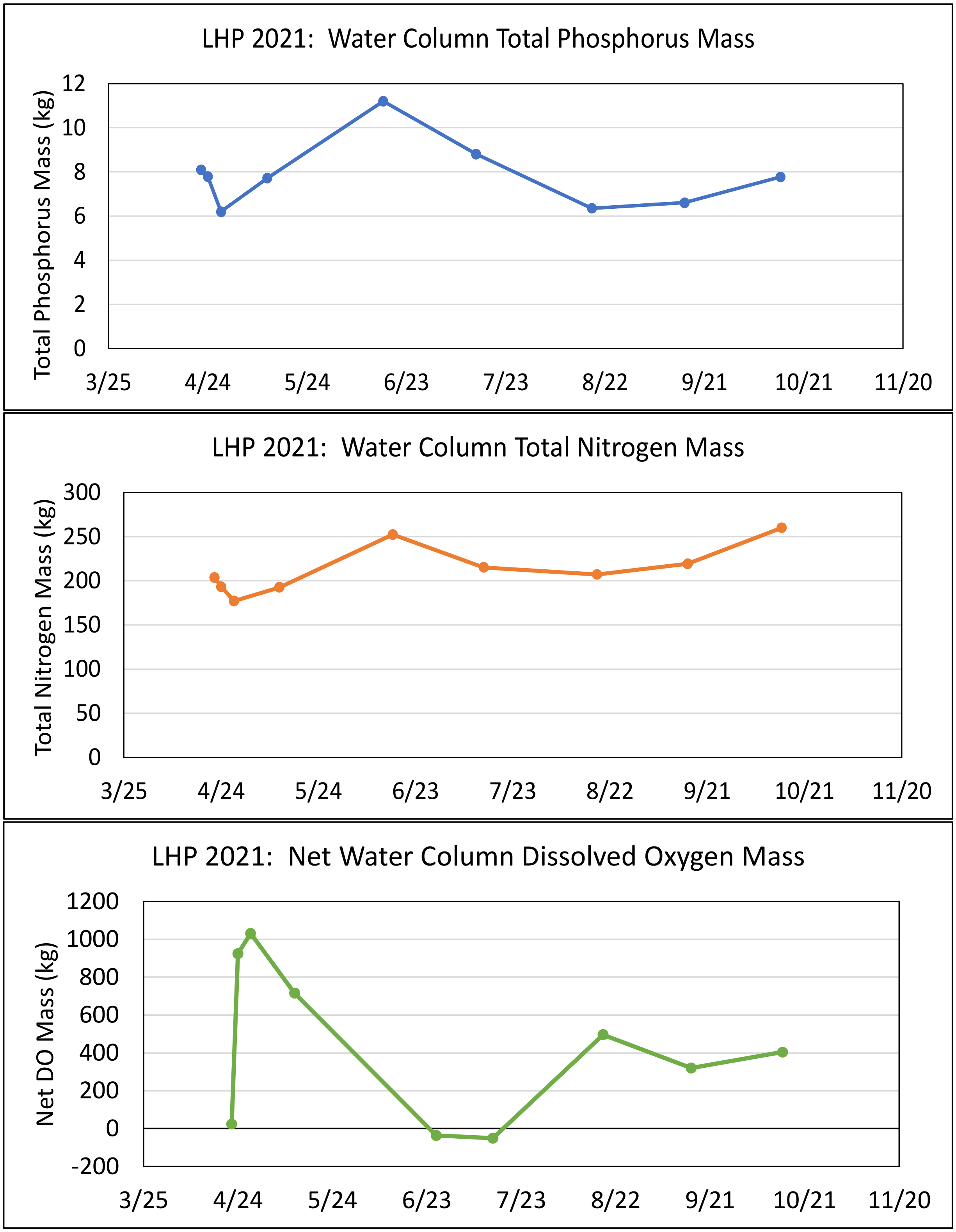


Figure V-18. Little Herring Pond 2021 Water Column DO, TP, and TN Mass. TP monthly mass averaged 8 kg with a range of 6.2 kg to 11.2 kg. TN monthly average was 220 kg with a range of 177 kg to 260 kg. Net DO mass was determined by comparing water column DO mass to expected DO mass if the water column was in equilibrium with the atmosphere. Net DO mass was well above equilibrium (*i.e.*, 0 kg net mass) in most profiles except for April 22, June 26 and July 14, which were at equilibrium.

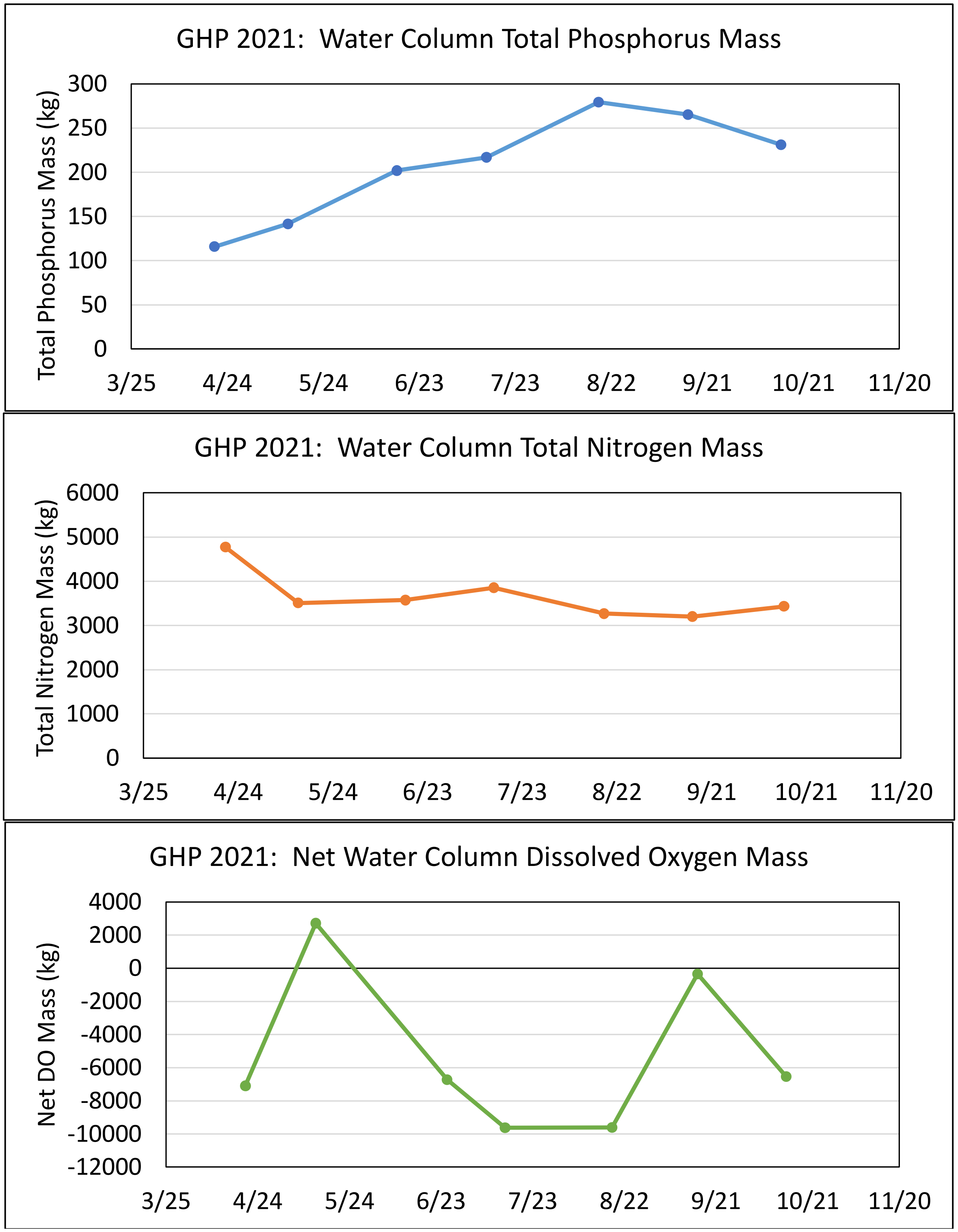


Figure V-19. Great Herring Pond 2021 Water Column DO, TP, and TN Mass. TP monthly mass increased from April through August and averaged 207 kg with a range of 116 kg to 279 kg. Monthly TN mass was relatively stable except for April and averaged 3,659 kg. Net DO mass was determined by comparing water column DO mass to expected DO mass if the water column was in equilibrium with the atmosphere (*i.e.*, 0 kg net mass). Net DO mass was well below equilibrium in most profiles except for May 13 and September 15, which were well above equilibrium and at equilibrium, respectively.

V.D. Phytoplankton Community

Phytoplankton communities are a mix of a large number of microscopic plants. Each of species that make up the community grow best when a particular set of factors, including light, temperature, and nutrients, are at optimal levels. These plants are grazed on by microscopic animals (*e.g.*, daphnia, rotifers) and have evolved various defense mechanisms, such as toxins, armor, etc., to make them less likely to be eaten. Of particular concern to humans are those that make toxins and rapidly grow large populations in optimal conditions (*i.e.*, bloom). The most problematic of these species tend to be cyanobacteria (also known as blue-green algae, cyanophytes, etc.).

Most ponds in southeastern Massachusetts have phytoplankton populations that include some cyanophytes. Cyanophytes can collect nitrogen directly from the atmosphere, so in situations with excessive phosphorus, they can meet their growth needs for nitrogen easily (nitrogen is close to 80% of the atmosphere). These types of situations lead to blue-green blooms which can cause skin, eye, and ear irritation upon direct contact and diarrhea in cases of excessive consumption. USEPA has issued drinking guidance for blue-green consumption for communities that rely on surface water sources and MassDPH recommends issuing a Public Health Advisory for recreational use of ponds if any of the following criteria are met:

1. A visible cyanobacteria scum or mat is evident;
2. Total cell count of cyanobacteria exceeds 70,000 cells/mL;
3. Concentration of the toxin microcystins exceeds 8 µg/L; or
4. Concentration of the toxin cylindrospermopsin exceeds 15 µg/L.[41]

The Town Department of Marine and Environmental Affairs (DMEA) has collected water samples for cyanobacteria and microcystins in GHP on a number of occasions including during 2021. These samples were collected in the cove north of Eagle Hill Dr (July, October) and the southern cove west of the stream outlet (July).[42] Observations during the July visit noted "particles" in the water column and the Board of Health issued public health advisory in July 2021. A 2020 public health advisory was issued for GHP from July 17 to September 4 also based on observations. None of 2021 samples exceeded the MassDPH numeric criteria for cells counts (maximum cell count was 17,000 cells/ml on October 14) or microcystins.

As part of the 2021 diagnostic survey of both GHP and LHP, CSP/SMAST staff collected monthly phytoplankton samples through vertical net tows between April and October 2021. Tows were conducted through the photic zone, as determined by a Secchi reading at both ponds deepest point. Samples were collected in brown bottles, preserved, and stored at 4°C until analysis. GHP and LHP samples were assayed for biomass, cell counts, and individual species (**Figures V-20 and V-21, respectively**).

None of the 2021 GHP or LHP samples exceeded the MassDPH cell count threshold. The maximum cell count among the seven samples in each pond was 2,267 cells/ml on October 14 in GHP. This lower count in the middle of the pond, as opposed to the 17,000 cells/ml from the DMEA sampling in the cove north of Eagle Hill Drive, suggests that the higher counts in the cove were either locally produced (*i.e.*, better growing conditions for blue-greens) or wind-

[41] https://www.mass.gov/info-details/guidelines-for-cyanobacteria-at-recreational-freshwater-locations (accessed 7/18/22).
[42] Personal communication, K. Tower, 11/18/21.

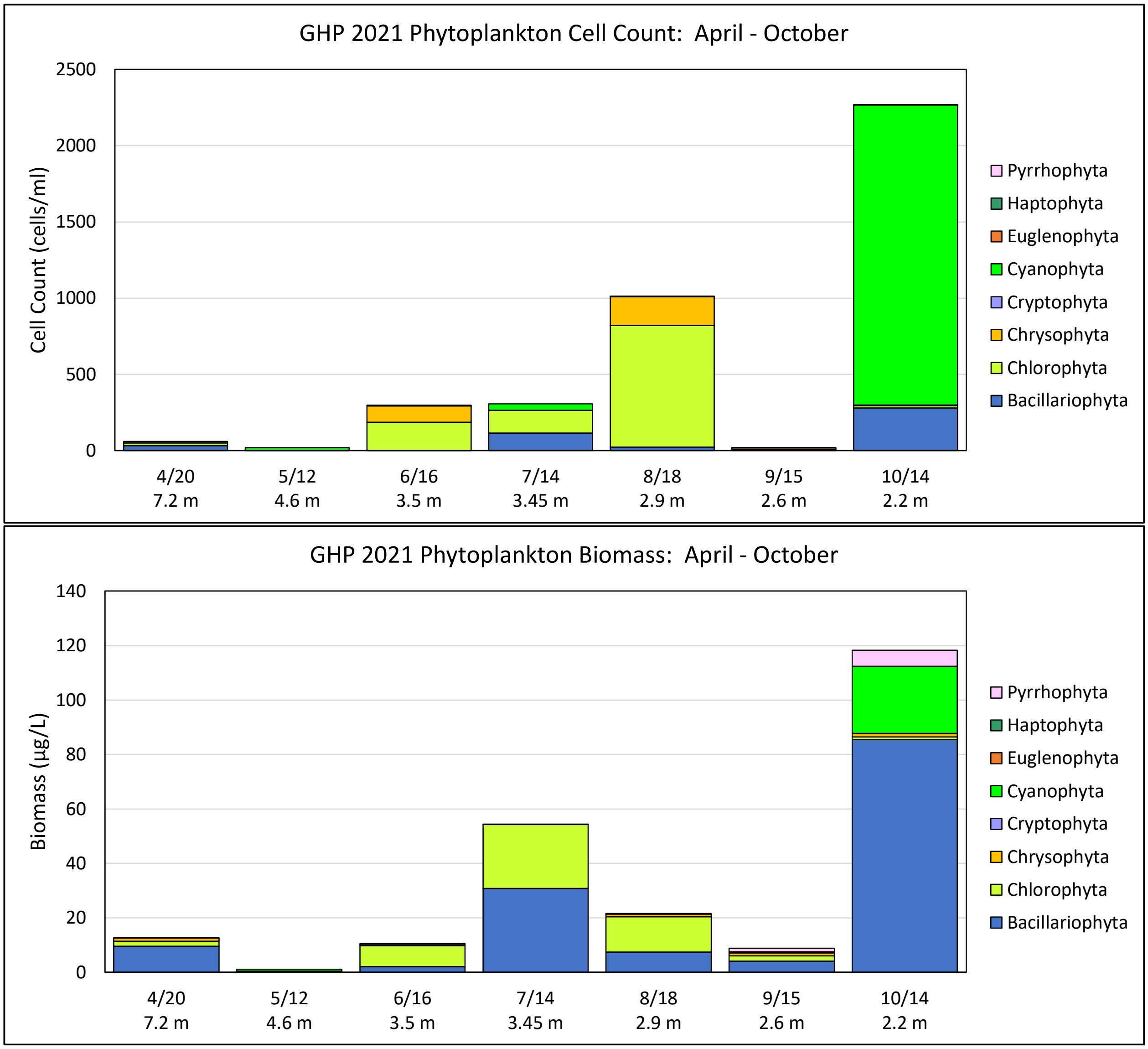
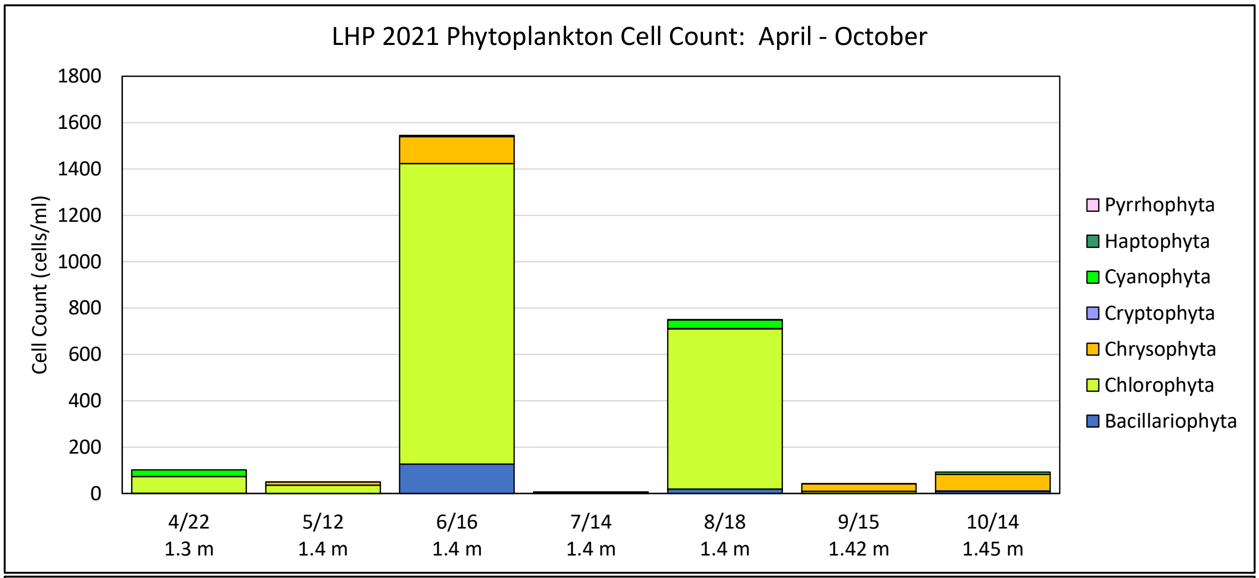


Figure V-20. GHP 2021 Phytoplankton Summary: Cell Counts and Biomass. GHP 2021 phytoplankton sampling generally showed a diverse population, low number of cyanobacteria species, occasional elevated biomass, and only one instance of high monthly biomass (October). Chlorophyta (*i.e.*, green algae) or bacillariophyta (*e.g.*, diatoms) were generally the predominant portions of the phytoplankton biomass (*i.e.*, >50%). Blue-green biomass was the highest percentage of the biomass in only one month (May), but this was also the month with the lowest total biomass (1 µg/L). In the October sample, 21% of the total biomass was cyanobacteria; October was also the month with the highest total biomass (118 µg/L). Phytoplankton cell counts in October were the higher recorded in GHP and these were only 3% of the MassDPH cell count criterion for issuing a Public Health advisory.



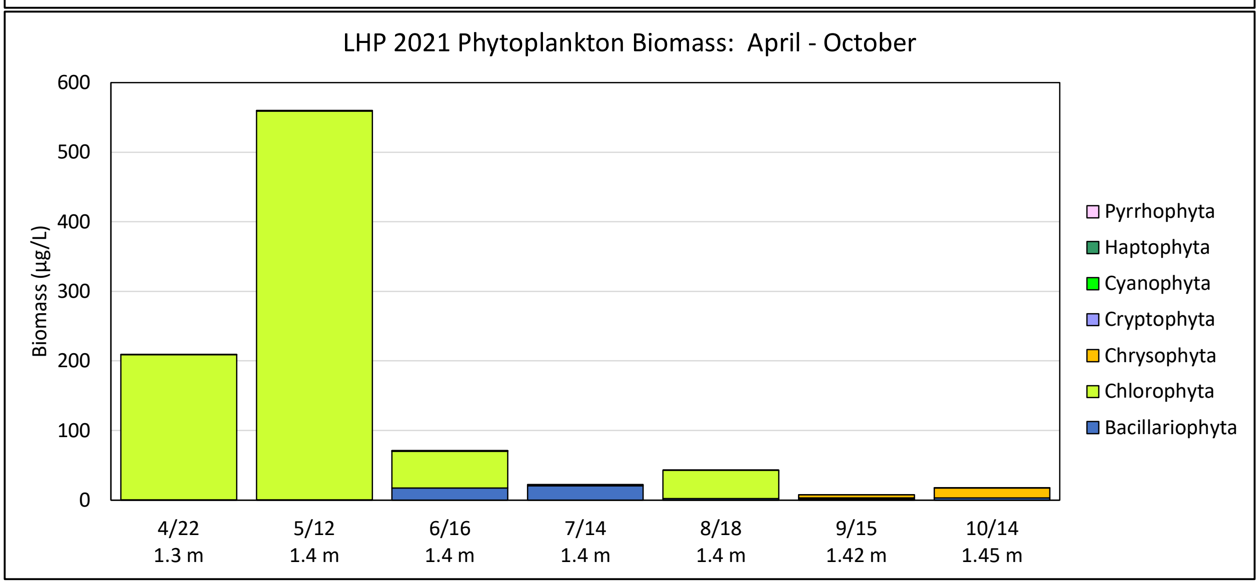


Figure V-21. LHP 2021 Phytoplankton Summary: Cell Counts and Biomass. LHP had higher biomass concentrations than GHP, but lower cell counts and very limited cyanobacteria. April and May biomass concentrations were higher than the maximum measured in GHP during 2021. April biomass was 209 µg/L, while May biomass was 560 µg/L. However, biomass levels decreased to 71 µg/L in June, 22 µg/L in July, 43 µg/L in August and less than 20 µg/L in September and October. This pattern suggests phytoplankton utilizing initial nutrient availability from spring warming of the pond, but much of the resulting growth streaming out to GHP and rooted plants changing the sediment gradients to keep nutrients in the sediments after May. Chlorophyta were ≥94% of the biomass in April, May, and August. In July, bacillariophyta was 92% of the biomass and in September and October, chrysophyta (or golden algae) were 60% and 83% of the sample biomass, respectively. Cyanobacteria were less than 1% of total biomass in all LHP samples and the maximum cyanobacteria cell count was 38 cells/ml or only 0.05% of the MassDPH cell count criterion for issuing a Public Health advisory.

driven circulation was concentrating cells in the cove. The highest cell count in LHP 1,544 cells/ml on June 16.

