

Savery Pond Management Plan and Diagnostic Assessment

FINAL REPORT

October 2021

for the

Town of Plymouth



Prepared by:

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Department of Marine and Environmental Affairs



Prepared By

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Cover photo: Savery Pond (E. Eichner, 11/12/19)

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Executive Summary

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Savery Pond is among the more than 400 ponds in the Town of Plymouth and one 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 2020, DMEA, CSP/SMAST, TMDL Solutions, and other Savery Pond stakeholders, including the Savery Pond Conservancy, developed a strategy to address data gaps for Savery Pond and develop a management plan based on diagnostic assessment of the pond, including review and integration of data gap data with previous water quality sampling. This Savery Pond Management Plan and Diagnostic Assessment provides a reasonable understanding of the Savery Pond ecosystem and uses the collected information and its synthesis to identify and assess potential management options and develop a recommended management plan.

Savery Pond is a 27-acre pond in southern Plymouth, located west of Old Sandwich Road and northwest of Route 3A. The pond has a maximum depth of 4 m, an average depth of 1.74 m, and a total volume of 192,418 cubic meters. The watershed to Savery Pond, based on USGS regional groundwater modeling, is 513 acres, although groundwater elevations, water quality data, and pumping records from the nearby John Holmes public water supply well suggest that the watershed area varies from year-to-year and between seasons. These variations suggest that the pond residence time generally varies from approximately 90 days to 220 days and may extend to greater than 800 days when groundwater levels and summer precipitation are low. The residence time, along with phosphorus inputs from the 9 houses and one cranberry bog within the watershed and adjacent to the pond that are mostly determining its water quality.

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.

Savery Pond is a Great Pond under Massachusetts law and, therefore, is a publicly owned resource. MassDEP classified Savery Pond as impaired by “harmful algal bloom” in the current Integrated List of all Commonwealth waters. This classification was a change from the previous integrated list and likely reflects the integration of the Massachusetts Department of Public Health (MassDPH) algal bloom closure list into MassDEP databases. At the time of the Plymouth Pond Atlas, the Massachusetts Department of Public Health had closures of Savery Pond in 2011 and 2014 due to cyanobacteria blooms; subsequent closures have occurred in 2015, 2016, and 2017.²

Review of water quality data showed that Savery Pond water quality is occasionally impaired usually during July or August. Data also showed that water quality is controlled by phosphorus and phosphorus concentrations are regularly high. Nutrient concentrations show that they increase significantly during the summer (shallow summer concentrations were up to 2X higher than spring concentrations) and summer water clarity is notably reduced. Phosphorus and chlorophyll concentrations regularly exceed thresholds for maintaining high quality ponds and lake water quality in the Plymouth ecoregion. Dissolved oxygen levels are usually acceptable except when the water column has occasional and temporary temperature stratification. Only 7 of the available DO readings (6%) were less than the state regulatory minimum. Four of these 7 readings occurred in July when nutrient concentrations are typically at their highest. July was also the month with the strongest water column temperature stratification readings. Transitory events can occur that can trigger significantly impaired conditions (*i.e.*, temporary temperature stratification causes hypoxia in bottom waters as noted in the 2016 continuous sensor deployment).

Review of water and phosphorus sources show that the summer increase in nutrient concentrations is due to increased water residence time within the pond. The Savery Pond water budget indicates that summer pumping rate at the nearby John Holmes public water supply well is usually >2X the September to May average rate. Review of past groundwater modeling in the area shows that increased well pumping expands the well capture area and draws water from within the Savery Pond watershed. When this occurs during the summer, the amount of groundwater flowing through Savery Pond decreases and that increases the water residence time in the pond. Increased residence time increases the concentrations of phosphorus and nitrogen in the pond. Preliminary estimates of residence times based on water quality measurements suggest that the residence time in the pond increases from the 48 days determined from USGS regional groundwater modeling to 220 days on average during the summer and to over 800 days during years when increased pumping is also accompanied by low summer precipitation and low groundwater levels. Increased residence time leads to increased phosphorus and nitrogen concentrations and the greater availability of nutrients leads to greater phytoplankton growth and decreased clarity.

Monthly phytoplankton sampling during April to October as part of the 2020 data gap surveys showed that blue-greens/cyanobacteria became the dominant cell type during the high phosphorus summer growing season. However, the highest blue-green cell count in 2020 was 465 cells/ml in July, well less than the MassDPH 70,000 cells/ml cyanobacteria threshold established as a blue-green direct contact advisory level. It should be noted, however, that 2020

² Savery Pond Conservancy website (<https://www.saverypond.org/algal-blooms#>!; accessed 1/22/21).

was a high groundwater year, so summer pond water residence times would have been less than during 2016 when there was a pond closure. The phytoplankton sampling shows that summer conditions generally favor blue-green growth and longer residence times will create even more favorable conditions by supporting increased available phosphorus in the water column.

Review of the watershed sources of phosphorus found that the two primary sources were septic system leachfields on 9 properties adjacent to the pond and the cranberry bog to the west of the pond; these sources were each is 38% of the annual load. The other P sources to the Savery Pond water column were: road runoff (12%), atmospheric load on the pond surface (7%), pond sediment release (5%), and roof runoff (1%). Total average phosphorus load to the water column is 13 kg/yr. Review of water quality data confirmed that this load is consistent with pond water column measurements. Comparison of water column total phosphorus and nitrogen mass generally showed that changes in the water column concentrations were directly related to seasonal changes in the residence time of water within the pond. Loads from the watershed sources were relatively constant and the summer input from sediments was small.

The water quality review in the diagnostic assessment of Savery Pond showed the pond periodically does not meet water quality standards. The impairments include high phosphorus concentrations, low DO, diminished clarity and cyanobacteria blooms. These impairments do not occur every summer and seem to be enhanced by the combined impact of low groundwater levels, low summer precipitation, and high pumping of the nearby public supply well.

Project staff reviewed goals to maintain acceptable water quality in Savery Pond. This review found that April and May water quality conditions are generally acceptable: DO concentrations above the MassDEP minimum and clarity at or near the bottom. April and May water column chlorophyll and TP concentrations are higher than ecoregion guidelines, but these concentrations are likely acceptable because of the short pond residence time. Based on this review, staff recommended a TP concentration limit of 26 µg/L and a water column TP mass limit of 5 kg. Review of available water quality showed that these limits are generally attained in April, May, September, and October. In order to address the water quality impairments, project staff reviewed potential lake management options and identified three applicable options to the Savery Pond impairments: a) pond residence time management, b) watershed phosphorus reductions, and c) annual application of a water column settling agent (*i.e.*, alum):

POTENTIAL SAVERY POND MANAGEMENT OPTIONS

a) Pond Residence Time Management

Consistent pond residence time management would require limiting the pumping of the John Holmes public water supply well to maintain both short water residence time in the pond and acceptable water quality. Review of water quality data suggests that an upper limit of 0.41 million gallons per day (MGD) should sustain acceptable water quality in Savery Pond in the summer. Review of 2010 to 2020 pumping at the John Holmes well shows meeting this limit would require development of additional pumping capacity, an average 0.27 MGD and a maximum of 0.54 MGD, based on a review of past increases in summer pumping. Implementation of this managed pumping approach could attain acceptable water quality in Savery Pond on average without any reductions in watershed phosphorus loads or treatment of pond water column P.

Project staff recognize that developing additional capacity and implementing a pumping limitation at the John Holmes well is unattainable in the short-term and the Town would likely benefit from additional review through site-specific groundwater modeling and review of water conservation options. Even if this approach was selected, time would be required to develop sufficient funding to identify, plan, and implement sufficient additional pumping capacity to address any needed reduction in the summer pumping currently provided by the John Holmes well. Development of the potential cost of installation of a new public supply well in a location that did not negatively impact Savery Pond (or other Great Ponds) while fitting within the existing well network would require additional tasks outside of the scope of this project.

b) Watershed Phosphorus Reductions

Review of water quality found that acceptable water quality conditions could generally be attained year-round if annual phosphorus inputs could be reduced by 5 kg. This load is equivalent to the annual phosphorus additions from all existing septic systems in the watershed or the estimated annual TP load from the cranberry bog at the western end of the pond. Elimination of all controllable loads from road runoff, roof runoff, and sediment contributions combined would be insufficient to attain a 5 kg TP reduction. Removal of the wastewater phosphorus load would require the construction of a wastewater collection (sewer) system and treatment and discharge of the wastewater outside of the Savery Pond watershed. Potential options would be connection to the existing municipal system (which is approximately 12 km to the north of the pond) or construction of a satellite treatment facility. Each of these options would require time for planning and significant funding. Existing experimental alternative septic systems currently permitted by MassDEP would only attain half of the required 5 kg P removal. Complete elimination of the cranberry bog P load is unlikely and would require elimination of other P sources in order to achieve the 5 kg P removal target. It is likely that a refined characterization of the current bog would need to be completed to understand its P export pathways and options to reduce P export.

c) Annual Alum Application (*i.e.*, a water column settling agent)

Application of an annual settling agent within the pond water column was the third applicable option. Addition of aluminum salts each year would remove phosphorus from the water column prior to the summer period when the water residence time increases. Based on performance of alum applications in ponds where the sediments are the primary source of water column P, it is estimated that a May application would reduce the water column mass from an average of 4.6 kg to 1.9 kg. Watershed sources would then add 6.2 kg P until mid-September, but the residence time in the pond would decrease back to May levels by September due to decreased pumping at the John Holmes well. Estimated annual cost of an alum treatment would be \$15,134 to \$21,000 per year with additional costs for permitting (likely annual renewal of an initial permit through the Town Conservation Commission) and monitoring prior to the application, during the application, and post-application. This planning cost would need to be further refined through a procurement process and additional review of secondary impacts if this is a selected/preferred option during Town discussions. The estimated alum cost includes a mix of aluminum sulfate and sodium aluminate to try to attain a neutral pH application; actual proportions are determined by the pond water alkalinity and pH on the date of application.

The variations of the characteristics of Savery Pond creates challenges for defining appropriate management strategies. Comparisons of the variations in pond water quality and the pumping of the John Holmes well show that low groundwater elevations and low summer precipitation rates cause the most impaired conditions. Review of pumping and groundwater levels showed these conditions occurred in 2016 and available data shows that this is also when water quality conditions were most impaired. In contrast, available data in 2019 and 2020, when relative high groundwater conditions existed, showed reduced impaired conditions. Overall, it is recognized that planning for appropriate management may require some adjustments as more monitoring is conducted.

Based on these considerations and the above review of applicable options, TMDL Solutions and CSP/SMASST staff recommend the following steps for implementation of an adaptive management approach for the restoration of Savery Pond:

1. Review options to reduce summer water pumping at the John Holmes well to sustain a Savery Pond residence time of 120 days or less

Review of John Holmes well pumping rates suggest a 120 day residence time could be achieved at a pumping rate of 0.41 MGD or less. Pumping rates at the well from 2010 to 2020 were generally below this level from October to April. Average levels in May and September were 0.41 MGD. April water quality in Savery Pond was not impaired, but conditions in May and September were occasionally impaired.

Steps to review reduced pumping options:

- Review whether water conservation at large water users within the John Holmes well service area could reduce water demand and pumping at the well. Water conservation would reduce pumping demand and reduce the amount of additional pumping capacity that is needed.
- Evaluate options for developing new pumping capacity. Average monthly summer pumping rates at the John Holmes well from 2010 to 2020 were: 0.41 MGD in May, 0.58 MGD in June, 0.68 MGD in July, 0.60 MGD in August, and 0.41 MGD in September. Based on these readings, an average of 0.27 MGD water supply would be required to sustain the maximum average monthly water demand in July if the John Holmes well pumping was limited to 0.41 MGD. Maximum monthly water pumping rate was 0.95 MGD (July 2010); this rate would require an additional 0.54 MGD if the John Holmes well pumping was limited to 0.41 MGD.

Project staff recognize that developing new pumping capacity without accompanying water conservation steps is likely unattainable in the short-term and the Town would likely benefit from additional confirmation through development of an area-specific groundwater model. Even if this approach was selected, time would be required to develop sufficient funding to identify, plan, and implement sufficient supply capacity to address the increase in summer pumping currently provided by the John Holmes well. Development of the potential cost of installation of a new public supply well in a location that did not negatively impact Savery Pond (or other Great Ponds) while fitting within the existing well network would require additional tasks outside of the scope of this project.

2. **If pumping limits are not available/acceptable, pursue settling agent addition management option.**
 - An annual application of alum will not require limitations on pumping or changes in watershed phosphorus sources, but would require regular monitoring to assess its efficacy and long-term impacts. Regular monitoring required to implement this option will also help to refine interactions between well pumping, water residence time, groundwater elevations, and summer precipitation. Better understanding of these interactions could provide adaptive management options, such as a hybrid strategy incorporating both reduced limits on pumping and less frequent application of a settling agent.
3. **Try to avoid management of watershed phosphorus loads.**
 - Watershed phosphorus loads are relatively small compared to the size of the pond and would not need to be managed if a naturally short pond residence time was maintained. Efforts to eliminate the largest sources of watershed phosphorus would either be very costly (*i.e.*, wastewater) or uncertain (*i.e.*, the cranberry bog).
4. **Maintain regular monitoring of Savery Pond.**
 - Annual spring and late summer monitoring of Savery Pond will provide long-term data for the fluctuations seen in the current dataset. Review of this data on a regular basis (*e.g.*, every 5 years) will provide better insights into future management options.
5. **Address MassDEP TMDL provision once management approach is implemented and reliable water quality is regularly attained.**
 - Savery Pond is currently listed on the latest MassDEP Integrated List as an impaired water body requiring a TMDL. Towns have generally been held responsible by MassDEP for developing strategies to attain acceptable water quality in impaired waters. The diagnostic summary suggests that 26 µg/L TP and 5 kg water column TP mass are appropriate targets for acceptable water quality in Savery Pond. Once Plymouth and the other Savery Pond stakeholders decide on an acceptable water quality management strategy for Savery Pond, it is recommended that the strategy be implemented, water quality be monitored, and, once acceptable water quality conditions have been achieved, the Town should approach MassDEP with both the strategy and a proposed TMDL.

Implementation of these recommendations will require funding sources and close coordination among local project planners and local regulatory boards. Potential funding sources include local funds, state grants, state budget directives, and county funds. It is further recommended that the town contact appropriate officials to explore these options. TMDL Solutions and CSP/SMASST 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.³ 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.

Savery Pond was among the ponds initially prioritized for development of a management plan because of a number of recent cyanobacteria blooms and public health advisories, as well as a motivated community, including the Savery Pond Conservancy, an offshoot of the Friends of Ellisville Marsh. DMEA worked with CSP/SMAST and TMDL Solutions LLC to develop water quality data and other pond-specific information over a number of years, including collection of water quality samples and installation of continuous water quality sensors in 2016⁴ and collection and incubation of sediment cores in 2019.⁵

During 2020, CSP/SMAST and TMDL Solutions staff worked with the Town DMEA staff to develop a list of Savery Pond-specific data gaps and accompanying tasks that would need to be addressed to complete a pond management plan, including measurement and water quality sampling of stream outflow, characterization of the phytoplankton community, and assessment of the pond watershed. These activities would be combined with historic data, including Savery Pond Conservancy information, to develop a diagnostic assessment of the pond ecosystem, which, in turn, would be used to assess management options. This document, the Savery Pond Management Plan and Diagnostic Assessment, summarizes the results of these tasks, sets pond-

³ 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.

⁴ TMDL Solutions Technical Memorandum. Savery Pond 2016 Water Quality Monitoring. December 9, 2016. From: E. Eichner. To: K. Tower, Town of Plymouth. TMDL Solutions. Centerville, MA. 14 pp.

⁵ Results summarized in this plan.

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 Savery Pond generally functions 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 Savery Pond water quality.

II. Savery Pond Background

Savery Pond is a 27-acre⁶ pond in southern Plymouth, located west of Old Sandwich Road and northwest of Route 3A (Figure II-1). The pond has a maximum depth of 4 m, an average depth of 1.74 m, and a total volume of 192,418 m³ (Figure II-2). The first accurate US Geological Survey (USGS) topographic map including the pond was produced in 1933.⁷ A 1940 map update showed five buildings around the northeastern edge of the pond (Figure II-3). The 1940 refinement also showed two small cranberry bogs, one along the western shoreline (slightly smaller than the bog there today) and another bog where there is now a mostly flooded freshwater wetland⁸ along the stream to Ellisville Harbor. The 1951 USGS map update shows the addition of another cranberry bog to the south of the pond; the additional bog was in the same location as a portion of the bog that is there today and was approximately 90 m from the pond shoreline. Nine buildings were adjacent to the pond in 1951. By the 1967 map update, the number of buildings had increased to 12 and both of the two larger bogs had increased in area. A 1977 USGS aerial photograph showed the easternmost bog flooded and a large campground road network to the southwest of the pond. The most recent topographic maps began to be developed in 2012; available versions show roads and topography, but have not added buildings or cranberry bogs.

Savery Pond is listed in the Plymouth Pond and Lake Atlas⁹ as pond number 37 and in the MassDEP PALIS system as pond number 94136. Prior to the PPALS snapshot sampling review in the Atlas, Savery Pond had only limited sampling: a) 1970s-era town-wide pond water quality sampling¹⁰ and 2011 composite water column sampling.¹¹ The 2014 PPALS water quality snapshot results generally showed impaired, late summer conditions with high total phosphorus and total nitrogen concentrations, poor Secchi clarity, and dissolved oxygen concentrations with reduced saturation levels throughout the water column.¹²

⁶ The surface area of Savery Pond varies depending on the source: MassDEP lists its area as 29 acres, the delineated Town parcel for Savery Pond is 32 acres; determining the area based on historic aerial shows that the area fluctuates with groundwater, but the surface area is generally 27 acres.

⁷ The first available USGS topographic map of the area was in 1886, but the pond was incorrectly oriented. Subsequent updates included this orientation until it was corrected in 1933.

⁸ Some have labelled this abandoned bog "Bog Pond".

⁹ Eichner, E.M., B.L. Howes, and S. Horvet. 2015. Town of Plymouth Pond and Lake Atlas.

¹⁰ Lyons-Skwarto Associates. 1970. A Base Line Survey and Modified Eutrophication Index for Forty-One Ponds in Plymouth, Massachusetts. Volume V. Westwood, MA.

¹¹ Aquatic Control Technology, Inc. 2012. 2012 Water and Sediment Quality Survey of Savery Pond - Plymouth, MA. Sutton, MA. 34 pp.

¹² Eichner, E.M., B.L. Howes, and S. Horvet. 2015. Town of Plymouth Pond and Lake Atlas. Appendix B, p. B55.

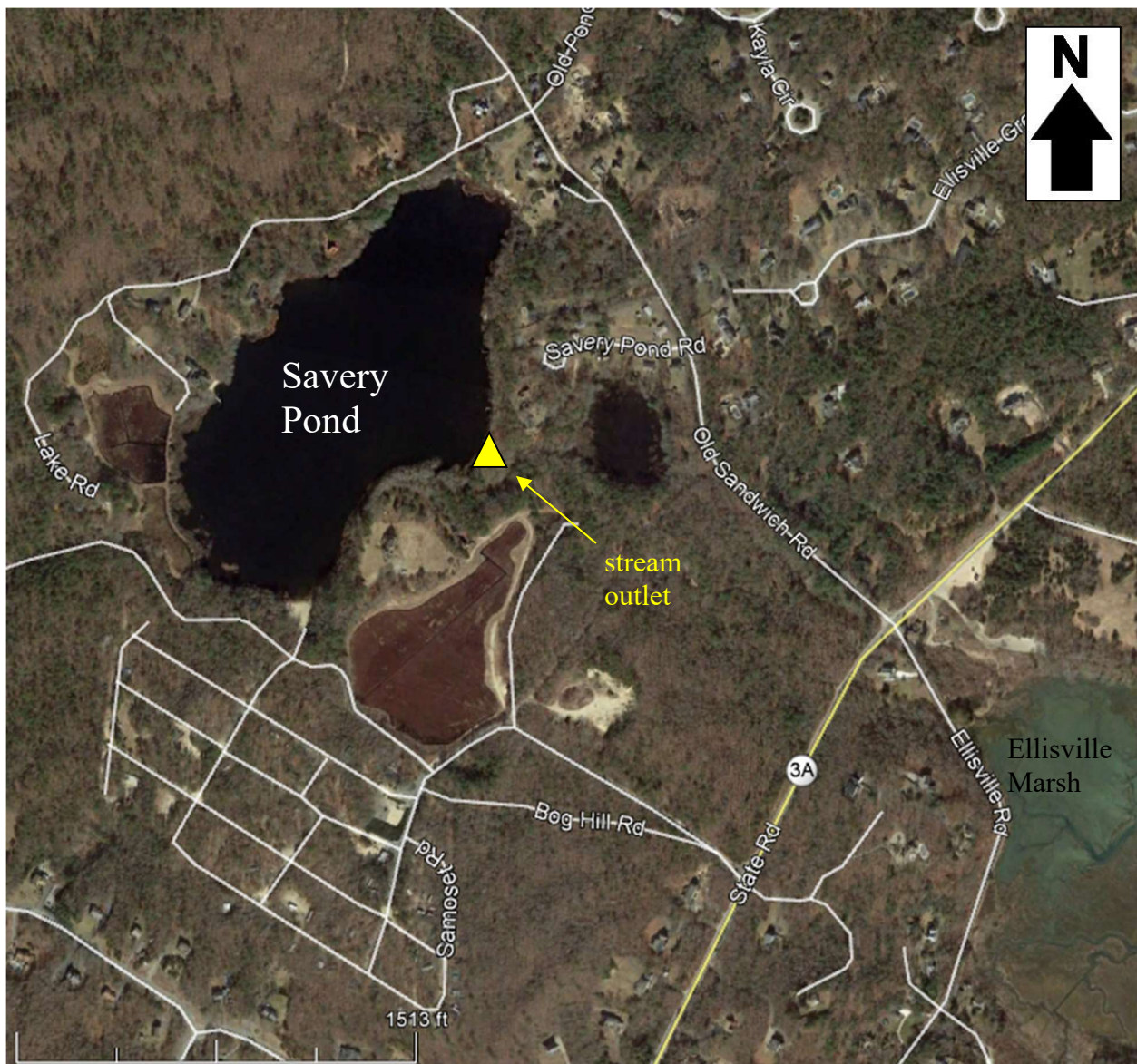


Figure II-1. Savery Pond Locus. Savery Pond is a 27 acre pond located west of Old Sandwich Road and northwest of Route 3A in Plymouth, MA. A stream connects Savery Pond to the Ellisville Marsh estuary, which is connected to Cape Cod Bay. Base map is 2/27/18 aerial photograph from Google Earth.

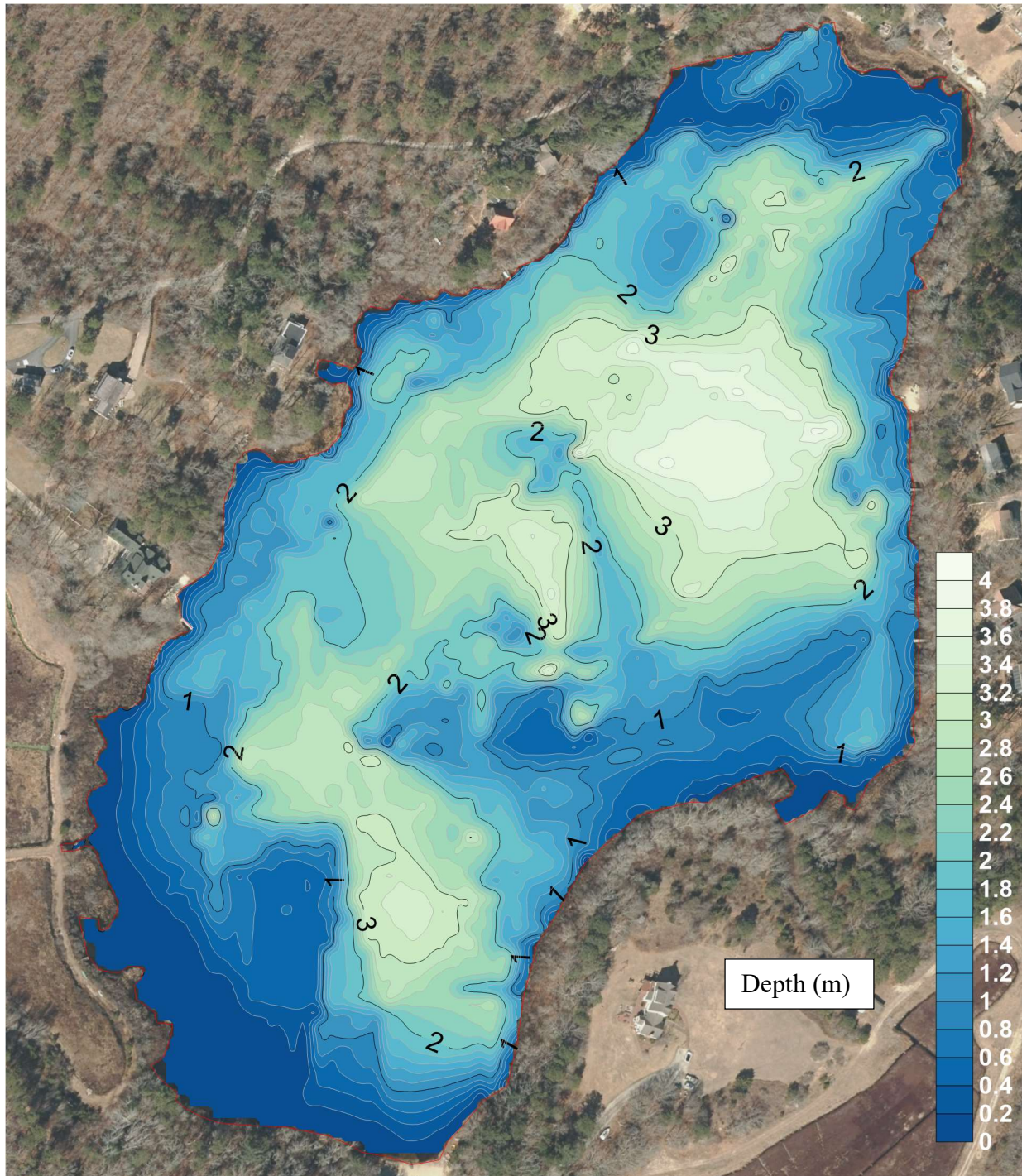


Figure II-2. Savery Pond Bathymetry. Bathymetry determined by CSP/SMASST between November 5 and November 20, 2020. All contours in meters. Bathymetric measurements were determined using a differential GPS mounted on a boat for positioning coupled to a survey-grade fathometer. This approach provided thousands of depth readings throughout the pond. Based on this survey, the total volume of Savery Pond was 192,418 cubic meters with a maximum depth of 4 m.