The GHP 2021 phytoplankton sampling generally showed a diverse population, low number of cyanobacteria species, occasional elevated biomass, and only one instance of high monthly biomass (October). Species counts in April and October were over 20, while counts in June, July, August and September were 10 or more. Only May had <5 species (with one blue-green). Only one species of blue-greens was noted in most samples, though the identified species changed. October was the only month with more than one species (3 species noted). Green phytoplankton (chlorophyta) generally had the greatest number of species (≥ 5 species in 5 of the 7 samplings). Chlorophyta or bacillariophyta (*i.e.*, diatoms) were generally the predominant portions of the phytoplankton biomass (*i.e.*, >50%). Blue-green biomass was the highest percentage of the biomass in only one month (May), but this was also the month with the lowest total biomass (1 µg/L). In the October sample, 21% of the total biomass was cyanobacteria; October was also the month with the highest total biomass (118 µg/L). The significant presence of diatoms throughout the summer generally indicates low nutrient waters.

LHP 2021 phytoplankton sampling had higher biomass concentrations, but lower cell counts and very limited cyanobacteria. April and May biomass concentrations were higher than the maximum measured in GHP during 2021. April biomass was 209 µg/L, while May biomass was 560 µg/L (see **Figure IV-21**). However, biomass levels decreased to 71 µg/L in June, 22 µg/L in July, 43 µg/L in August and less than 20 µg/L in September and October. This pattern suggests phytoplankton utilizing initial nutrient availability from spring warming of the pond, but much of the growth streaming out to GHP and rooted plants changing the sediment gradients to keep nutrients in the sediments after May. Chlorophyta were ≥94% of the biomass in April, May, and August. In July, bacillariophyta was 92% of the biomass and in September and October, chrysophyta (or golden algae) were 60% and 83% of the sample biomass, respectively. Cyanobacteria were less than 1% of total biomass in all LHP samples and the maximum cyanobacteria cell count was 38 cells/ml.

V.E. 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 is distributed. During the initial review of available Great Herring and Little Herring Ponds water column sampling results,[43] 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 of LHP and GHP on September 30, 2021 and October 20-22, 2021, respectively, using a differential GPS mounted on a boat for positioning coupled to a survey-grade fathometer an underwater video camera.[44] The

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

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

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 freshwater mussel species in southeastern Massachusetts 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*).[45] 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.[46] Reviews of available studies suggest mussels have complex responses to nutrient enrichment with both positive and negative impacts due to high or low loads.[47] A video survey was recommended for Great Herring and Little Herring Ponds 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 in both GHP and LHP. GHP had mussels in areas shallower than 8 m (**Figure IV-22**). Lack of mussels greater than 8 m is consistent with occasional summer hypoxia at this depth and anoxia in deeper depths (see **Figure V-5**). Other ponds in the Plymouth Ecoregion with extensive mussels and regular anoxia typically have a ring of mussels in shallow, well-oxygenated waters (*e.g.*, Upper Mill Pond in Brewster). LHP only had mussels along the shallowest margin of the pond (**Figure IV-23**). In some shallow ponds in the Plymouth Ecoregion with extensive rooted plant communities and some mussels, mussels appear to mostly occur only at the shallow and deep edges of the macrophyte communities.[48] Macrophytes and mussels seem to be competitors for bottom habitat, although they can coexist if both are at moderate densities.

Macrophyte abundance is a complex interaction of a number of factors, including sediment characteristics, nutrient and light availability and pond depth.[49] 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.[50] The plant survey was completed to provide insights into the influence of macrophytes on GHP and LHP phosphorus and potential interactions with various water quality management actions.

GHP and LHP had very different distributions of macrophytes with relative sparse distribution in GHP and distribution across the entire bottom in LHP. Most of the LHP pond bottom had at least 50% bottom coverage by macrophytes with extensive areas of 75% coverage and smaller

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

[46] *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.

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

[48] *e.g.* Walkers Pond in Brewster (Eichner et al., 2014)

[49] 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.

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

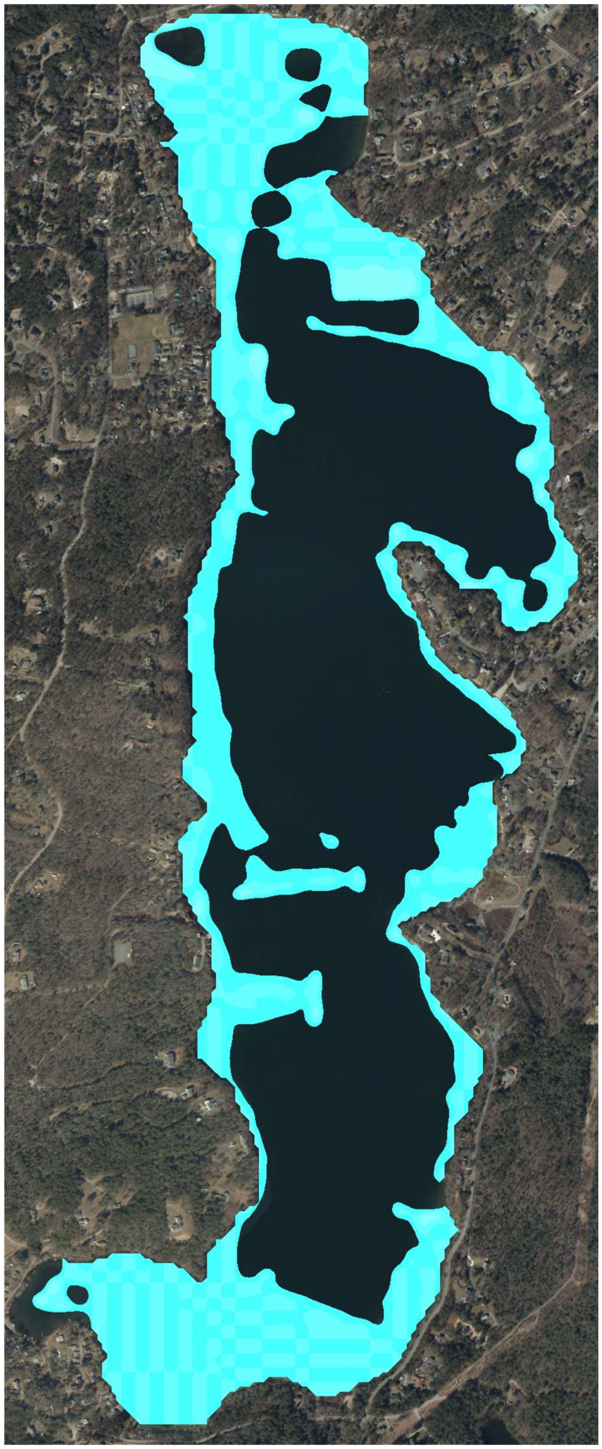

Figure IV-22. Great Herring 2021 Freshwater Mussel Survey. CSP/SMAST staff completed an underwater video survey October 20-22, 2021, to determine the distribution freshwater mussels in GHP. Cameras were synced with dGPS and recorded at five frames per second. Staff determined mussel presence within each video frame (approximately 0.25 m^2 of lake bottom). Indicated areas had at least one mussel in each frame with many frames showing high mussel density. Mussels were not present in areas deeper than 8 m, which tends to be the depth of occasional hypoxia. 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.

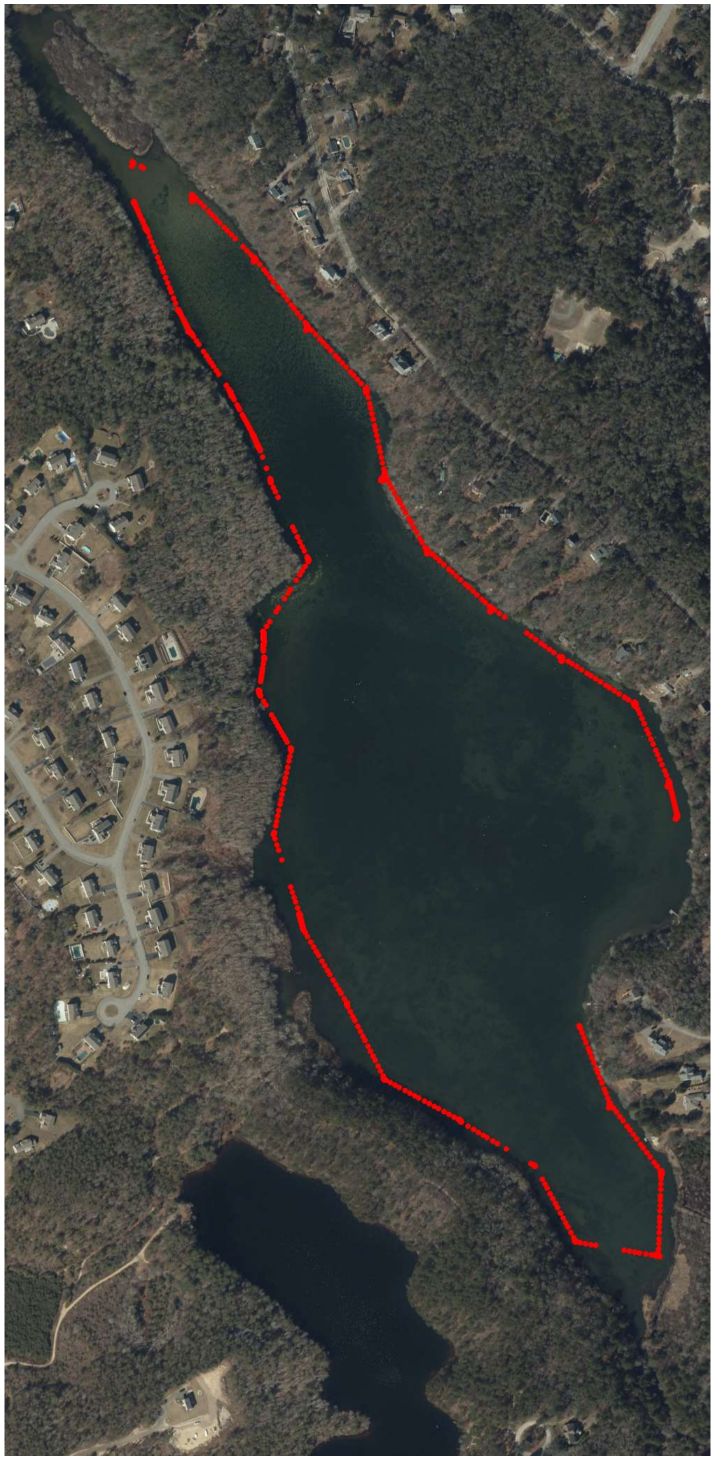

Figure IV-22. Little Herring 2021 Freshwater Mussel Survey. CSP/SMAST staff completed an underwater video survey September 30, 2021, to determine the distribution freshwater mussels in LHP. Cameras were synced with dGPS and recorded at five frames per second. Staff determined mussel presence within each video frame (approximately 0.25 m^2 of lake bottom); map shows individual mussels. Mussels were only present in the shallowest areas, but were mostly around the margin of the whole pond. 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.

pockets of 100% bottom coverage (**Figure IV-24**). There were some observations of epiphytic filamentous green algae on some of the plants in the middle of the pond; this type of growth in high density macrophyte beds is typically associated with excessive nutrients. The high density coverage would be consistent with 2021 clarity readings showing light always reaches the bottom at the deepest point in LHP. This coverage appears to be an increase in bottom coverage noted in the late 1970's where a portion of the deepest areas to the pond outlet were free of macrophyte coverage (see **Figure IV-5**) and the expansion would be consistent with increases in available nutrients. Also, although speciation of the macrophytes was not part of the macrophyte surveys, review of individual frames from the survey suggests that the macrophytes in LHP continue to be the same plant (*i.e.*, *Elodea*) identified in the late 1970's review.

GHP had much sparser macrophyte coverage, although there were pockets with higher densities: the southern cove, near the inlet from LHP and around the northern and northwestern margins, and in relatively shallow areas extending from the western shoreline (**Figure IV-25**). Each of these higher density areas are likely due to a combination of depth (*i.e.*, light availability), substrate materials (*e.g.*, sand vs cobbles), and nutrient availability (*e.g.*, higher concentrations near high density development along the northwestern shore). For example, the sediments near the inlet area from LHP would tend to be enriched in nutrient particles settle out of the water column as they transition from high energy flow in the connecting stream to relatively quiescent pond waters in GHP. The relative sparseness of rooted plants in GHP compared to LHP reinforces that the GHP plant community and phosphorus cycling is dominated by phytoplankton. It is not known whether the 2021 GHP macrophyte distribution is different from past distributions since historical macrophyte surveys were not available.

V.F. Sediment Core Collection and P Regeneration Measurements

The nutrients measured in the water column are the result of additions from the watershed and additions or removals by the sediments. In order to measure the potential additions and removals by the sediments, as well as the conditions that cause these actions, CSP/SMAST collected sediment cores from both Great Herring and Little Herring Ponds and measured the nutrient interactions under aerobic and anaerobic conditions.

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 occur for phosphorus when DO

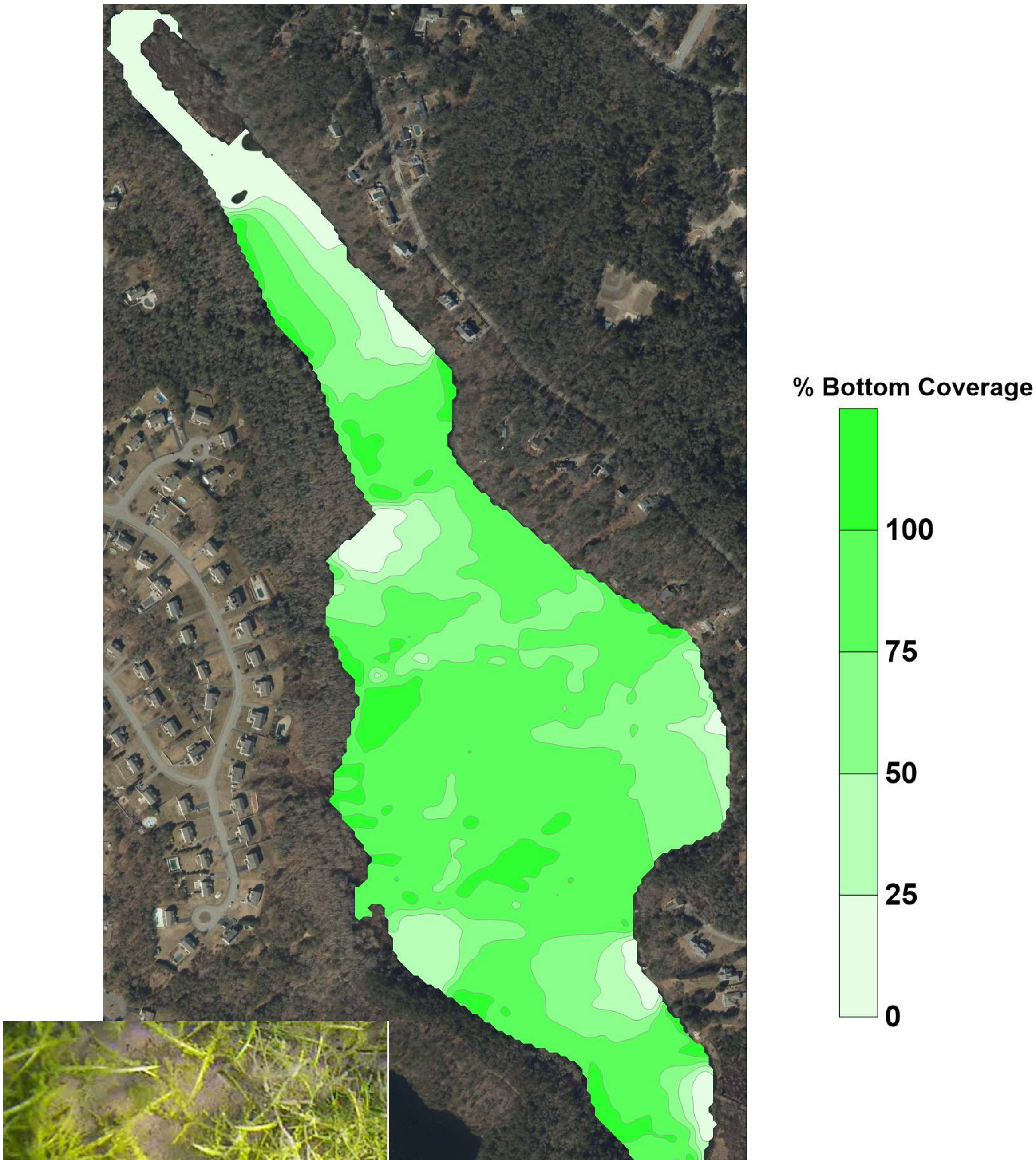

Figure IV-24. Little Herring Pond 2021 Macrophyte Survey. CSP/SMAST staff completed an underwater video survey September 30, 2021, to determine the distribution macrophytes or rooted plants in LHP. Cameras were synced with dGPS and recorded at five frames per second. Staff reviewed each video frame (approximately 0.25 m^2 of lake bottom) to determine the macrophyte coverage of the pond bottom (0% to 100%) within each frame. Macrophytes were distributed across the entire pond bottom with extensive areas of >50% bottom coverage. Density distribution did not seem to be related to depth. Inset shows a representative video frame, which appears to show Elodea, which is the same macrophyte identified in a late 1970's plant survey (Lyons-Skwarto Associates).

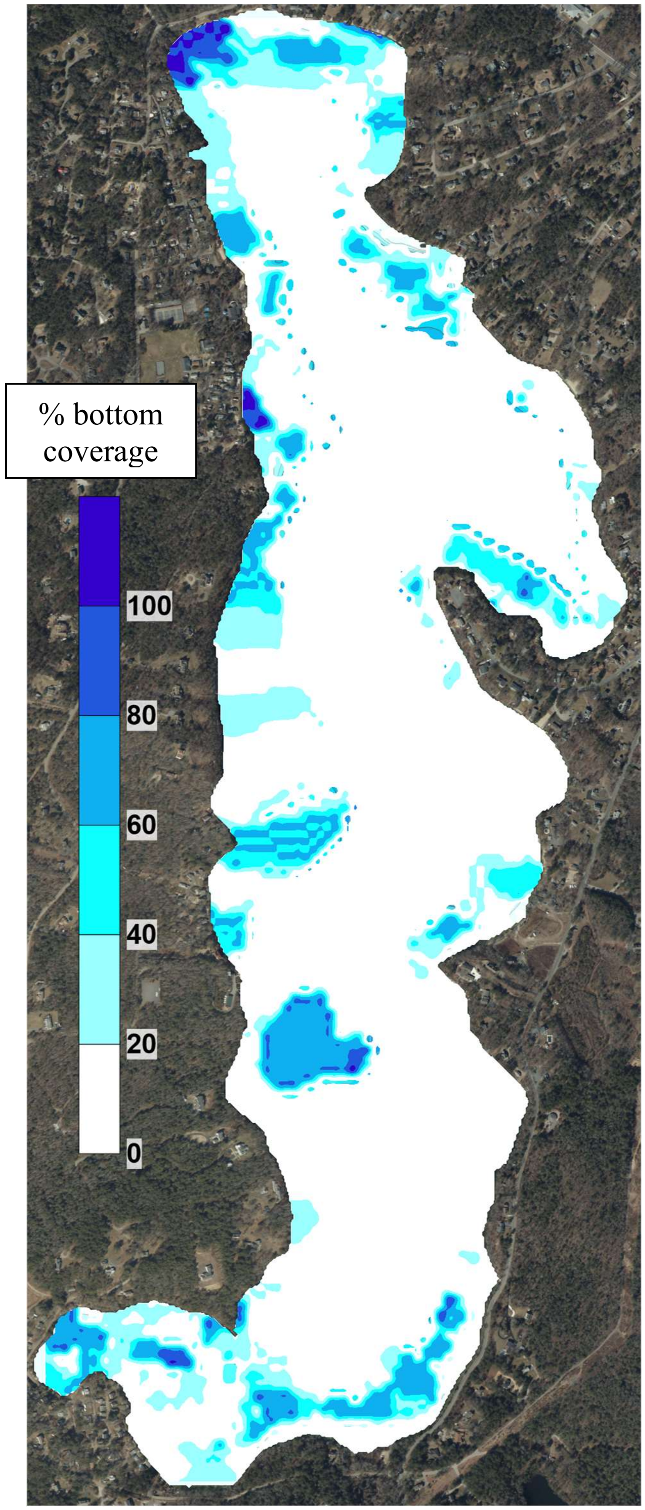

Figure IV-25. Great Herring Pond 2021 Macrophyte Survey. CSP/SMAST staff completed an underwater video survey October 20-22, 2021, to determine the distribution macrophytes or rooted plants in GHP. Cameras were synced with dGPS and recorded at five frames per second. Staff reviewed each video frame (approximately 0.25 m^2 of lake bottom) to determine the macrophyte coverage of the pond bottom (0% to 100%) within each frame. Macrophytes were generally sparsely distributed with pockets of higher density: the southern cove, near the inlet from LHP and around the northern and northwestern margins, and in relatively shallow areas extending from the western shoreline.

concentrations drop to near anoxic levels in pond 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.[51] Some research has also found that macrophyte beds can be net sources of phosphorus to the water column even in aerobic conditions.[52] 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.[53] 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.