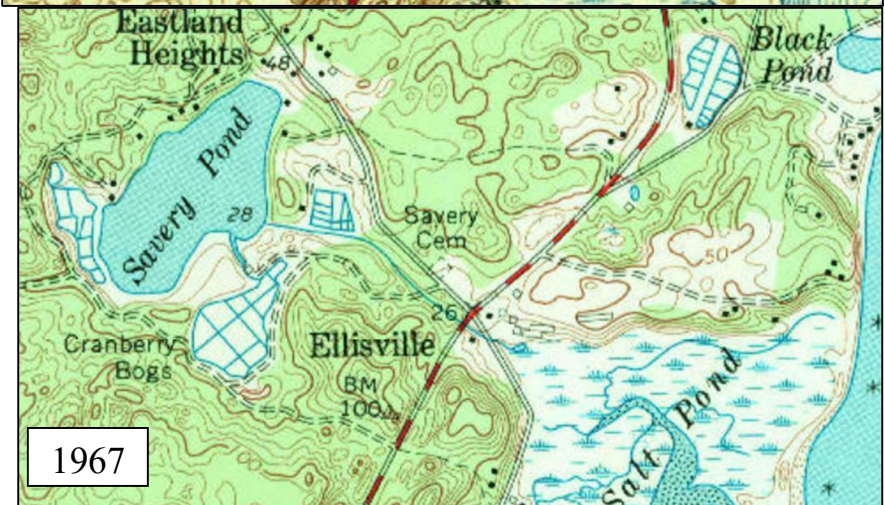
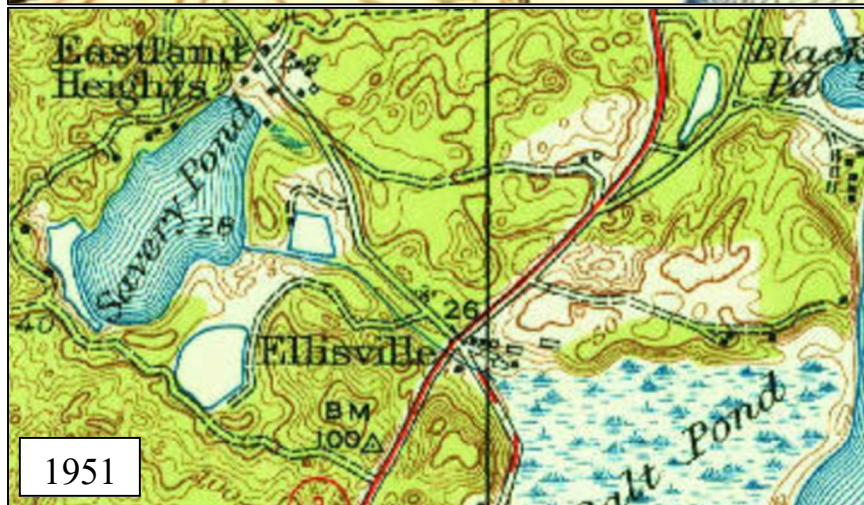


Figure II-3. Historic US Geological Survey Topographic Maps of the Savery Pond Area. The first USGS topographic map of the Savery Pond area was completed in 1886 and had an incorrect pond orientation. This orientation was corrected in 1933 and the 1940 map was the first to show buildings located around the pond, as well as two cranberry bogs. Another bog was added on the 1951 map. A 1977 aerial photograph (not shown) included the addition of the road network associated with the campground south of the pond.

Given that its surface area is greater than 10 acres, Savery Pond is considered a Great Pond under Massachusetts law.¹³ In the most recent Massachusetts Department of Environmental Protection (MassDEP) Integrated List, Savery Pond is listed as Segment# MA94136 and classified as a Category 5 water.¹⁴ Category 5 waters are impaired waters and are required to have a Total Maximum Daily Load (TMDL) developed to address the cause of the impairment. Savery Pond is listed as impaired by “harmful algal bloom.” At the time of the Pond Atlas, the Massachusetts Department of Public Health had closures of Savery Pond in 2011 and 2014 due to cyanobacteria blooms; subsequent closures have occurred in 2015, 2016, and 2017.¹⁵ Bacterial testing¹⁶ at beach areas at the time of the Pond Atlas (2014) showed no detections for indicator bacteria.

Given the impaired classification by the state and its frequent algal blooms, the Town DMEA began working with a team from CSP/SMASST and TMDL Solutions to address some of the identified Savery Pond data gaps necessary to develop a pond management plan. Following the completion of the Town Pond Atlas, the following data needs were identified as critical for the development of a management plan: a) assessment of pond sediments to measure potential phosphorus release and conditions that trigger release, b) surveys of aquatic plants, phytoplankton, freshwater mussels, bathymetry, and water column conditions, and c) measurement of stream outflow and accompanying water quality. Once all this data was collected, it could be synthesized with other complementary system characterization information, such a watershed delineation, land use assessment, and updated water column data, to complete a pond assessment that would identify management priorities in the subsequent management plan.

While the Town DMEA, CSP/SMASST and TMDL Solutions team worked to secure adequate funding for development of the management plan, a number of data collection activities were completed. In the summer of 2016, DMEA staff with the assistance of CSP/SMASST installed an YSI 6600 V2 sonde and three HOBO temperature recorders over the deepest point in Savery Pond and TMDL Solutions reviewed the resulting data.¹⁷ The sonde had sensors for temperature, dissolved oxygen, chlorophyll a, and depth and the data review found that the pond water column had regular temperature layering that isolated deeper waters, but this layer structure was periodically disrupted and the whole water column was mixed. This layering contributed to low dissolved oxygen events and high phosphorus concentrations, especially in waters close to the bottom of pond. In spring 2019, the Town had CSP/SMASST collect and incubate sediment cores and again installed a sonde in the pond. The Friends of Ellisville Marsh/Savery Pond Conservancy also produced a number of reports summarizing data gathered to date,¹⁸ installed a stream gauge at the pond outlet, and conducted a bathymetric survey of the pond.¹⁹

¹³ MGL c. 91 § 35 asserts that all ponds greater than 10 acres are “Great Ponds” and are publicly-owned.

¹⁴ Massachusetts Department of Environmental Protection. December, 2019. Massachusetts Year 2016 Integrated List of Waters, Final Listing. CN 470.0. Worcester, MA. 357 pp.

¹⁵ Savery Pond Conservancy website (<https://www.saverypond.org/algal-blooms#!>; accessed 1/22/21).

¹⁶ Typically, *Enterococci* or *E. coli*, which are intestinal bacteria, are tested for at bathing beaches under the requirements of the state and federal laws and are the bacteria testing that is referred to in state water quality regulations. Cyanobacteria are plants and sometime reporting on “bacteria” confuses the cyanobacteria and bacteria testing.

¹⁷ TMDL Solutions Technical Memorandum. December 9, 2016. Savery Pond 2016 Water Quality Monitoring.

¹⁸ Friends of Ellisville Marsh, Inc. 2017. Savery Pond 2016 Cumulative Date Report. 37 pp.

¹⁹ Friends of Ellisville Marsh, Inc. 2017. A Bathymetric Survey of Savery Pond. 4 pp.

As part of the development of this Management Plan, project staff reviewed and synthesized all available Savery Pond data and collected the following additional data in 2019/2020 to address the previous identified data gaps:

1. Phytoplankton, Mussel, Rooted Plant, and Water Quality Surveys: Staff determined the density and location of freshwater mussels and submerged aquatic rooted plants, and collected monthly phytoplankton, water quality samples, and field profiles between April and September. During the mussel/plant survey, project staff also completed a new bathymetric survey.
2. Stream Survey: Staff collected water quality samples and streamflow measurements at the Savery Pond outlet stream monthly for 12 months, as well as installing a stream gauge collecting continuous measurements.

All collected data, recent and historic, was reviewed and synthesized to provide a detailed understanding of the Savery Pond ecosystem, which is summarized in the pond assessment portion of this report. This updated understanding was then used to develop the management plan portion of this report. This portion reviews available management techniques, identifies those that are applicable to the specific water quality impairments in Savery Pond, and reviews potential implementation issues, including preliminary cost estimates and regulatory permitting concerns.

III. Savery Pond Regulatory and Ecological Standards

As mentioned above, much of the legal basis for management of ponds and lakes in Massachusetts is based on the surface area of a given water body. Savery Pond has a surface greater than 10 acres, which means that it is a Great Pond under Massachusetts Law²⁰ and subject to Massachusetts regulations. As such, local Town decisions regarding management may be subject to state review, including incorporation into any comprehensive wastewater management planning supported by MassDEP. Massachusetts maintains regulatory standards for all its surface waters.²¹ 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 bacteria. Additional distinctions are made between warm and cold water fisheries.

Based on its characteristics, Savery Pond would be classified as a Class B water and warm water fishery under the state Surface Water regulations. Savery Pond is not specifically identified within the classification tables in the state regulations,²² but freshwater ponds not specifically listed in these tables are designated as Class B and are “presumed High Quality Waters.”²³ Because of its regulatory status, the project team have focused on the state warm water regulatory standards for the purposes of the Savery Pond diagnostic review and water quality management planning, which mean the following numeric standards would 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

²⁰ MGL c. 91 § 35

²¹ 314 CMR 4.00

²² 314 CMR 4.06

²³ 314 CMR 4.06(4)

- d) bacteria (*Enterococci*) shall not exceed 61 colonies per 100 ml at bathing beaches (with variations available for multiple samples or use of different indicator species).

The accompanying MassDEP descriptive standards for 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 recreation. Where designated in 314 CMR 4.06, they shall be suitable as a source of public water supply with appropriate treatment (“Treated Water Supply”). Class B waters shall be suitable for irrigation and other agricultural uses and for compatible industrial cooling and process uses. These waters shall have consistently good aesthetic value.”²⁴

As mentioned above, MassDEP is required under the Clean Water Act to provide a listing of the status of all surface waters compared to the state regulatory standards. This “Integrated List” has waters assigned to five categories including Class 5 waters, which fail to attain state standards and are therefore classified as impaired. Class 5 waters are required to have a maximum concentration or load limit (also known as a TMDL) defined for the contaminant causing the impairment.²⁵ The Massachusetts Integrated List is updated every two years and submitted and approved by the Environmental Protection Agency (EPA). As previously mentioned, Savery Pond is listed in the most recent Massachusetts Integrated List as a Category 5 (impaired) water.²⁶ This designation was new in the 2016 list; Savery Pond was designated as a Category 2 water in Integrated Lists prior to 2016. Category 2 waters are “attaining some uses; other uses not assessed.” The 2016 list states that the reason for the Savery Pond category change was due to “new data/assessment,” which was likely integration of MassDEP listings with the MassDPH cyanobacteria closures database. In the last 16 years, MassDEP has approved phosphorus TMDLs for only three ponds in Massachusetts, one of which was in Plymouth (White Island Pond).²⁷

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/SMASST with the goal of providing reliable data for future prioritization of pond assessments, management plans, and TMDL development.²⁸ The CCC used initial 2001 snapshot results from over 190 ponds and lakes to develop potential ecoregion-specific nutrient thresholds.²⁹ 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.³⁰ These ecoregion-specific

²⁴ 314 CMR 4.05(3)(b)

²⁵ 40 CFR 130.7 (CFR = Code of Federal Regulations)

²⁶ Massachusetts Department of Environmental Protection. December, 2019.

²⁷ USEPA TMDL tracking: <https://www.epa.gov/tmdl/region-1-approved-tmdls-state#tmdl-ma> (accessed 10/27/20).

²⁸ The Cape Cod PALS Snapshot has been completed every year between 2001 and 2020.

²⁹ 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.

³⁰ 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-

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, these threshold ranges provide initial guidance for assessing conditions in Savery Pond.

One additional Savery Pond management issue to consider is any potential impacts the pond or pond management activities might have on Ellisville Harbor, a tidal salt marsh system. Ellisville Harbor was designated as an Area of Critical Environmental Concern (ACEC) in 1980.³¹ Although Savery Pond is not within the boundaries of the ACEC, given that the stream outflow from the pond flows into the ACEC, management activities should ensure that the resources goals of the ACEC are sustained.

IV. Diagnostic Assessment: Savery Pond

The diagnostic assessment of Savery Pond includes results from 23 recent water column samplings collected over a number of years and seasons. Available data was predominantly collected during the primary management period (April to September) for two years: 2016 and 2020. Available data included:

- monthly sampling during 2020 (April to October; field profiles of dissolved oxygen (DO) and temperature and Secchi clarity readings and collection of water quality samples),
- two samplings in April 2019 (profiles and samples) and one in May 2019 (samples and incomplete profiles),
- at least monthly sampling during 2016 (May to September) with two samples per month in June, August, and September (a continuous sensor array for DO, temperature, and chlorophyll a was also installed at 2.4 m depth with three HOBO temperature loggers at shallower depths),
- 2015 samplings once in August and September with four additional sets of dissolved oxygen and temperature profiles with Secchi clarity readings (no water quality samples) in July, August, and October, and
- one sampling in August 2014.³²

Water column data provides an understanding of the conditions in the water column, but additional types of information are also needed to understand the causes of concentrations measured in the water column data. The present diagnostic summary reviews all available data and assesses the sources of Savery Pond impairments. With this more detailed understanding of the Savery Pond ecosystem, management options were developed to lower water column phosphorus levels and associated ecosystem impairments.

All water quality laboratory assays results were provided by the Coastal Systems Analytical Facility at School for Marine Science and Technology, University of Massachusetts Dartmouth. All assays were the same utilized for the Town of Plymouth PALS Snapshot in 2014 and

011. US Environmental Protection Agency, Office of Water, Office of Science and Technology, Health and Ecological Criteria Division. Washington, DC.

³¹ Mass.gov ACEC tracking: <https://www.mass.gov/service-details/ellisville-harbor-acec> (accessed 10/27/20).

³² There is also 2017 water column DO and temperature profile information that was collected on eight dates by FOEM and was made available after the Management Plan was completed. The 2017 profiles are consistent with the available data reviewed here and are included in Appendix A.

discussed in the Plymouth Ponds Atlas.³³ All samplings including field profiles and Secchi clarity readings were completed according to procedures in the Town of Plymouth Quality Assurance Project Plan for the Plymouth PALS Monitoring Program.³⁴ Project staff reviewed all data, both laboratory results and field collected data, to address reliability and consistency. Collectively, these data and the present resulting summary provide the basis for the assessment of impairments within the Savery Pond ecosystem, as well as the review of management options to address those impairments.

IV.A. Water Column Data Review

IV.A.1. Water Column: *In Situ* Field Data

Pond field data for Savery Pond included water column profiles of dissolved oxygen (DO) and temperature, as well as measurements of clarity using a Secchi disk. In the available data, there are 21 complete matching DO and temperature profiles and 22 Secchi clarity measurements. Profiles vary between having readings collected every meter and every half meter. A minimum of two profiles were available for each month between April and October with three available in June, four in July, five in August, and three in September.

Profile data generally show that Savery Pond has DO and temperature conditions that vary by depth, by season, within seasons, and from year to year. Extremes in this variability are likely the sources of the algal blooms that occasionally occur. In 2016, eight temperature profiles between the end of May and the middle of September generally showed well-mixed, isothermic conditions throughout the water column except for the May 31 and July 26 profiles (Figure IV-1). The July 26 temperature profile had sufficient temperature difference at 3 m depth that water would have been temporarily temperature stratified with the shallower water separated from deeper water, while the May 31 profile had a weaker stratification at a 3.5 m depth. Typically, when strong enough stratification occurs, even in shallow ponds like Savery, the sediment oxygen demand is sufficient to significantly reduce the DO in the water column. In the July 26 DO profile, DO concentrations at 2.5 m and deeper were less than the MassDEP minimum, while the May 31 profile showed a decreased DO concentration at 3.5 m, but it was above the MassDEP minimum (see Figure IV-1). It should be noted that by the next temperature profile after the July 26 profile (August 10), the stratification was no longer present and all profile DO concentrations were above the MassDEP minimum.³⁵

Review of 2016 DO concentrations throughout the water column found that the DO did not decrease significantly until the July 26 profile, but had high variability throughout the monitoring period and no consistent pattern. In the May 2016 profile, total water column DO was 56 kg below atmospheric saturation (100% saturation). This deficit increased to 151 kg in the June 13 profile and then DO levels increased to 54 kg above saturation in the June 22 profile. In the July 26 profile, the water column DO deficit was 329 kg below saturation, but then DO mass increased to 64 kg below saturation in the August 10 profile before decreasing again to 316 kg

³³ Eichner, E.M., B.L. Howes, and S. Horvet. 2015. Town of Plymouth Pond and Lake Atlas.

³⁴ Tower, K. and E. Eichner. 2020. Plymouth Ponds and Lakes Stewardship (PALS) Project Monitoring Program and Pond Management Plans, Quality Assurance Project Plan, 2020-2022. Approved by MassDEP, 10/1/20. 56 pp. Original Plymouth PALS QAPP was approved in 2015, renewed in 2017, and renewed again in 2020.

³⁵ Review of 2017 FOEM profiles received after the

below saturation in the August 23 profile. The two September 2016 profiles (September 7 and 20) were 401 kg and 378 kg below saturation.

Because of concerns that the events leading to the phytoplankton blooms were transitory and might be occurring between water column samplings, Town, CSP/SMASST, and TMDL Solutions staff installed a series of continuous temperature recorders throughout the water column to measure their duration and water quality impacts.³⁶ Three HOBO temperature recorders (at 0.5 m, 1.5 m, and 2 m depths) and a YSI 6600 V2 sonde (at 2.4 m depth) were installed at the deepest point in the pond and programmed to record temperature every 30 minutes between June 13 and October 7, 2016 (*e.g.*, over 5,500 readings at each depth). Review of this data showed there was strong temperature stratification in the water column during 27% of the deployment (Figure IV-2). During the deployment, there were 72 events of strong stratification with the majority (44%) lasting 30 minutes or less. The events were spread evenly over the deployment period, but there were five events that lasted longer than one day and the longest lasted over 7 days. These strong stratification events created conditions where sediment oxygen demand lowered DO concentration in bottom waters: 63% of the readings at 2.4 m between May 31 and August 23 were less than the MassDEP DO minimum of 5 mg/L (see Figure IV-2).³⁷

³⁶ TMDL Solutions Technical Memorandum. December 9, 2016. Savory Pond 2016 Water Quality Monitoring.

³⁷ DO sensor failed after August 23.

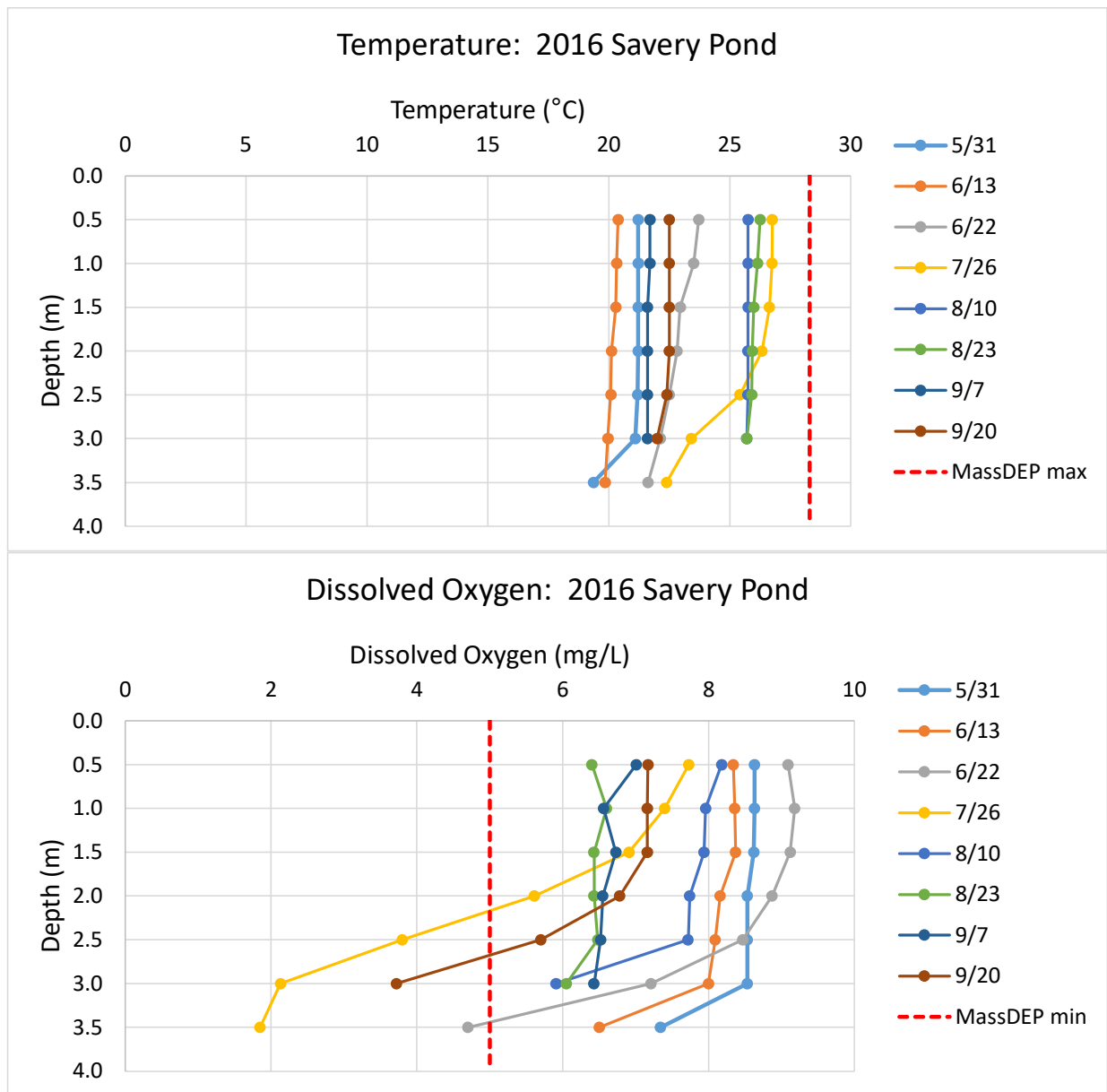


Figure IV-1. 2016 Temperature and Dissolved Oxygen Profiles: Savery Pond. Eight temperature profiles were collected in 2016 between the end of May and the middle of September. Temperature profiles generally showed well-mixed, isothermic conditions throughout the water column except for the May 31 and July 26 profiles, which showed some temperature stratification. DO profiles generally showed concentrations above the MassDEP regulatory minimum concentration (5 mg/L) except for the June 22, July 26, and September 20. Most of the profiles showed DO loss at the deepest reading. Review of DO mass within the water column showed that up to 401 kg less than atmospheric saturation (100% saturation) with highest deficits beginning in the July 26 profile but with evidence of water column mixing addressing the deficits in the August 10 profile.