In order to measure potential sediment nutrient regeneration within Great Herring and Little Herring Ponds, CSP/SMAST staff collected and incubated 16 intact sediment cores with three collected in LHP and 13 collected in GHP (**Figure V-26**). These undisturbed sediment cores were collected by SCUBA divers on April 24, 2021, while DO concentrations were aerobic throughout the water column in both ponds and the full pool of iron-bound phosphorus in the sediments was intact. Observations of surface sediments in all cores suggested oxidized conditions. 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 Great Herring and Little Herring Ponds in April 2021. 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 GHP when dissolved oxygen concentrations drop to less than 1 mg/L; conditions that were measured in GHP in July, August, and September 2021. LHP 2021 DO measurements did not have any anaerobic conditions.

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

[52] 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.

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

LHP cores were collected at depths between 0.6 m and 1.35 m, while GHP cores were collected at depths between 4.2 m and 11.4 m. Incubation of the cores showed that there generally was a 7 day delay before the chemical release phase was initiated. This chemical release phase was sustained for 42 days, so the anaerobic only release phase was initiated after 49 days of anaerobic conditions. Core incubation under anaerobic conditions was continued for another 21 days after the chemical release phase ended and anaerobic release only began (i.e., cores were incubated for a total of 70 days) 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 between the ponds and depending on oxygen conditions (aerobic vs. anaerobic) (**Figure V-27**). In GHP, sediments exposed to aerobic conditions removed P from the water column and at a similar rate for both shallow and deep sediments. Average aerobic P removal rate over the GHP pond area would be 1.3 kg/d. As these sediments were exposed to anaerobic conditions, they initially released P at the same rate (*i.e.*, chemical release) regardless of depth and after the completion of chemical release, the long term anaerobic release was approximately half of the chemical release rate again with no significant difference between depths where the sediments were collected. These findings suggest that there is a ready pool of available P in the GHP sediments that can be rapidly released if they are exposed to anaerobic conditions. GHP had anaerobic conditions recorded in the July, August, and September 2021 profiles (see **Figure V-5**), so anaerobic conditions over the deepest sediments occurred for more than 60 days.

LHP sediments reacted a bit differently than GHP sediments. Under aerobic conditions, LHP sediments removed P from the water column at 2X the average rate in GHP (see **Figure V-27**).

Figure V-26. Great Herring and Little Herring Ponds 2021 Sediment Core Locations. Orange circles show the locations of 13 sediment cores collected in Great Herring Pond, while yellow circles show location 3 sediment cores collected in Little Herring Pond. All cores were collected on April 24, 2021. Base map is a 10/23/21 aerial from Google Earth.

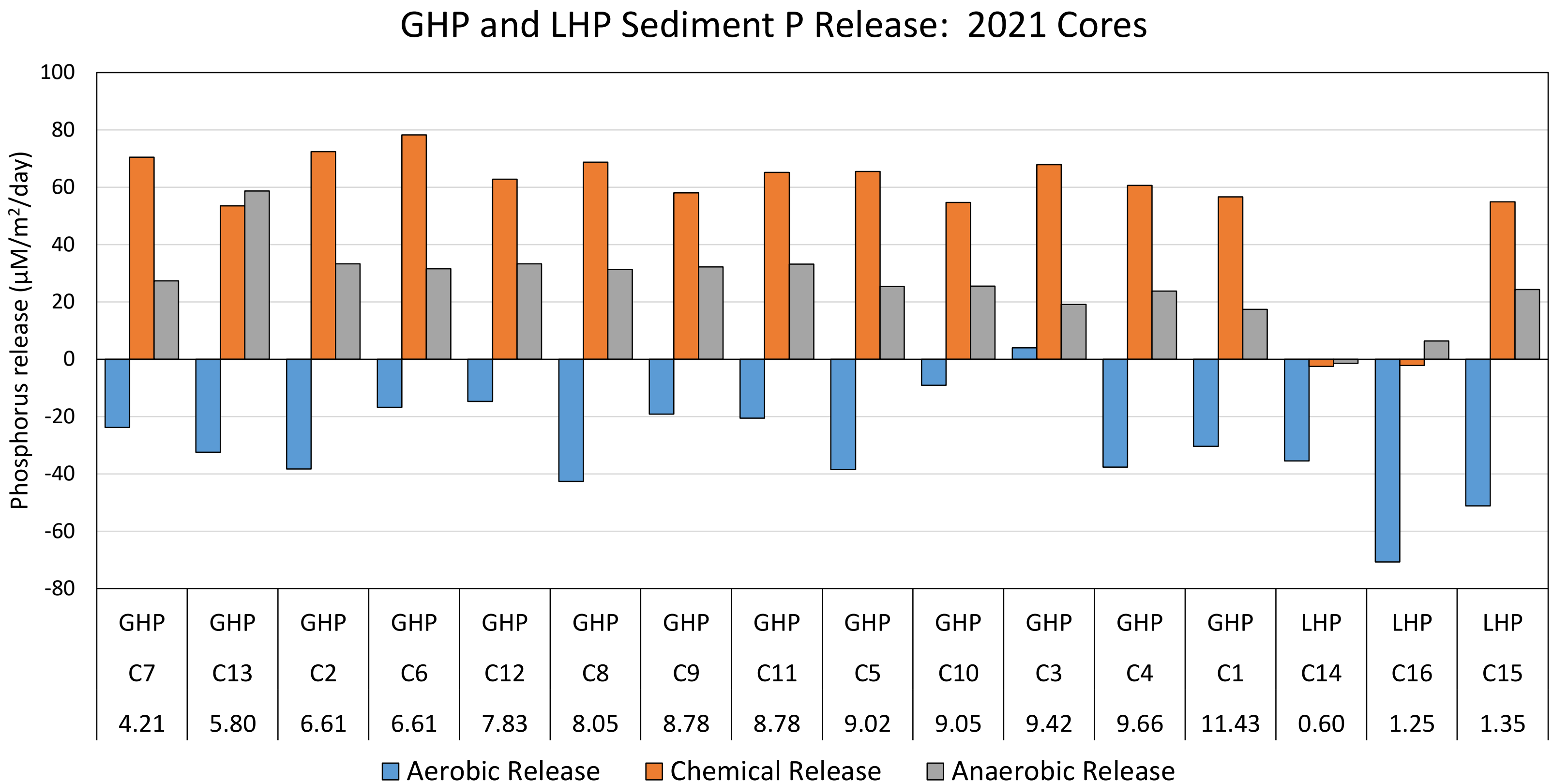

Figure V-27. Great Herring and Little Herring Ponds Phosphorus Release from Collected 2021 Sediment Cores. Average P release measured during aerobic and anaerobic incubation of the cores collected at GHP and LHP on April 24, 2021 are shown. Core incubations showed that under aerobic conditions, which is generally experienced by all sediments in LHP and GHP sediments to 8 m depth, pond sediments were removing P from the water column (*i.e.*, negative P release rates). Average aerobic P removal was greater in LHP than GHP, but not statistically different. Low chemical and anaerobic release rates in shallow LHP cores suggest there is little P retained in these sediments and it is winnowed into the deeper portions. Core 15 in the deepest portion of LHP had chemical release and anaerobic rates similar to those in GHP. Chemical release and anaerobic release in GHP had no significant difference in release rates with depth (*i.e.*, between those sediments that were occasionally exposed to anoxic/hypoxia and those that were only exposed to aerobic conditions). Chemical release rates tended to be 2X higher than long-term anaerobic release rates. Chemical release phase began 7 days after the initiation of anaerobic conditions and were sustained for 42 days (*i.e.*, all iron:P bonds are broken). Anaerobic incubation of cores continued for another 21 days after the chemical release phase was completed to ensure that anaerobic P release though microbial remineralization had stabilized.

Given the smaller area of LHP, this P removal rate would translate to 0.5 kg/d in LHP. The two shallowest cores in LHP (C14 and C16) had very little P available for release under anaerobic conditions. The deeper core in LHP (C15) had chemical release and long-term anaerobic release rates similar to those measured in GHP. These differences suggest that only small amounts of P are retained in the shallow areas of LHP and that any P collected under the usual aerobic conditions in LHP is winnowed into the deeper portions of the pond (*i.e.*, the areas greater than 1.25 m in **Figure V-16**).

In GHP, 2021 profiles readings suggest that anoxic conditions were sustained in the deepest waters throughout most of the summer, but sediment core release rates suggest that a relatively small amount of P was released. Anoxic conditions were first measured at 12 m depth in the July 14 profile, it expanded to 9 m depth in the August 18 profile, and then decreased to 12.5 m in the September 15 profile. These profiles showed that anoxia was sustained for greater than 78 days in GHP from July through September at deepest depths (>12 m), while sediments from 9 m to 12 m were exposed to anoxia for approximately 30 days. Combining this information with the bathymetric surface area shows that GHP sediments released approximately 30 kg during July to September 2021 anoxic conditions (range was 30 to 44 kg). Review of water column TP data on August 18 shows good agreement between the increase in TP mass 9 m and deeper and the estimated TP addition based on the sediment core TP release rates. This finding suggests that while temperature profiles showed no stratification on August 18, the bottom waters likely did not extensively mix with the rest of water column between July 14 and August 18. Using the same parameters, if anaerobic conditions were sustained at 9 m over the same period in 2021, the deep sediment TP release would approximately double.

The estimated TP mass in the water column increased by approximately 60 kg between July 14 and August 18, which suggests that factors other than the sediments caused the rise in TP mass. It is also worth noting that the aerobic P removal rates in the shallower portions of GHP showed that these sediments removed approximately 80 kg during the same period (range 32 to 149 kg removal). The collective review of these results shows that if anoxia is sustained in the bottom waters for long enough, it can release a significant P mass to the water column, but water column mixing is required to move the deep P mass into the shallower water column to impact phytoplankton growth.

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 (<9 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 (>9 m depth based on 2021 readings) and would include sustaining aerobic conditions in the water column and/or chemically binding the P to remain in the sediments.

V.G. GHP and LHP Watershed Review and Physical Characteristics

V.G.1. GHP and LHP Watershed Delineation and Water Budget

Developing an accounting of all water entering and leaving a pond is a water budget. 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 water budget for ponds in the LHP/GHP Ecoregion is usually some form of Equation 1. The primary water input and output is typically groundwater; groundwater discharges into the pond from watershed and pond water discharges back to groundwater system on the downgradient side. This relationship is often altered by stream inflow and/or outflow; stream outflow in particular can be a faster discharge option for pond water and will often become the primary pathway for water to leave a pond. 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. Aside from groundwater and surface water leaving the pond, the other primary water outflow is evapotranspiration from the pond, due to evaporation off the pond surface and transpiration from emergent and shoreline plants.

Equation 1: General Ecoregion Pond Water Budget/Estimated LHP Water Budget

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

In the Plymouth-Carver-Kingston-Duxbury (PCKD) aquifer system where LHP and GHP are located, watersheds to ponds and lakes are defined mostly by groundwater elevations. Groundwater elevations are measured over a large area within a small number of days and this data is synthesized to produce contours of the same elevation, similar to what would be seen on a topographic map. These contours are impacted by municipal drinking water wells, streams and rivers, and the orientation of the ponds relative to the groundwater elevations, since ponds are large areas of the same elevation. These elevations can also be used as calibration or validation data for groundwater models, which also typically include recharge inputs and characteristics of the underlying hydrogeology. Many, but not all, of the ponds in the PCKD aquifer had watershed delineations completed during the creation of the latest US Geological Survey (USGS) regional groundwater model.[54] Unfortunately, the GHP/LHP system was not included among these delineations.

Since the modeled watersheds for GHP and LHP were not completed, project staff used available groundwater elevation data and the available PCKD modeled outputs to create reasonable approximations of the GHP and LHP watersheds (**Figure V-28**). The estimated GHP and LHP watersheds were bracketed to the west by the Wareham River watersheds delineated for its

[54] Masterson, J.P., Carlson, C.S., and Walter, D.A. 2009. Hydrogeology and simulation of groundwater flow in the Plymouth-Carver-Kingston-Duxbury aquifer system, southeastern Massachusetts: U.S. Geological Survey Scientific Investigations Report 2009–5063. 110 pp.

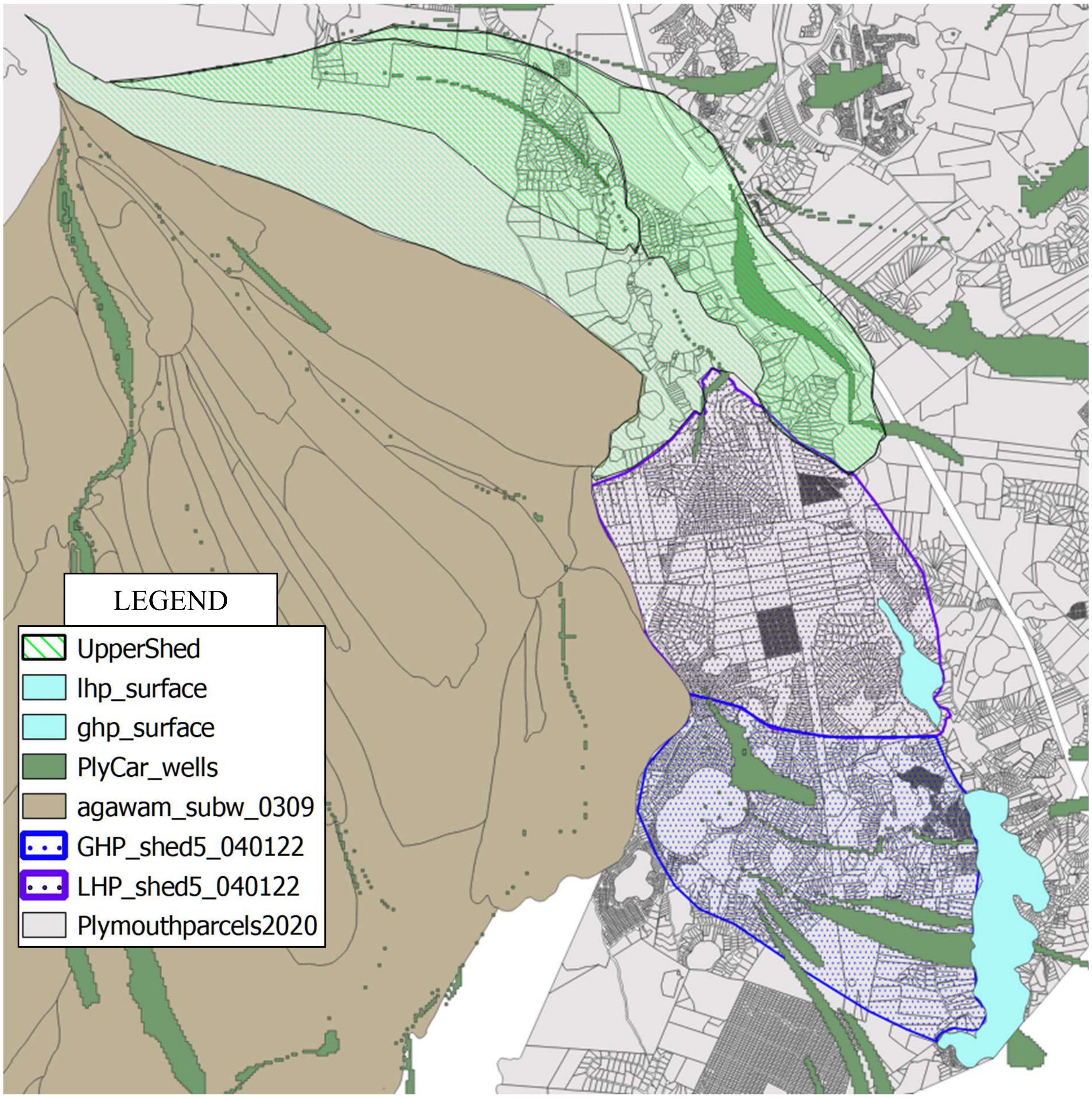

Figure V-28. LHP and GHP Watersheds (Estimated). Watersheds were delineated by project staff using existing US Geological Survey modeled watersheds to other ponds and wells (Masterson and others, 2009) and regional groundwater contours (Hansen and Lapham, 1992). UpperShed is the combined watersheds to Bloody Pond, Little Long Pond, and Long Pond from the 2009 USGS groundwater model. The Wareham River MEP watershed (Agawam_subw0309; Howes and others, 2014) is also based on the 2009 USGS modeling. The direct LHP watershed area is 970 ha. The direct GHP watershed is 930 ha, but also includes the stream between LHP and GHP. Overall watershed to LHP includes portions of the UpperShed that flow through the upgradient pond watersheds. Overall estimated watershed recharge to LHP is in reasonable balance with the measured average outflow, while GHP measure outflow shows that 43 to 48% of the watershed input flows out into groundwater along the eastern shoreline of GHP.

Massachusetts Estuaries Project assessment[55] while the northern portions of the LHP watershed were bracketed by USGS modeled watersheds of Halfway Pond and Bloody Pond.[56] The regional groundwater contours[57] also showed that the pond water flowed back into the groundwater system along the eastern edge of both LHP and GHP. Based on these methods, the watershed areas contributing directly to LHP and GHP are 970 ha and 930 ha, respectively.

An additional variation on the GHP water budget is the water withdrawals by the nearby North Sagamore public drinking water supply wells. As noted in **Figure II-6**, there are two wells located near the GHP outlet with a combined average pumping rate of 0.34 MGD (range of 0.21 to 0.48 MGD). This slightly alters the estimated water budget equation for GHP to:

Equation 2: Estimated GHP Water Budget

$$\text{groundwater}_{\text{in}} + \text{streamflow}_{\text{in}} + \text{surface precipitation} + \text{imported wastewater} + \text{stormwater} = \text{groundwater}_{\text{out}} + \text{streamflow}_{\text{out}} + \text{public water supply withdrawal} + \text{surface evapotranspiration}$$

The combined LHP/GHP whole watershed area is further complicated by defining the water contributions from ponds along the upper edges of the LHP watershed and the internal subwatershed flows to the stream between LHP and GHP. The northern portions of the LHP direct watershed intersect the shorelines of Bloody Pond, Long Pond, and Round Pond and includes this upper watershed also includes Little Long Pond and Gallows Pond. Groundwater flow among these ponds is complicated by the interconnections between the watersheds and the likely discharge of only a portion of the watershed flow from a given pond to the nearby downgradient pond. An example of this is the watershed flow to Bloody Pond, which includes its watershed plus portions of watershed flow to Long Pond and direct watershed flow from Little Long Pond, as well as the portion of Little Long Pond that flows into Long Pond.