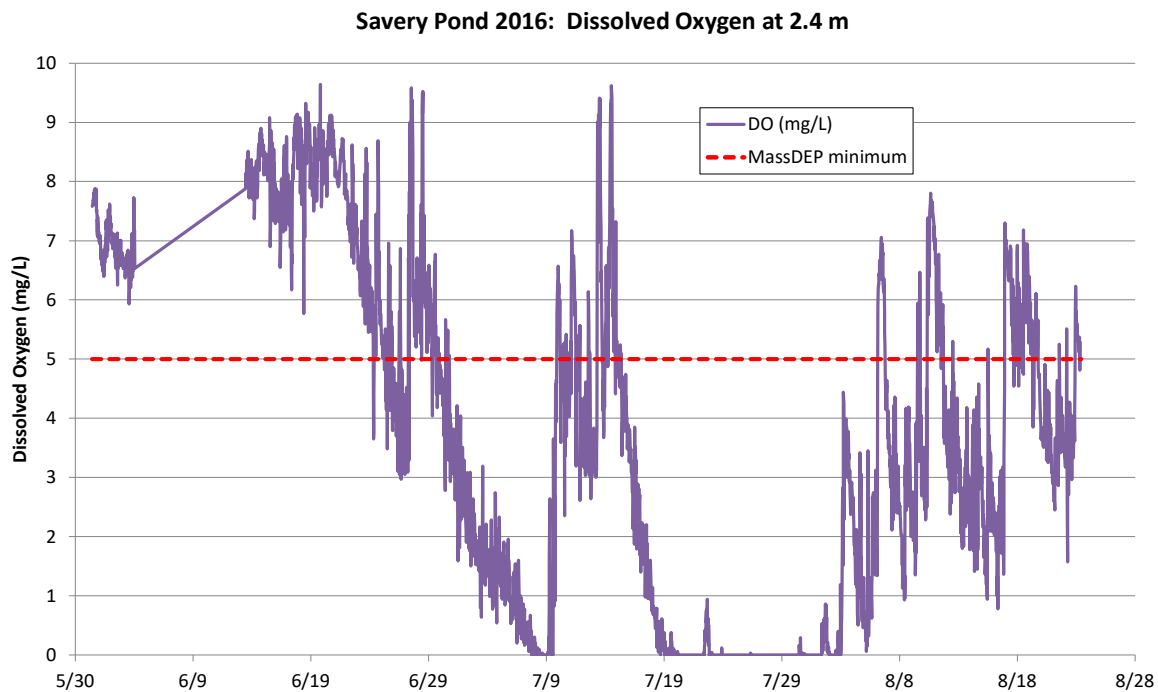
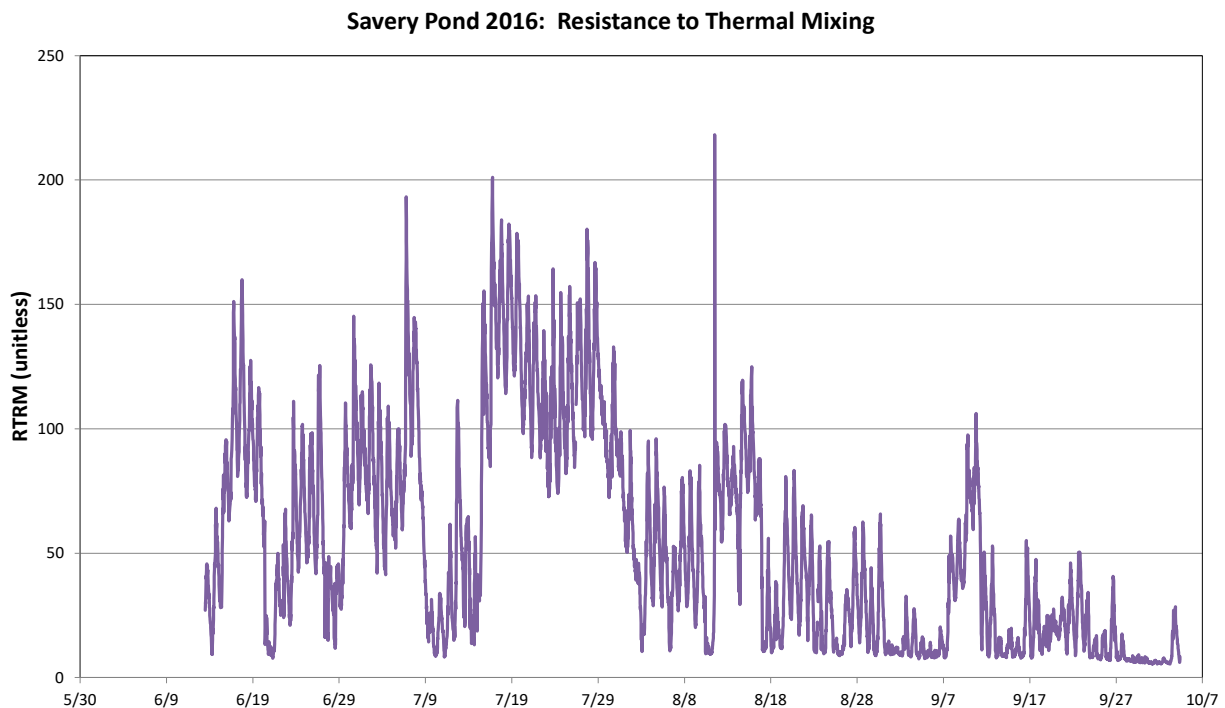


Figure IV-2. 2016 Continuous Readings of Thermal Mixing and Dissolved Oxygen. Temperature was recorded every 30 minutes at four depths in 2016 between May and October, including 2.4 m depth, where DO was also recorded. Temperature differences at 0.5 and 2.4 m depths were significant enough to cause temperature stratification in 44 events or 27% of readings. More than half (63%) of DO concentrations at 2.4 m were less than the MassDEP minimum (5 mg/L) between May 31 and August 23. Figures modified from TMDL Solutions Tech Memo (December 9, 2016).

Water column profiles in 2020 had a different pattern than in 2016. Temperature profiles in 2020 were generally slightly warmer than corresponding 2016 profiles, but DO loss was generally low compared to 2016 (Figure IV-3). DO mass was significantly below atmospheric saturation in the August and October 2020 profiles: 563 kg and 227 kg below saturation, respectively. The relative balance in DO mass in the water column prior to the August 18, 2020 profile was due to DO saturation levels above 100% in the shallower portions of the water column. DO saturation levels from the pond surface to 2 m in the April 7, May 27, June 23, and July 21 were all greater than 100% saturation with maximum readings of 108% in the July profile. The August 18, 2020 profile, in contrast showed DO loss, having saturation levels of 71% to 74% at all measured depths; this profile suggests stratified high oxygen demand within the deeper water followed by a water column mixing event that mixed the oxygen demand throughout the water column. Collectively, the 2020 profiles reinforce the changeable nature of water column conditions in Savery Pond and how this seems to be caused by alternating stratification and mixing with variable durations and intensity.

Water column clarity readings were relatively consistent between 2014 and 2020, but also showed the changes between years with the biggest differences in 2020. Collectively, available Secchi readings showed an annual seasonal loss of 2 to 2.5 m of water column clarity in summer (Figure IV-4). April and May clarity readings had clarity to the bottom (3 to 3.5 m), while minimum readings, typically in late July/early August were generally between 1 and 1.5 m. Readings in 2020 were collected between April and October, 2017 readings were between June and September, 2016 readings were between May and September, 2015 readings were between July and October and only one or two readings were collected in 2014 and 2019. April and May 2020 clarity readings generally seemed to be in line with previous readings, but readings in June and July were approximately 0.5 m greater than readings from previous years, while the August 2020 reading was more than 1 m greater and the September and October readings had clarity to the bottom. The September 2020 was so different than previous readings that it was a statistical outlier. These improvements in clarity in the late summer 2020 readings were consistent with higher DO in 2020.

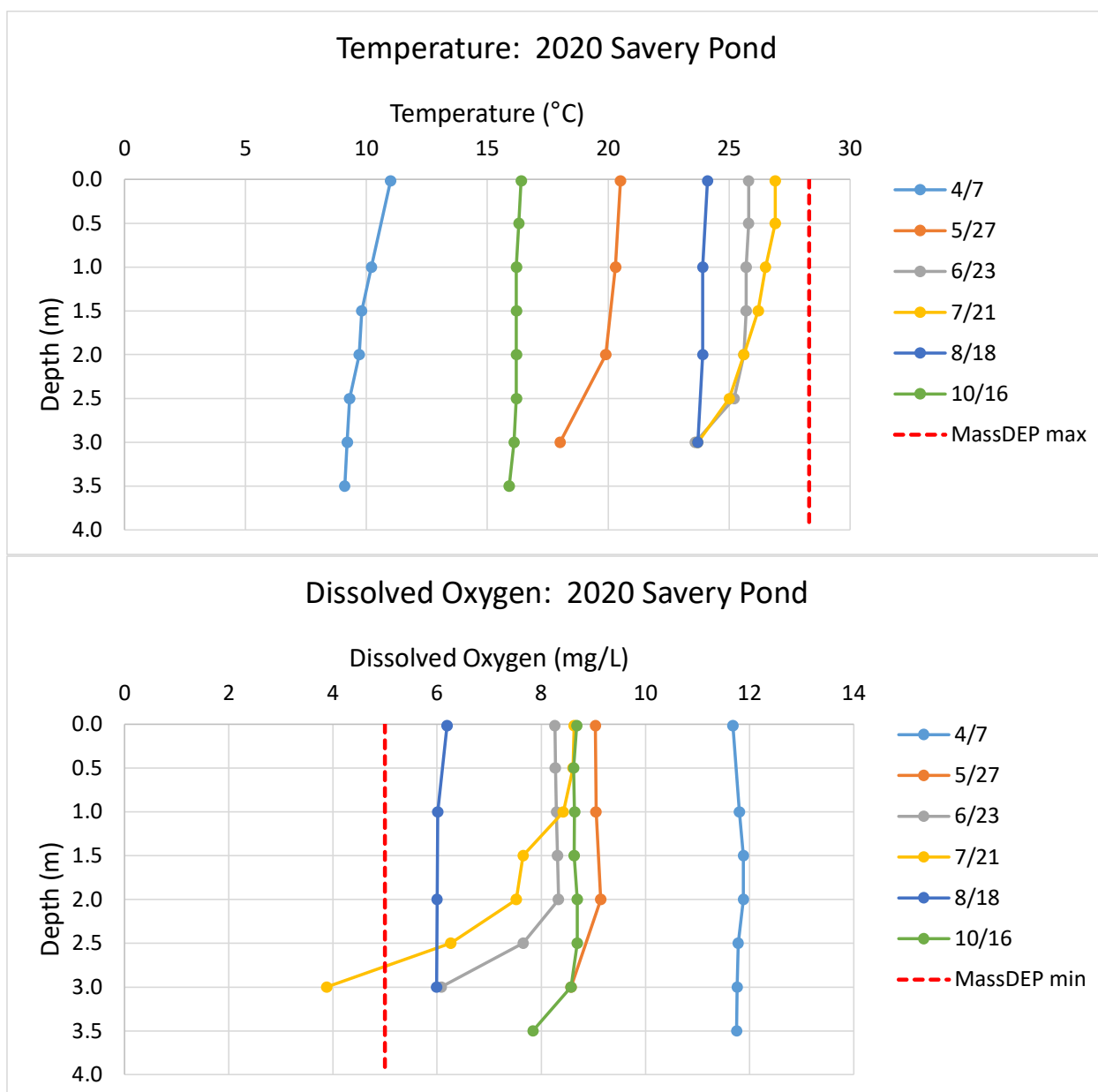


Figure IV-3. 2020 Temperature and Dissolved Oxygen Profiles: Savery Pond. Six temperature profiles were collected in 2020 between April and October. Temperature profiles generally showed well-mixed, isothermic conditions throughout the water column with slightly higher temperatures than in 2016 on corresponding profiles. DO profiles showed a mix of configurations with some showing impacts of sediment oxygen demand, similar to 2016, but others showing similar concentrations throughout the water column. Review of saturation levels found that many profiles have shallow DO concentrations well above (>105%) atmospheric equilibrium (100% saturation), while other profiles had saturation levels throughout the water column that were well below equilibrium (e.g., August 18 saturation levels were all 74% saturation or less). The variability of these profiles suggests that deep low oxygen, stratified conditions were occurring similar to 2016, but were occurring between the profile measurements and mixing of the water column was spreading the oxygen deficit throughout the water column.

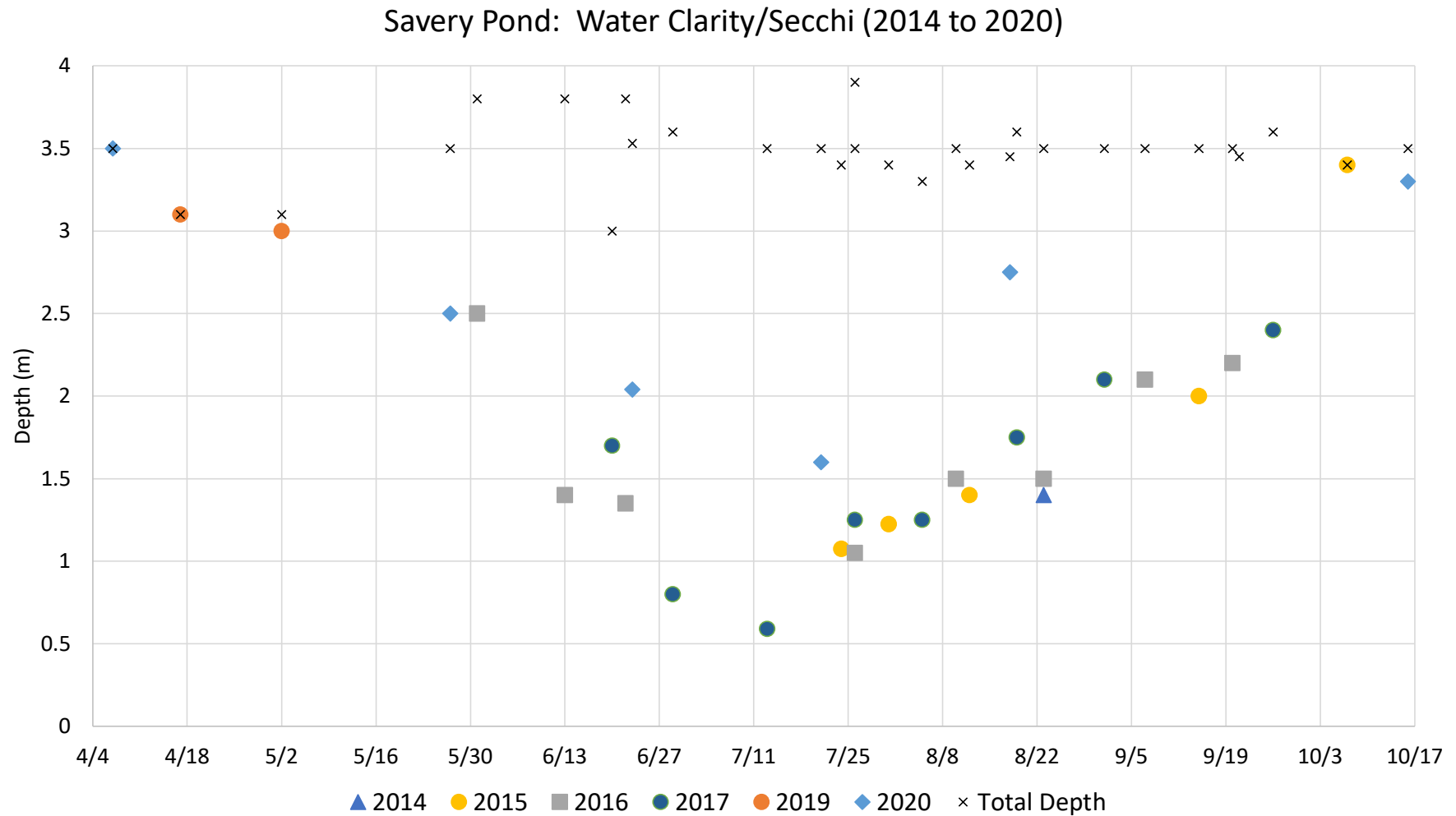


Figure IV-4. Savery Pond Secchi Clarity Measurements 2014-2020. Water column clarity readings generally followed a consistent pattern, but 2020 readings were generally higher in throughout the summer. Readings in 2015, 2016, 2017, and 2019 collectively showed loss of 2 to 2.5 m of clarity between April/May and late July/early August followed by recovery to spring levels by early October. June to September 2020 clarity readings were 0.5 to 1.5 m higher than previous readings; these improvements in clarity were consistent with higher DO readings in 2020.

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

During 16 of the 23 Savery Pond monitoring events, water samples were collected for laboratory analysis, including monthly April to October sampling in 2020. All available laboratory assays were completed at the Coastal Systems Analytical Facility at School for Marine Science and Technology, University of Massachusetts Dartmouth. All assay techniques were the same utilized for the Town of Plymouth PALS Snapshot in 2014 and discussed in the Plymouth Ponds Atlas.³⁸ Collection of samples for laboratory analysis were completed according to procedures in the Town of Plymouth Quality Assurance Project Plan for the Plymouth PALS Monitoring Program.³⁹

Review of available Savery Pond water column nutrient (*i.e.*, nitrogen and phosphorus) and chlorophyll *a* concentrations showed highly enriched conditions. All total phosphorus concentrations, both shallow and deep, exceeded the 10 µg/L Ecoregion TP threshold, while 90% of shallow and deep total nitrogen concentrations exceed the 0.31 mg/L Ecoregion TN threshold (Figure IV-5). The average shallow TP concentration was 27 µg/L (n=21), while the average shallow TN concentration was 0.57 mg/L (n=20). The average shallow chlorophyll *a* concentration was 5.5 µg/L (n=21) with 90% of readings exceeding the 1.7 µg/L Ecoregion chlorophyll *a* threshold. Generally deep average TP, TN, and chlorophyll *a* concentrations were higher than shallow average concentrations, but none of the shallow and deep average concentrations were significantly different ($p < 0.05$) during either the spring (April) or late summer (August/September). However, comparison of spring and late summer average concentrations showed that shallow TP and deep TN were significantly higher in the summer compared to the spring.

Review of TP, TN, and chlorophyll *a* concentrations on individual sampling dates have the same changeable characteristics seen in the DO and temperature profiles and show why the shallow and deep averages were not significantly different. During 2016, TP had three individual profiles where deep concentrations were higher than shallow concentrations, which would be consistent with sediment regeneration of TP (June 13, July 26, and September 7) (Figure IV-6). The four other 2016 profiles had similar concentrations at shallow and deep depths: May 31, August 10, August 23, and September 20. Similar TP profiles were measured in 2020 (Figure IV-7). The pattern of these concentrations is consistent with temperature and DO profiles and consistent with periods of sediment TP release (during temperature stratification) followed by complete water column mixing and isothermal conditions.

Shallow and deep TN concentrations in both 2016 and 2020 tended to be similar (except for August 10, 2016 and July 21, 2020). Similar shallow and deep TN concentrations would be consistent with lack of prolonged bottom anoxia and regular water column mixing. Significant TN sediment release typically requires more sustained anoxia than TP sediment release.

Chlorophyll *a* concentrations also generally showed a similar pattern, but with differences in timing of maxima and how they relate to TP or TN on individual dates. For example, 2016 chlorophyll concentrations were exceptionally high in August, especially compared to very low August 2020 levels. Average water column TP concentrations on August 23, 2016 were

³⁸ Eichner, E.M., B.L. Howes, and S. Horvet. 2015. Town of Plymouth Pond and Lake Atlas.

³⁹ Tower, K. and E. Eichner. 2020. Plymouth Ponds and Lakes Stewardship (PALS) Project Monitoring Program and Pond Management Plans, Quality Assurance Project Plan, 2020-2022..

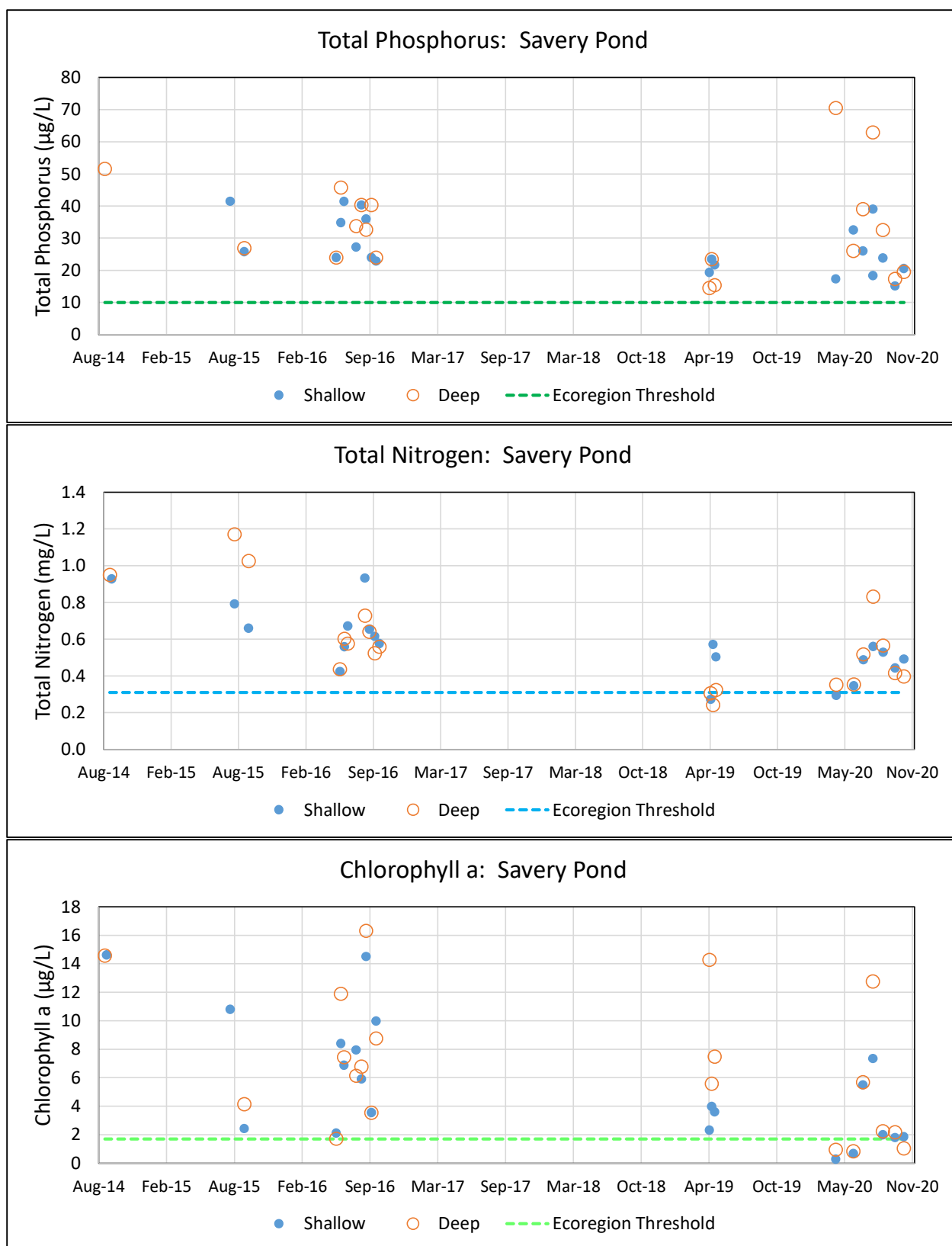


Figure IV-5. Savery Pond: Shallow and Deep Water Column Total Phosphorus, Total Nitrogen, and Chlorophyll a concentrations. All TP, 90% of TN, and 88% of chlorophyll a concentrations exceeded their respective Ecoregion thresholds (dashed horizontal lines).

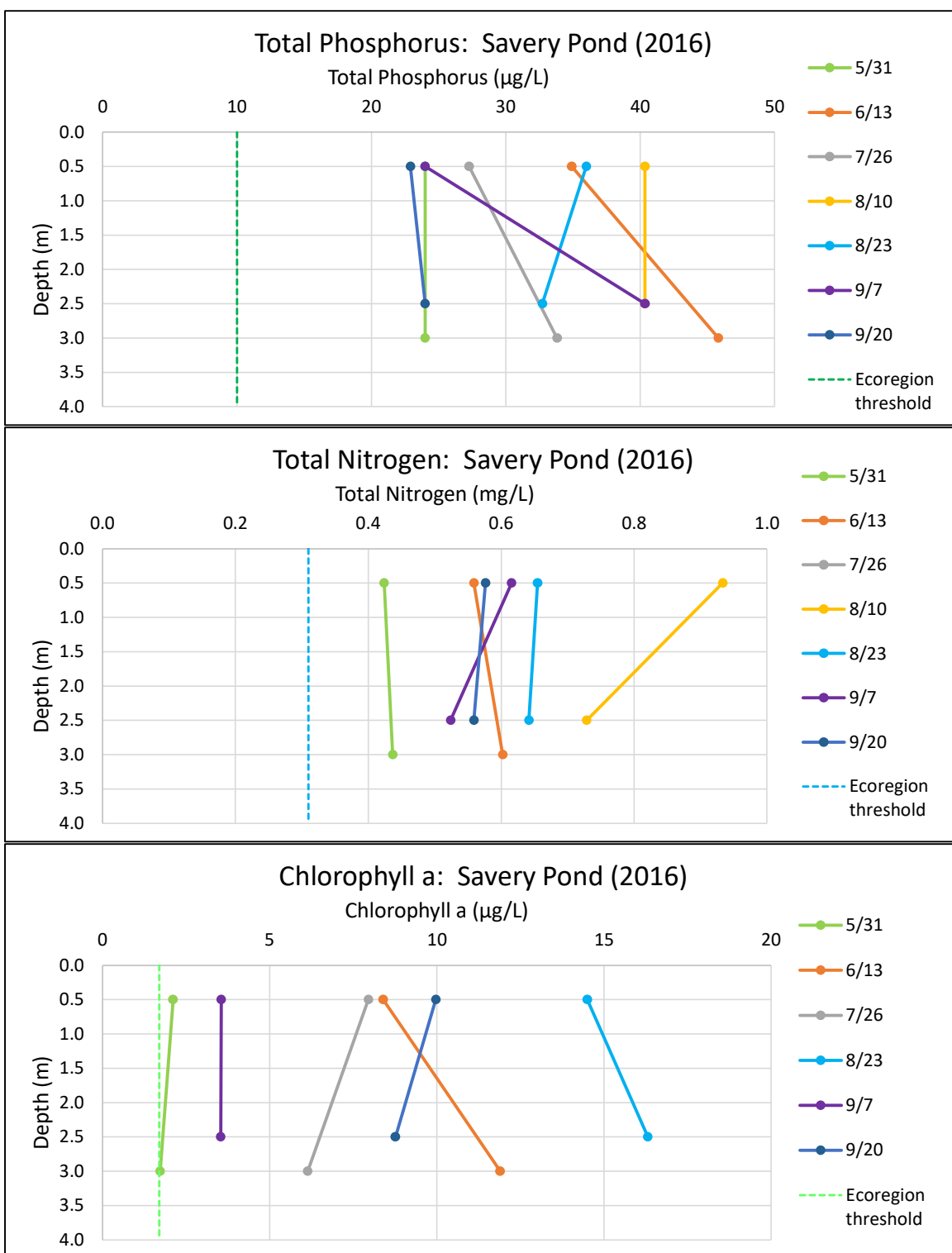


Figure IV-6. 2016 TP, TN, and Chlorophyll a Profile concentrations. Concentrations show changeable water column conditions: some show same concentrations at shallow and deep depths (*i.e.*, well mixed conditions), while others show significant differences with depth (*i.e.*, stratified conditions). Lack of consistent pattern throughout the monitoring period also shows regularly changing water column conditions. 2016 sampling occurred between May and September. All samples for the three parameters exceed their respective Ecoregion thresholds (dashed vertical lines).