Flow out of LHP has been measured in 2009, 2011-2013, and monthly readings in April through October 2021. The average outflow from the three complete years (2011-2013; n=210) was 9.9 cfs (or 0.27 m^3/s), but review of groundwater levels suggests that 2011 had exceptionally high groundwater elevations (see **Figure V-13**). As such, using only 2012 and 2013 readings, the average LHP outflow was 9.6 cfs. For comparison, the monthly 2021 readings averaged 0.23 m^3/s (8.2 cfs). Using the 2012/2013 flow as a validation target and USGS model inputs, the estimated watershed flow based on the delineated watersheds is 9.8 cfs (**Table V-1**). This estimated flow assumes that only 2% of the Bloody Pond watershed recharge is transferred into of the LHP watershed even though the current contour interpretation shows a larger portion of the Bloody Pond shoreline intersecting the LHP watershed. Review of the LHP outflow also means that none of the watershed flow into LHP is discharged back to groundwater along the eastern edge of the pond, even though this is suggested by the interpretation of the groundwater contours. Lack of groundwater outflow in ponds with a stream outlet is common in the LHP/GHP ecoregion. This data review also suggests that there is variability in all these factors and that groundwater fluctuations are an important consideration when evaluating flow rates.

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[55] Howes B.L., R.I. Samimy, E.M. Eichner, S.W. Kelley, J.S. Ramsey, and D.R. Schlezinger. 2014. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Wareham River, Broad Marsh and Mark's Cove Embayment System, Wareham, Massachusetts, SMAST/DEP Massachusetts Estuaries Project, Massachusetts Department of Environmental Protection. Boston, MA. 187 pp.

[56] Masterson, J.P., Carlson, C.S., and Walter, D.A. 2009.

[57] Hansen, B.P. and W.W. Lapham. 1992.

Table V-1. GHP and LHP Water Budgets. GHP and LHP water budgets rely on USGS modeled groundwater recharge areas and recharge and precipitation rates (Masterson and others, 2009), USGS regional groundwater contours (Hansen and Lapham, 1992), and HPWA measured streamflows (2009, 2011-2013). Values are rounded to reflect uncertainties, so inflow and outflow are slightly different (<0.05% difference). The GHP watershed budget includes a portion of watershed flows that discharges back to groundwater along the eastern shoreline. Annual average residence time of water within GHP and LHP based estimated flows are 7 months and 13 days, respectively.

LHP Water Budget

IN		**OUT**	
Source	**m3/yr**	**Sink**	**m3/yr**
Groundwater[a]	8,380,000	Groundwater[e]	0
Pond Surface Precipitation[b]	393,000	Pond Evapotranspiration[f]	226,000
Wastewater (imported water)[c]	11,300	Stream Outflow[g]	8,560,000
Stormwater[d]	0		
TOTAL	8,784,300	TOTAL	8,786,000

GHP Water Budget

IN		**OUT**	
Source	**m3/yr**	**Sink**	**m3/yr**
Groundwater[h]	6,060,000	Groundwater[e]	8,350,000
Stream Inflow[i]	9,700,000	Pond Evapotranspiration[f]	1,140,000
Pond Surface Precipitation[b]	1,990,000	PWS Withdrawal[k]	470,000
Wastewater (imported water)[c]	0	Stream Outflow[l]	7,840,000
Stormwater[j]	44,000		
TOTAL	17,794,000	TOTAL	17,800,000

Notes:

a. LHP groundwater in includes portions of watershed flow from Little Long Pond, Bloody Pond, and Long Pond plus LHP watershed area delineated for this project (see **Figure V-28**).

b. Pond surface precipitation is based on 47 in/yr input used in USGS regional groundwater modeling (Masterson and others, 2009); this approximates 2000-2021 average at Plymouth Airport (48.48 in/yr; NOAA (accessed 5/6/22).

c. Wastewater input is based on 20 houses in LHP watershed with public water; no other properties with public water accounts were noted in the combined LHP/GHP watershed (personal communication, R. Gallo, NE Service Company, July 2021).

d. No stormwater outfalls or overland flow were noted around LHP.

e. Groundwater output based on balancing measured stream outflow and estimated watershed inputs; pond discharge back to groundwater is consistent with orientation of regional groundwater contours.

f. Pond evapotranspiration rate is based on 20 in/yr recharge rate for ponds used in USGS regional groundwater modeling (Masterson and others, 2009).

g. Stream outflow from LHP is based on 2012-2013 average (9.6 cfs; n=141).

h. Groundwater in to GHP based on watershed area delineated for this project (see **Figure V-28**).

i. Stream inflow to GHP is based on LHP outflow plus 1.3 cfs, which is average difference between LHP outflow and GHP inflow in 209 matched readings (2009, 2011-2013).

j. Stormwater inputs are based on average annual frequency of storms in Plymouth and runoff generated and precipitation in 2015 CSP/SMAST and 2019 TMDL Solutions measurements.

k. Public water supply withdrawal is based on average pumping by North Sagamore Water District (0.34 MGD; 0.53 cfs; 2009-2020).

l. Stream outflow from GHP is based on 2012-2013 average (8.8 cfs; n=141)

Comparison of the estimated LHP watershed inflow to the pond volume means that the average residence time of water in LHP is approximately 13 days. Project staff reviewed other measurements and these generally showed that this is a reasonable approximation. For example, if the low 2021 average flow of 8.2 cfs is used, the LHP residence time is approximately 15 days, while using the high 2011 average flow of 10.6 cfs results in a residence time of approximately 12 days.

The flow into GHP from the stream connecting LHP and GHP is also complex; the stream watershed likely picks up portions of outflow from Triangle Pond, Big Rocky Pond, and Island Pond. Flow readings collected by HPWA at the LHP outlet and the GHP inlet in 2009, 2011-2013 (n=209) showed that the flows at the GHP inlet were on average 1.3 cfs greater than the LHP outlet flow, but this varied from year to year. In 2011, flow into GHP was 2.3 cfs (22%) higher than the outflow from LHP. In 2012, it was 19% higher, but in 2013 flow into GHP was only 5% higher than the outflow from LHP. An estimated stream watershed from the northern portion of the GHP watershed in **Figure V-28** showed that flow estimates would need to include portions of watershed recharge from five different ponds, none of which have delineated watersheds in the latest USGS groundwater model and most of which would cause redistribution of recharge to GHP and LHP. Groundwater contours also suggest that no significant inflows to the stream come from areas east of the stream. Additional review also showed that there is a public water supply withdrawal in the same area too. Given all of these factors, it is not surprising that the flow differences are so variable. For the purposes of the water budget, staff decided to add the average additional 1.3 cfs to the LHP outflow based on the historic readings as a basis for the inflow to GHP.

The combined estimated watershed input to GHP, including LHP inflow and its watershed is 19.9 cfs. Combining the stream inflow and the GHP watershed flow estimates with the measured GHP stream outflow shows that a large portion of the flow into GHP (44% to 54%) leaves the pond via groundwater along the eastern shoreline. This is different than LHP, where all of the watershed flow left via the stream, but is consistent with the longer GHP shoreline oriented to enhance groundwater discharge. Using all of the sources of GHP inflow, the residence time of water in GHP is 7.2 months (range of 6.6 to 7.7 months depending on streamflow variation).

V.G.2. Great Herring and Little Herring Ponds Phosphorus Budget

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 phosphorus inputs and outputs to a pond and is confirmed by measured water column concentrations. Phosphorus enters GHP and LHP 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 both GHP and LHP.

External phosphorus loads to GHP and LHP vary depend on the pathway of entry. Phosphorus travels very slowly within sandy aquifers relative to groundwater flow; P travel rates are typically 1 to 2% of groundwater flow rates.[58] Septic system TP plumes move very slowly in sandy aquifer systems as phosphorus binds to iron coating sand particles; as these binding sites

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

are gradually used up the phosphorus travels toward the pond. 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 will impact the nitrogen concentrations in GHP and LHP. Since phosphorus movement in the aquifer is relatively slow, 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. But this distance can vary depending on groundwater flow rates; higher rates will result in properties 2,500 to 3,000 ft from the pond having regular impacts on the pond water quality within the typical wastewater management planning horizons (*i.e.*, 20 to 30 years).

Determining a refined nitrogen load to GHP and LHP would require a number of steps beyond current resources, but reasonable estimates can be developed. Project staff reviewed the building sizes in the two watersheds, 2020 Census occupancy estimates, etc. and applied the MEP nitrogen loading values (**Table V-2**). This review assumed a 50% attenuation rate in the ponds in the Upper LHP watershed (*i.e.*, Long Pond, Bloody Pond, etc.). The resulting nitrogen loading estimate for LHP was 8,300 kg/yr. Since the average measured nitrogen mass in the LHP outlet stream was 12.7 kg/d, the estimated nitrogen attenuation in LHP would be 44%, which is reasonable given its very short residence time. A more refined nitrogen loading analysis would require review of available water quality, volume, and depth characteristics for all the ponds in the Upper LHP watershed, as well as those in the LHP direct watershed (see **Figure V-28**) plus a more detailed review of watershed land uses, water use, and wastewater treatment. A similar review of GHP found an estimated nitrogen attenuation rate of 34%, but this review required additional assumptions based on the amount of groundwater outflow, as well as a number of larger ponds within the GHP direct watershed. Nitrogen attenuation in larger ponds is usually closer to 50%, so a more refined effort would be required if water quality problems were noted in the Cape Cod Canal, which would be more sensitive to nitrogen than phosphorus.

The phosphorus loading review to GHP and LHP was more detailed, but also required a number of specific adjustments specific for each of the ponds. One of the adjustments was the review of groundwater flow rates around GHP and LHP. Typically in the Cape Cod/Plymouth Ecoregion, groundwater flow rates are estimated at 1 ft/d for planning purposes and this flow rate usually means watershed phosphorus loading analysis focusses on the properties within 300 ft of the pond. When project staff completed this review for GHP and LHP, the projected P loads were too low to reasonably match the measured water column concentrations. Closer review of the water table contours in the areas close to LHP and GHP found that groundwater flow rates to LHP were closer to 4 ft/d, while the rates to GHP varied from the north (3 ft/d) to the south (1.5 ft/d). Incorporation of these findings meant that current phosphorus loading to LHP and the northern portion GHP occurred from properties up to approximately 1,600 ft from the pond shoreline, while the southern portion of GHP approximated the usual 300 ft distance. Project staff reviewed the available ages of septic systems and houses and estimated the distance to the pond for leachfields based on each parcel configuration, layout, and review of historical aerial photographs. After this review, staff determined whether P loading from either the house, the septic system or both on each property were reaching the respective ponds. Other P loading factors were based on Plymouth-specific or Plymouth Ecoregion measurements/estimates.

Table V-2. Phosphorus and Nitrogen Loading Factors for Great Herring and Little Herring Ponds Watershed Estimates. Listed below are factors used in the development of the watershed phosphorus and nitrogen loading estimates for GHP and LHP. Nitrogen loading factors are the generally the same as those utilized in Massachusetts Estuaries Project assessment of Plymouth Harbor, but the wastewater flow was based on average residential occupancy. Listed sources are the primary basis, but most have been confirmed by other sources and/or modified to better reflect GHP and LHP characteristics and the Plymouth setting. 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			
People per house	2.51		2020 US Census population and 2016-2020 estimated households
Wastewater flow	55	gpd/person	Title 5 criterion (310 CMR 15)
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	Estimate	kg/yr	based on previous measurements summarized in this report
Atmospheric N deposition on pond surface	1.09	mg/L	MEP; MassDEP-approved
Common Factors			
Watershed Recharge Rate	27	in/yr	Masterson and others, 2009
Precipitation Rate	47	in/yr	Masterson and others, 2009
Building Area	Measured	ft2	MassGIS coverage
Road Area	Measured	ft2	MassGIS coverage
Driveway Area	1,029	ft2	Estimate based on Shubael Pond measurements (Eichner and others, 2021)

The LHP review of watershed land use found that 128 to 178 septic systems and houses are currently adding phosphorus to the pond (**Figure V-29**). Houses range in age from 7 to 81 years old, while leachfields range in age from 2 to 58 years old. During the initial review, Town staff reviewed available Board of Health records to determine the age of septic systems within 300 ft of the pond.[59] During the final review, project staff assumed that all properties developed before 1980 had had the septic system leachfield replaced and assigned the year 2000 for determining the age of these properties largely based on the review of the properties within 300 ft. Load estimates for septic systems, roof areas, road areas, driveway areas and the pond surface were developed based on estimated groundwater travel time and the range of loading factors. Lawn areas were not delineated because of phosphorus limits on turf fertilizers in Massachusetts.[60] Comparison of the phosphorus loading results to the measured water column data suggest that the number of houses adding phosphorus to LHP is closer to 178 properties rather than 128. The water column TP measurements showed that the mass of TP varied between 6.2 kg and 11.2 kg. Comparison of these TP masses to stream outflow measurements show that there is some likely variation in residence times and sediment uptake, but the balance is reasonable with available data. Wastewater is the predominant source of phosphorus (87%) to LHP (**Figure V-30).** Overall, the LHP P budget is in reasonable balance with measured water quality and can be used to assess water quality management of LHP.

A similar review for GHP included the average measured stream input of P from LHP (0.46 kg TP/d), stormwater inputs based on past measurements, and estimated phosphorus loads from between 116 and 158 septic systems and houses (**Figure V-31)**. At the annual water residence time estimated from the water budget (7.2 months), a balance with the April 2021 measured water column TP mass (prior to sediment impacts) was achieved at the higher end of the range of houses adding P to GHP. Review of the water column TP mass showed that it increased from April through August. These TP mass readings could be achieved with by increasing the residence time and adding in the estimated sediment additions based on the sediment core incubations. If the annual residence time was increased by 50% (to 10.8 months), something suggested by the decrease in stream outflow, the estimated water column TP mass match the measured readings in July and October. The peak water column mass in August 2021 was matched by increasing the annual residence time by 60% and adding deep sediments estimated by the sediment cores.[61]

Review of the 2021 stream outflow readings largely confirmed that the suggested adjustments in pond residence time were reasonable for balancing the GHP P budget. Measured outflow from GHP in April 2021 was 0.26 cubic meters per second (cms), but decreased to 0.18 cms in July (31% decrease) and then to 0.11 cms in August (58% decrease). These decreases closely match the estimated residence time decreases in the balancing of the P budget. This largely confirms that the estimated watershed inputs to GHP are in balance with the water column measurements and are a reasonable basis for management of P and water quality in GHP.

[59] K. Tower, personal communication.

[60] 330 CMR 31.00

[61] Sediment core TP estimates matched what was measured in 2021 in the deep portions of the water column.

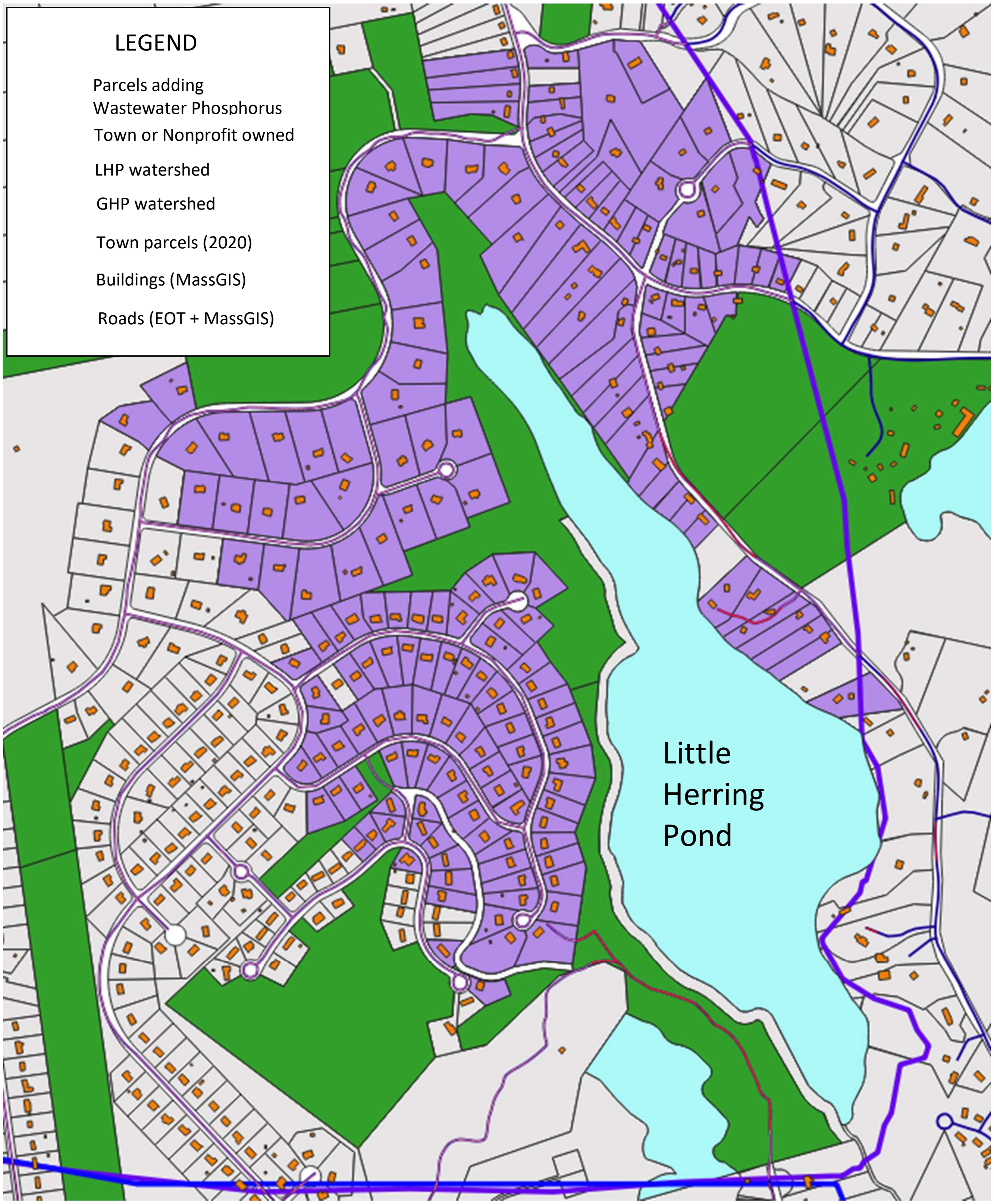

Figure V-29. LHP Watershed Parcels Reviewed for Phosphorus Loading Budget. Project staff developed P loads from land uses within the LHP watershed. Parcels shaded purple are currently contributing P to the pond (based on 4 ft/d groundwater flow rate), while parcels shaded green are town-owned open space or owned by non-profit organizations. Parcels within the watershed (purple outline) but shaded gray are not contributing P to the pond at this time either because they are undeveloped or their septic systems are not old enough to reach the pond.

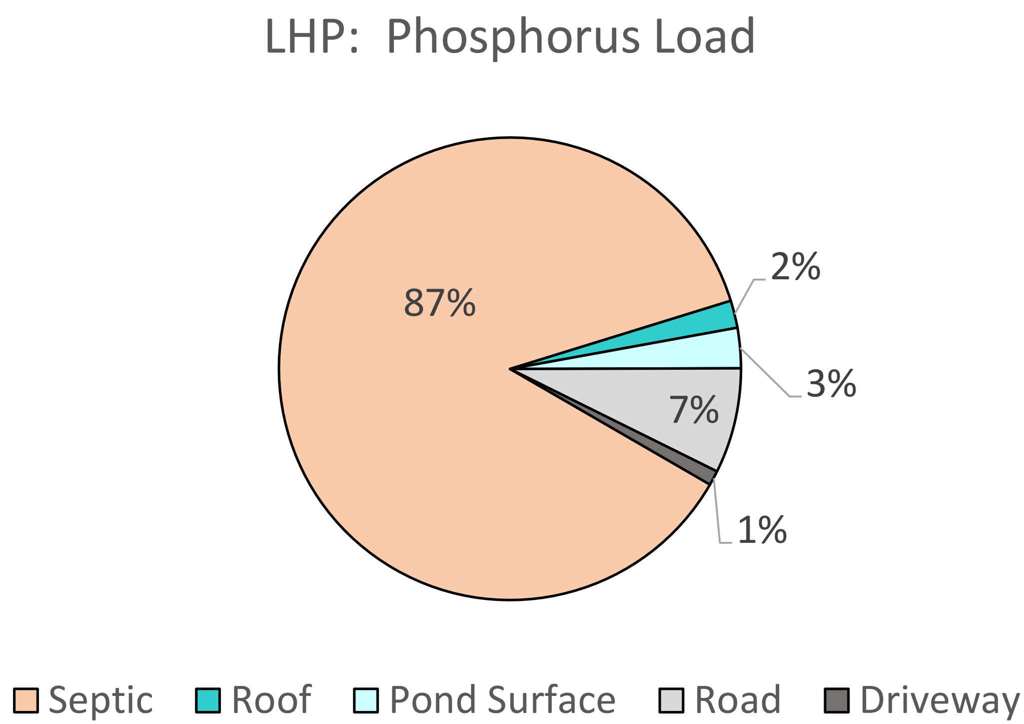

Figure V-30. LHP Phosphorus Budget. Project staff reviewed properties potentially adding P to the LHP water column. This review looked at septic systems, houses, roads, driveways and their estimated age and distance to LHP. Considering P groundwater travel times near LHP, this review watershed found that 128 to 178 septic systems and houses are currently adding phosphorus to the pond. Houses ranged in age from 7 to 81 years old, while leachfields range in age from 2 to 58 years old. Using P loading factors developed from the Plymouth Ecoregion, staff determined that septic system wastewater is the primary source of P (87%) to LHP. Since sediment cores showed no P additions under aerobic conditions and aerobic conditions were measured throughout 2021, there was no adjustment required in the P budget for summer anaerobic sediment additions to the LHP water column and are a reasonable basis for evaluation of water quality management in LHP.