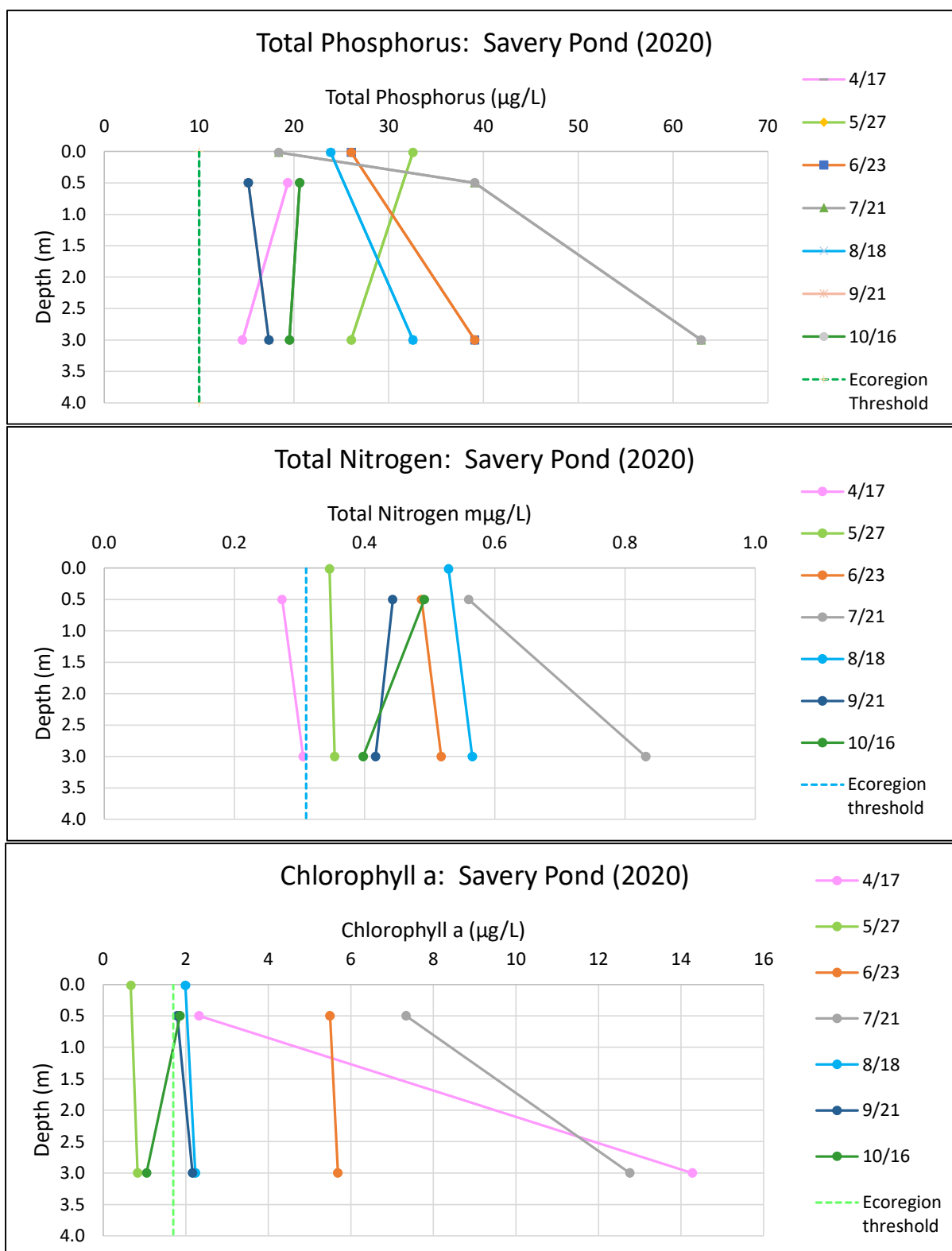


Figure IV-7. 2020 TP, TN, and Chlorophyll a Profile concentrations. Profile concentrations show changeable water column conditions: some show same concentrations at shallow and deep depths (*i.e.*, well mixed conditions), while others show significant differences with depth (*i.e.*, stratified conditions). Lack of consistent pattern throughout the monitoring period also shows regularly changing water column conditions. 2020 sampling occurred between April and October. Respective Ecoregion thresholds are shown as dashed vertical lines.

approximately 34 µg/L with the shallow concentration higher than the deep concentration, while the corresponding chlorophyll a concentrations were 14.5 µg/L and 16.3 µg/L, respectively (see Figure IV-6). In contrast, the August 18, 2020, shallow and deep TP concentrations were 23.9 and 32.6 µg/L, while the chlorophyll a concentrations were 2 µg/L and 2.2 µg/L, respectively. The 2020 TP and chlorophyll a maxima occurred in the July 21 sampling; it is notable that the shallow July 2020 and July 2016 concentrations were similar.

Further comparison of monthly readings shows large shifts in chlorophyll a concentrations. For example, the shallow July 26, 2016 concentration was 8.0 µg/L and the August 23 concentration was 14.5 µg/L. Two weeks later (September 7) the shallow concentration was 3.6 µg/L (see Figure IV-6). A similar pattern was measured in 2020, though shifted one month earlier (see Figure IV-7). The pattern in the monthly chlorophyll samples in both 2016 and 2020 suggests periods of high growth followed by die-off and transfer of degraded pigment (and phytoplankton biomass) to the sediments. Comparison of shallow and deep water total pigment concentrations (chlorophyll a + pheophytin a⁴⁰) tends to support this idea with almost all paired water column samples having higher deep concentrations. Review of the 2016 continuous chlorophyll monitoring showed that concentrations changed rapidly at 2.4 m, which would be consistent with concentration profiles also being impacted by water column mixing, as well as particle settling (Figure IV-8).

Comparison of nitrogen and phosphorus concentrations showed that phosphorus is the key nutrient for determining water quality conditions in Savory Pond. As a rule of thumb, if the ratio between nitrogen and phosphorus is significantly greater than 16 (also known as the Redfield ratio), phosphorus is the limiting nutrient.⁴¹ Phosphorus-limited freshwater systems generally have N to P ratios that are 2 to 5 times higher than the Redfield ratio of 16 (*e.g.*, 32 to 80). Calculation of this ratio needs to account for phytoplankton that have the ability to utilize organic phosphorus, not just inorganic phosphorus. The average shallow N:P ratio in Savory Pond was 45 (or 2.8X the Redfield ratio threshold) with a range of 19 to 64 (*n* = 18) (Figure IV-9). Deep waters had a slightly lower ratio (38) indicative of greater TP release from the sediments. Late summer ratios (*i.e.*, 52 shallow, 50 deep) were higher than the spring (*i.e.*, 41 shallow, 30 deep), but these differences were not statistically significant.

It should also be noted that pH readings generally were below the MassDEP surface water regulations range (6.5 to 8.3), but this would be expected within this ecoregion where there is naturally low alkalinity because of the lack of carbonate in the surrounding aquifer material. Average pond surface water pH in the ecoregion is 6.16.⁴² Average shallow pH in Savory Pond based on all the available data was 6.15 with a range of 5.5 to 6.5. Increases in pond pH in this ecoregion are generally measured in nutrient-enriched settings; photosynthesis from extensive phytoplankton populations consumes hydrogen ions causing pH to increase.⁴³ Savory pH may be moderated by the short pond water residence time.

⁴⁰ Pheophytin a is a photosynthetic pigment and one of the primary initial chemical breakdowns of chlorophyll a. Combined pheophytin a and chlorophyll a concentrations, thus provides a measure of current chlorophyll a and recently degraded chlorophyll a. In Savory Pond, chlorophyll a averaged 65% of the combined pigments.

⁴¹ Redfield, A.C., B.H. Ketchum, and F.A. Richards. 1963. The influence of organisms on the composition of sea-water, in *The Sea*, (M.N. Hill (ed.). New York, Wiley, pp. 26-77.

⁴² Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas.

⁴³ pH is the negative log of the hydrogen ion concentration.

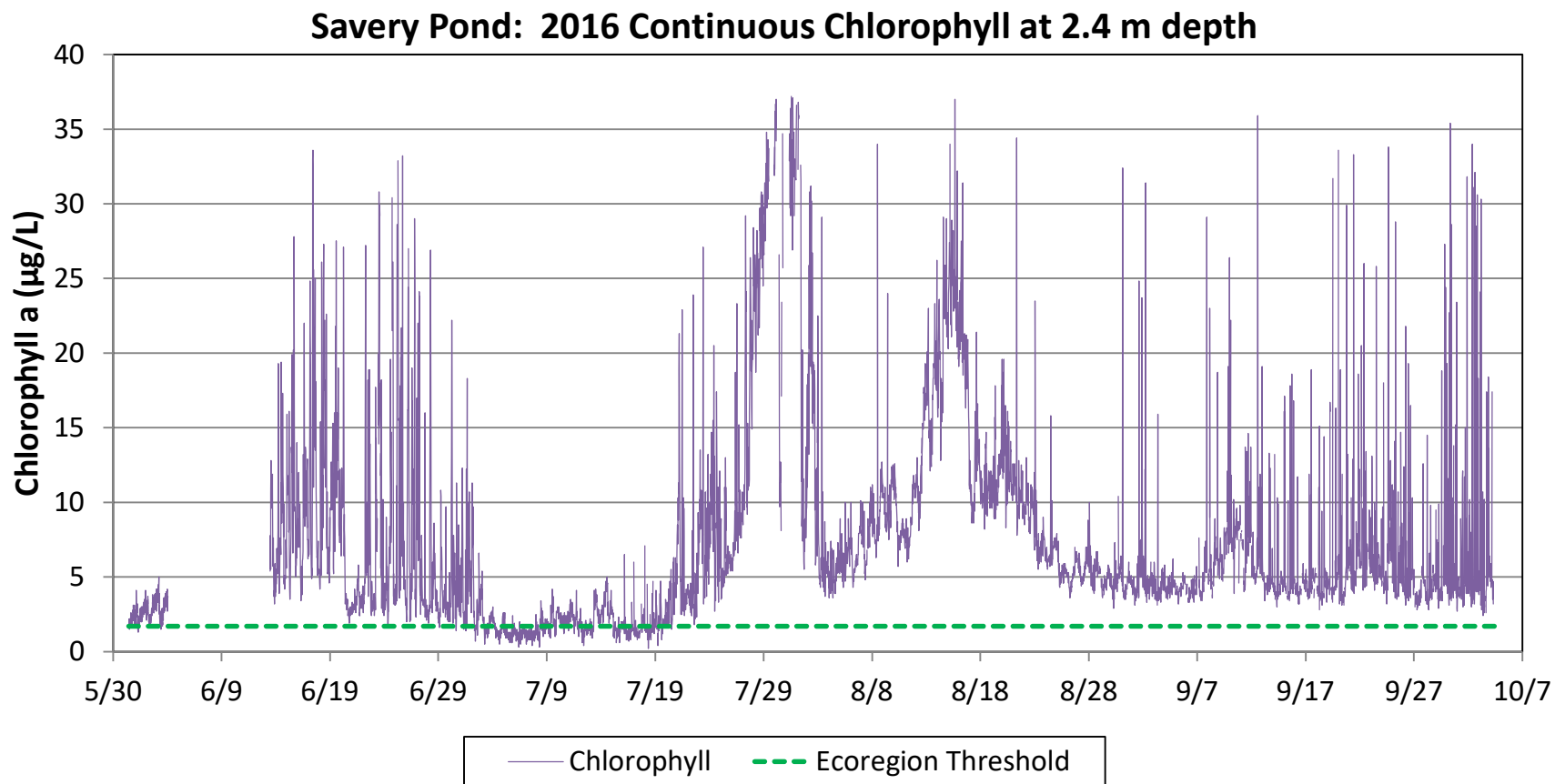


Figure IV-8. Savery Pond 2016: Continuous Chlorophyll Recording. As part of installing an array of continuous monitoring devices in 2016, a sonde with a chlorophyll sensor was installed at 2.4 m depth and programmed to record readings every 30 minutes (see TMDL Solutions Technical Memorandum, December 9, 2016). Review of the sensor record showed that concentrations changed rapidly, often changing 5 to 10 µg/L in a given day. It is thought that these rapid changes are due to a complex mix of water column mixing, phytoplankton population growth and death, and particle settling. Monthly snapshot results also reflect this variability, though to a lesser extent because of the greater time between readings. The Ecoregion threshold was only met for approximately two weeks in July.

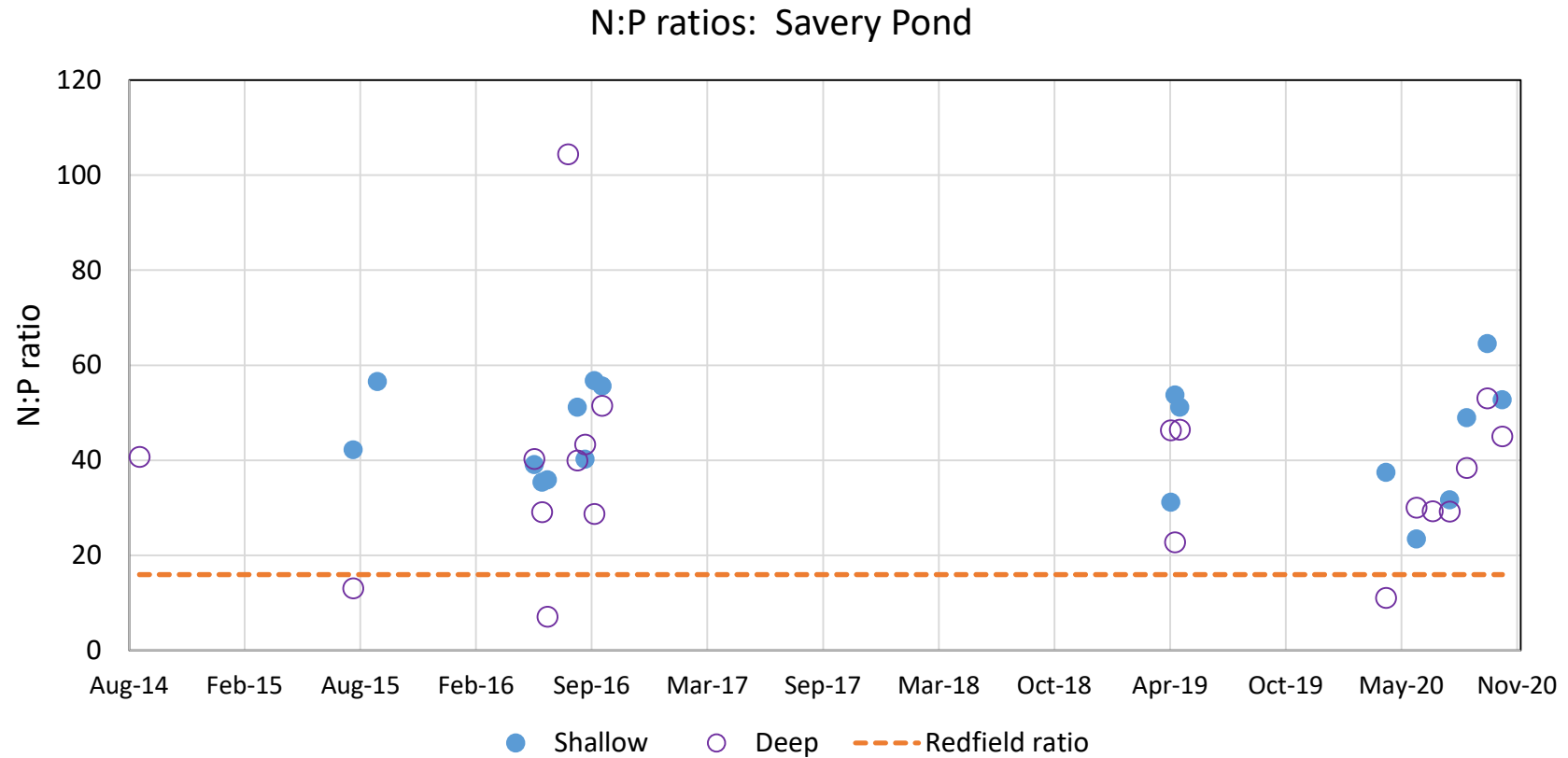


Figure IV-9. Savery Pond N:P ratios: 2014 to 2020. The average shallow N:P ratio in Savery Pond was 45 (or 2.8X the Redfield ratio threshold) with a range of 19 to 64 (n = 18). The deep water average was 38, which was likely indicative of TP release from the sediments. Late summer ratios (*i.e.*, 52 shallow, 50 deep) were higher than the spring (*i.e.*, 41 shallow, 30 deep), but these differences were not statistically significant. Phosphorus-limited freshwater systems generally have N to P ratios that are 2 to 5 times the Redfield ratio.

TP and TN concentrations from each available sampling were used with water volumes per depth increment determined from the bathymetry to estimate N and P water column mass. Total water column TP seems to show changeable conditions, but definitive conclusions are limited by the available data. The April 2020 water column mass was 7.5 kg, but was 3.4 kg and 4.5 kg in April 2019 and 3.4 in early May 2019 (5/2) (Figure IV-10). Comparison of these readings suggest that the April 2020 mass is an outlier, but the number of readings is too limited to definitively rule it out. If the spring water column masses from 2019 are only considered, the average water column mass increases by approximately 2 kg during the summer with the maximum addition increasing the water column mass by 4 kg (August 10, 2016). During 2016, the TP water column mass reached a maximum in the August 10 profile and then decreased in all the remaining profiles. In 2020, the TP water column mass peaked in the July 21 profile and then decreased in all subsequent profiles. The September 2020 water column TP mass was the lowest estimate (3 kg) among all available June to September estimates.

Water column TN mass estimates were in closer agreement among the various years with gradual increases to maximums on the same dates as the TP peaks followed by decreasing water column masses in all subsequent profiles. Average spring water column TN mass was 68 kg with an average June to September addition of 60 kg (average mass = 128 kg). The maximum water column TN mass was 181 kg (August 14, 2014).

Application of the same approach to DO loss showed that 2016 and 2020 had different patterns likely related to fluctuating stratification (see Figure IV-9). In 2016, which had six readings between the end of May and the early September, DO loss fluctuated over an approximately 250 to 300 kg range, peaking at maximum of 401 kg loss in the September 7 profile. Significant DO loss began in the June 13 profile in 2016 (151 kg). In 2020, which had four readings over approximately the same period as 2016, DO loss increased by approximately 70 kg between June and July profiles then increased to a maximum of 563 kg lost by the August 18 profile. The July 21 profile, which was the profile before the August 18 profile, had a water column DO loss of only 90 kg (or less than the June 13, 2016 loss). The water column profiles where DO loss was the largest were due to DO loss throughout the water column and were usually accompanied by isothermic conditions. These measurements suggest that significant DO loss occurred in stratified conditions just prior to the isothermic profile measurements, probably accompanied by relatively quiescent, cloudy conditions to limit photosynthetic DO inputs, and the isothermic profile measurements reflect mixing of those DO depleted conditions throughout the water column. It also notable that despite significant water column DO depletion, only 4% of all readings were below the MassDEP minimum concentration again reinforcing the spread of DO loss throughout the water column.

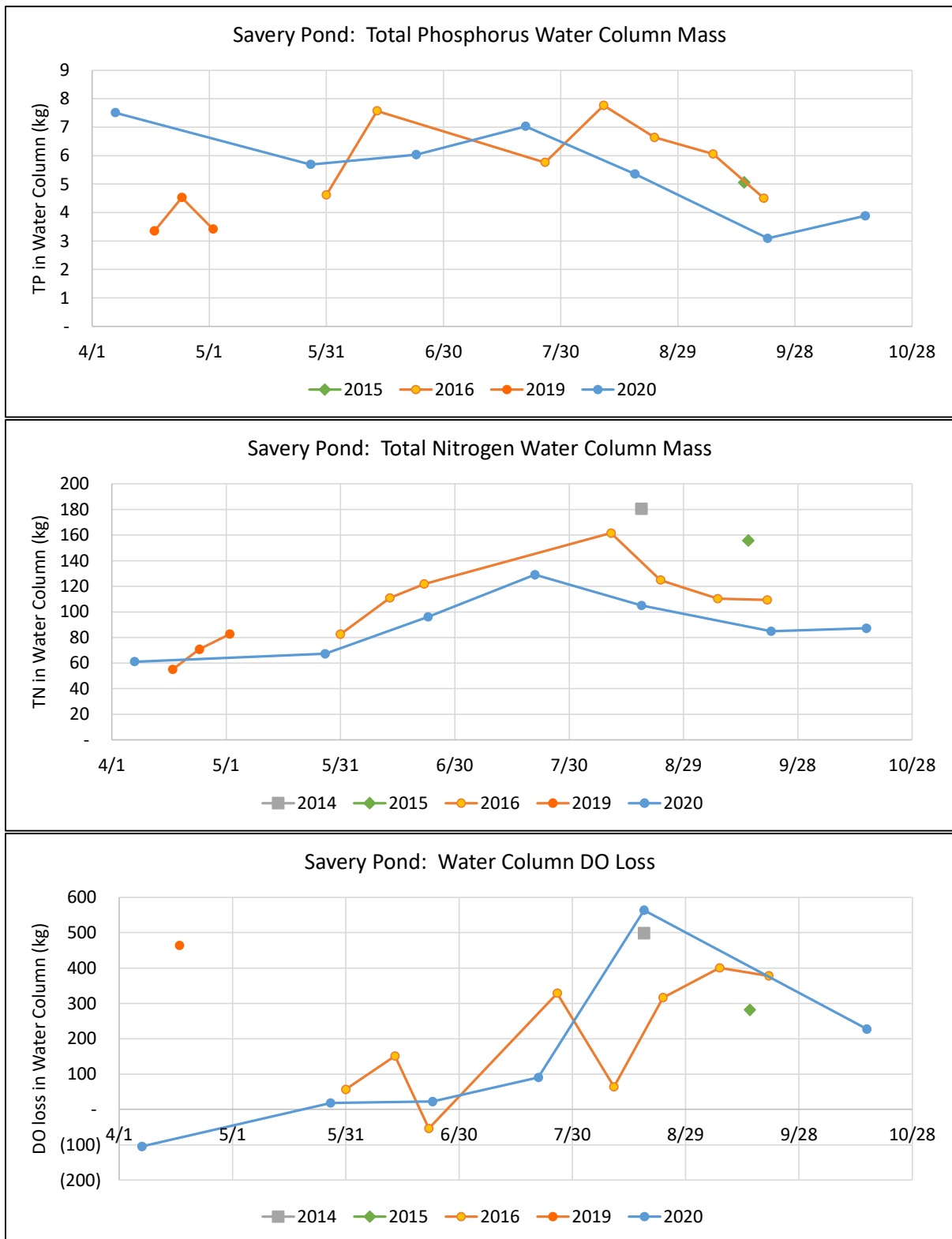


Figure IV-10. Savery Pond Water Column Mass: TP, TN, and DO Loss: 2014 to 2020. Two years with summer-long monitoring had differences in timing of TP and TN water column additions, but had an average summer addition of 2 kg and 128 kg, respectively, with peaks at higher levels. DO loss in 2016 fluctuated more than 2020, but 2020 had higher maximum.

IV.B. Savery Pond Biotic Community Surveys

IV.B.1. Phytoplankton – Phytoplankton Community

Since Savery Pond has a long history of closures due to algal blooms, CSP/SMASST recommended that the town include regular monthly sampling of the phytoplankton community as a 2020 data gap survey to evaluate how the population changes through the growing season and what species dominate during different portions of the spring and summer. Assessment of phytoplankton community composition along with complementary measurements of chlorophyll, nutrients and other 2020 data, was sought to gain a better understanding of the conditions that might lead to algal blooms and the role the phytoplankton community plays in the water quality in Savery Pond.

CSP/SMASST staff collected phytoplankton samples through vertical net tows monthly from April through October 2020. Tows were conducted through the photic zone, as measured by a Secchi reading at the pond's deepest point. Samples were collected in brown bottles, preserved and stored at 4°C until analysis by Phytotech, Inc. Phytoplankton were identified to the genus level with cell counts per milliliter and biovolume per milliliter measures.

The phytoplankton tow results showed that the Savery Pond phytoplankton community was diverse and changed throughout the spring and summer 2020. Cyanobacteria (*i.e.*, blue-greens or cyanophytes) were generally part of the phytoplankton population and became the dominant cell type in the July and August tows, but cyanobacteria cell counts were low, reaching a maximum of only 465 cells/ml (July 21 tow), which is well below the 70,000 cells/ml threshold that MassDPH has established as a blue-green direct contact advisory level.⁴⁴ Figure IV-11 shows the plankton community cell counts and biomass totals grouped by plankton divisions and Table IV-1 shows the dominant species based on both cell counts and biomass.

In the 2020 baseline (April 7) tow, the cell count was very low (0.45 cells/ml) with *Botryococcus braunii*, a green algae,⁴⁵ representing 97% of the cell count and *Peridinium cinctum*, a dinoflagellate,⁴⁶ representing 76% of the total biomass (0.06 µg/L). In the tow, a total of nine species were present and these were distributed across six divisions. Cyanobacteria were 0.3% of the total phytoplankton cell count, 0.1% of the total tow biomass, and only one species was counted (*Synechocystis*).