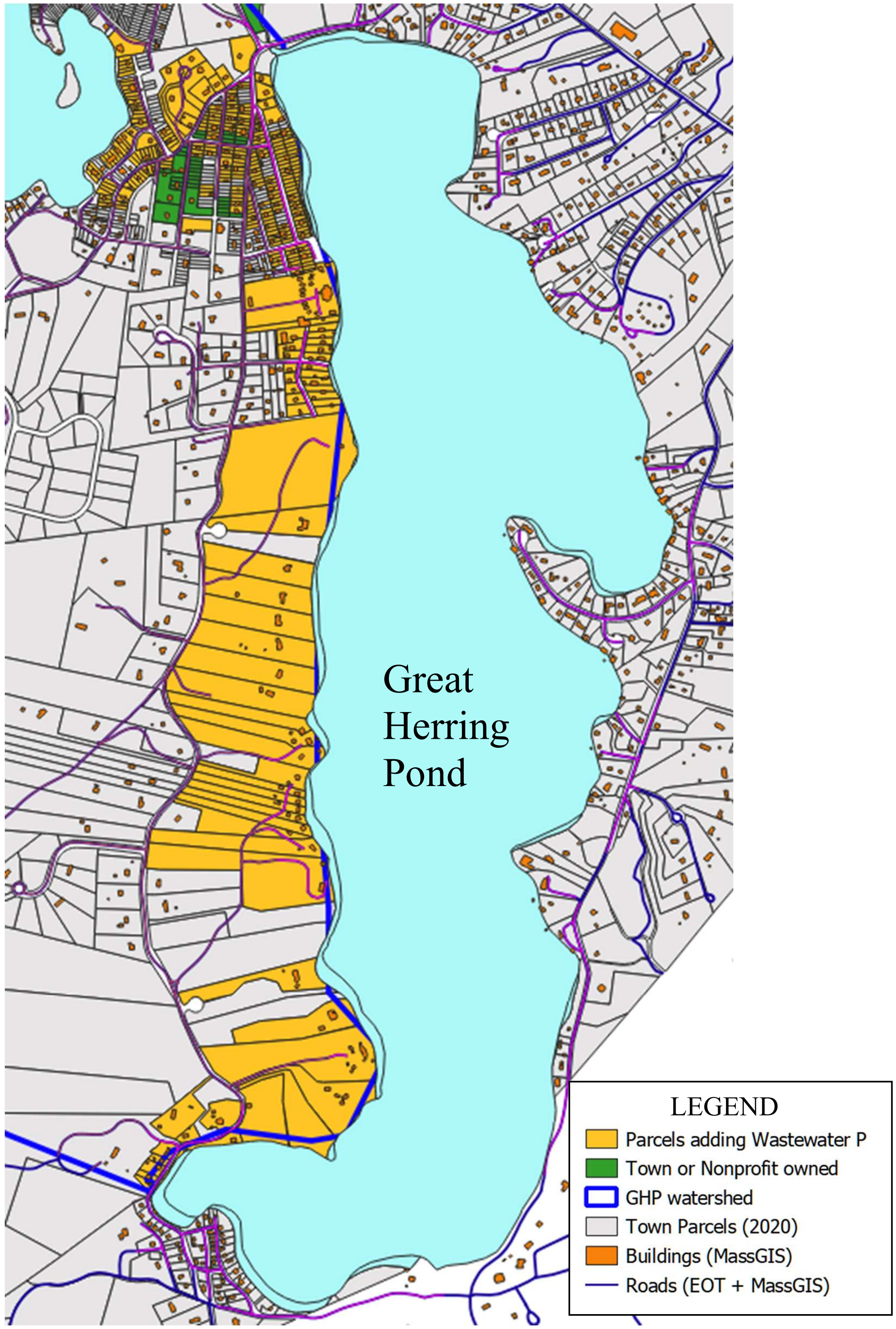

Figure V-31. GHP Watershed Parcels Reviewed for Phosphorus Loading Budget. Project staff developed P loads from land uses within the GHP watershed. Parcels shaded orange are currently contributing P to the pond (based on varied groundwater flow rates), while parcels shaded green are town-owned open space or owned by non-profit organizations. Parcels within the watershed (blue outline) but shaded gray are not contributing P to the pond at this time either because they are undeveloped or their septic systems are not old enough to reach the pond.

The overall phosphorus loading budget to GHP shows that approximately half of the steady state P load to the pond is stream input from LHP with another 35% from septic systems near GHP (**Figure V-32**). During the summer, when anoxic conditions occur in the deeper portions of the pond, LHP stream inflow and septic P loads decrease to 44% and 32% of the overall load, respectively, and sediment additions were 13% of the load. Road runoff and pond surface deposition generally make up the remainder of phosphorus loads to GHP in both scenarios. This comparison of GHP loads and water column mass show that the pond watershed loads are relatively consistent with water column measurements and that most of the variation in water column mass seems to be related to seasonal increases in pond residence time.

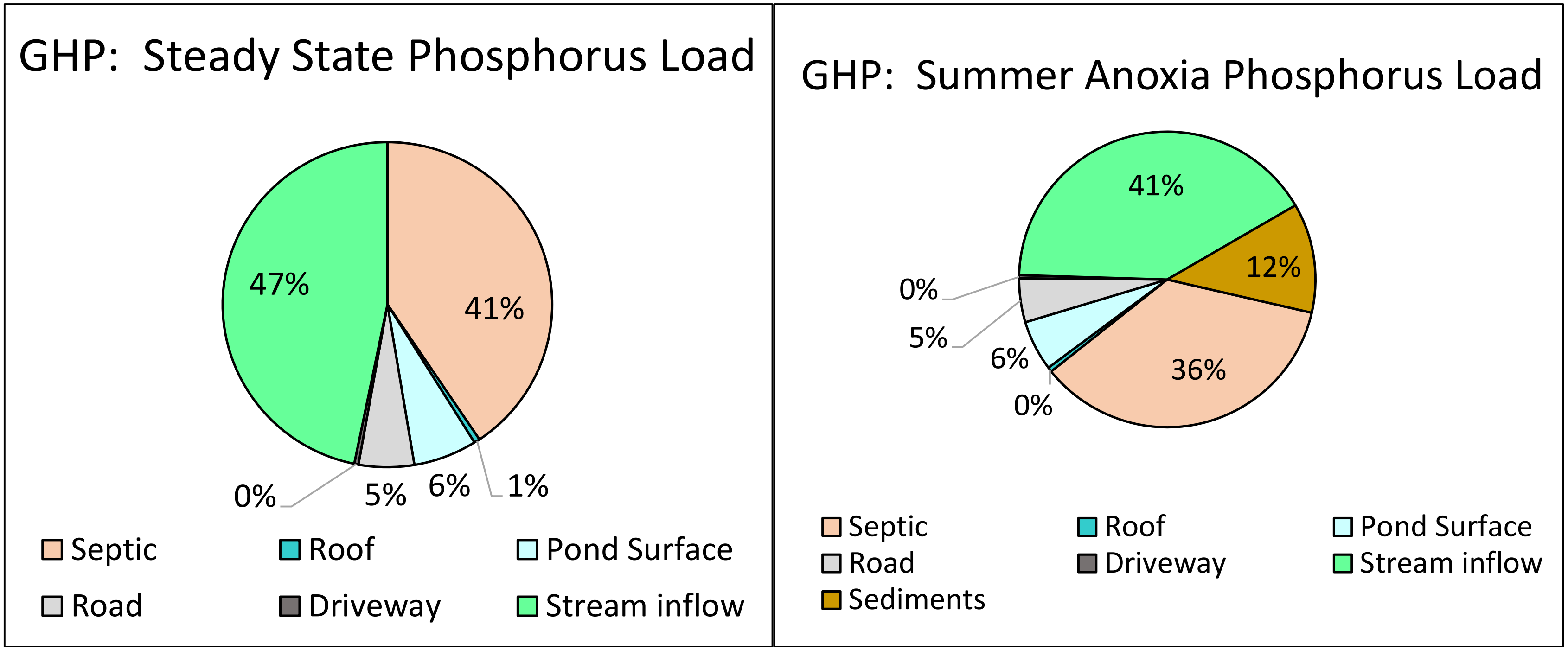

Figure V-32. GHP Phosphorus Budget. Project staff reviewed properties potentially adding P to the GHP water column. This review looked at septic systems, houses, roads, driveways and their estimated age and distance to GHP. Considering P groundwater travel times near GHP, this review watershed found that 116 and 158 septic systems and houses are currently adding phosphorus to the pond. Using the annual water residence time estimated from the water budget (7.2 months), a balance with the April 2021 measured water column TP mass (prior to sediment impacts) was achieved at the higher end of the range of house count adding P to GHP. Increases in water column TP mass during summer is largely due to changes in water residence time of the pond, *i.e.*, the watershed additions remain the same, but the water column mass increases because less flows out of the pond. Further review found that the estimated sediment P additions during periods of deep anoxia helped to further explain increases in the water column TP mass measured in August (*i.e.*, the greatest extent of anoxia). The P budget shows that stream inputs from LHP and GHP watershed septic systems tend to be the largest contributors to the GHP water column mass throughout the year, even with summer sediment additions, with stream inputs from LHP being the largest source (41% to 47% of the P budget). This review largely confirms that the estimated watershed inputs to GHP are in balance with the water column measurements and are a reasonable basis for management of P and water quality in GHP.

V.H. Great Herring and Little Herring Ponds Diagnostic Summary

The diagnostic assessment of GHP and LHP showed that GHP has impaired water quality, but LHP generally does not. GHP has regular bottom anoxia even in when the water column is well-mixed, while LHP has well-oxygenated conditions throughout the summer. Exceptionally high DO in LHP is due the natural characteristics of the pond including shallow depth, consistent light penetration to bottom, a very short residence time (14 to 24 days), and extensive rooted plant coverage of its bottom sediments. Phosphorus, nitrogen, and chlorophyll levels in LHP are high, but the lack of impairment in DO or clarity suggests that these are acceptable conditions for this pond. The only potential concern identified in LHP was the presence of epiphytic filamentous algae on some of the plants in the middle of pond during the September 30, 2021 macrophyte survey. Given that this was late in the summer season and without a refined understanding of whether this algae is present throughout the summer, we are recommending that it be monitored, but no other management is required for LHP. GHP, on the other hand, has regular occurrences of anoxia and hypoxia during the summer, loss of significant clarity, and high phosphorus, nitrogen, and chlorophyll levels. Review of relative phosphorus and nitrogen levels show that phosphorus control is the key to water quality management in both ponds. Review of relative phosphorus inputs show that watershed wastewater inputs are the largest source of phosphorus to LHP and the second largest source to GHP. The largest source of phosphorus to GHP is streamflow from LHP. The diagnostic assessment has the following summary findings:

<u>REGULATORY/POLICY:</u>

1. GHP and LHP are both Great Ponds.[62] Both ponds are part of a state-designated Area of Critical Environmental Concern (ACEC).[63]
2. LHP has a surface area of 81 acres, but a maximum depth of only 1.5 m.[64] LHP is assigned to Category 2 in the most recent MassDEP Integrated List: "Attaining some uses; other uses not assessed."[65]
3. GHP has an area of 413 acres with a maximum depth of 15 m.[66] GHP is assigned to Category 5 (impaired waters requiring a TMDL) in the most recent MassDEP Integrated List due to low dissolved oxygen (DO).[67] A Total Maximum Daily Load (TMDL) defines the contaminant causing the impairment and establishes the level of the contaminant where acceptable water quality will be attained.
4. Both ponds have characteristics that would classify them as Class B, warm water fisheries under Massachusetts surface water regulations.[68] State regulations for Class B waters have four numeric standards, including requiring ponds to attain 5 mg/L DO, and a descriptive narrative standard that states in part that Class B waters are: "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

[62] Ponds greater than 10 acres in surface area are publicly owned "Great Ponds" under Massachusetts law (MGL c. 91 § 35).

[63] Designated in 1991; https://www.mass.gov/service-details/herring-river-watershed-acec (accessed 3/3/02)

[64] Based on the bathymetry created in this management plan (see Figure V-16).

[65] Massachusetts Department of Environmental Protection. November 2021 Final Massachusetts Integrated List of Waters for the Clean Water Act 2018/2020 Reporting Cycle.

[66] Based on the bathymetry created in this management plan (see Figure V-17).

[67] Massachusetts Department of Environmental Protection. November 2021 Final Massachusetts Integrated List of Waters for the Clean Water Act 2018/2020 Reporting Cycle.

[68] 314 CMR 4.00

recreation" Given the depth of GHP, it is surprising that it has temperature readings that allow the entire water column to regularly mix during the summer.

HISTORICAL WATER QUALITY MONITORING

5. Historical water quality monitoring of both ponds has been conducted by the Herring Ponds Watershed Association (HPWA) and the Town of Plymouth Department of Marine & Environmental Affairs (DMEA). Among the most important data historically collected has been temperature and dissolved oxygen (DO) profiles, Secchi clarity readings, and streamflow measurements. Nutrient data (*i.e.*, phosphorus and nitrogen) is more limited in the available historical data, but available data shows phosphorus availability controls water quality conditions.
    - GHP historical profile data generally show similar temperatures throughout the water column (*i.e.*, well-mixed conditions) and regular bottom water hypoxia and anoxia. Secchi readings show an average loss of 2.5 m of clarity between spring and summer. Deep anoxia would allow sediment release of phosphorus if sustained for long enough. This phosphorus could cause algal blooms.
    - LHP has extensive profile data collected in 1976 that showed well-mixed temperature conditions and acceptable DO concentrations. The 1976 survey also showed the pond had dense submerged aquatic throughout most of its bottom. HPWA and DMEA water quality data collected since 1976 are generally consistent with the prior data.
    - Historical streamflow readings show that that flow out of GHP was generally less than the flow out of LHP. As a linked system, it would be expected that the flow out of GHP would be greater than the flow out of LHP; usually streamflow increases as the size of the watershed increases. Streamflow readings noted an increase in flow between the flow out of LHP and the flow into GHP.
6. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) and TMDL Solutions collected stormwater runoff flows and water quality samples around GHP in 2016[69] and 2020[70], respectively. Extrapolation from this data was used to determine stormwater nutrient inputs to GHP. No direct stormwater discharges to LHP have been identified.

2021 DIAGNOSTIC ASSESSMENT FINDINGS

7. CSP/SMAST collected water quality measurements in LHP and GHP on 10 dates between April and October 2021. Measurements in each pond included temperature and DO profiles, Secchi clarity readings, collection of water quality samples at consistent depths, and phytoplankton tows. Flow and water quality samples were collected monthly at the stream outlet from each pond. Sediment cores were collected in each pond and incubated to measure phosphorus and nitrogen release or retention under aerobic and anaerobic conditions.
8. Review of the water quality data showed that LHP had similar DO, temperature, total phosphorus (TP) and total nitrogen (TN) concentrations throughout the water column and throughout the 2021 samples. All Secchi disk readings showed light regularly reached the bottom of the pond. All DO concentrations were above the MassDEP minimum,

[69] CSP/SMAST Technical Memorandum. Great Herring Pond Stormwater Monitoring Project results. February 24, 2016.
[70] TMDL Solutions Technical Memorandum. Eagle Hill 2019 Stormwater Monitoring Results. February 4, 2020.

although many of the profiles had saturation levels >110% likely due to photosynthesis additions. Comparison of nutrient concentrations showed that phosphorus controls water quality conditions in LHP.

9. Review of GHP water quality data showed that the pond water column was well-mixed, but had strong thermal stratification on June 25 and July 14. Hypoxia developed in the deepest waters in June, became anoxia in July and persisted to September. The August 18 profile had anoxia to 9 m, while the July and September profiles only had anoxia >12 m depth. Secchi readings were consistent with historical readings and decreased from 7.2 m in April to 2.2 m in October. Shallow TP concentrations increased between April and July to 2X the Ecoregion threshold (10 µg/L TP) and then tended to fluctuate; the deepest readings increased substantially beginning in June and peaking in August. Chlorophyll a concentrations increased from June to October, peaking at levels >10X the Ecoregion threshold (1.7 µg/L). Comparison of nutrient concentrations showed that phosphorus controls water quality conditions in GHP.
10. Review of historical and 2021 water flow data showed that LHP has a complex watershed inflow, but most of the outflow is through the stream heading to GHP. GHP also has a complex water budget with stream inflow as the largest source, but the outflow is nearly equally divided among stream outflow and groundwater outflow. Data review also showed that flow varies from year-to-year and typically decreases from the spring to the late summer. August 2021 flow readings were the lowest among the 2009, 2011-2013 historical readings.
11. Combining 2021 water column water quality data with 2021 bathymetric data showed that TP mass in LHP averaged 8 kg, while GHP TP mass increased from 116 kg in April to a peak of 279 kg in August. Review of stream export data showed that LHP and GHP TP export was relatively consistent 0.44 kg/d and 0.36 kg/d, respectively, but historical 2011 export was much higher.
12. Sediment core incubations showed that LHP and GHP cores consistently removed TP from the water column under aerobic conditions, while all but the shallow LHP cores released TP when anaerobic conditions developed. Cores began chemical release of TP (*i.e.*, breaking of iron:P bonds) 7 days after the initiation of anaerobic conditions and required 42 days to complete the release of this phosphorus source. The estimated mass of TP release based on GHP core incubations matched the water column TP mass measurements based on the timing and extent of anoxic conditions measured in the water column profiles. Cores showed that TP release will be relative consistent depending on the depth of anoxia.
13. Development of phosphorus budgets for the ponds showed that fast watershed groundwater flow rates to LHP (~4 ft/d) and the northern portion of GHP (~3 ft/d) expanded the area of each of the watersheds contributing phosphorus to the ponds.
14. The LHP phosphorus budget was in reasonable balance with the measured water quality data in the pond. Watershed review found that 128 to 178 septic systems and houses are currently adding phosphorus to the pond. The septic system load from the high end of this range combined with loads from driveways, roads, roofs, and atmospheric deposition on the pond surface balance the measured water quality in the pond. The water residence time matching the estimated phosphorus input and the measured water column data was 24 days. Watershed wastewater is the 87% of the phosphorus added to LHP.
15. The GHP phosphorus budget was in reasonable balance with the measured water quality data in the pond. Watershed review found that 116 to 158 septic systems and houses are

currently adding phosphorus to the pond. The septic system load from the high end of this range combined with loads from driveways, roads, roofs, and atmospheric deposition on the pond surface balance the measured April TP mass in the pond. The water residence time matching the estimated phosphorus input and the measured water column data was 7.2 months. Stream TP inflow from LHP was 47% of the April TP mass, while watershed wastewater is the 41% of the phosphorus added to GHP.

16. Review of GHP stream outflow explained the increased water column TP mass throughout the summer. Review of the watershed, LHP inputs, and sediment released during anoxic conditions were not sufficient to explain the measured increase in water column TP. Variations in the water budget based on 2021 GHP outflow showed that a 58% decrease in outflow from April to August explained the measured increase in the water column TP mass.

VI. GHP and LHP Water Quality Management Goals and Options

Based on the results in the Diagnostic Assessment above, Great Herring Pond is impaired, while Little Herring Pond is generally not. However, the major source of phosphorus to GHP is phosphorus inputs from LHP. Review of available water quality data clearly identifies phosphorus control as the primary path to improving water and habitat quality throughout GHP. Identified impairments in GHP include:

a) regular deep water dissolved oxygen concentrations less than the Massachusetts regulatory minimum,
b) regular deep hypoxia and anoxia in deep portions of the water column sufficient to prompt sediment release of phosphorus,
c) shallow water phosphorus and chlorophyll concentrations greater than Ecoregion thresholds, and
d) loss of water clarity during the summer (~5 m in 2021).

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.[71] 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 GHP is on MassDEP's most recent list of waters as being impaired, but LHP is not, the Town has greater flexibility in defining a TMDL for LHP. However, since MassDEP has only defined one nutrient TMDL for freshwater ponds in the Plymouth/Cape Cod Ecoregion in the last 10 years, defining a TMDL and the management goals primarily rests with the Town of Plymouth.

The management goals discussed in this Plan focus almost exclusively on water quality and ecosystem issues. There may be other management goals that further consideration by stakeholders will reveal (e.g., use of the pond surface, control of access points, etc.). If this arise during the implementation of the Management Plan, project and Town staff will discuss whether

[71] 314 CMR 4.00 (CMR = Code of Massachusetts Regulations)

they can be addressed in a revised version of the plan or whether they will require additional data collection.

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 GHP and allow the Town to attain regulatory compliance.

VI.A. GHP and LHP TMDL and Water Quality Goals

As documented above, GHP 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 during the summer, but the extent of the anoxia varies depending on the impacts of temperature and temporary temperature stratification. During 2021, the minimum depth of anoxia in monthly DO profiles was 9 m, but in available historical profiles the minimum depth was 8 m. The phosphorus budget findings show that LHP is the largest source of phosphorus to GHP, although watershed wastewater inputs are only slightly less than LHP inputs. The review of the phosphorus budget, streamflow measurements, and watershed inputs also showed that the increases in TP concentrations measured in GHP during the summer are primarily due to increasing residence time, but there are some relatively small additional impacts from sediment TP additions due to anoxia.

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. This approach mirrors the approach used in establishing the nitrogen TMDLs for estuaries in southeastern Massachusetts, which are the largest set of nutrient TMDLs in the state. These nitrogen 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 would 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[72]), 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 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

[72] Fish and birds

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 nutrient TMDLs in Massachusetts has been limited with only one completed within the Plymouth/Cape Cod Ecoregion over the past 10 years. However, previous work on nutrient thresholds for ponds in the Ecoregion were developed through the initial 2001 Cape Cod Pond and Lake Stewardship (PALS) water quality snapshot sampling program. The 2001 Cape Cod PALS snapshot included sampling of over 190 ponds.[73] Review of this data using a USEPA nutrient criteria method determined that an appropriate total phosphorus concentration for Cape Cod ponds was between 7.5 to 10 µg/L.[74] 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 are more or less sensitive to phosphorus additions depending on their individual characteristics (*e.g.*, watershed size, residence time, depth, etc.).

Establishing an acceptable total phosphorus mass in GHP can look to available water quality data to see when acceptable water quality conditions occurred. Review of 2021 and historical GHP data show that April conditions usually have acceptable water quality conditions throughout the water column: high clarity, all DO concentrations above the MassDEP minimum and low TP concentrations. In 2021, April TP concentrations combined with volume readings resulted in an estimated TP mass of 116 kg in GHP. In May 2021, the estimated water column TP mass had increased to 142 kg and clarity had decreased to 4.6 m from 7.2 in April, but DO was acceptable throughout the water column and the total estimated DO mass was essentially the same as in April. By June, the TP mass had increased to 202 kg, DO concentrations at depths >10 m were less than the MassDEP minimum, and clarity had decreased to 3.2 m. If the 2021 data is used as guidance, these results suggest that the acceptable TP mass in GHP is close to 116 kg. If this mass is dissolved in the GHP volume, the resulting concentration is 11 µg/L; TP concentrations measured near the surface (0.5 m) in 2021 were 8.5 µg/L.

As discussed above, the estimated TP mass in GHP increased to a maximum of 279 kg in 2021. Comparison of the changes in stream outflow and sediment additions suggest that most of the increase in the TP mass was due to decreases in the outflow (August 18 outflow was 0.11 m^3/s), which increased the residence time. Approximately 30 kg of this mass was due to sediment additions from prolonged deep anoxia. Further review found that decreasing the GHP water column load to 50 kg in April would allow them to match 116 kg in August if stream outflow levels decreased as they did in 2021. Attaining 50 kg would require a 66 kg/yr decrease in TP additions to GHP. Review of historical streamflow information showed that GHP stream outflow only attained August 2021 rate less than 1% time, so there is likely some conservatism included in the 50 kg/yr threshold, but this is likely warranted given that 2021 is the only year

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

[74] 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)

with streamflow readings collected predominantly during low groundwater conditions (see **Figure V-13**).

Removing 66 kg/yr of TP additions to GHP could be accomplished a number of ways. Review of the phosphorus budget shows that septic system within the GHP watershed add approximately 90 kg/yr and the LHP stream input adds approximately 100 kg/yr. Reducing these sources individually or in some combination could reduce the TP input to the 50 kg/yr threshold. Treatment of the sediments to reduce the summer input could remove the majority of the 30 kg added in 2021, but this would need to be combined with stream and/or septic reductions in order to attain the target threshold.

In order to review potential management strategies, TMDL Solutions and CSP/SMAST staff selected 50 kg TP as an appropriate initial water column mass target for achieving restoration and as a potential phosphorus TMDL for GHP. This goal was selected to ensure acceptable TP, chlorophyll and DO concentrations throughout the year and was largely informed by review of the 2021 sampling results and consideration of historical monitoring, especially past streamflow readings. Given the limits on available data, the 50 kg TP threshold could be modified as additional water quality data is collected, but is the best available at this time.

VI.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 GHP, the stream inflow from LHP and watershed septic system loads are the primary phosphorus sources and the sources 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 Great Herring Pond.

The review of management options in **Table VI-1** incorporated the results from the GHP Diagnostic Summary above and, based on the lake-specific characteristics, this review found that reducing the streamflow load from LHP or the GHP watershed wastewater P reduction or some combination are the primary applicable options for water and habitat quality management in GHP. This option has a number of issues to resolve including:

1) the best way to reduce LHP streamflow TP input,
2) the best type of wastewater technology for the GHP watershed (*e.g.*, sewering or somewhat experimental phosphorus reducing septic systems),
3) the GHP watershed area where wastewater should be treated based on the differences in land use densities in different portions of the watershed, and
4) the likely timing for implementing reductions.

The details of the options are discussed below.

Given that discussion of wastewater management could take a number of years to resolve, the Town may want to consider management options for reducing in-lake sediment P additions or experimental P reducing management options. These options will not provide adequate reduction to restore the system on their own, but implementation could lower the frequency of impaired conditions for a number of years. Most of the applicable actions are in-lake management techniques that will address the 12% of the summer GHP water column P load. Another short term management option would be to address the 5% of the P load that comes from stormwater. Although this load is small, the Town may be able to implement some improvements in the largest contributors rapidly. Experimental options to treat P export from LHP to GHP may also be considered, but will require extensive monitoring to document their performance and also will be insufficient on their own given that complete removal of LHP phosphorus export to GHP is not adequate on its own to attain the GHP P threshold. Implementation of these smaller reductions could provide some additional time for planning the implementation of the longer term options. Each of these partial, temporary options are discussed below.

Table VI-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 Great Herring Pond, have no track record in Massachusetts or the Ecoregion, 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 VI-1a. WATERSHED PHOSPHORUS LOADING CONTROLS: Address watershed sources of phosphorus entering the pond, typically: a) septic system phosphorus discharges from properties within travel time to the pond, b) stream inflow, c) road runoff from stormwater, and d) excess fertilizers from lawn or turf applications. Other additions can occur from pond-specific sources, such as connections to other ponds or ditches/pipe connections to areas outside of the watershed.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of uses in Ecoregion	Applicability to Great Herring Pond
Wastewater P reductions	• Sewering • Alternative Septic Systems • Septic Leachfield Setbacks, replacement, or movement • PRBs (Iron) – Shoreline or leachfield (experimental)	• 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 • Shoreline PRBs will involve habitat disruptions	• Brewster BOH septic leachfield setback regulation • Some Town preliminary sewer plans include properties around ponds	<u>Applicable:</u> wastewater is second largest P source (41%) in overall lake P budget; could also apply to LHP watershed to reduce largest P source to GHP (LHP stream = 47% of load to GHP)
In Stream P reductions	• Iron, Al or other absorbents additions (including PRB) in stream channel • Restoration of wetlands/bogs	• Relatively low cost	• Experimental • May have wetland permitting issues	• None exclusively for P removal (focus on N removal)	<u>Applicable (experimental):</u> LHP stream = 47% of load to GHP
Fertilizer P reductions	• Restrict P in lawn fertilizers • Restrict lawn areas • Require natural buffers near pond • 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	<u>Applicable, but already implemented:</u> state regs limit P for residential uses
Stormwater P reductions	• Remove or infiltrate direct stormwater discharge • Recharge outside of watershed • Runoff treatment using BMPs	• Rerouting discharge usually 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 • Potential rerouting may be limited by existing building/road layouts	• Not specifically done for ponds in the past, but is now being discussed in many MA municipalities	<u>Applicable:</u> Direct discharges are only 5% of the overall load, but Eagle Hill Rd is largest source and has recently been redesigned

Table VI-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 or remove the sediment P source or physical removal/limitation for plant growth. Some of these techniques are difficult to implement in the GHP Ecoregion due to sandy aquifer hydrogeology.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of uses in Ecoregion	Applicability to Great Herring 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 • Variable success • Needs power	• Santuit Pond, Mashpee & Skinequit Pond, Harwich (Solar Bees) • Flax Pond, Harwich (Living Machine)	<u>Applicable, but benefit unclear</u>: GHP tends to have temporary stratification, so it regularly circulates, questions about whether circulation will be enhanced by usual applications
Dilution, Decreased residence time	• Add water to pond • Increased flow through pond	• Increased flushing • Can add treatment additives • Changes in stream outlet configuration may be low cost	• Dilution would require source outside of watershed • Changes in stream outlet may not be permittable	• Dilution mostly a hard geology/ stream fed solution; need water source • Increased outflow has not been completed in Ecoregion	<u>Applicable, but experimental</u> Will require further evaluation of stream outflow, possible redesign and what increased summer flow might be at different pond elevations
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 VI-1b (continued). 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 or remove the sediment P source or physical removal/limitation for plant growth. Some of these techniques are difficult to implement in the GHP Ecoregion due to sandy aquifer hydrogeology.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of uses in Ecoregion	Applicability to Great Herring 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)	Applicable: but sediments are only 12% 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)	Not applicable; 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	Not applicable (primary P sources are watershed sources)

Table VI-1b (continued). 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 or remove the sediment P source or physical removal/limitation for plant growth. Some of these techniques are difficult to implement in the GHP Ecoregion due to sandy aquifer hydrogeology.

OPTION	Option Variations	Advantages	Disadvantages	Examples of uses in Ecoregion	Applicability to Great Herring 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	<u>Not applicable:</u> GHP has ephemeral stratification; 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)	<u>Not applicable</u> (experimental); would likely have significant regulatory hurdles; phytoplankton levels generally low

Table VI-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 uses in Ecoregion	Applicability to Great Herring 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	<u>Applicable, but benefit unclear</u>: GHP anoxia tends to very limited (>12 m), could address hypoxia to limit anoxia; would only address 12% of P load
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	<u>Not applicable</u>: GHP has only ephemeral stratification
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	<u>Not applicable</u>; does not address P additions and may increase available P in the pond

Table VI-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 uses in Ecoregion	Applicability to Great Herring 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 • White Island Pond, Plymouth: 2013 & 2014 • Lovell's Pond, Barnstable: 2014 • Cliff Pond, Brewster: 2016 • Uncle Harvey's Pond, Orleans, 2021	Alum application: <u>applicable</u>: but will only address 12% of summer water column P; may have mussel permitting issues; may want to consider annual spot applications to reduce water column P Iron application: <u>not applicable</u>: sufficient iron generally exists, low DO negates use Calcium application: <u>not applicable</u>: generally used in waters where pH ≥ 8 Lanthanum application: <u>not applicable</u>: concerns about biotoxicity, bioaccumulation, especially in low pH settings

Table VI-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 uses in Ecoregion	Applicability to Great Herring 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 12% 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 VI-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 in Ecoregion.					
OPTION	Option Variations	Advantages	Disadvantages	Examples of uses in Ecoregion	Applicability to Great Herring 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 <u>not applicable</u>, 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 Ecoregion 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	<u>Not applicable:</u> bottom fish are not cause of GHP impairments

Table VI-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 in Ecoregion.**					
OPTION	Option Variations	Advantages	Disadvantages	Examples of uses in Ecoregion	Applicability to Great Herring 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 Ecoregion 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 Ecoregion and lack of peer reviewed studies should be considered experimental and would likely have significant regulatory hurdles

Table VI-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 in Ecoregion.

OPTION	Option Variations	Advantages	Disadvantages	Examples of uses in Ecoregion	Applicability to Great Herring 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 wetlands/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 Ecoregion 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; Town may want to consider experimental approach
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 Barnstable 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

VI.C. Applicable Management Options

VI.C.1. Watershed Phosphorus Management

Stream inflow from LHP is the largest source of phosphorus to GHP (see **Figure V-32**). The primary phosphorus source to LHP is septic system wastewater, so it is also the primary source of TP to the stream inflow into GHP. Septic system wastewater effluent from the GHP watershed is also the second largest source of TP to GHP (see **Figure V-32**). The load from each of these sources alone is greater than the 50 kg/yr P target. Potential strategies to address the septic system P load need to address: 1) the difference between the loading in the two watersheds, 2) reliability of wastewater technology, and 3) potential timeframes for reducing the septic P loads.

Removing all the wastewater from the LHP input via sewering would not be sufficient on its own to attain the 50 kg/yr P target in GHP (**Figure VI-1**). Septic system P account for 87% of the LHP P budget with 13% including sources that are uncontrollable (*e.g.*, pond surface deposition) or diffuse enough that they would be difficult to control (*e.g.*, roof and driveway runoff). There are a number of variables associated with LHP outflow, but collecting wastewater and its associated TP and discharging it outside of the LHP watershed or treating the wastewater to remove all P and discharging it within the LHP watershed would remove approximately 87% of the TP in the LHP stream outflow/GHP inflow. This reduction would reduce the spring GHP water column TP mass to approximately 66 kg without any additional reductions in the GHP watershed.

If wastewater alone was addressed as the management option to attain the 50 kg/yr P target, 60 to 70 residences in the GHP watershed would need to have their wastewater TP removed in addition to removing wastewater TP within the LHP watershed. Review of the land use pattern in the upper portion of the GHP watershed suggests that the relatively high density in the area between GHP and Island Pond would be optimal for wastewater collection system that could connect 60 to 90 residences. This area has more than 75 residences (*i.e.* the midpoint of the range), so prioritization of sewer connections could be for those properties closest to the GHP shoreline.

The closest portion of the existing town sewer collection system is approximately 12 km north of LHP and development of a plan to extend piping to LHP and GHP would likely require extensive discussion about a number of issues, including funding, potential connection of properties in between the current system and LHP/GHP, use of municipal treatment plant capacity, etc. Creation of a separate satellite wastewater treatment facility would require similar discussions with the additional issues of selecting and acquiring a property or properties for siting of a treatment facility and discharge of the treated effluent, ecological reviews to ensure no adverse downstream impacts, and state and local permitting. Likely costs for either of these sewer proposals would be several million dollars.

Another wastewater option to reduce watershed TP additions would be the installation of innovative/alternative (I/A) septic systems with phosphorus reduction, although this has a number of significant potential hurdles to overcome. There are currently no phosphorus removal technologies for innovative/alternative (I/A) septic systems approved for general use in Massachusetts.[75] There are three phosphorus removal technologies that are approved for piloting

[75] MassDEP Title 5 Innovative/Alternative Technology Approval website (March 30, 2022 approval list). https://www.mass.gov/doc/summary-table-of-innovativealternative-technologies-approved-for-use-in-massachusetts/download.

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."[76]

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.

Use of these P removal septic systems would have to be more extensive than if sewering was pursued. Use of any of these technologies on all the septic systems currently contributing TP to only LHP would be insufficient to attain the 50 kg/yr TP target for GHP. If they were used on 70 to 100 of the properties in the GHP watershed currently contributing TP and used in the LHP watershed, the 50 kg/yr TP target for GHP could be attained.

Extensive use of any of these piloting technologies would also require some regulatory and 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 the required installations to meet the GHP TP target would be more than 200 systems, this type of approach would require some sort of special approval from MassDEP. In addition, the costs for monitoring would likely also be extensive. Since these are also somewhat experimental systems, this approach would also need some discussions about contingencies if the systems fail to perform as intended.

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 $574.[77] Applying inflation adjustments and assuming a 20 year annual cost life cycle, these costs applied to all the properties contributing TP in the LHP watershed plus 70 to 100 properties in the GHP watershed would have an estimated cost of $5.4 to $7.4 million.

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[76] *Ibid*.

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

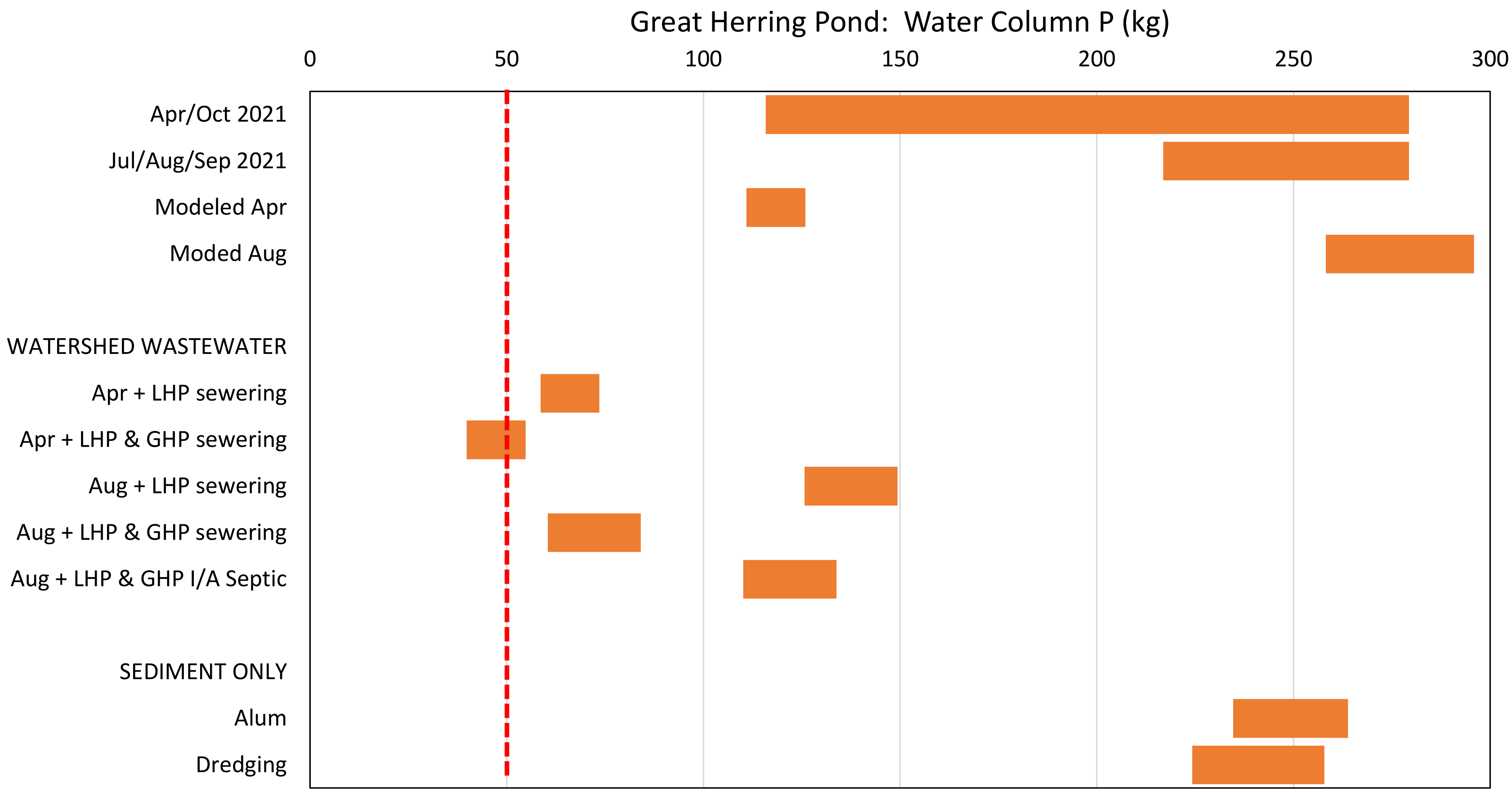

Figure VI-1. Great Herring Pond: Comparison of Selected Phosphorus Management Options to Attain TP Water Column Threshold. Project staff compared the potential performance ranges for applicable phosphorus management options to the recommended 50 kg TP water column threshold mass (red dashed line). This review showed that the P loading modeling reasonably matched the current measured water column P with variations depending on residence time of water in GHP. Using the model, staff found the shorter residence time in April requires less P removals to reach the threshold than the longer residence time in August. The only identified option for attaining the threshold was removal of wastewater P from both the LHP stream input (via sewering) and the 60-70 houses in the GHP watershed, but in August, when the residence time can increase by up to 58%, the additional houses in the GHP watershed would need to have their wastewater P removed to attain the threshold. This figure does not include performance of an in-stream PRB option; additional characterization of this option will be addressed in the final version of this plan. This analysis suggests that additional discussions should be conducted regarding adaptive management and/or discussions of goals for water quality.