In the subsequent tow (May 27), the cell count (0.53 cells/ml) remained approximately the same as the April 7 tow and green algae remained the dominant division, but the dominant species changed to *Sphaerocystis Schroeteri*. In the tow, a total of 10 species were present and these were distributed across three divisions. Greens were also the predominant portion of the biomass (69%) with *Closterium* species (52%) and *Sphaerocystis Schroeteri* (16%) accounting for most of the greens in the total biomass (0.09 µg/L). The cyanobacteria concentration was too low to count in the May 27 tow.

⁴⁴ Massachusetts Department of Public Health. Guidelines For Cyanobacteria in Freshwater Recreational Water Bodies in Massachusetts. Boston, MA.

⁴⁵ Green algae = Chlorophyta

⁴⁶ dinoflagellates = Pyrrhophyta

The June 23 tow had the maximum cell count and biomass concentration among the 2020 phytoplankton samples. The species count increased to a total of 21 species across seven divisions. The total cell count was 943 cells/ml with 86% as Chrysophyta (golden algae) mostly composed of two species: *Dinobryon divergens* (55%) and *Chrysosphaerella* species (24%). *Dinobryon* is a species that forms large colonies that are difficult for zooplankton to eat and can obtain energy from both photosynthesis and eating bacteria. Blooms of *Dinobryon* species can happen in freshwater ponds; blooms tend to have an unpleasant fishy odor.⁴⁷ Although Chrysophyta were the predominant cell type, green algae (Chlorophyta) were the predominant (73%) source of biomass in the June 23 tow with *Staurastrum* species as the dominant green algae species (62% of the overall biomass). *Staurastrum* species are single-celled green algae. Only one species of cyanobacteria (*Dolichospermum* species) was identified in the June 23 tow and they were 4% of the total phytoplankton cell count and 1% of the total tow biomass.

In the July 21 tow, the cell count and biomass concentration decreased from the June 23 peaks, but cyanobacteria became the dominant cell type. Green algae remained as the dominant biomass, representing 61% of the total. Blue-greens were 38% of the tow biomass total. Cyanobacteria were 85% of the overall cell count (545 cells/ml) with five species counted. *Dolichospermum* species were the most prevalent species (63% of the total) within the cyanobacteria cell count. The total blue green cell count was 465 cells/ml, which is well below the 70,000 cells/ml MassDPH direct contact advisory level. Overall, 21 species were counted in the tow and these were distributed across six divisions. The July 21 water quality samples had the highest water column mass of TP (7 kg) and TN (129 kg) during the 2020 summer (see Figure IV-11).

IV.B.2. Rooted Plant and Freshwater Mussel Survey

Extensive populations of freshwater mussels and macrophytes (*i.e.*, aquatic rooted plants or submerged aquatic vegetation, SAV) have the potential to alter nutrient cycling and can complicate development of pond management strategies, especially those that involve treatment of the sediments. Following the 2016 Savery Pond water column monitoring,⁴⁸ the spatial extent of the freshwater mussel and macrophyte communities were identified as potential data gaps and were incorporated into the 2020 data gap surveys to support the diagnostic assessment.

CSP/SMASST staff completed an underwater video survey on November 5 and 20, 2020 to determine the distribution of freshwater mussels and macrophytes in Savery Pond. The video survey was conducted using a submerged video camera linked to a dGPS and recording at five frames per second. Each frame represents approximately 0.25 m² of pond bottom and the video record was reviewed frame-by-frame for mussel valves and plant coverage/density.

⁴⁷ University of California Santa Cruz phytoplankton database

(<http://oceandatacenter.ucsc.edu/PhytoGallery/Freshwater/dinobryon.html>) (accessed 2/9/21).

⁴⁸ TMDL Solutions Technical Memorandum. Savery Pond 2016 Water Quality Monitoring. December 9, 2016.

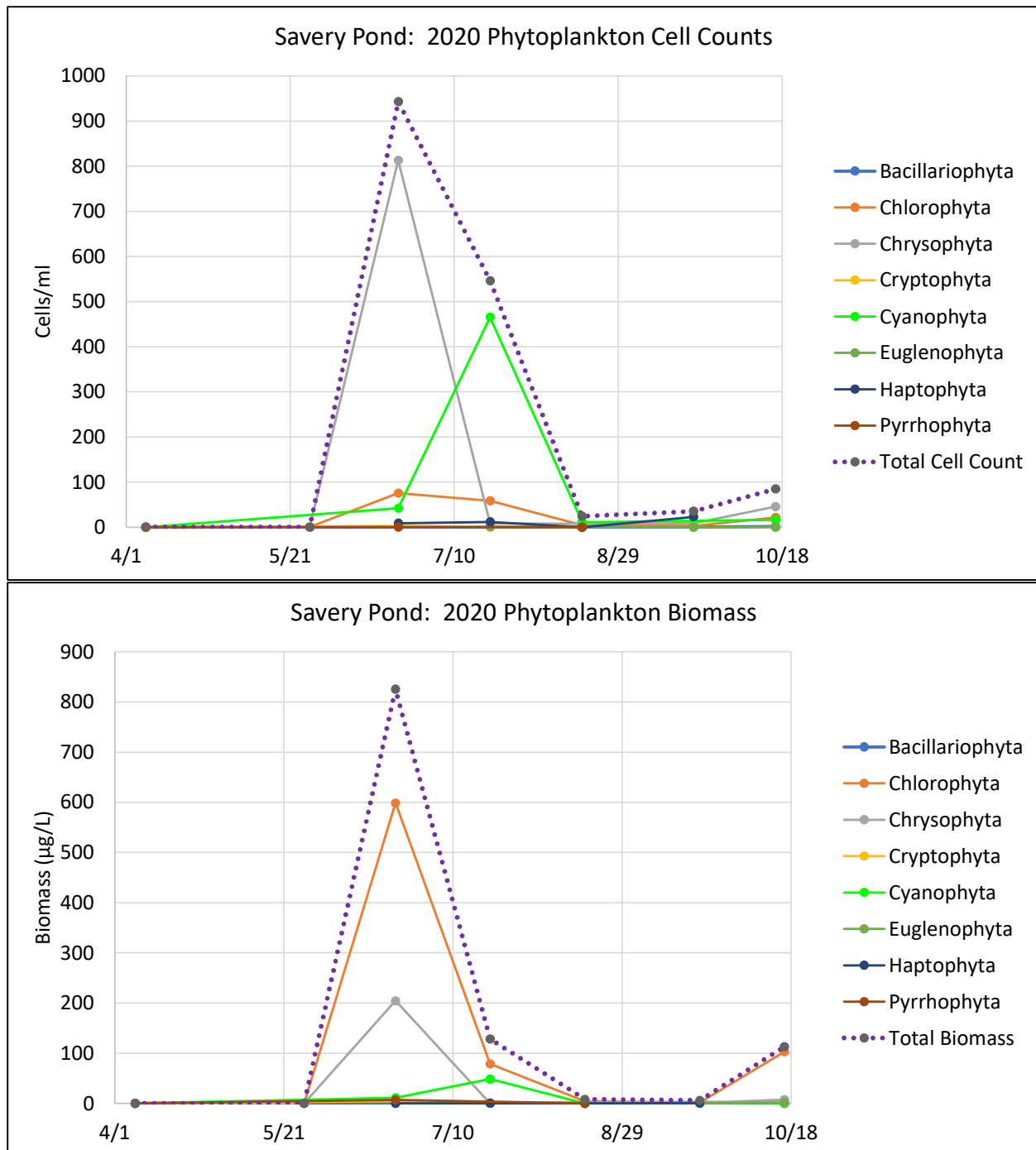


Figure IV-11. Savery Pond 2020 Phytoplankton Cell Counts and Biomass. Vertical phytoplankton tows through the water column photic zone were collected monthly, April through October 2020. Cell counts and biomass levels were generally low throughout the monitoring period with the maximum levels in the June 23 tow. Cyanobacteria (*i.e.*, Cyanophyta) were the most prevalent cells in the July 21 tow, but maximum level (465 cells/ml) was well below the MassDPH 70,000 cells/ml cyanobacteria threshold established as a blue-green direct contact advisory level. Green algae (*i.e.*, Chlorophyta) was the dominant phytoplankton biomass from May to August.

Table IV-1. Savery Pond: 2020 Phytoplankton Summary. Seven vertical phytoplankton tows through the water column photic zone were collected monthly between April and October 2020. Maximum cell count and biomass totals occurred in June 23 tow. Species counts were generally high from June to October. Cyanobacteria (*i.e.*, blue-greens) were the most prevalent cell types in July and August, which also were when the greatest number of cyanobacteria species were present. Green algae (*i.e.*, Chlorophyta) were the dominant biomass division in May, June, July, August, and October.

2020 Tow date	Total Cell Count	Total Biomass	# of divisions	# of species	# of blue-green species
	Cells/ml	µg/L			
4/7	0.45	0.06	6	9	1
5/27	0.53	0.09	3	10	0
6/23	942.75	825.44	7	21	1
7/21	545.94	128.43	6	21	5
8/18	24.33	8.27	8	27	7
9/21	35.32	5.94	5	24	0
10/16	84.71	113.02	5	21	2

2020 Tow date	Dominant cell count						Dominant biomass					
	Division	Cells/ml	% of total	species	Cells/ml	% of total	division	µg/L	% of total	species	µg/L	% of total
4/7	Chlorophyta	0.45	98%	Botryococcus braunii	0.44	97%	Pyrrhophyta	0.05	76%	Peridinium cinctum	0.05	76%
5/27	Chlorophyta	0.46	87%	Sphaerocystis Schroeteri	0.45	84%	Chlorophyta	0.06	69%	Closterium	0.05	52%
6/23	Chrysophyta	813.05	86%	Dinobryon divergens	522.67	55%	Chlorophyta	598.51	73%	Staurastrum	513.20	62%
7/21	Cyanophyta	465.12	85%	Dolichospermum	342.67	63%	Chlorophyta	78.78	61%	Mougeotia	61.37	48%
8/18	Cyanophyta	10.93	45%	Woronichinia naegeliana	6.50	27%	Chlorophyta	4.65	56%	Synura	2.78	34%
9/21	Haptophyta	23.24	66%	Chrysochromulina parva	23.24	66%	Bacillariophyta	2.10	35%	Surirella	2.04	34%
10/16	Chrysophyta	45.75	54%	Chrysosphaerella	30.05	35%	Chlorophyta	103.20	91%	Cosmarium	94.48	84%

Many of the freshwater mussel species in the Plymouth ecoregion are listed by the Massachusetts Natural Heritage Program as endangered species or species of special concern, including the Tidewater Mucket (*Leptodea ochracea*) and Eastern Pondmussel (*Ligumia nasuta*).⁴⁹ Surveys completed by CSP/SMASST in other Plymouth ecoregion ponds have shown some ponds to have extensive mussel populations, while others have no mussels present.⁵⁰ Reviews of available studies suggest mussels have complex responses to nutrient availability with both positive and negative impacts due to high or low loads.⁵¹ Generally, freshwater mussels are restricted to areas that do not experience regular hypoxia.⁵² A visual survey was recommended for Savery Pond as a relatively low cost approach to assess whether special consideration would be needed to protect mussels as management strategies are developed.

The freshwater mussel survey did document the presence of mussels in Savery Pond, but only 4 live individuals were noted in the video survey (Figure IV-12). All individuals were in a cluster in the NE portion of the pond and were less than two feet from the shoreline in two feet of water. Based on this review, sediment management options could avoid significant impacts on the mussel population by implementing options in waters deeper than 1 m.

The macrophyte survey found that plants tended to grow very densely (75% to 100% of bottom coverage) around the margins of the main deep basin and very sparsely (close to 0%) below approximately 2 m depth throughout most of the pond (see Figure IV-12). This density of macrophytes would be competitive with phytoplankton for available nutrients, although macrophytes derive a majority of their nutrients from the sediments, rather than the water column.

Although speciation was not part of the macrophyte survey, staff noted that most of the rooted plants were bladderworts and lilies. These species were consistent with 2012 survey, which included “floating plants” and noted lilies, bladderwort, watershield, and floating heart as dominant species, but did not include density evaluations.⁵³ The 2020 plant distribution is notably more extensive, however, than the 1970 Lyons Skwato summary.⁵⁴ The submerged aquatic plant map in the 1970 summary showed much more limited macrophytes (35% of the total pond area) with bladderwort again noted as the predominant species (see Figure IV-12). This comparison suggests that macrophytes have become a much more dominant portion of the ecosystem, perhaps due to the increased availability of suitable sediment substrate.

⁴⁹ <http://www.mass.gov/eea/agencies/dfg/dfw/natural-heritage/species-information-and-conservation/mesa-list/list-of-rare-species-in-massachusetts.html>

⁵⁰ e.g., CSP/SMASST Technical Memorandum: Eagle Pond and Cedar Pond Technical Support Project: Bathymetry, Submerged Aquatic Vegetation and Mussel Surveys, Water Bird Survey. December 18, 2012.

⁵¹ Strayer, D.L. 2014. Understanding how nutrient cycles and freshwater mussels (Unionoida) affect one another. *Hydrobiologia*. 735: 277-292.

⁵² 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.

⁵³ Kadis, I. June 22, 2012. Arnold Arboretum Botanist.

⁵⁴ Lyons-Skwato Associates. 1970.

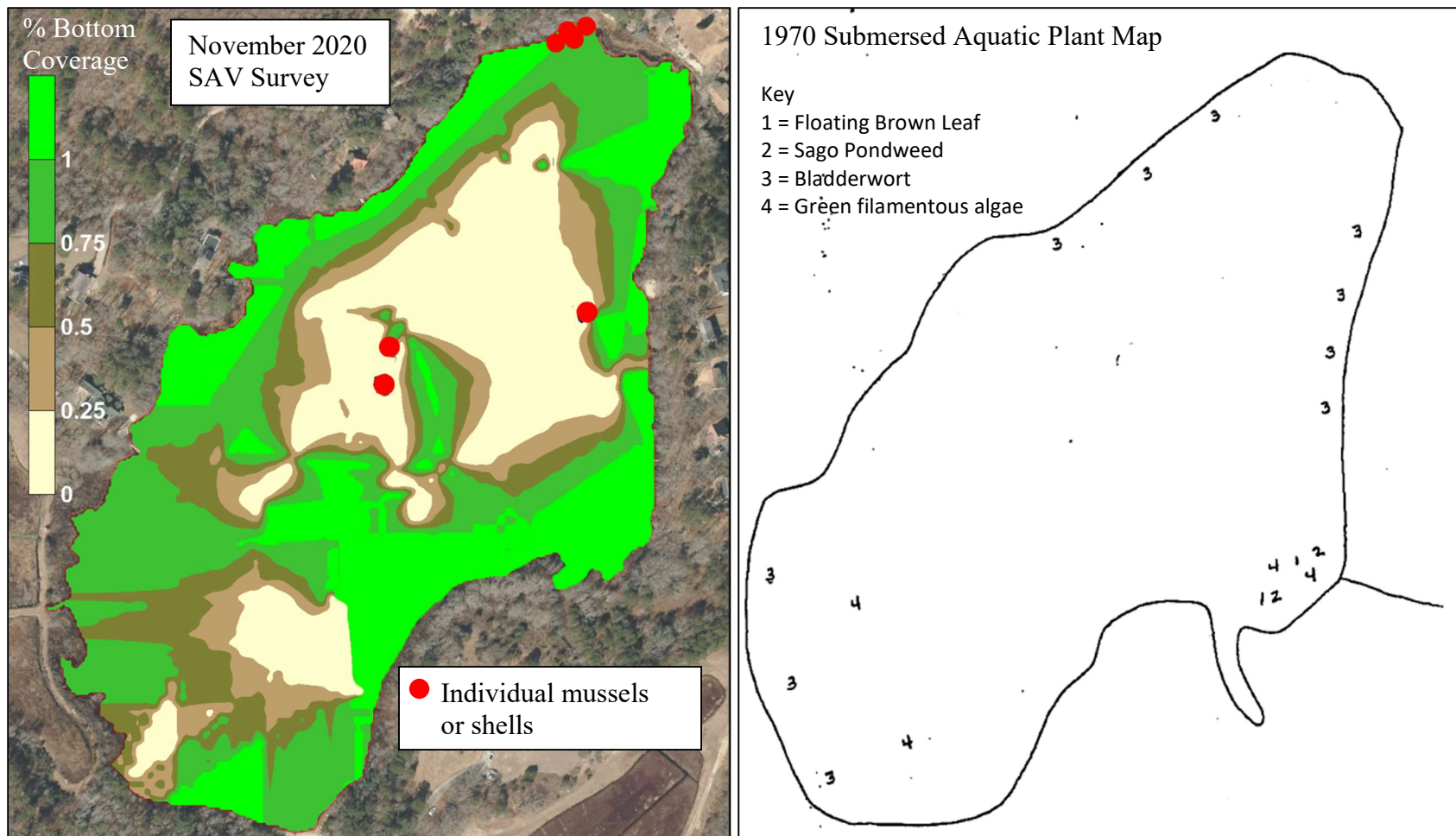


Figure IV-12. Submerged Aquatic Vegetation (2020 and 1970) and 2020 Mussel Survey. As part of the 2020 data gap surveys for the Savery Pond diagnostic assessment, CSP/SMASST staff completed a video survey of the pond bottom and reviewed each frame (~0.25 square meter) to determine plant density and presence of freshwater mussels. Only 4 individual mussels were identified, all in a cluster along the NE shoreline in two feet of water. Mussel shells were identified in 3 other locations. Plant density was generally greater than 75% throughout the pond to approximately 2 m depth; deeper than 2 m generally had very few aquatic plants. The 2020 plant density and bottom coverage appears to be much more extensive than an available 1970 survey (Lyons-Skwarto Associates, 1970), which showed only limited plants at limited portions of the pond shoreline.

IV.C. Sediment Core Incubation Data

Sediment regeneration of nutrients regularly occurs in ponds, can vary by pond, and within portions of the same pond. Regeneration begins as organic detritus (such as phytoplankton, aquatic plant material or fish) settles to the bottom and is decomposed by the sediment microbial community (*i.e.*, biodegradation). The bacterial decomposition of detrital material breaks it down into its constituent chemicals, including inorganic nutrients. Some chemicals are subsequently bound with sediment materials to form solid precipitates that remain buried in the sediments, while others are released in dissolved forms to the overlying pond water column. If the sediment bacterial population consumes more oxygen than is available during this process, then hypoxic/anoxic conditions occur in water overlying the sediments 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 occurred under oxic conditions can break and dissolved forms of the constituent chemicals can be re-released into the water column. This kind of transition and release of inorganic phosphorus occurs when dissolved oxygen concentrations decrease in near-sediment waters. Once phosphorus is released from the sediments into the water column, it is a source of fertilizer for plants, including phytoplankton and rooted plants.

Review of Savery Pond historic data showed that the bottom waters occasionally became anoxic, but it was unclear how much phosphorus and nitrogen might be released from the sediments and how long the anoxic conditions would need to last to prompt sediment nutrient release. Because resolving these issues was important to developing reliable restoration and management strategies, measurement of sediment nutrient release was identified as an important data gap that needed to be addressed during the diagnostic evaluation of Savery Pond.

In order to measure potential sediment nutrient regeneration within Savery Pond, CSP/SMASST staff collected and incubated eight intact sediment cores collected from various locations and depths (Figure IV-13). These undisturbed sediment cores were collected by SCUBA diver on April 24, 2019. Cores are collected in early spring in order to have bottom waters fully oxygenated and before anoxic events that would release phosphorus might occur. The cores were incubated at *in situ* temperatures to measure nutrient regeneration from the sediments under oxic and anoxic conditions. Water column samples were also collected one week prior to the core collection, the day of the core collection and roughly one week after the collection in order to evaluate changes in water column nutrient mass, due to regeneration and particle settling. Water column TP, TN, and chlorophyll a concentrations were not significantly different ($p < 0.05$) before (4/17) and after (5/2) the core collection. The DO profiles near the collection date did show some signs of net sediment oxygen uptake, but all depths had DO concentrations greater than 8 mg/L.

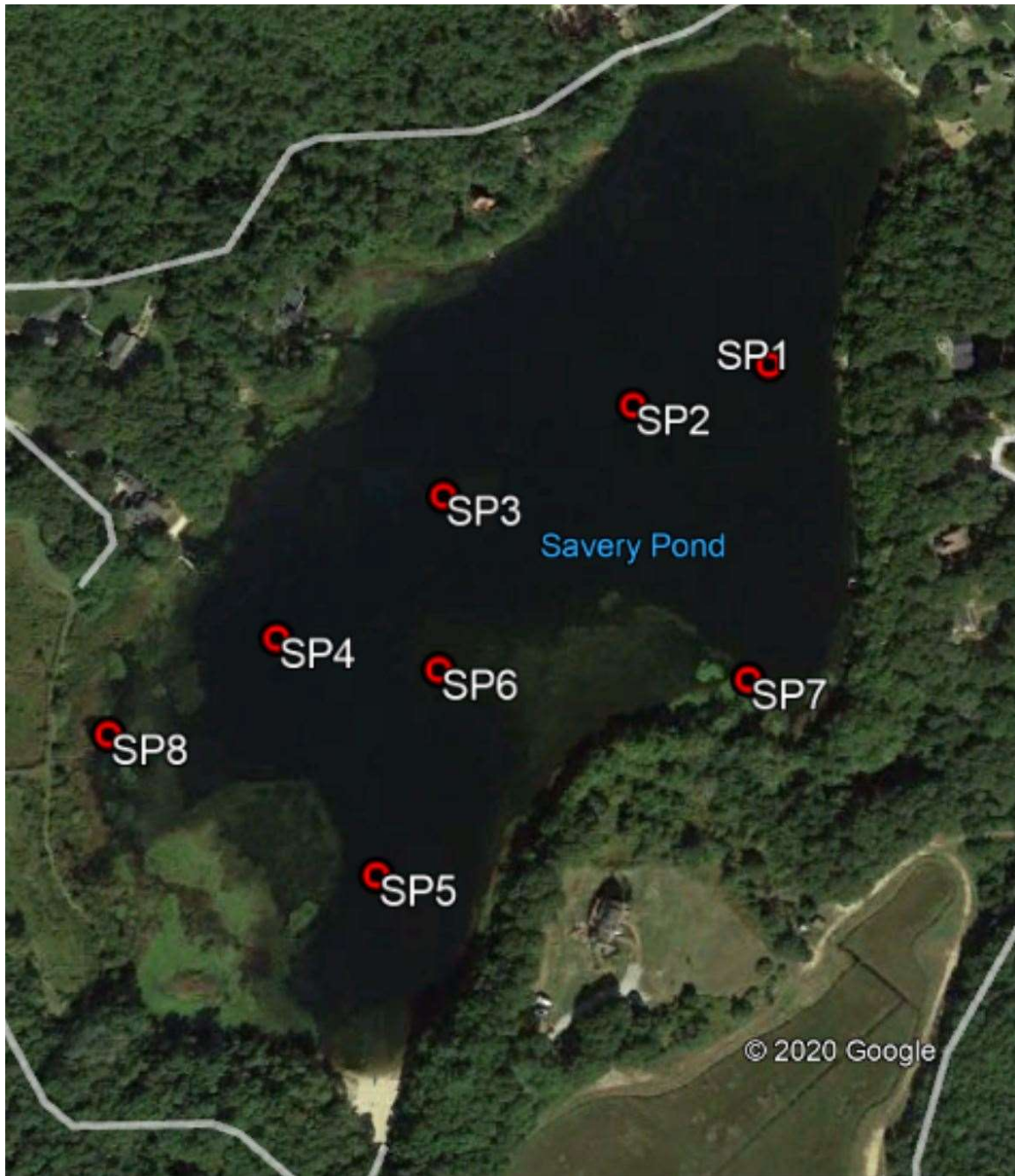


Figure IV-13. Savery Pond 2019 Sediment Core locations. Red circles show the location of eight undisturbed sediment cores collected by SCUBA diver in Savery Pond on April 24, 2019. Base map is from Google Earth.

During the collection and subsequent incubation of the sediment cores, standard handling 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 to first sustain aerobic conditions, matching conditions when dissolved oxygen in pond bottom waters is near atmospheric equilibrium (as usually found in April/May and October/November). Dissolved oxygen is then removed and sediment conditions move through a redox sequence that begins with chemical phosphorus release (initial severing of weak iron:phosphorus chemical bonds at the onset of anaerobic conditions) and continues with phosphorus release through anaerobic respiration alone; this process creates the same conditions those experienced in the water column when dissolved oxygen concentrations drop to less than 1 mg/L (conditions that occur for varying periods in Savary Pond during the summer) (see Figure IV-2). The laboratory followed standard methods for water sample analysis as currently used by the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

Review of the core incubation results showed characteristics that are important for any future nutrient management planning. In general, deep sediments (>3 m water depth) consistently added phosphorus to the water column under both aerobic and anaerobic conditions, while shallower sediments retained phosphorus during aerobic conditions, but added phosphorus to the water column once oxygen was removed (Figure IV-14). Under aerobic conditions, which DO profiles suggest most of the sediments regularly experience (see Figure IV-3), the pond-wide P flux balance between shallow and deep sediments throughout the pond would result in a slight retention of P (2.5 grams per day), which translates to a 0.1 kg removed during the estimated 48 day residence time (see below). Once anaerobic conditions occur, the chemical release of P does not occur until 8 days later. Once chemical release is initiated, deep core release rates increased slightly, but shallow cores switched from removing phosphorus to releasing phosphorus at a rate >2X the deep core release rate. Once the chemical release phase concluded after 33 days, anaerobic release from both the shallow and deep sediments continued, but at significantly lower rates (both shallow and deep anaerobic release rates were approximately a third of the respective chemical release rates). The core results suggest that deep sediments in Savary Pond are a regular and relatively constant, but small, source of phosphorus to the water column, while shallower sediments have the potential to release significant P if anaerobic conditions are shallower than 3 m depth and are sustained for greater than 8 days.