Reductions in other GHP watershed inputs would be insufficient on their own to achieve the 50 kg TP threshold. Roof runoff, road and driveway runoff, and direct precipitation on the pond surface collectively add 21 to 27 kg/yr TP. Direct precipitation is 8 to 13 kg of the total and cannot be reduced by local management activities. Road and driveway runoff is estimated to be 12 kg, of which most is estimated from previous direct runoff measurements in 2015 and 2018. These direct measurements found that the highest loads were on Eagle Hill Road, which is on a peninsula off the downgradient side of GHP. Since these loads are on a peninsula, opportunities to remove TP especially in the lowest points where stormwater collects would be arduous. Other stormwater sources along Herring Pond Road could be infiltrated into the ground rather than discharging into the pond, but possibilities of direct infiltration would need to be assessed at each site and the benefit of TP removal would be relatively small in the overall P budget.

In summary, implementation of sewering and piloting phosphorus-reducing septic systems within the Great Herring and Little Herring Ponds watershed could remove sufficient phosphorus to attain the TP water column threshold for GHP. Implementation of a strategy reworking current wastewater treatment technologies would be a long-term management goal and require a number of steps including: a) identification of sites for wastewater treatment and effluent discharge, b) identification of sewer service areas and potential piping strategies, c) selection of wastewater treatment technology, and d) discussion of cost breakdowns, including how potential betterments and/or tax increases might be split. 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.

VI.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 wastewater TP additions. Staff reviewed the potential impact of in-pond actions (*i.e.*, alum treatment, hypolimnetic aeration, and sediment dredging) based on the measured 2021 summer sediment addition (29 kg) and an estimated maximum sediment addition based on anaerobic conditions established at 8 m depth using the 2021 timing of anoxic conditions (40 kg). These approaches resulted in a range of estimated TP removals of 10 to 38 kg. Given that sediment TP additions tend to be at their maximum in the late summer, these reductions would be 3% to 14% of the late summer 2021 water column mass. If the projected removals carried over into the spring, water column mass would be 80 to 110 kg, well short of the 50 kg TP target. Complete carryover of the late summer reduction to the spring would be unlikely given that spring water column conditions tend to be aerobic throughout the water column and, as such, sediments usually tend to be removing phosphorus anyway.

However, each of these in-pond actions could be combined with more limited watershed wastewater reductions in order to the achieve the 50 kg TP target or as an interim solution while wastewater options are discussed. Preliminary planning costs based on a 20 year lifecycle for the three in-pond techniques to remove between 10 and 38 kg are: $139,000 to $191,000 for three alum treatment (125 acres) over 20 years, $400,000 to $1.6 million for an aeration system, and $9.9 to $20 million for dredging of the pond. Additional costs would be incurred for permitting and associated monitoring. Three alum treatments are assumed based on the sediment load as a portion of the total P inputs and how frequently sediment regeneration would return to current conditions; this longevity assumes no P reduction management activities in the watershed. Dredging will likely have a slightly longer longevity because there would likely be an accompanying increase in the pond volume, but its longevity will also be limited if no accompanying watershed P reduction actions occur. Dredging also has a number of technical issues that will need to be overcome given the depth of the pond. Sediment treatment performance is also usually optimal in pond systems where sediment regeneration is the primary source of water column TP, which is not the case in GHP. More extensive reviews of these options can be completed if the Town chooses to pursue any of these options alone or in combination with watershed P reductions.

VI.C.3. Stream P Management

One interim, experimental option that the Town could consider would be the treatment of stream water between LHP and GHP through the use of an in-stream Permeable Reactive Barrier (PRB) and/or expanded wetlands/bog restoration for the bogs along the stream. PRBs have a long history of use in groundwater treatment with a wide use of variety of materials designed to address various contaminants, including hydrocarbons and, more recently, nutrients. Groundwater PRBs usually involve trenching or injection of the treatment material (*e.g.*, woodchips, emulsified vegetable oil, iron filings,[78] etc.) with a monitoring well network both upgradient and downgradient of the PRB array used to assess the removal of the contaminant. Recently, experiments have been completed installing many of the same materials used in groundwater PRBs in permeable containers and placing the containers in streams to passively treat nutrients (**Figure VI-2**).[79,80] These experiments have looked at various types of materials, the longevity of treatment and replacement frequency for the materials, types of installation vs flow, etc. The details of this approach are not standardized or refined, hence why it is still experimental, but given the configuration of the stream between LHP and GHP, an experimental installation would likely provide some reduction in TP load from LHP. It would also provide the Town with some P reductions while time is taken to work out the details of a more permanent wastewater solution. P removal rates in PRBs at the concentrations measured in the stream between LHP and GHP in 2021 are generally 20 to 40% range.[81] Project staff are available to assist the Town and other LHP/GHP stakeholders if subsequent discussions result in consensus about pursuing this option.

The Town may also want to consider an option to refurbish the cranberry bogs along the stream provided the current owners are amenable. The stream could be rerouted to increase its time within the bog systems and enhance the opportunities for the associated plant community to remove phosphorus, while also increasing habitat diversity. Similar examples have been developed or are in development throughout southeastern Massachusetts, including along Eel

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[78] McCobb, T.D., and LeBlanc, D.R., 2011, Water-quality data from shallow pond-bottom groundwater in the Fishermans Cove area of Ashumet Pond, Cape Cod, Massachusetts, 2001–2010: U.S. Geological Survey Data Series 588, 13 p., at http://pubs.usgs.gov/ds/588

[79] Carleton, George & Glowczewski, Jessica & Cutright, Teresa. (2021). Design and Preliminary Testing of an In-Field Passive Treatment System for Removing Phosphorus from Surface Water. Applied Sciences. 11. 3743. 10.3390/app11093743.

[80] McDowell, Rich & Hawke, M. & McIntosh, J. (2007). Assessment of a technique to remove phosphorus from streamflow. New Zealand Journal of Agricultural Research - N Z J AGR RES. 50. 503-510. 10.1080/00288230709510318.

[81] Penn C, Chagas I, Klimeski A, Lyngsie G. A Review of Phosphorus Removal Structures: How to Assess and Compare Their Performance. Water. 2017; 9(8):583. https://doi.org/10.3390/w9080583.

Figure VI-2. Experimental In-stream PRB. Permeable Reactive Barrier (PRB) installed in a cranberry bog stream in Barnstable, MA. Installations of these types of PRBs require performance monitoring, consideration of design characteristics to ensure flow-through and avoid upstream flooding, and selection of PRB media to remove phosphorus. Photo courtesy of A. Unruh, Town of Barnstable.

River and Beaver Dam Brook in Plymouth[82] and Cold Spring Brook in Harwich.[83] Both projects were coordinated with the Massachusetts Division of Ecological Restoration along with funding from the Towns and a variety of other partners.

VI.C.4. Floating Treatment Wetlands

Another experimental option that the Town asked to consider was the installation of floating wetlands. Floating wetlands have a variety of designs, structures, and settings that generally involve emergent wetland plants growing on tethered mats or rafts (**Figure VI-3**). These types of systems generally remove P as inorganic P through uptake by the plants and root/rhizosphere microbial community. This mode of P removal calls into question how well they would work in most Plymouth Ecoregions ponds because the phosphorus pool in ponds and lakes is dominated by organic P forms and there is generally little inorganic P. Since the uptake of P requires contact with the roots, current designs have mat/raft roots dangling in pond water, although some older designs have included pumps to move water through cells of rooted plant arranged across the surface of the mat/raft. Given that there are no standardized designs and a large number of unknowns about likely performance, these types of projects are experimental, but could be an experimental application for GHP or LHP provided appropriate monitoring and maintenance of the plants (*i.e.*, their growth, density, senescence, etc.) accompanies the installation to quantify the P removal and characterize all the features involved in the installation.

Only one installation of this type has been completed on a freshwater pond in the Ecoregion. In 1992, a "Lake Restorer" was installed in Flax Pond in Harwich. Flax Pond is downgradient of the Town landfill and septage lagoons and had extremely impaired water and habitat quality. The Restorer was a raft with a wind-powered pump (that was later replaced by solar panels) that brought pond water through a number of wetland cells on the surface of the raft before returning the water to the pond. The Restorer also included a number of underwater blades than turned to produce upwelling, bringing deep waters to the surface. Most of the available monitoring focused on the pond water column and this showed that the Restorer gradually <u>increased</u> water column TP concentrations likely due to the upwelling causing resuspension of sediment TP.[84]

By 1996, Flax Pond was hypereutrophic and a revised version of the Restorer was installed. In 1999, the revised Restorer was removed. In 2002-2003, after the floating wetland system had been removed, monitoring showed that the pond was mesotrophic/oligotrophic based on lower TP concentrations. This improvement in water quality conditions was likely caused by most of the TP remaining in the sediments rather than being regularly stirred into the water column.

[82] https://www.massaudubon.org/get-outdoors/wildlife-sanctuaries/tidmarsh/news-events/new-restoration-work-underway (accessed 11/14/22)

[83] https://harwichconservationtrust.org/cold-brook-eco-restoration-project/ (accessed 11/14/22).

[84] Eichner, E. 2004. Flax Pond Water Quality Review, Final Report to the Town of Harwich. Cape Cod Commission. Barnstable, MA. 24 pp.

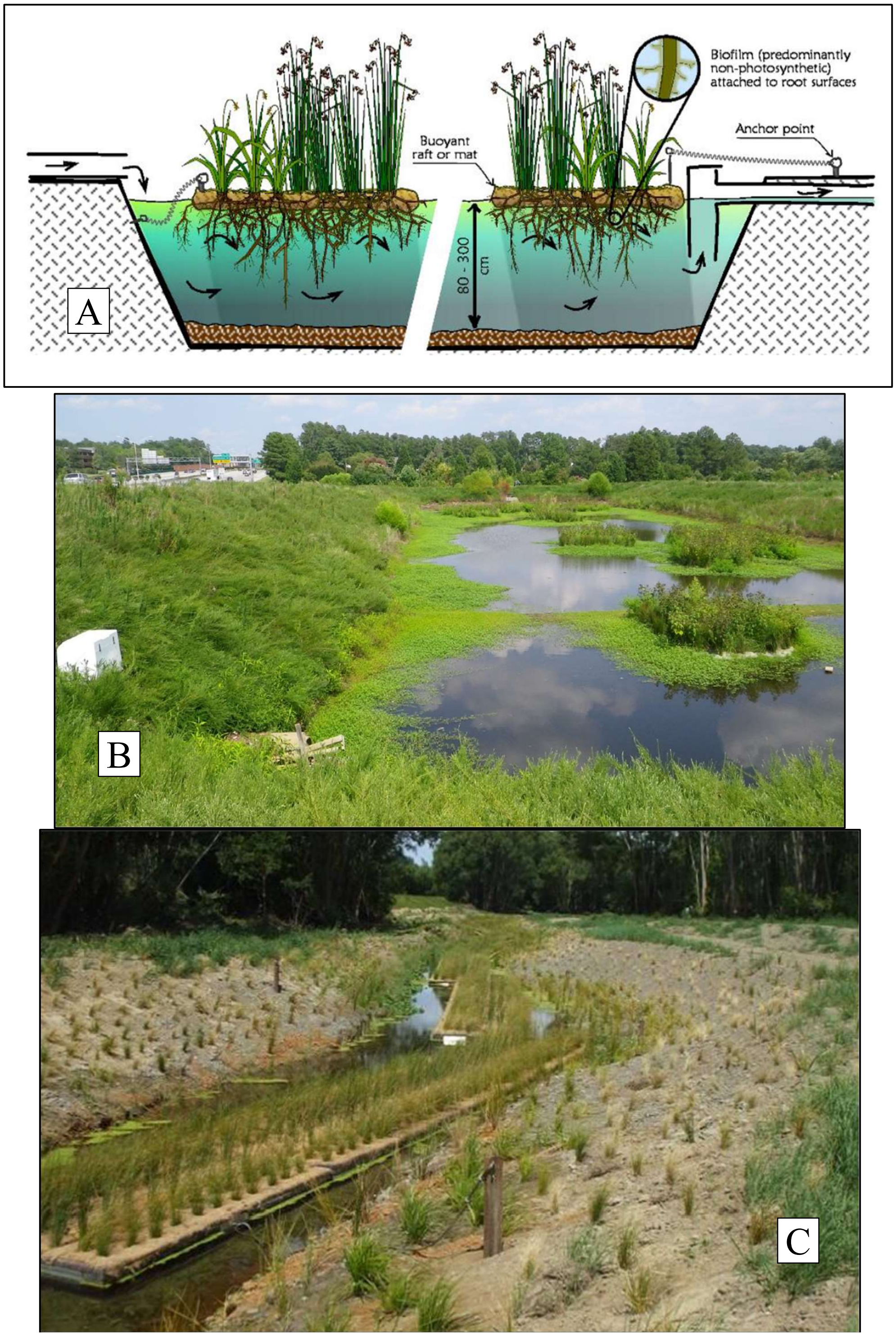

Figure VI-3. Floating Wetland Examples. Floating wetlands have typically been installed in situations with high nutrient values and highly designed flows (*e.g*. treating wastewater or stormwater). Current designs generally involve emergent wetland plants with roots in water growing on tethered mats or rafts (A shows typically cross-section from Tanner, *et al.*, 2011). Notable P removal generally require high concentrations of inorganic P, rather than the organic forms typically found in lake/ponds, and coverage of a significant portion of the water surface: B is stormwater basin in North Carolina (9% coverage pond surface by floating wetlands; Hunt, *et al*., 2012), while C is agricultural drainage channel in Tukipo River, New Zealand (Tanner, *et al.*, 2011).

Much has been learned about floating wetlands over the last 20 years, but part of the on-going difficulty with the approach is that most of the phosphorus in pond water is in organic forms, *i.e.*, incorporated into phytoplankton and, as such, is unavailable for rooted plants on a floating wetland. Most installations have been in highly controlled settings (*e.g.*, stormwater detention ponds, wastewater settings, or mesocosms) that have higher concentrations of ortho-phosphorus or soluble reactive phosphorus than would be found in pond water.[85] They also generally have a high TSS and particulate load that can settle out in the detention ponds, thus depositing particulate nutrients to the sediments. Key parameters to consider in design of floating wetlands include percentage of pond cover, types of plants included, and how monitoring is designed.

Review of floating wetland in storm detention basins have found that the percentage of the basin covered by wetland needs to be quite high to attain notable TP removal. A North Carolina review storm detention basin retrofits with floating wetlands recommended that TP credits for removal should only be offered if 20% or more of the stormwater basin was covered by floating wetland that achieved roughly a 30% decrease in TP leaving a detention pond.[86] In LHP, 20% coverage would be 16 acres of floating wetlands, while in GHP, 20% coverage would be 84 acres. There may be some benefit in a small installation for testing in a more confined area of either pond.

Whatever the selected area, an installation would likely require a number of rafts and maintenance and monitoring of each raft. Monitoring of these types of systems have to include pond water for area-specific and pond-wide changes, sediments under the mat/raft to gauge whether there is enhanced particulate nutrient deposition to the sediments, and regular harvesting of the plants to gauge uptake of nutrients. Based on past monitoring, most of the nutrient removal occurs in sedimentation and plant growth, so regular harvesting and sediment analysis with accompanying nutrient analysis is a key component of system performance. It is also important to plan for winter-time freezing, so that the floating wetland system is not damaged.

VI.C.5. Shoreline Filter Media

As with floating wetlands, there have been a variety of P sorption/retention media designs that have been installed along pond and lake shorelines to remove phosphorus in the pond or just before it enters the pond. The media options have included iron filings, aluminum-enhanced zeolites, and biochar. These media have been developed to adsorb phosphorus, binding it permanently to the media. Placement of this media has been done through permanent installation of the media or in removable containers (*e.g.*, tube bags). As with floating wetlands, most of these uses have been in situations under conditions of high phosphorus (usually orthophosphate) concentrations. Some of these approaches are more well-established (*e.g.*, iron filings in shoreline permeable reactive barriers) than others (*e.g.*, biochar in bags anchored to a shoreline).

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[85] Colares GS, Dell'Osbel N, Wiesel PG, Oliveira GA, Lemos PHZ, da Silva FP, Lutterbeck CA, Kist LT, Machado ÊL. Floating treatment wetlands: A review and bibliometric analysis. Sci Total Environ. 2020 Apr 20;714:136776. doi: 10.1016/j.scitotenv.2020.136776. Epub 2020 Jan 17. PMID: 31991269.

[86] Hunt, W.F., R.J. Winston, and S.G. Kennedy. 2012. Evaluation of Floating Wetland Islands (FWIs) as a Retrofit to Existing Stormwater Detention Basins. Final Report to NC DENR – Division of Water Quality, 319(h) project. 71 pp.

Only one installation of this type has been completed in the Ecoregion to address phosphorus loading: installation of an iron-filings permeable reactive barrier along Fishermans Cove in Ashumet Pond in Falmouth/Mashpee. Wastewater discharge at the Joint Base Cape Cod (née Massachusetts Military Reservation) treatment facility infiltration beds had created a large plume with exceptionally high inorganic phosphorus concentrations (>5 mg/L) (**Figure VI-4**). After years of pond and plume characterization, a permeable reactive barrier (PRB) was installed along a portion of the Cove shoreline. This installation involved dewatering and excavation of a shallow trench along the shoreline to install the iron filings slightly inshore of the groundwater seepage face; dewatering proved to be a significant challenge.[87] The 2004 cost was $305,600 or approximately $1,000 per ft of shoreline (approximately $479,000 in 2022 dollars).[88] Inorganic P concentrations decreased approximately 1 mg/L after going through the PRB. Given that GHP and LHP watershed P sources/septic system leachfields are much more spread out, it would be very expensive to treat the whole shoreline: estimated $14.6 million for LHP and approximately $28.8 million for the GHP shoreline. Refinements for this type of approach could include targeted treatment of selected watershed areas or treating individual systems at their leachfields. The Town could also pursue pilot treatments with variations in the application and accompanying monitoring to narrow the possible options.

Other materials proposed for phosphorus removal from surface waters have included biochar (essentially highly processed charcoal), aluminum-enhanced zeolites, alum sludge, clay, etc.[89] Most of these have been tried in bench-scale installations, but a few have had larger scale experiments. Zeolites are naturally occurring microporous crystalline minerals that can have a variety of filtering characteristics, often have aluminum naturally as a component, and can be processed to enhance particular features. Alum sludge is residual material remaining after treating drinking water from surface water sources (*i.e.*, rivers and lakes). Each of these materials has some promise, but are at various stages of experimentation and do not have standardized installation procedures or performance results. Biochar has recently received more attention due to its carbon-removal capacity, though TP and ortho-P removals seem to be better in high concentration settings (*e.g.*, wastewater treatment plants) and some instances seem to show loss of the capacity with time.[90] One recent experimental biochar installation in a lake setting was found in New Jersey (**Figure VI-5**). All of these temporary installations need to be investigated as to P removal under relatively low, mostly organic P that have been measured in LHP and GHP. Project staff can assist the Town in sorting through these options if it is decided to further explore these strategies. All of the above approaches will also require permitting.

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[87] CH2M Hill. 2005. Ashumet Pond Geochemical Barrier for Phosphorus Removal Installation Summary Report. Prepared for Air Force Center for Environmental Excellence/Massachusetts Military Reservation. AFCEE ENRAC F41624-01-D8545; Task Order 0071. 152 pp.

[88] https://www.usinflationcalculator.com/

[89] Vandana P. D. Jaspal & K. Khare. 2021. Materials for phosphorous remediation: a review. *Phosphorus, Sulfur, and Silicon and the Related Elements*. 196:12, 1025-1037, DOI: 10.1080/10426507.2021.1989683.

[90] Perez-Mercado, L.F., C. Lalander, C. Berger, and S.S. Dalahmeh. 2018. Potential of Biochar Filters for Onsite Wastewater Treatment: Effects of Biochar Type, Physical Properties and Operating Conditions. *Water.* 10: 1835; doi:10.3390/w10121835.