The eight day lag before the onset of chemical P release (*i.e.*, breaking phosphorus:iron chemical bonds) likely is due to readily available nitrate-nitrogen (see Figure IV-14). Nitrate-nitrogen reduction is energetically richer,⁵⁵ so bacteria utilize this source before reducing the iron which breaks the phosphorus:iron bonds. Nitrate-nitrogen was released from sediments under aerobic conditions at 26X the P chemical release rate, so there should be sufficient nitrate-nitrogen to explain the lag in anaerobic P release. Overall, N release rates showed little difference between shallow and deep sediments and were significantly higher under aerobic conditions compared to anaerobic conditions. All cores had net nitrogen flux out of the sediments under both aerobic and anaerobic conditions, which means that the sediments are a source of recycled N in summer.

⁵⁵ Stumm, W. and J.J. Morgan. 1981. *Aquatic Chemistry*. John Wiley & Sons, Inc., New York, NY.

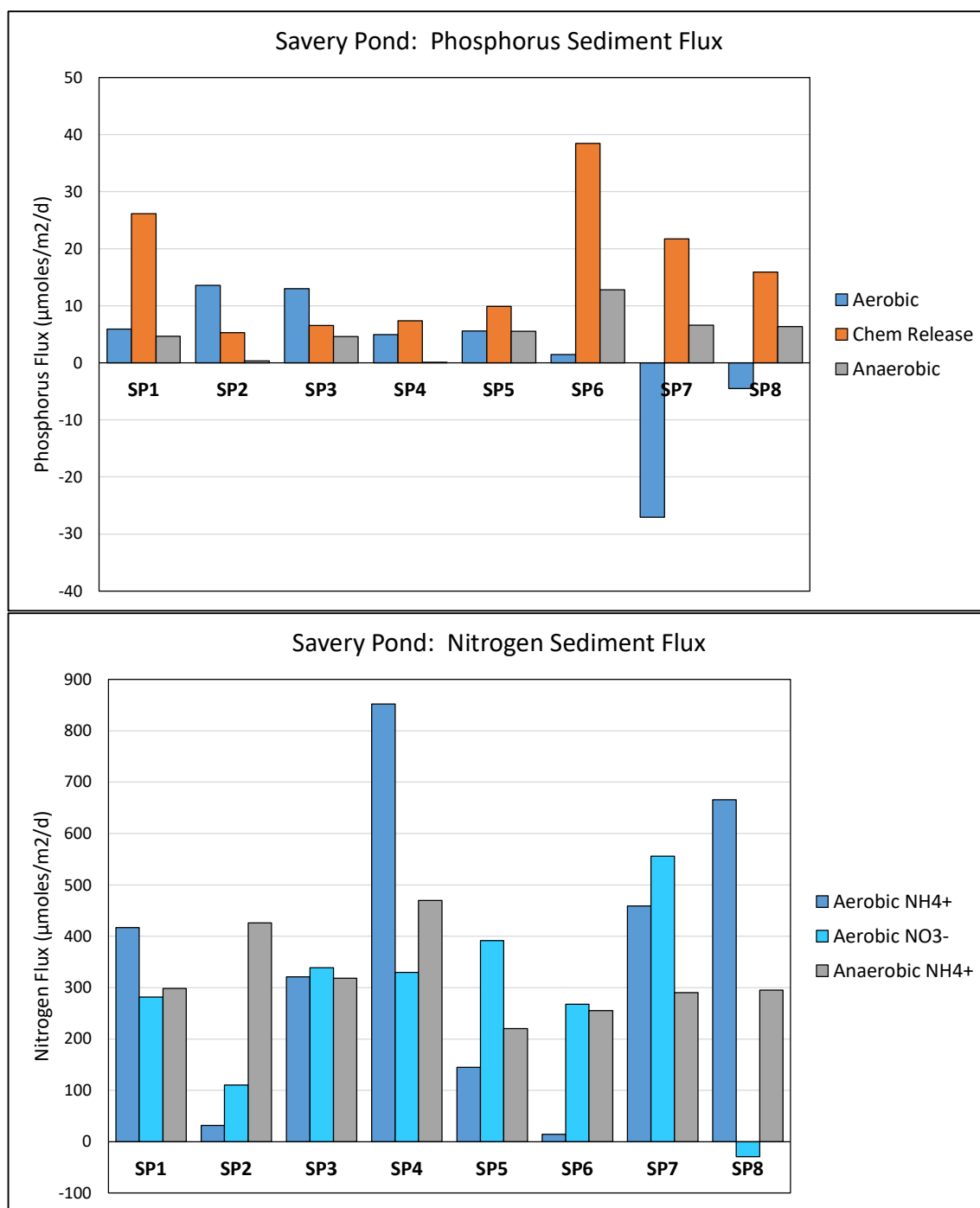


Figure IV-14. Savery Pond Sediment Flux Rates: Nitrogen and Phosphorus. Eight sediment cores were collected from Savery Pond in April 2019 and incubated to measure N and P flux under aerobic and anaerobic conditions. Under aerobic conditions, which DO profiles show tend to be the prevalent conditions for most of the sediments in Savery Pond, cores collected from deep areas (cores SP1 to SP5; 3 to 3.8 m depths) released P and N, while shallow cores (cores SP6 to SP8; 1.0 to 1.2 m depths) also released N, but generally retained P. Anaerobic conditions caused P to be released from the shallow sediments (especially during the initial chemical release), while N release rates were not significantly different. These results showed that the depth and duration of low DO conditions will impact sediment P release, while N release is generally higher during aerobic conditions regardless of depth.

Review of the core results show that sediment contributions of phosphorus and nitrogen to the Savery Pond water column will depend on water column dissolved oxygen concentrations, the depth of anoxic conditions, and the length of time that anoxic conditions are sustained. Review of the continuous DO recordings collected in 2016 at 2.4 m depth (see Figure IV-2), showed that anoxic conditions occurred 32 times for a total of 20 days' worth of anoxic conditions between May 31 and August 23. Most of these anoxic events were transitory with 17 of them lasting 58 minutes or less.⁵⁶ Among the longer events, only one was longer than the 8 days of anoxic incubation required to get to the chemical release phase of sediment phosphorus flux. This prolonged event lasted 15.9 days from July 18 to August 2. The first water quality sampling after this event was on August 10 and had the highest TP water column mass estimated from all available data (see Figure IV-10). Based on the incubation results, the sediments would have released between 0.3 and 0.5 kg of phosphorus during this 16 day event with the variation depending on how much of the shallow sediments were exposed to anoxia.

The overall review of the sediment results with the water column DO concentrations shows that the sediments are generally in aerobic release condition. This condition means that the pond sediments are generally retaining a small amount of phosphorus. Review of the continuous DO monitoring in 2016 shows that the sediment P release can occur, but even under relatively extreme circumstances, the release mass tends to be relatively small.

IV.D. Savery Pond Watershed Review and Physical Characteristics

Savery Pond is located within the Plymouth-Carver-Kingston-Duxbury (PCKD) aquifer system. The PCKD aquifer system is generally a mix of sandy, highly permeable materials that were deposited over bedrock during the last intercontinental glaciation approximately 15,000 years ago. This aquifer system is the source of Plymouth's drinking water and is the source water for all the town's lakes, ponds, rivers, and streams and freshwater discharge to all the estuaries. The watersheds to freshwater ponds within this aquifer system are predominantly defined by groundwater flow and water table topography rather than land surface topography. Ponds and lakes, like Savery Pond, are depressions in the land surface that intersect the aquifer water table and, thus, are part of the groundwater system. Groundwater systems like the PCKD aquifer are dynamic and change seasonally and year-to-year based on changes in precipitation, water supply pumping, and groundwater elevations. These changes have the potential to impact groundwater flowpaths and, thus, watershed delineations, which in turn can impact the water and nutrient budgets to freshwater ponds. The watershed to Savery Pond appears to be notably impacted by these dynamic changes.

The most recent US Geological Survey (USGS) regional groundwater modeling project placed Savery Pond within the Ellisville Moraine, which is an area where previously deposited glacial materials were reworked as the edge of one of continental glacier lobes readvanced during a cooling period.⁵⁷ The USGS model represents the collection and interpretation of hundreds of groundwater elevations, streamflow readings, and geologic information from well logs and

⁵⁶ The 2016 DO sensor recorded readings every 30 minutes, so recorded anoxic events with both the previous and subsequent DO readings greater than 1 mg/L would have a maximum event length of 29 minutes on either side of the recording (2x29=58 minutes).

⁵⁷ 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 p.

geologic borings collected throughout the PCKD model domain. The steady-state conditions in this groundwater model, which were based on 2005 water supply well pumping, showed that Savery Pond was in an area of the aquifer with water table elevations between 25 and 30 ft above sea level and a watershed of 513 acres (Figure IV-15). Using this watershed area with the volume determined from the new bathymetry (see Figure II-2) and the average recharge rates used in the USGS modeling, the average residence time of water within Savery Pond would be 0.13 years or 48 days.

Review of water quality data and the watershed nutrient loading estimates (discussed below) show that this residence time is too short to be consistent with the phosphorus and nitrogen mass measured within the pond water column. Closer review of the average input values used in the USGS model provide insights into why the local conditions at Savery Pond are likely different than described in the regional model.

Review of precipitation rates and pumping rates at two nearby public water supply wells (John Holmes Well and Ellisville Well) suggests that these two factors likely play a significant role in determining the water quality in Savery Pond by seasonally increasing the residence time. The John Holmes Wells is approximately 1 km west of Savery Pond and its Zone II contributing area⁵⁸ includes the uppermost portions of the Savery Pond watershed (Figure IV-16). In the USGS model, the John Holmes Well had an assigned average water withdrawal of 0.25 million gallons per day (MGD). While this rate was accurate at the time of the model construction, review of monthly pumping rates between 2010 and 2020 showed this well had a higher average pumping rate of 0.39 MGD and a monthly maximum of 0.95 MGD (July 2010) (Figure IV-17).⁵⁹ Review of summer (June to August) pumping rates showed the John Holmes well averaged 0.62 MGD (>2.4X the average USGS pumping rate). Recent Ellisville Well pumping rates, in contrast, were more closely aligned with those used in the USGS model.

Higher year-round and seasonal pumping from the John Holmes Well would tend to expand its groundwater capture area. Lower annual and seasonal precipitation would tend to compound this expansion. Collective review of these factors suggests that the decreased watershed area resulting from seasonally increased pumping and decreased recharge could cause the water residence time in Savery Pond to fluctuate as much as 32% based on precipitation alone and 49% based on pumping at the John Holmes Well alone. Further evaluation of these linked factors could be evaluated through a transient groundwater model, which is outside of the scope of this project, but development of this type of model could also incorporate the seasonal changes in pumping and recharge. Further review of these issues is discussed in the water budget section (below).

⁵⁸ Zone II delineations are required under MassDEP criteria to be delineated based on 180 days of pumping at the well's safe yield with no recharge from precipitation; this is a conservative approach, but the results show that summer pumping of the John Holmes well at rates greater than what was incorporated into USGS regional modeling likely cause reductions in the Savery Pond watershed area.

⁵⁹ Based on data supplied by the Town (personal communication, 2/16/21, K. Martin, Water & Wastewater Engineer).

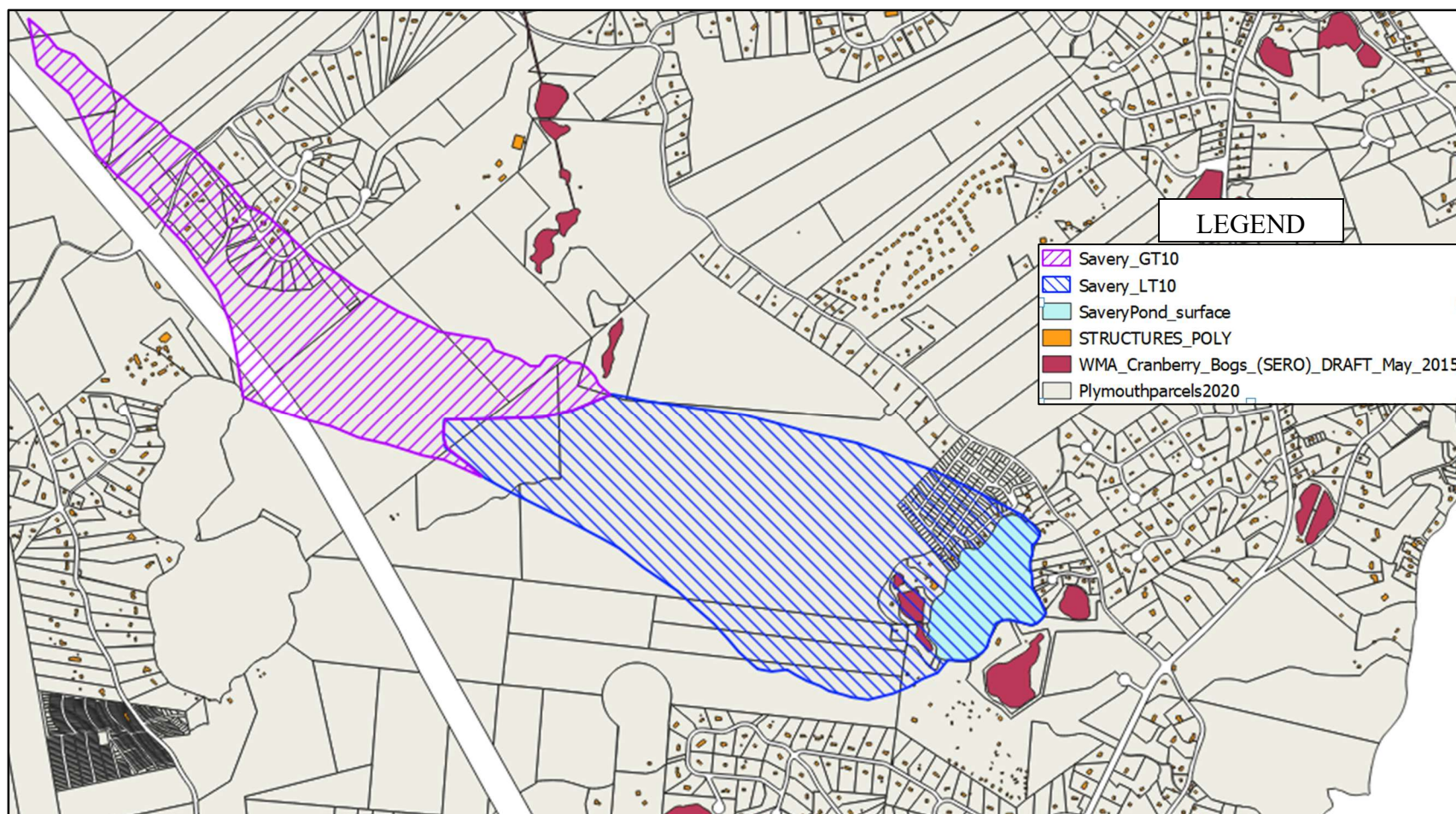


Figure IV-15. Savery Pond USGS Watershed. The watershed to Savery Pond was delineated by the US Geological Survey as part of a regional groundwater model for the Plymouth-Carver-Kingston-Duxbury aquifer system (Masterson, Carlson, and Walter, 2009). The watershed was delineated with groundwater time of travel zones as part of the overall Massachusetts Estuaries Project effort that included the watershed delineation to Plymouth Harbor with subwatersheds to each Great Pond and major stream/river. The blue pattern is the less-than-10 year travel time portion of the watershed and the purple area is the greater-than-10 year travel time portion of the watershed. The total area of the watershed is 513 acres. The modeled watershed is based on 2005 groundwater conditions, including average public water supply pumping at the time.

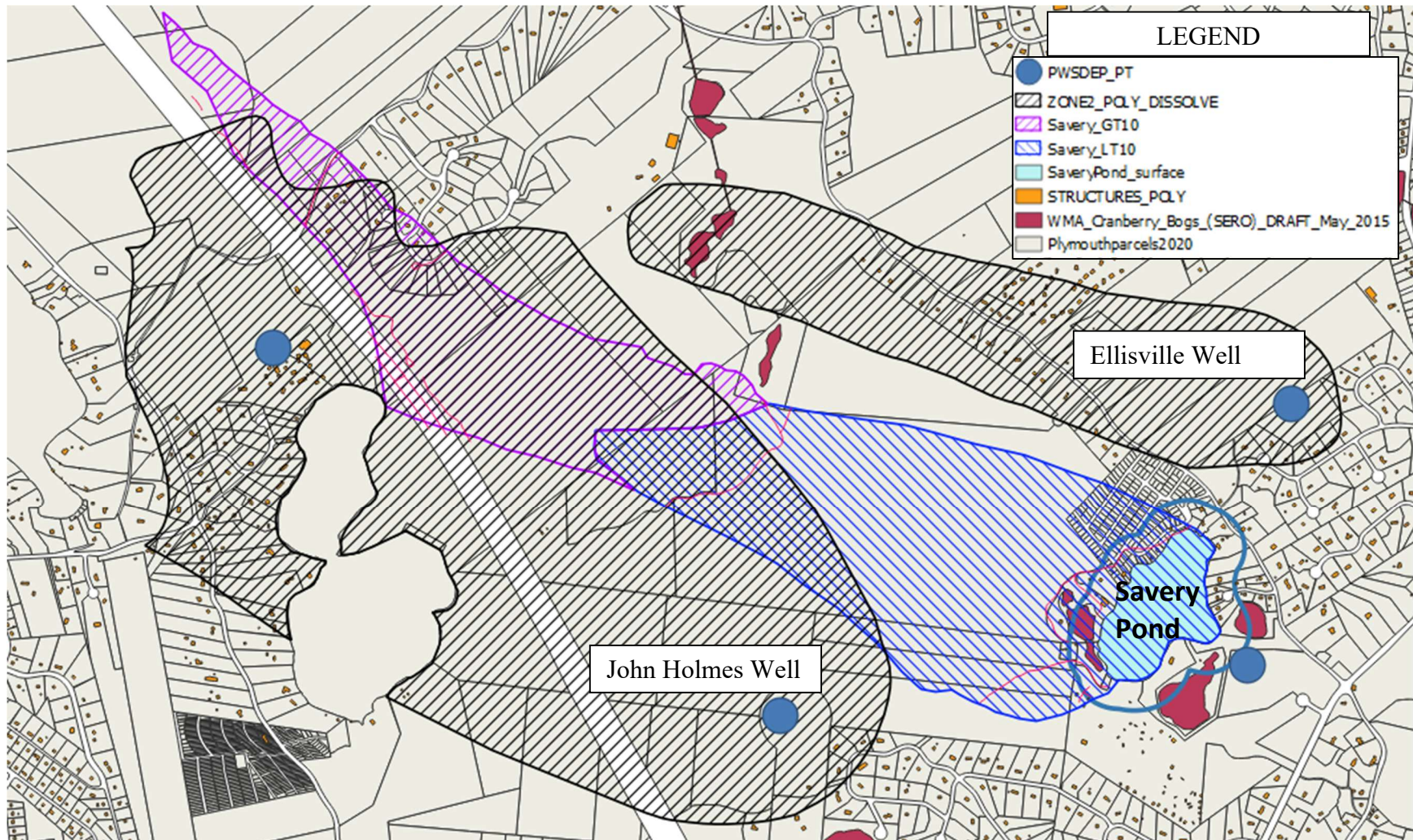


Figure IV-16. Savery Pond Watershed and Contributing Areas of Nearby Public Water Supply Wells. The MassDEP-approved Zone IIs for the public water supply wells near Savery Pond are shown. Zone II delineations are based on 180 days of pumping at safe yield with no recharge from precipitation, so they are based on conservative conditions. However, review of pumping records at the John Holmes Well consistently showed rates above the USGS steady-state conditions that were the basis for the Savery Pond watershed. Higher pumping rates and lower precipitation rates typically occurring in the summer would tend to expand the well capture area into the Savery Pond watershed area. This overlap would tend to reduce the groundwater flow through the pond, lengthen the residence time of water in the pond and elevate the nutrient concentrations within Savery Pond.

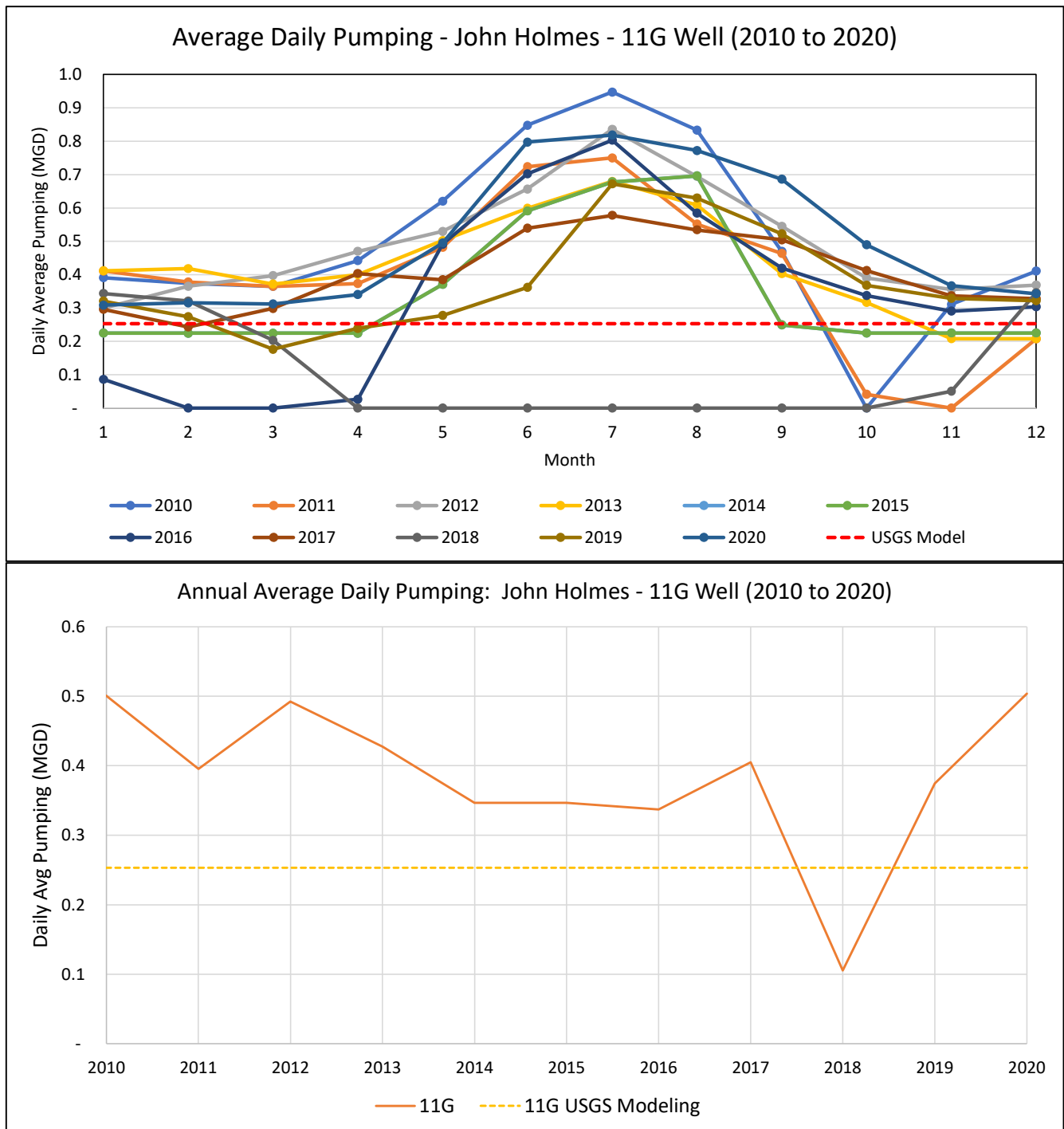


Figure IV-17. Well Pumping at John Holmes Well (2010 to 2020). The John Holmes well had annual pumping rates that were generally higher than the 0.25 MGD that was included in the USGS groundwater modeling that was the basis for the Savery Pond watershed delineation. In addition, summer pumping rates were regularly 2X to 3X greater than the USGS rate. Higher pumping from this well would tend to expand its capture area into the Savery Pond watershed area. Resolving the impacts of fluctuations in the capture area for the well and Savery Pond would require development of a transient groundwater model that could incorporate changes in pumping and precipitation/recharge.

IV.D.1. Savery Pond Water Budget

A water budget for a pond accounts for all water entering and leaving a pond. Ensuring that the volumes of water entering and leaving a pond balance 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 the water, the relative magnitude of each pathway also provides guidance for development and prioritization of management strategies.

The primary water input source to kettle ponds in the Plymouth/Cape Cod/Islands Ecoregion is typically groundwater from their watershed. Additional input sources to consider would be imported drinking water recharged through septic systems, stormwater runoff from impervious surfaces, and precipitation on the pond surface. Water movement out of the pond is typically through pond water returning to the groundwater aquifer along the downgradient side of the pond and evapotranspiration off the surface of the pond, but if a stream or herring run outflow is present (like in Savery Pond), this usually becomes the primary exit pathway for water out of the pond. Savery Pond has no direct stormwater runoff inputs, water supply for parcels within the watershed is from private on-site wells,⁶⁰ and it has a streamflow output, therefore, the water budget balancing of source and sink volumes for Savery Pond is represented in the following equation:

$$\text{groundwater}_{\text{in}} + \text{pond surface precipitation} = \text{groundwater}_{\text{out}} + \text{stream outflow} + \text{surface evapotranspiration}$$

Among these pathways, stream outflow and surface precipitation can be directly measured. Groundwater_{in} is usually estimated based on recharge within the pond watershed, while surface evaporation is generally estimated from precipitation and meteorological conditions based on previous regional measurements. Groundwater_{out} is usually estimated based on difference.

Streamflow out of Savery Pond has been directly measured over a period of months three times, although the continuous recording during the data gap surveys for this project was the only time flow was recorded throughout a whole hydrologic year. Project staff installed a water level gauge from 11/12/19 to 10/3/20 (after 10/3, the stream was dry). Average daily flow during the 2019 to 2020 stream collection period was 493 cubic meters per day (m³/d) (Figure IV-18). Friends of Ellenville Marsh (FOEM) had previously installed a water level recorder at the same site and recorded levels from May 2018 through November 2018.⁶¹ The USGS groundwater model report notes that streamflow data was collected for more than one hydrologic year (December 12, 1969 to September 30, 1971) at Savery Pond Creek, but does not specify how many readings were collected, where they were collected, or how they were collected.⁶² The USGS 1969 to 1971 flow was 0.33 cubic feet per second (807 m³/d) or 64% higher than the 2019/2020 average. The USGS regional model streamflow from Savery Pond was 0.6 cfs or 198% higher than the 2019/2020 average. The 1969 to 1971 USGS flow readings would have been collected prior to the installation of the public water supply wells in the area.⁶³

⁶⁰ Personal communication, K. Tower, Environmental Technician, Town of Plymouth

⁶¹ Friends of Ellenville Marsh. 2019. Savery Pond 2018 Water Levels and Streamflow. 39 pp.

⁶² Masterson, J.P., Carlson, C.S., and Walter, D.A., 2009. Table 2-3.

⁶³ Ellenville well was installed in 1980, while the Savery Pond well was installed in 2002 (Wright-Pierce, 2006).

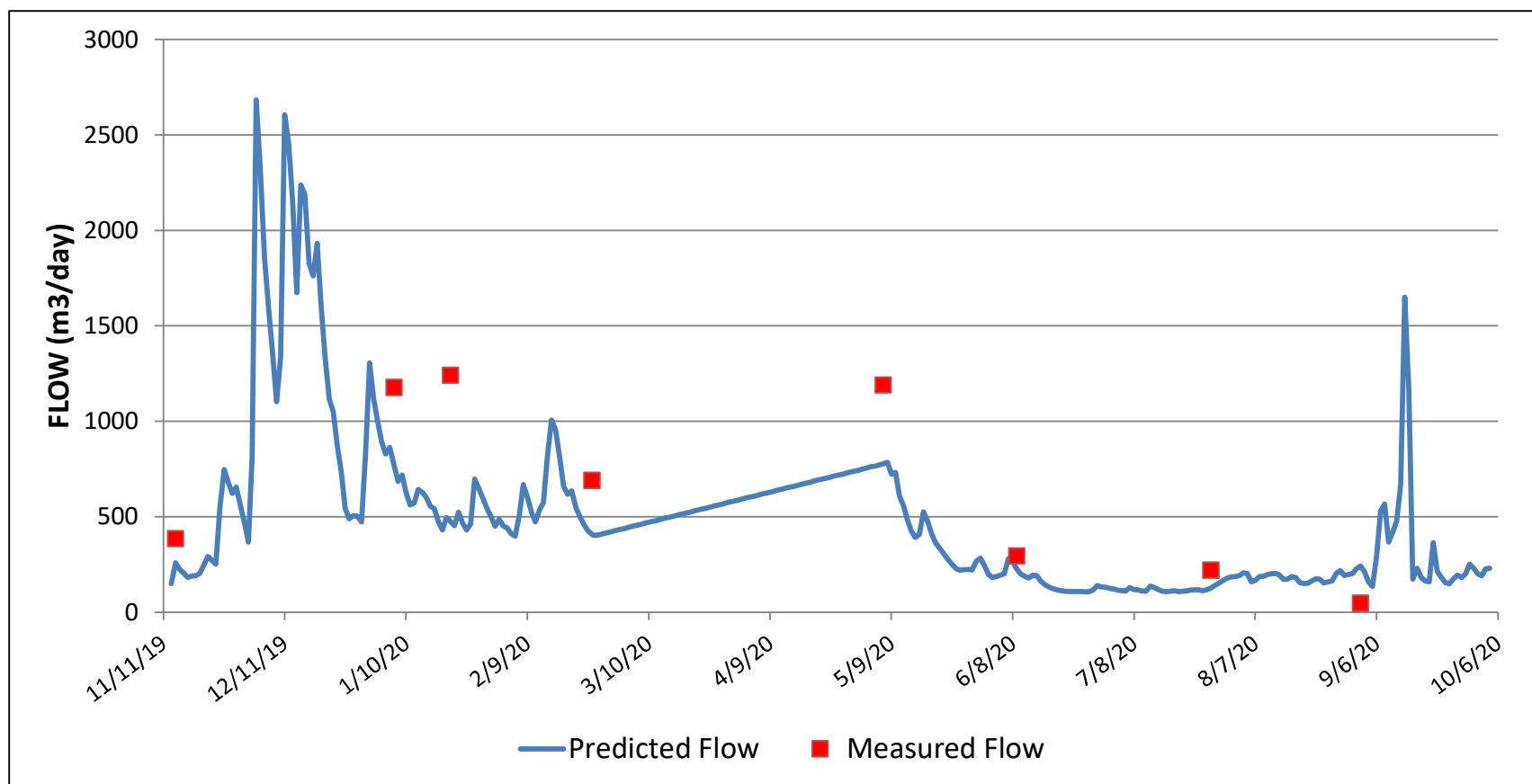


Figure IV-18. Stream Outflow from Savery Pond (November 2019 to October 2020). A continuous gauge recorded water levels from 11/12/19 to 10/3/20 (after 10/3, the stream was dry). Average daily flow during the 2019 to 2020 stream collection period was 493 cubic meters per day (m^3/d). This flow was 39% less than the annual USGS measured flow in 1969 to 1971 and 66% less than the USGS modeled flow in the most recent regional groundwater model (Masterson and others, 2009). Review of groundwater levels in the 2019 to 2020 period suggest that the 2019/2020 measured flow should be representative of above average groundwater elevations.

In hydrogeologic settings similar to Savery Pond, precipitation and groundwater flows are linked; a portion of precipitation reaches the groundwater (*i.e.*, recharge) and the amount of this recharge is important to determining the elevation of the water table (*i.e.*, the top of the aquifer). The closest long-term daily precipitation station to Savery Pond is Plymouth Airport, which is approximately 16 km northwest of Savery Pond and has available readings since 1996.⁶⁴ The East Wareham station used in the USGS modeling is approximately the same distance away from Savery Pond. There are two other closer stations, but their recording record is much shorter: one approximately 4.3 km southwest of Savery Pond in Plymouth has reading since November 2019 and another 9.5 km southeast in Sandwich has readings since June 2015. Comparison of these more limited datasets to Plymouth Airport data show that Plymouth Airport data is reasonably representative of the readings at these other stations.

Plymouth Airport annual precipitation between 2000 and 2020 varied between 33.68 and 62.22 inches with an annual average of 48.4 inches (Figure IV-19). Precipitation in 2016 was the lowest recorded within the 2000 to 2020 timeframe (33.68 in), while 2019 was the highest recorded (62.22 in). Review of summer precipitation (June to August) showed it was more variable than annual precipitation; 2016 had the lowest summer precipitation between 2000 and 2020 (4.28 in). Between 2010 and 2020, summer precipitation was also below average from 2015 to 2017 and then again in 2020. Lower precipitation during the summer would be associated with higher pumping rates at the John Holmes well and less groundwater discharge to Savery Pond.

In the development of the USGS regional groundwater model, the authors reviewed daily precipitation data from 1931 through 2006 for an East Wareham weather station. This review determined that average annual precipitation was 47 in/yr. This data was combined with daily temperature data at the same station and analyzed using an automated Thornthwaite method that incorporates estimates of soil-moisture capacity to determine how much of precipitation recharges the aquifer, how much fills void spaces in the soil, and how much is either transpired or evaporated from the soil.⁶⁵ This review determined that 27 in/yr (or 57% of annual precipitation) was an appropriate annual average recharge rate for the PCKD aquifer model. The authors further refined the analysis to determine separate recharge rates for ponds (20 in/yr), cranberry bogs (10 in/yr) and wetlands (8 in/yr). Areas with public water supply were also determined and these areas were assigned 85% of assigned public well pumping rates (*i.e.*, the authors assumed a 15% consumptive loss).

Review of groundwater levels show that 2016 pond water quality readings were collected during low groundwater levels, while 2019 readings were collected during high groundwater levels. The longest record of groundwater elevations closest to Savery Pond is from well PWW-494, which is located in Myles Standish State Forest and has monthly water level readings collected by the USGS since July 1985.⁶⁶ Groundwater elevations at Savery Pond would be approximately 70 ft lower and the ranges would be somewhat dampened because Savery Pond is closer to the ocean, but the general trends should be similar since Savery Pond is within the same portion of the aquifer.

⁶⁴ <https://www.ncdc.noaa.gov> (accessed 2/17/21)

⁶⁵ Masterson, J.P., Carlson, C.S., and Walter, D.A., 2009. pp. 52-62.

⁶⁶ <https://nwis.waterdata.usgs.gov> (accessed 2/19/21)

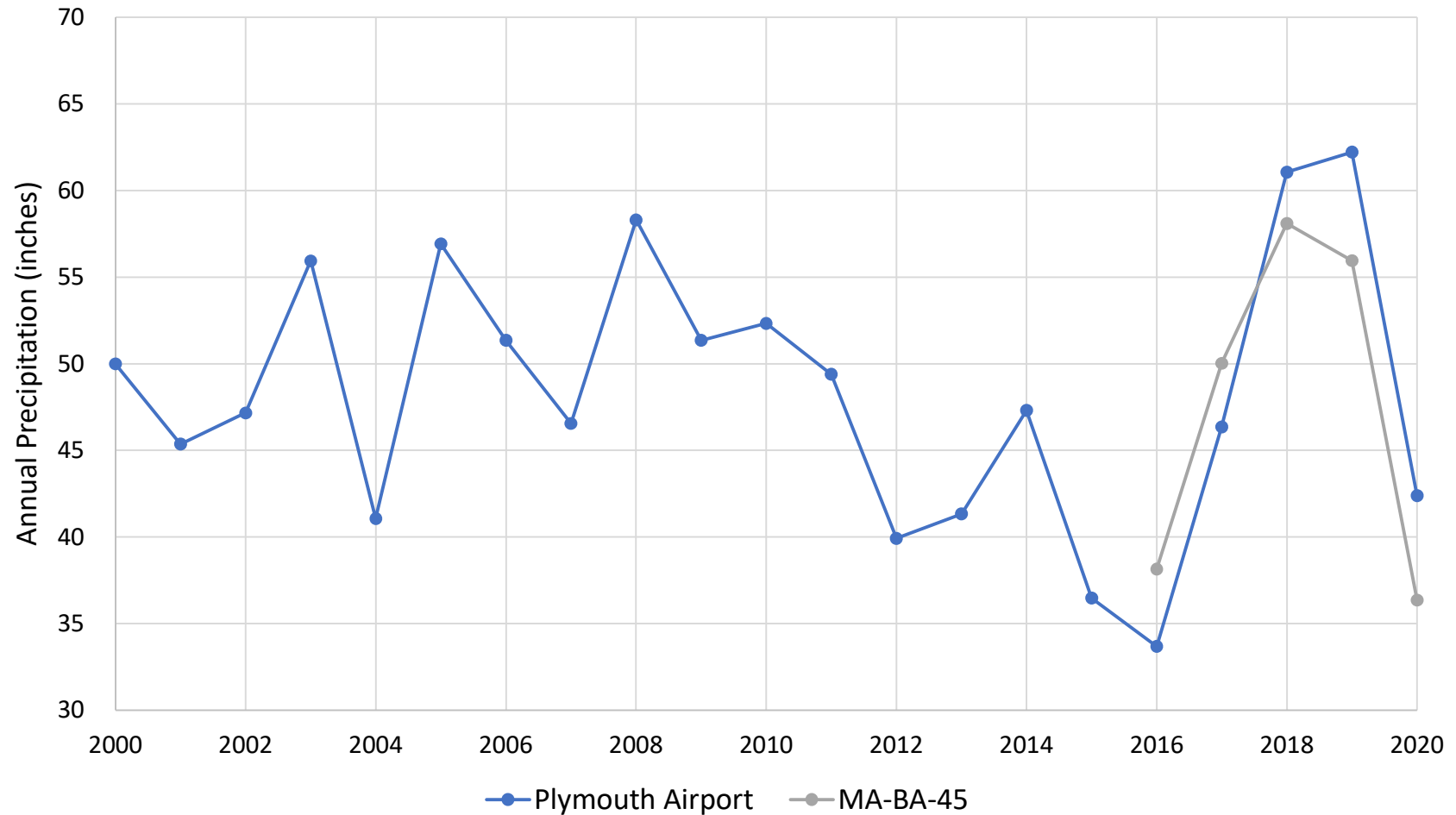


Figure IV-19. Plymouth Airport Precipitation (2000 to 2020). Annual precipitation between 2000 and 2020 varied between 33.68 and 62.22 inches. Precipitation in 2016 was the lowest annual amount recorded between 2000 to 2020, while 2019 was the highest recorded. Review of summer precipitation (June to August) showed it was more variable than annual precipitation, that 2016 was also the lowest summer precipitation between 2000 and 2020. Also shown are readings at a gauge closer to Savery Pond (9.5 km to the southeast), which has a more limited record, but comparable precipitation to the amounts measured at the airport.

Groundwater levels were below average throughout 2016 with monthly readings below the 25th percentile of historic levels beginning in June and continuing to decrease throughout the rest of the year; the December 2016 elevation was the lowest recorded in the 2000 to 2020 dataset (Figure IV-20). In contrast, groundwater levels in 2019 and 2020 were above average and mostly above the 75th percentile for most of the year. Lower groundwater levels mean less flow through Savery Pond (*i.e.*, longer residence time) and lower stream outflow.

Collectively, the review of water budget components show that Savery Pond has changeable water flows moving through the pond from year to year and these changes are significant enough to alter water quality measurements in the pond. Table IV-2 shows estimates of an annual Savery Pond water budget based on USGS regional groundwater modeling and estimates of potential summer conditions in high and low groundwater years. Water residence time in the pond based on USGS modeling is 48 days, while summer estimates in low and high groundwater conditions have annualized residence time estimates of 827 days and 213 days, respectively.

Table IV-2. Savery Pond Water Budget Estimates. Available data shows that watershed area and precipitation have wide variability and this alters the amount of water that flows through the pond. Water flow during the primary summer water quality management period (June through August) is particularly variable. Summer groundwater estimates below include reduction in watershed recharge due to increase pumping of the John Holmes well (estimated as reduction to area roughly equivalent to the LT10 recharge area shown in Figure IV-16). All values, including residence times, converted to annual rates to ease comparison to USGS estimates.				
IN		OUT		
USGS Watershed and Model Settings				
Source	m ³ /yr	Sink	m ³ /yr	Pond residence time (days)
Groundwater	1,343,018	Stream Outflow	535,800 ¹	48
Pond Surface Precipitation	131,993	Groundwater	883,044	
		Pond Evapotranspiration	56,167	
TOTAL	1,475,011		1,475,011	
Summer Low Groundwater Estimate (<i>e.g.</i> , 2016) ²				
Groundwater	72,901	Stream Outflow	42,452 ³	827
Pond Surface Precipitation	12,020	Groundwater	35,564	
		Pond Evapotranspiration	6,905	
TOTAL	84,921		84,921	
Summer High Groundwater Estimate (<i>e.g.</i> , 2019) ⁴				
Groundwater	282,918	Stream Outflow	56,602 ⁵	213
Pond Surface Precipitation	46,647	Groundwater	246,165	
		Pond Evapotranspiration	26,797	
TOTAL	329,565		329,565	
Notes:				
1. USGS modeled outflow was 0.6 cfs. Measured flow in 2019/2020 hydroyear was 0.18 cfs.				
2. Summer low groundwater estimate based on 2016 summer precipitation (4.28 in between June and August) and USGS modeled relationships between precipitation and recharge for land, water and wetlands.				
3. Stream outflow estimate based on 75% of June to August 2019 measured average				
4. Summer high groundwater estimate based on 2019 summer precipitation (16.61 in between June and August) and USGS modeled relationships between precipitation and recharge for land, water and wetlands.				
5. Stream outflow estimate based on June to August 2019 measured average				

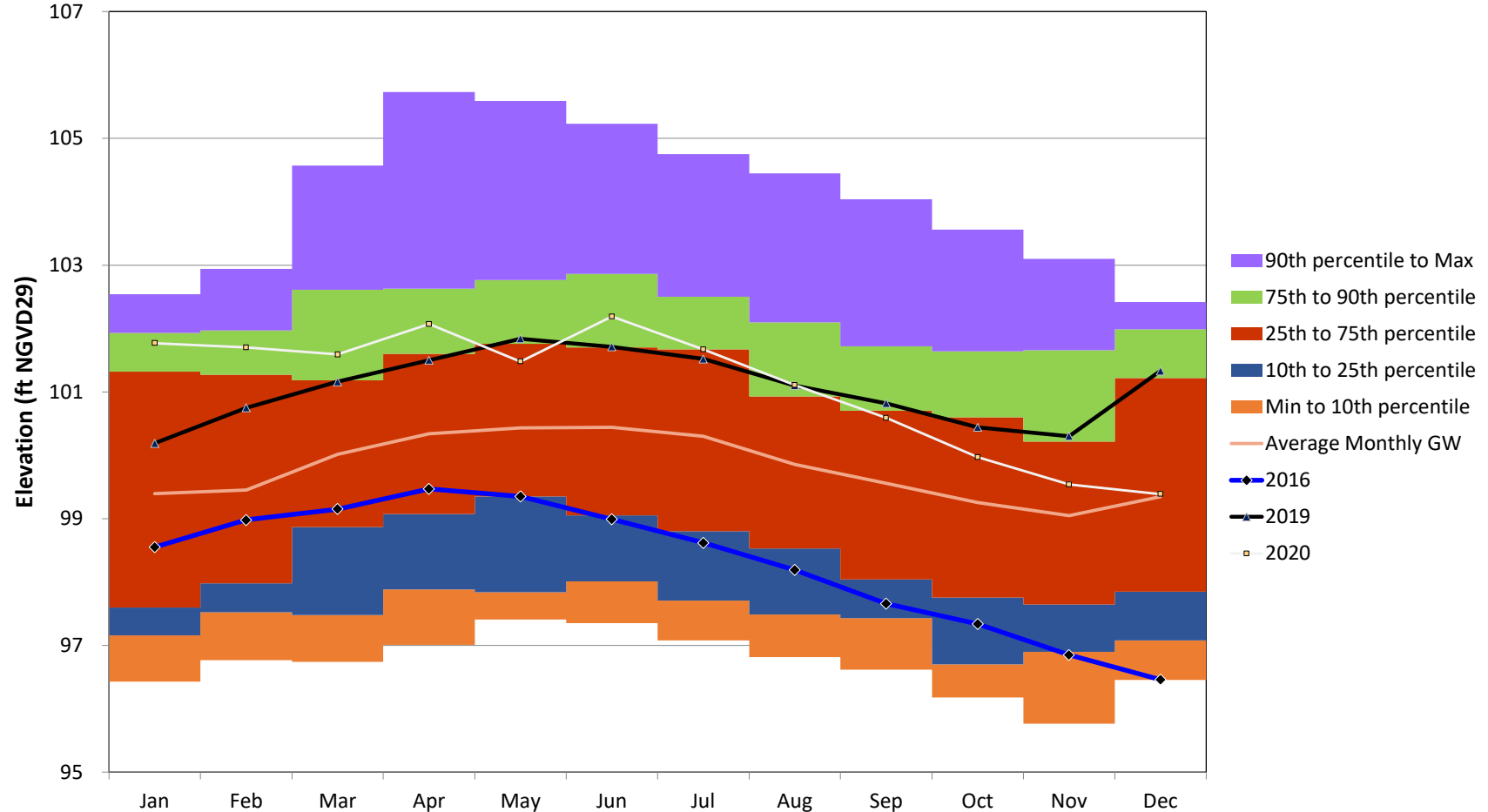


Figure IV-20. Plymouth Groundwater Elevations (2000 to 2020). The closest USGS long-term groundwater elevation monitoring well to Savery Pond is PWW-494, which is located in Myles Standish State Forest. Monthly water elevation readings have been collected by the USGS since July 1985. Groundwater elevations at Savery Pond would be approximately 70 ft lower and the ranges would be somewhat dampened because Savery Pond is closer to the ocean, but the general trends should be similar. Groundwater levels show that 2016 elevations were consistently below average, decreasing below the 25th percentile of all readings beginning in June with lower percentiles throughout the year, concluding with the lowest December elevation in the 2000 to 2020 record. In contrast, levels in 2019 and 2020 were above average and generally above the 75th percentile throughout the year.

IV.D.2. Savery Pond Watershed Nutrient Inputs and Land Use

As noted above, the key nutrient controlling the water quality in Savery Pond is phosphorus. Phosphorus travels slowly (*e.g.*, 0.01-0.02 ft/d⁶⁷) relative to groundwater flow (*e.g.*, 1 ft/d⁶⁸) in sandy aquifer materials like those surrounding Savery Pond. Nitrogen, another important nutrient, generally travels with the groundwater and is generally in the form of nitrate. Since phosphorus movement in the aquifer is slow, management of phosphorus inputs to ponds generally focusses on properties within 100 m of the pond shoreline except where there are direct surface water inputs from streams, pipes or stormwater runoff. Shoreline properties have phosphorus impacts on pond water quality within typical wastewater management planning horizons (*i.e.*, 20 to 30 years). In order to contribute phosphorus or nitrogen to the pond via groundwater transport, properties must be within the watershed (*i.e.*, on the upgradient side of the pond). Properties on the downgradient side of the pond overlie groundwater flowing away from the pond; the only way for phosphorus or nitrogen to discharge to the pond from these properties is via overland flow or through stormwater conveyances such as pipes or trenches to the pond.

In order to begin to assess potential phosphorus inputs from development within the Savery Pond watershed, project staff reviewed Town Assessor and Board of Health records for parcels upgradient of the pond and within the watershed. Initially 24 parcels were identified that were completely or partially in the Savery Pond watershed and within 300 ft of the pond (Figure IV-21). Many of these parcels are historic “wood lots” located northwest of the pond; most of these are grouped, so that four or more are under common ownership and form a functionally larger lot.⁶⁹ Most of the wood lots in the Savery Pond watershed are owned by the Plymouth Conservation Commission. The review of the parcels found that nine of the developed parcels could be contributing phosphorus to the pond based on their distance to the pond and the ages of the buildings. Most of these parcels were single family residences with two other parcels listed by the Town Assessor as primarily residential properties, but including other non-residential uses. Houses on these properties range in age from 17 to 95 years old (average 54 years old). With the help of Town staff, project staff also reviewed Board of Health records for these nine properties to identify the distance from the leaching components of their septic systems to the pond and the date of their installation. Among houses with records,⁷⁰ septic leaching components averaged 17 years old and ranged in age from 3 to 46 years old. Neighborhood review of these residences found that 5 of the 9 are currently occupied year round.⁷¹

Once the properties potentially contributing phosphorus to Savery Pond were identified, staff used phosphorus loading factors based on region-specific and appropriate literature values to develop loads for various sources. Previous pond phosphorus budgets in the Savery Pond ecoregion have typically used a septic system loading rate of 1.0 lb P/yr developed by the Maine Department of Environmental Protection for use in sandy soils (Table IV-3). Available studies have generally confirmed that this is a reasonable factor. Review of published phosphorus

⁶⁷ Robertson, W.D. 2008. Irreversible Phosphorus Sorption in Septic System Plumes? *Ground Water*. 46(1): 51-60.

⁶⁸ 1 ft/d is typically used as a planning number in the ecoregion that includes Plymouth. Site-specific flow rates vary depending on sub-surface materials and location in the aquifer.

⁶⁹ Wood lots were originally small parcels (5,000 sqft or less) created for creating timber rights; some trace their original creation to the early 1700's. Remnant areas of these lots remain scattered throughout southeastern Massachusetts.

⁷⁰ Some of the houses did not have septic system records on file with the Board of Health.

⁷¹ Personal communication, P. Schwartzman, October 12, 2020.