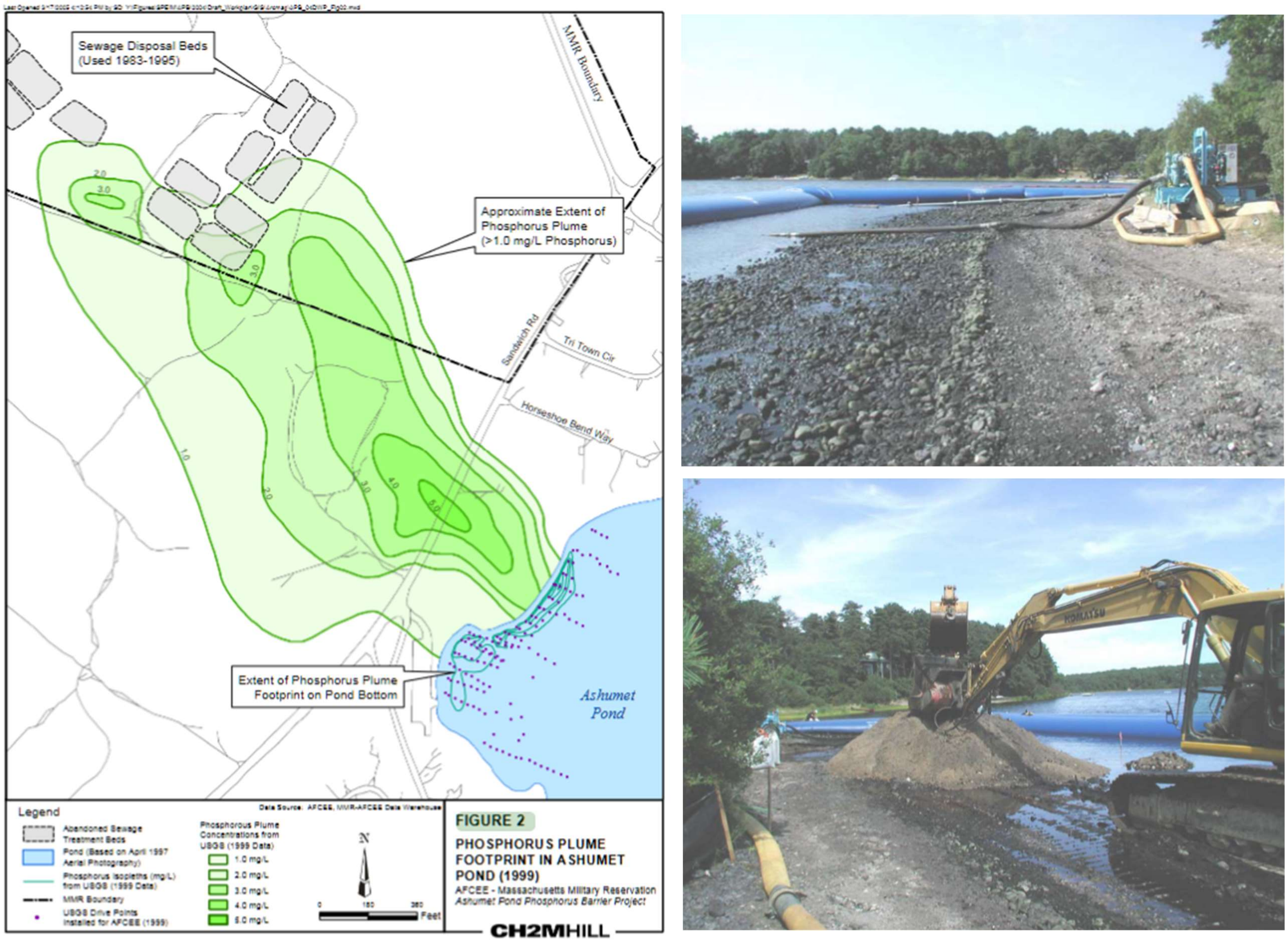

Figure VI-4. Ashumet Pond Phosphorus Plume and Excavation and Dewatering to install Iron Filings PRB to treat phosphorus. P concentrations in plume were > 5 mg/L. PRB was installed along ~300 ft of shoreline. From CH2M Hill (2005).

Figure VI-5. Biochar socks installed in Lake Hopatcong, NJ. The New Jersey Department of Environmental Protection recently provided a grant to the Lake Hopatcong Commission to test biochar use in an effort to adsorb phosphorus from lake water. Lake Hopatcong is a 14 m deep, ~2,600 acre lake/reservoir with a phosphorus TMDL and a lake management organization, the Lake Hopatcong Commission. Source: https://www.lakehopatcongfoundation.org/news/biochar-installations (accessed 9/5/22).

VII. Summary and Recommended Plan

Great Herring Pond (GHP) and Little Herring Pond (LHP) are both community resources for the Town of Plymouth. Both ponds are classified under Massachusetts law as Great Ponds, or publicly-owned resources, with surface areas of 419 acres and 81 acres, respectively. The two ponds share a watershed with streamflow from LHP flowing into GHP and then flowing out of GHP and into the Cape Cod Canal. The importance of the two ponds was acknowledged in their inclusion in the 1991 designation of the Herring River Area of Critical Environmental Concern (ACEC).[91]

The area near the ponds has seen expansive growth in development over the past 80 years and public concerns have increased that accompanying water quality conditions have worsened. In order to begin to address these concerns, the Town of Plymouth Department of Marine & Environmental Affairs (DMEA) asked TMDL Solutions LLC and the Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) develop a management plan for the GHP/LHP system. The present Management Plan is primarily composed of two sections: 1) a Diagnostic Summary of how GHP/LHP system generally functions based on the available historic water column data and data gap information collected in 2021 and 2) a Management Options Summary evaluating strategies to address water quality problems that occasionally occur in GHP.

In order to begin to develop management strategies, project staff began by looking at the current regulatory standing of the two ponds outside of the ACEC designation. Key regulatory provisions that apply to GHP/LHP include a) their classification as Class B warm water fisheries under Massachusetts Department of Environmental Protection (MassDEP) surface water regulation criteria,[92] and b) their status on the most recent EPA-approved Massachusetts Integrated List of surface waters.[93] In the Integrated List, GHP is classified as an impaired water due to low dissolved oxygen, while LHP is assigned to Category 2 for attaining fish, other aquatic life, and wildlife use, but other uses, such as swimming or boating, have not been assessed.

The Diagnostic Summary portion of the GHP/LHP Management Plan compared and evaluated previously collected historical data and refined contemporary water quality surveys completed in 2021 to address known data gaps. Historical information collected and reviewed included streamflow data collected by the Herring Pond Watershed Association (HPWA), water quality results collected on 26 dates by both the Town DMEA and the HPWA, GHP stormwater runoff data collected by CSP/SMAST[94] and TMDL Solutions,[95] and data collected in an 1970's-era survey of Plymouth Ponds.[96] This review of available historical data found that there were a number key data gaps that needed to be addressed prior to the evaluation of water management options. These data gaps included:

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[91] https://www.mass.gov/service-details/herring-river-watershed-acec (accessed 3/3/02)

[92] 314 CMR 4.00

[93] Massachusetts Department of Environmental Protection. November 2021 Final Massachusetts Integrated List of Waters for the Clean Water Act 2018/2020 Reporting Cycle.

[94] CSP/SMAST Technical Memorandum. Great Herring Pond Stormwater Monitoring Project results. February 24, 2016. .

[95] TMDL Solutions Technical Memorandum. Eagle Hill 2019 Stormwater Monitoring Results. February 4, 2020.

[96] Lyons-Skwarto Associates. 1970. A Base Line Survey and Modified Eutrophication Index for Forty-One Ponds in Plymouth, Massachusetts. Volumes I-V. Westwood, MA.

a) Delineation of the watershed to the GHP/LHP system and each pond,
b) Estimating the watershed sources of phosphorus to each pond,
c) Measuring sediment contributions to water column phosphorus concentrations
d) Measuring how the phytoplankton population varies throughout the summer and the factors that favor the growth of various portions of the population,
e) Surveying the extent of rooted plants (*i.e.*, macrophytes) and freshwater mussels, and
f) Combining all available data to understand how water quality in the two systems varies during 2021 and what the available historical data shows about variations from year to year.

The Diagnostic Summary showed that LHP is nutrient-rich, but generally has acceptable water quality conditions. LHP is very shallow (*i.e.*, maximum depth is 1.5 m) with light consistently reaching the bottom, which allows macrophytes to grow densely throughout the whole pond bottom. Comparison of the pond watershed and the historical and 2021 stream outflow showed that water remains in LHP for a very short time (12-15 days on average), but this residence time may vary based on groundwater fluctuations. Water column phosphorus and nitrogen concentrations were high (*i.e.*, greater than current Ecoregion thresholds), but dissolved oxygen (DO) concentrations were also always above the MassDEP minimum throughout the 2021 summer and there was no evidence of significant loss to sediment oxygen demand. Comparison of the phosphorus and nitrogen concentrations showed that phosphorus controls the water quality conditions in LHP. Review of the phytoplankton population showed relatively low biomass concentrations except in May and cyanobacteria populations were consistently low and usually only a minor portion of the overall phytoplankton population. The phytoplankton population did increase DO levels well above saturation, which would also be consistent with high nutrient levels. Comparison of the 2021 macrophyte coverage to the 1970's-era coverage showed an increase in coverage, but the older survey did not provide a density assessment similar to the one completed in 2021. The 2021 macrophyte survey noted some epiphytic growth on plants in the middle of the pond, which may be a sign of excessive phosphorus, but given that the survey was completed on only one date, it is a sign that should be monitored rather than managed at this point. Sediments in LHP are retaining phosphorus under the regular aerobic conditions in the pond, but there is significant phosphorus that could be released if the pond ever become anoxic. Septic system wastewater is the primary source (87%) of phosphorus measured in the LHP water column. Overall, LHP seems to have relatively healthy conditions, albeit with high nutrient levels.

GHP is much larger and deeper than LHP (15 m maximum depth) and has an average residence time of 7 months, but this tends to vary with longer residence times in late summer (estimated 58% increase). Although GHP is deep enough to have temperature stratification, this only occurred intermittently and the water column usually was well-mixed from the surface to the bottom. In spite of this, GHP had regular anoxia in the deepest waters (>12 m) from July through September and had anoxia from the 9 m to the bottom in August 2021. Review of nitrogen and phosphorus concentrations showed that phosphorus controlled water quality conditions and that total phosphorus (TP) concentrations at all depths exceeded the current Ecoregion threshold from May through October. Deep TP concentrations increased to >10X the Ecoregion threshold in August. Development of a phosphorus budget to account for all phosphorus sources showed that in the spring the two primary sources of phosphorus to GHP are stream inflow from LHP (47% of the overall budget) and septic system wastewater within the GHP watershed (41%). In the summer, the deep anoxia causes sediment additions of phosphorus to pond water column, but these account for only 16% of the overall summer phosphorus budget; stream inputs from LHP (39%) and septic system wastewater (34%) remain the largest sources of TP to GHP even when sediment sources are added to the water column. Review of streamflow readings showed that a larger factor in causing an increase in 2021 water column TP concentrations was the decrease in stream outflow from GHP. Comparison of groundwater elevations during 2021 showed they were below average from April through August and this likely contributed to the decrease in stream outflow, which would also increase the pond residence time. Review of the 2021 monthly phytoplankton sampling results showed that biomass levels were generally lower than LHP, but GHP cell counts were higher in August and reached a maximum of 2,267 cells/ml in the October 14 sample. This level is only 3% of the MassDPH criterion for issuing a Public Health Advisory, even though the majority of the cells were cyanobacteria. Based on a review of water quality and residence times, project staff recommended a water column TP mass of 50 kg in order to attain acceptable water quality in GHP. Overall, GHP has impaired water quality conditions with excessive nutrient levels, regular hypoxia/anoxia less than MassDEP regulatory minima, and occasional conditions that favor cyanobacteria growth. Cyanobacteria cell counts were well below MassDPH guidance levels for issuing a Public Health Advisory, but MassDPH guidance also suggest that advisories may be issued based on visual observations and/or toxin measurements.

Project staff reviewed management options to attain the recommended 50 kg TP mass in the GHP water column and found that most options would need to address septic system wastewater TP from the GHP watershed or via stream from LHP. Treatment of the sediments alone to reduce summer TP inputs would be insufficient to attain the 50 kg TP goal. Review of the LHP watershed land use, septic systems, and groundwater travel times estimated 128 to 178 septic systems and houses are currently contributing TP to the LHP water column, while 116 to 158 septic systems and houses are currently contributing TP to the GHP water column. Review of wastewater management options found that if all LHP watershed wastewater and its associated TP was collected and discharged outside of the LHP watershed (*i.e.*, sewering), the spring GHP water column TP mass would be reduced to approximately 66 kg without any additional reductions in the GHP watershed. In order to attain the 50 kg TP goal, an additional 60 to 70 residences in the GHP watershed would need to have their wastewater TP removed. This long-term management strategy incorporates the anticipated increase in TP mass due to the summer increase in residence time. The increased summer residence time tends to reduce the benefits of in-pond sediment treatments. Project staff also reviewed the use of currently permitted phosphorus-reducing septic systems, but these would require a larger number of installations than is currently allowed under current MassDEP permitting (currently assigned to the "piloting" category) and have greater cost uncertainties associated with their installation. Wastewater solutions are long-term because they will require significant discussions about funding, timing, and design. Project staff also reviewed the applicability of some potential interim, experimental management options, including in-stream or shoreline experimental Permeable Reactive Barriers (PRBs), restoration of the cranberry bogs between LHP and GHP to increase nutrient uptake, and floating wetlands. Most of these interim solutions could be completed at lower cost and a shorter time than long-term solutions, but their experimental status means they will require flexibility in design and installation, as well as extensive monitoring to document their P removal.

Based on the findings in the Diagnostic Assessment and Management Option review, TMDL Solutions and CSP/SMAST staff recommend a series of long-, mid- and short-term goals for implementing an adaptive management approach for the restoration of Great Herring and Little Herring Ponds:

LONG TERM MANAGEMENT GOALS

Long term management goals to involve development of a wastewater management strategy for GHP. The diagnostic assessment shows that wastewater phosphorus is the primary source of water column TP concentrations and phosphorus control is the key for managing water quality in GHP and LHP. Reducing wastewater TP to GHP will require addressing wastewater additions to both LHP and GHP. Specific long term goals are:

- **Sewer Little Herring Pond and portion of the Great Herring Pond watershed**
    - 128 to 178 houses in the LHP watershed are currently contributing TP to LHP and GHP via stream outflow
    - 116 to 158 houses in the GHP watershed are currently contributing TP to GHP
    - Sewering and removal of wastewater phosphorus from all the houses in the LHP watershed (128 to 178 houses) and 60 to 70 houses in GHP watershed would attain the proposed GHP water column phosphorus threshold (50 kg)
    - Seek opportunities to incorporated into updated Town Comprehensive Wastewater Management Planning tasks
    - Seek separate funding opportunities through state grants to review sewering feasibility options, costs, permits
    - Should Feasibility Study prove applicable, Town and partners would move forward with planning, permitting and funding stage.
    - Form Partnerships: Buzzards Bay Coalition, AD Makepeace, Southeastern Regional Planning and Economic Development District (SRPEDD), Town of Bourne, Cape Cod Commission

INTERIM MANAGEMENT GOALS

Although watershed wastewater phosphorus reductions will address the water quality impairments in GHP, there are some **temporary interim phosphorus reduction options** that the Town should consider. These options will not individually reach the goal of removing the impairments in GHP, but they could provide some reductions in the impairments. All of these options will require monitoring to establish their efficacy and some are experimental and will likely require additional investigation to refine potential costs and regulatory hurdles. Specific interim goals to explore further are:

- In Stream Phosphorus Removal - Carters River
    - Restoration of the wetlands between LHP and GHP to slow flow and increase contact time
    - Instream Permeable Reactive Barrier. Use of iron/alum-enhanced materials within stream to bind phosphorus
- Permeable Reactive Barrier – shoreline to LHP and selected shoreline sections of GHP or near individual leachfields

    - PRBs have typically been used for distinct groundwater plumes rather than diffuse septic system plumes. May have some options for nearshore or near-leachfield installations, but feasibility and cost may be prohibitive.
- Floating Wetlands – LHP and/or GHP
    - Floating wetlands have typically been used in highly controlled systems like stormwater basins, where inorganic phosphorus is readily available and natural system functions do not need to be addressed. P removal in these cases is typically on the order of 20% with additional issues regarding monitoring, maintenance, and management of the wetlands. Generally not applicable, but Town may wish to explore on a limited, experimental basis.
- Spot Alum Treatment - GHP
    - Although a traditional alum treatment of the deepest portion of the pond will not adequately address the impairments in GHP because the sediments are only 12% of the summer phosphorus budget, treatment of the entire water column in the spring may remove sufficient phosphorus to prevent algal blooms during the following summer. This approach would depend on an annual application and the year-to-year fluctuations in water levels/stream flow and may require special regulatory permitting.
- Evaluate direct discharge stormwater improvement options - GHP
    - Stormwater inputs are a relatively small portion of the overall phosphorus budget to GHP (5%), but the Town is encouraged to explore opportunities and feasibility of infiltrating of any direct discharges when updates or upgrades are considered. The Town may also consider an overall stormwater assessment of municipally owned stormwater discharges and explore infiltration and treatment options. Designs may be constrained by land area for infiltration structures, but discussion of alternative designs is encouraged.

SHORT TERM MANAGEMENT GOALS

Development of long term and interim management goals will benefit from continued targeted monitoring in GHP and LHP and selection of a water quality management goal. As such, it is recommended that the Town consider the following short term goals:

- Develop and implement a Monitoring Plan that will continue through the implementation of any interim or long term strategies, as available funding allows, with the following recommendations
    - **Deep Spot Water Quality Sampling in both GHP & LHP:**
      GHP (monthly: April – October and LHP (annual: August/September)
      GHP monthly between April and October at six depths (0.5 m, 3 m, 8 m, 9 m, 10 m, and 1 m off the bottom) and annually at LHP during August/September at two depths (0.5 m and 1 m). Each sample collection will be accompanied by dissolved oxygen and temperature profile readings (0.5 m and each meter to at least 12 m in GHP and 0.15 m, 0.5 m, and 1 m in LHP) and Secchi clarity and station depth readings. All collected samples assayed for standard PALS parameters (total phosphorus, total nitrogen, chlorophyll-a, pheophytin-a, pH, and alkalinity) plus ortho-P at the Coastal Systems Analytical Facility at SMAST using the same procedures utilized during the data collection for the Management Plan. A minimum of 10% of the total sample count will be accompanied by QA samples.

Cyanobacteria sampling for parameters matching MassDPH criteria at a minimum: cell counts and toxins. Consider assays for phytoplankton speciation from sample collection through photic zone.

- **Continuous Monitoring in GHP Deep Spot (optional)**
  In GHP consider installation of continuous monitoring platforms (sondes) installed at 3 m and 10 m depths between April and October and programmed to record dissolved oxygen, temperature, depth, and chlorophyll a every 15 minutes. Sonde data will allow better understanding of temporary temperature stratification and deep anoxia in GHP, which has been indicated as a key for sediment phosphorus release.

- **Stream Flow Measurements at LHP and GHP outflows**
  Year-round monitoring of flow and water quality at Carters River/LHP outflow and GHP outflow. Monthly streamflow velocity measurements with water quality sample collection on the same date. Streamflow measurements should follow same cross-sectional measurement methods utilized during the data collection for the Management Plan. Collected samples should be assayed for following parameters: pH, Alkalinity, Chlorophyll-a, Phaeophytin, Total Pigments, Total Phosphorus, Total Nitrogen, and Ortho-Phosphate.

- **Stage-Discharge Curves at LHP and GHP outflows (optional)**
  Develop Stage-Discharge Curves at LHP and GHP outflow via installation of a stream gauge at each streamflow monitoring location. These gauges will record continuous water level recordings. These recordings will be combined with monthly streamflow measurements to evaluate whether reliable stage-discharge relationships can be developed for the two outflow locations. Continuous recordings will allow interpolation of flow rates between instantaneous readings and more complete record of outflows and nutrient export at the two locations.

- **Annual Review of Data**
  SMAST and/or TMDL Solutions to conduct annual review of data providing Technical Memorandum (draft and final) summarizing monitoring results and comparing to past monitoring, as well as recommendations for future monitoring and management activities.

- **Select a target restoration threshold of 50 kg TP mass within the GHP water column as a preliminary water quality target threshold, but avoid a TMDL designation until attainment of satisfactory water quality.**
  - GHP is listed in MassDEP's most recent Integrated List as impaired and requiring a TMDL. However, MassDEP has only created one phosphorus TMDL in southeastern Massachusetts in the last 10 years.
  - 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.

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 regional planning funds. It is further recommended that the town contact appropriate regulatory officials to explore these options. TMDL Solutions and CSP/SMAST staff are available to further assist the town with implementation, adaptive monitoring, and regulatory activities.

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