Table IV-3. Phosphorus and Nitrogen Loading Factors for Savery Pond Watershed Estimates. Listed below are factors used in the development of the watershed phosphorus and nitrogen loading estimates for Savery Pond. Nitrogen loading factors are the same as those utilized in Massachusetts Estuaries Project assessment of Plymouth Harbor (Howes and others, 2017). Listed sources are the primary basis, but most have been confirmed by other sources and/or modified to better reflect conditions in Plymouth.			
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 surface P load	45	mg/sqft	measurements in Crystal Lake Management Plan; road lengths within 100 m buffer
Roof surface P load	0.23	kg/ha/yr	Waschbusch, <i>et al.</i> , 1999 modified by P groundwater velocity
Atmospheric P deposition on pond surface	5 to 8	mg/m2/yr	Reinfelder, <i>et al.</i> , 2004
Lawn: Fertilizer load	0.02	lb P/ac/yr	Literature review adjusted to account for statewide fertilizer P restrictions
Nitrogen			
Wastewater flow	Measured water use	Adjusted for consumptive use	Town records
Wastewater N coefficient	23.63	mg/L	MEP; MassDEP-approved
Road surface N load	1.5	mg/L	MEP; MassDEP-approved
Roof surface N load	0.75	mg/L	MEP; MassDEP-approved
Atmospheric N deposition on pond surface	1.09	mg/L	MEP; MassDEP-approved
Common Factors			
Watershed Recharge Rate	27	in/yr	Masterson, <i>et al.</i> , 2009
Precipitation Rate	44.2	in/yr	MEP; MassDEP-approved
Building Area	Actual	ft2	MassGIS aerial photo review
Road Area	Actual	ft2	Mass. DOT records
Lawn: Area	measured	ft2	Aerial photo review

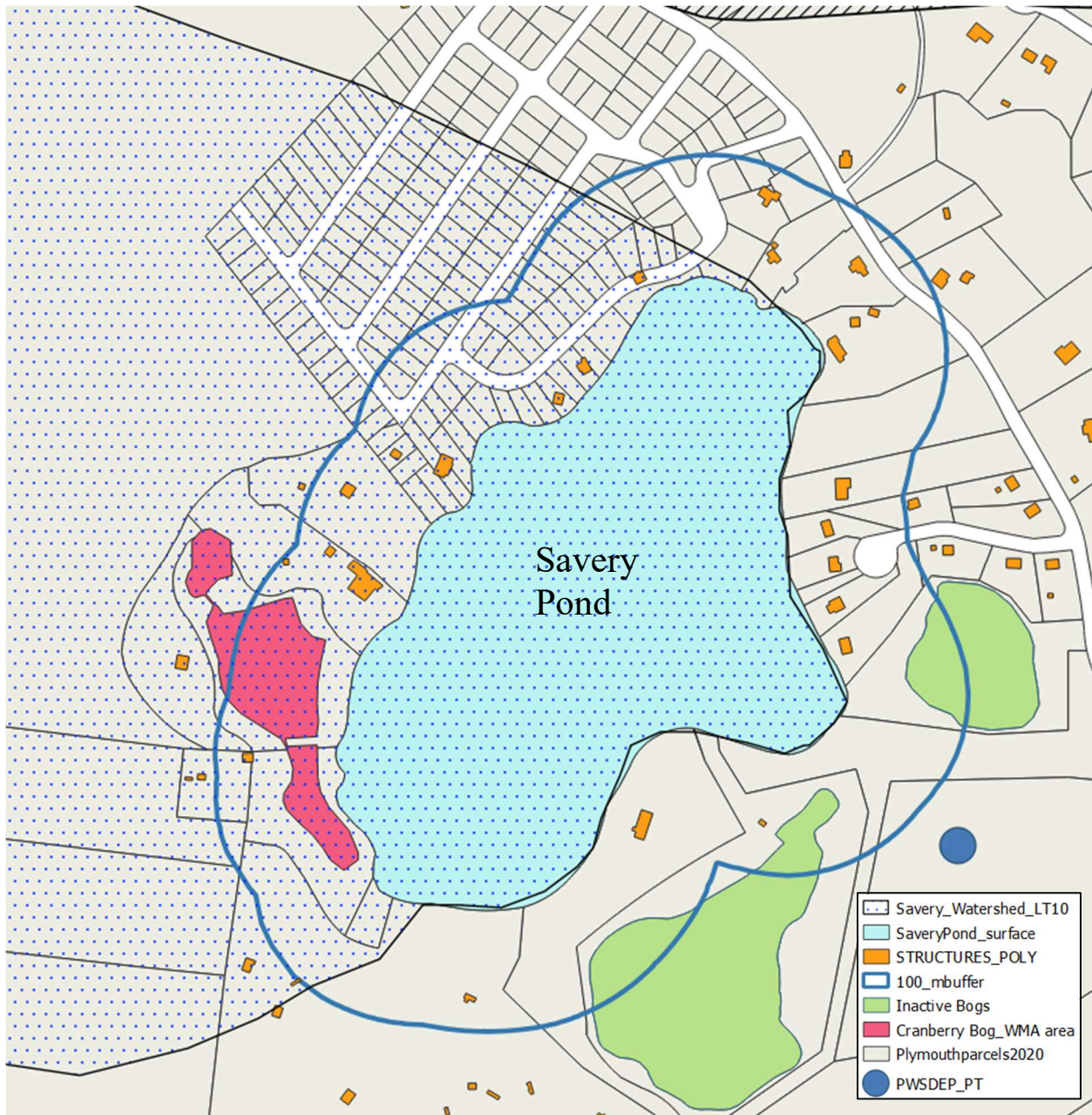


Figure IV-21. Savery Pond Watershed Parcels Reviewed for Phosphorus Loading Budget. Watershed parcels upgradient of the pond and parcels downgradient of the pond but within 100 m were reviewed for potential phosphorus additions to the pond. None of the downgradient parcels had identified features that would contribute P to the pond. The age of the buildings and the on-site septic system (OSS) leachfields in upgradient parcels were determined and compared to likely phosphorus travel time to the pond. Nine residences were identified as having buildings and OSS old enough to have P reaching the pond. Additional identified watershed P sources were the cranberry bog within the watershed (red), roads within the 100 m buffer, and atmospheric deposition on the pond surface.

loading factors have shown that annual *per capita* phosphorus loads range from 1.1 to 1.8 pounds, while sandy soil retention factors range between 0.5 and 0.9. Combining these factors together results in an annual *per capita* wastewater load to a pond in sandy soil of between 0.11 and 0.9 lb. If one assumes two people per house⁷², the *per capita* range results in an average individual septic system load to the pond of 0.2 to 1.8 lbs, which has a mid-point of 1 lb per septic system per year. Combining this estimate with the age of individual septic system leachfields upgradient of Savery Pond resulted in an estimated total 2020 wastewater phosphorus load to Savery Pond of 3.2 to 5.0 kg/yr depending on the slow or fast phosphorus travel time, respectively.

Similar to septic phosphorus contributions, lawn fertilizer phosphorus contributions to ponds also have a number of considerations, including soil types, fertilization rates, irrigation and recharge rates, and fertilizer formulations. The Massachusetts Legislature passed an act in 2012 and accompanying regulations were established in 2015 that prohibited the application of turf fertilizers containing phosphorus except when a soil test indicates phosphorus is needed or a lawn is being established.⁷³ Past reviews of homeowner fertilizer practices in the region have generally showed that higher application rates were utilized by lawn services than homeowners and that shifts from seasonal to year-round occupancy also increased fertilizer application rates.^{74,75} These reviews also noted wide ranges of application rates, which further suggests that individual homeowner practices are important, especially in situations where the number of houses with potential impacts are limited. Project staff reviewed aerial photographs of watershed properties adjacent to the pond and found that only 3 had lawns. Based on the factor in Table IV-3 and the measured lawn areas, the total annual phosphorus load from lawns near Savery Pond was estimated as 0.01 kg P/yr.

Another source of phosphorus loading to surface waters is direct atmospheric deposition to the pond surface, through both precipitation and dry deposition. The most extensive local dataset of chemical constituents in precipitation is from a station in Truro at the Cape Cod National Seashore. These results, which were collected through the National Atmospheric Deposition Program, include many factors, but did not regularly include phosphorus and samples that did include phosphorus generally had detection limits too high for accurate measurements.⁷⁶ However, the primary airflow over southeastern Massachusetts during the summer is from the southeast, which is air that was last over land in New Jersey. The New Jersey Department of Environmental Protection measured phosphorus in atmospheric deposition from 1999 through 2003.⁷⁷ Although data is not available to assess whether loads were modified in the passage of the air over the Atlantic Ocean, phosphorus deposition across all 10 sites in the New Jersey

⁷² Average residential occupancy in Plymouth for the 2010 US Census was 2.65 people per house.

⁷³ 330 CMR 31.00 (<http://www.mass.gov/eea/docs/agr/pesticides/docs/plant-nutrient-regulations.pdf>)

⁷⁴ Howes, B.L., E. Eichner, and A. Unruh. 2016. Updated Watershed Nitrogen Loading from Lawn Fertilizer Applications within the Town of Orleans.

⁷⁵ Howes, B.L. and L.M. White. 2005. Watershed Nitrogen Loading from Lawn Fertilizer Applications within the Town of Orleans, Massachusetts. University of Massachusetts – Dartmouth, School of Marine Science and Technology, Coastal Systems Program. New Bedford, MA.

⁷⁶ Gay, F.B. and C.S. Melching. 1995. Relation of Precipitation Quality to Storm Type, and Deposition of Dissolved Chemical Constituents from Precipitation in Massachusetts, 1983-85. U.S. Geological Survey, Water Resources Investigation Report 94-4224. Marlborough, MA. 87 pp.

⁷⁷ Reinfelder, J.R., L.A. Totten, and S.J. Eisenreich. 2004. The New Jersey Atmospheric Deposition Network. Final Report to the NJDEP. Rutgers University, New Brunswick, NJ. 174 pp.

monitoring network was relatively consistent, varying between 5 and 8 mg/m²/yr (see Table IV-3). Review of other northeastern datasets suggests that these rates are reasonable.⁷⁸ Application of these factors to Savery Pond resulted in an estimated atmospheric phosphorus load to the pond surface of 0.6 to 0.9 kg P/yr.

Stormwater runoff is another potential watershed phosphorus source. Runoff is the result of precipitation on impervious surfaces, such as roofs or roads. Since roof runoff within the Savery Pond watershed is usually discharged to the land surfaces, phosphorus from roof runoff would again be subject to travel time considerations, as well as travel through the vadose zone to reach the groundwater. Project staff determined the roof areas of upgradient properties, the ages of the buildings, and used a range of roof runoff factors (*e.g.*, phosphorus concentrations, subsurface attenuation, etc.) to estimate roof loads for all the buildings close to Savery Pond and within the watershed. Based on the range of phosphorus groundwater travel time, roof loading varied between 0.03 and 0.07 kg P/yr. Since there are no direct overland stormwater discharges to Savery Pond, stormwater phosphorus loading from roads was based on the area of roads within 100 m of the pond. Consideration of the same factors as roof runoff, the road phosphorus load to Savery Pond was estimated as 1.4 kg P/yr.

Finally, staff estimated the phosphorus load from the adjacent cranberry bog at the western edge of the pond. Among all the watershed sources, phosphorus contributions from the cranberry bog are the most uncertain because individual bog management practices and interaction with the groundwater play a large role in how much phosphorus (and nitrogen) are exported from an individual bog. Measurements of annual phosphorus exports from individual bogs in southeastern Massachusetts have areal rates of 0 to 1.7 kg/ac. For Savery Pond, staff used a rate of 1.6 kg/ac based on net measurements from three nearby bogs⁷⁹ and determined the cranberry bog area based on MassDEP Water Management Act permitting.⁸⁰ The annual cranberry bog load to Savery Pond was estimated as 5.0 kg/yr.

Calculation of the annual watershed P budget includes the sum of the inputs from all the various sources. Using the phosphorus loading factors listed in Table IV-3, ages of the houses and septic systems, and distances to the pond, project staff estimated the annual watershed phosphorus loads to Savery Pond between 10.5 and 12.4 kg P/yr. Assuming aerobic sediment conditions within the pond, sediments would add an additional 0.6 kg P/yr to the pond water column. The best estimate of the annual phosphorus load to Savery Pond is 13 kg/yr.

Since nitrogen is not the key management nutrient and might offer additional insights into watershed/water column interactions because it behaves differently in the environment, staff also developed a set of watershed nitrogen loads. Since nitrogen moves with the groundwater and is largely unattenuated in aquifer systems, the nitrogen loading review focused on the entire Savery Pond watershed, not just the properties adjacent to the pond. Review of the entire watershed found there were 22 developed residential properties within the watershed. Using input values

⁷⁸ Vet, R. *et al.* 2014. A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. *Atmospheric Environment*. 93 (2014): 3-100.

⁷⁹ Demoranville, C. and B. Howes. 2005. Phosphorus Dynamics in Cranberry Production Systems: Developing the Information Required for the TMDL Process for 303D Water Bodies Receiving Cranberry Bog Discharge. Prepared for MassDEP. 139 pp.

⁸⁰ MassDEP Water Management Act cranberry bog GIS layer. From J. McLaughlin, MassDEP SERO.

developed for Plymouth during the Massachusetts Estuaries Project (MEP) assessment of Plymouth Harbor⁸¹ (key factors are listed in Table IV-3), project staff estimated the watershed nitrogen load to Savery Pond as 454 kg N/yr. This load would likely be associated with winter conditions, since summer conditions would likely be subject to the groundwater flow changes discussed in the water budget section above.

In addition to the watershed loads of phosphorus and nitrogen, what is measured in the pond water column is also dependent on internal loads from the sediments and the residence time of water within Savery Pond. As discussed above, both of these factors are variable and somewhat interlinked. As discussed in the water quality review, there are 17 estimates of the water column phosphorus mass and 19 estimates of the nitrogen mass in the water column. These estimates are mostly based on samples collected in 2016 and 2020 and both sets of estimates cover April to October (see Figure IV-10).

Sediment nitrogen regeneration rates from the core measurements were relatively consistent and did not vary with depth. Since anaerobic conditions did not develop throughout 2020 and the water column remained aerobic throughout the year, sediment nitrogen contributions to the mass of nitrogen in the water column would be relatively stable throughout the growing season (*i.e.*, April – October). As such, the only variation in the TN water column mass should be dependent mostly on changes in the pond residence time. In April water column measurements, the average water column N mass was 62 kg with a range of 55 to 71 kg (three readings in 2019 and 2020). Review of all April nitrogen sources (*i.e.*, sediment aerobic nitrogen flux balanced with estimated particle settling and watershed N inputs) with a 48 day residence time (based on the regional USGS model) results in a 60 kg estimated water column nitrogen mass. This mass in the middle of the measured April range in N mass (55 to 71 kg).

Review of the well pumping rates suggests that April water supply withdrawals in some years may reduce the pond residence time even prior to the usual summer increase in pumping. Pumping at the John Holmes well in 2019 and 2020 differ by approximately a third. April 2019 pumping at the John Holmes well was 0.24 MGD, similar to the average of 0.26 MGD from January to March. These rates approximate the USGS regional model pumping assigned to the well. In contrast, April 2020 pumping was 40% higher (0.34 MGD) with an average of 0.31 MGD from January to March.

Using the changes in the measured water column nitrogen masses in 2019 and 2020, it is possible to back calculate estimated pond water residence times. These calculations show that estimated residence times were slightly higher in May (62 to 67 days) and then gradually increased to a maximum of 115 to 145 days in August before declining in September and then again in October. The high end of the August residence time range is relatively consistent with the high groundwater, summer estimate based on water flows (see Table IV-3). This review also suggest that the sediments are only a minor contributor to the water column nitrogen mass and that the estimated nitrogen load from the watershed is accounting for all the nitrogen sources to Savery Pond (Figure IV-22).

⁸¹ Howes B., R. Samimy, S. Kelley, J. S. Ramsey, E. Eichner, and D. Schlezinger. 2017. Massachusetts Estuaries Project Linked Watershed-Embayment Model to Determine the Critical Nitrogen Loading Threshold for the Plymouth Harbor, Kingston Bay and Duxbury Bay Estuarine System, Towns of Plymouth, Kingston and Duxbury, Massachusetts, Massachusetts Department of Environmental Protection. Boston, MA. 234 pp.

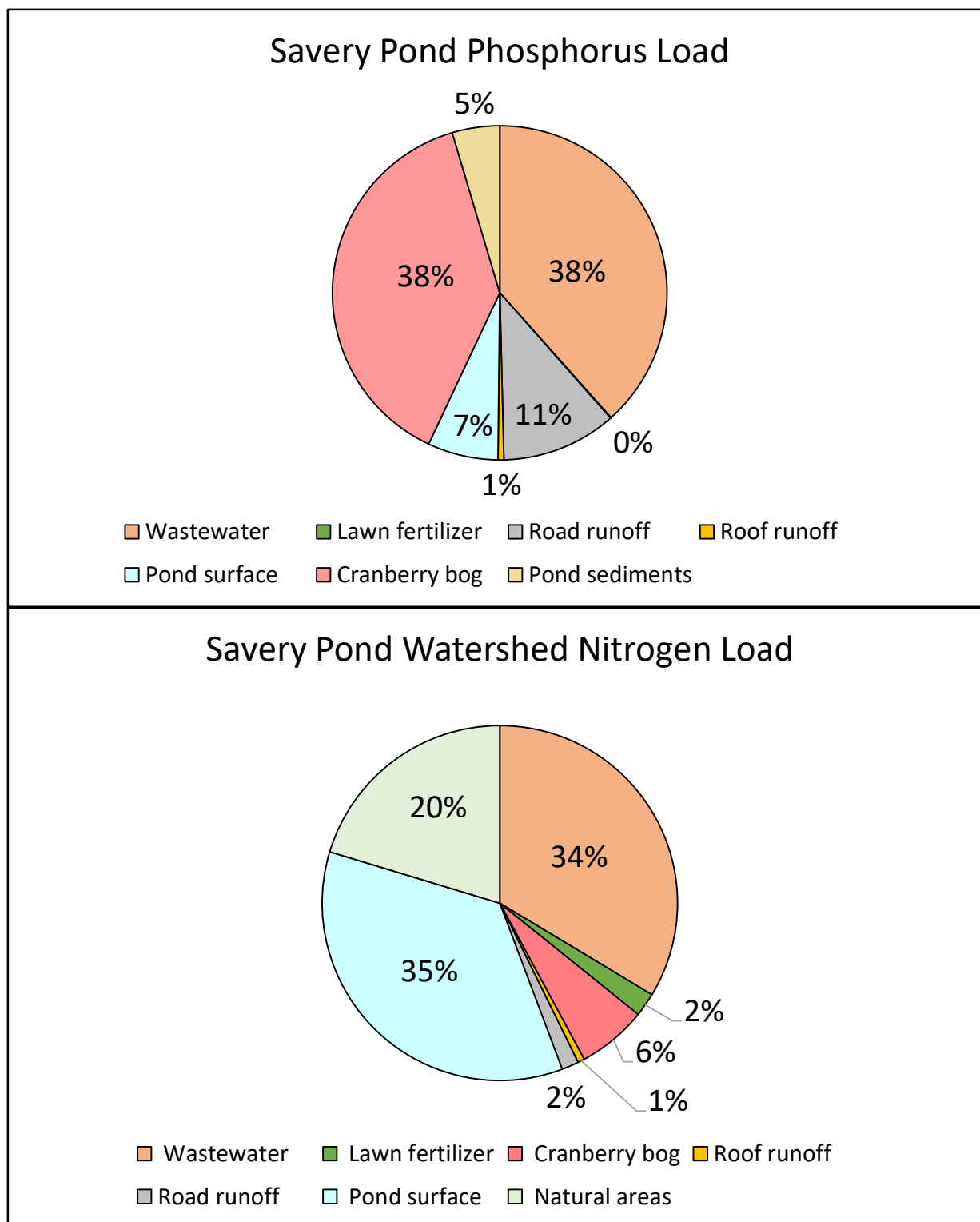


Figure IV-22. Savery Pond Annual 2020 Phosphorus and Nitrogen Budgets. Annual nitrogen budget is 454 kg N/yr, while the annual phosphorus budget is 13 kg P/yr assuming aerobic water column conditions year-round.

Matching watershed phosphorus loading to pond water column mass was a bit more challenging because in addition to all the interlinked factors in the nitrogen loading assessment, phosphorus regeneration from the sediments varies significantly within each year, as well as between years. Water column TP mass generally showed an increase of 2 to 3 kg between April and June, sustained high levels June through August, and then a decrease to April levels in October. As with nitrogen there are only 2 to 4 mass readings per month and most of the readings were collected in 2016 or 2020. Review of low groundwater period (2016) showed water column TP masses 1.5 to 2 kg higher than the TP mass at the higher groundwater elevations/inflow.

Review of watershed phosphorus inputs, potential sediment contributions, and variations in pond water residence times suggest that seasonal residence time fluctuations are the key process causing year to year shifts in water column phosphorus mass in Savery Pond and periodically significantly magnifies the impact of the relatively constant phosphorus loading. Review of the sediment core incubation results show that under aerobic conditions that tend exist most of the time in Savery Pond, the sediments are either removing or adding a small amount of phosphorus to the water column (-0.12 kg or +0.08 during the 48 day residence time based on the USGS watershed). During anaerobic conditions, sediments P loads were also relatively minor except during periods of increased release. Core incubations showed that sustained anaerobic conditions are required for notable sediment phosphorus release and these were only measured by the continuous recorder deployment in 2016 and were not measured in any of the DO profiles collected in 2016 or 2020.⁸² Based on the 16 days of anaerobic conditions measured in 2016, the sediments would have added 0.3 and 0.5 kg. Since anaerobic conditions are relatively infrequent and the largest release only occurs after 8 days of sustained anaerobic conditions, the sediments are generally not a significant contributor to the summer increase in the water column TP mass.

Review of the watershed sources of phosphorus showed that the overall estimated load was a reasonable match for the water column measurements and that residence time changes accounted for most of the change in water column phosphorus mass. Loads from septic system wastewater and the adjacent cranberry bog were the predominant sources (see Figure IV-22). Watershed loads without sediment loads were estimated at 5.0 to 8.4 kg during a summer residence time, while average measured water column mass in June to August was 6.6 kg with a maximum of 7.8 kg (see Figure IV-10).

Based on these evaluations, higher water column phosphorus mass measurements are mostly due to longer pond residence time. Highest water column P mass will be during years where low groundwater and low summer precipitation both occur. Low summer precipitation will tend to cause increased public water supply pumping, which will compound low groundwater conditions. Among the available measurements, 2016 is the only year when both of these conditions were measured. Anaerobic water column conditions were also measured in 2016. Based on the available data, low groundwater and low precipitation result in longer residence times, which in turn, leads to anaerobic conditions and larger sediment contributions of phosphorus to the water column.

⁸² The seven 2017 DO profiles, received after the Management Plan was completed, showed increased frequency of low DO in deepest waters (4 of 7), but also showed that they were not continuous (see Appendix A).

IV.E. Savery Pond Diagnostic Summary

Savery Pond is a 27-acre freshwater pond located west of Old Sandwich Road and northwest of Route 3A within the Town of Plymouth. The lake has a maximum depth of 4 m, an average depth of 1.74 m, and a total volume of 192,418 cubic meters. It has a 2,050,309 square meter watershed located mostly to the north of the pond, an outlet stream to Ellisville Marsh, and a water residence time that varies significantly with the season. The estimated annual pond water residence time ranges from 48 days to 145 days with even longer times during summers with low groundwater levels and low precipitation.

Water quality data has been collected from Savery Pond 23 times since 2014 with two years where data was collected at least monthly during the summer (April to September in 2016 and 2020). Collected data has included temperature and dissolved oxygen profiles, clarity readings, and laboratory assay results from water samples. Complementary data was collected to address identified data gaps in 2016, 2019, and 2020. In 2016, a continuous sensor array was installed at 2.4 m depth with three HOBO temperature loggers at shallower depths. This deployment provided insight into intermittent low oxygen events, as well as temporary thermal stratification that occurs in the pond water column. In 2019, sediment cores were collected and incubated to measure phosphorus and nitrogen flux from the sediments under aerobic and anaerobic conditions. In 2020, TMDL Solutions and CSP/SMASST team worked with the Town to identify and address additional data gaps that would need to be filled in order to complete a pond management plan. Data gap surveys included a year of streamflow monitoring and water quality samples (2019 to 2020), an aquatic plant survey, and phytoplankton population monitoring. This report reviews all the available data and presents a refined assessment of the lake ecosystem and the complex inter-relationships among its components. This diagnostic assessment provides a reasonable understanding of how the water quality conditions are created in Savery Pond and how they change throughout the year and from year-to-year. Developing this understanding allows the reliable prediction of the impact of potential management strategies to address the pond's water quality impairments.

Collectively, the available data showed that Savery Pond water quality was periodically impaired usually during July or August. Data also showed that water quality is controlled by phosphorus and phosphorus concentrations are regularly high. Dissolved oxygen levels are usually acceptable except when the water column has occasional and temporary temperature stratification. Only 7 of the DO readings (6%) from profile measurements were less than the state regulatory minimum. Four of these 7 readings occurred in July when nutrient concentrations are typically highest. July was also the month with the strongest water column temperature stratification. However, more frequent readings show that transitory events can occur that can trigger significantly impaired conditions (*i.e.*, temporary temperature stratification causes hypoxia in bottom waters as noted in the 2016 continuous sensor deployment). Overall review of nutrient concentrations show that they increase significantly during the summer (shallow concentrations were up to 2X higher than spring concentrations).

Review of water and phosphorus sources show that the summer increase in nutrient concentrations is not due to sediment additions, but is due to longer water residence time within the pond. Review of the water budget shows that the nearby John Holmes public water supply well increases its summer pumping by 2X the September to May average. Review of past

groundwater modeling in the area shows that increased well pumping expands the well capture area into the Savery Pond watershed. This expansion reduces the amount of groundwater flowing through the pond and, therefore, increases the water residence time in the pond. Increased residence time increases the concentrations of phosphorus and nitrogen in the pond. Preliminary estimates of residence times based on water quality measurements suggest that the residence time in the pond increases from the 48 days determined from USGS regional groundwater modeling to 145 days on average during the summer and to over 200 days during years when increased pumping is also accompanied by low summer precipitation and low groundwater levels. Increased residence time leads to increased phosphorus and nitrogen concentrations in pond waters and the greater availability of nutrients leads to greater phytoplankton growth and decreased clarity.

Monthly phytoplankton sampling during April to October 2020 showed that blue-greens/cyanobacteria become the dominant cell type during the summer as phosphorus concentrations increase. However, the highest blue-green cell count in 2020 was 465 cells/ml in July, well less than the MassDPH 70,000 cells/ml cyanobacteria threshold established as a blue-green direct contact advisory level. It should be noted, however, that 2020 was a high groundwater year, so summer pond water residence times would have been less than during 2016. The phytoplankton sampling shows that summer conditions generally favor blue-green growth and longer residence times will create even more favorable conditions for cyanobacteria growth by increasing the available phosphorus in the water column.

Review of the sediment core incubations generally shows that the sediments are a minor contributor to the water column nutrient concentrations and do not vary much other than during exceptional anaerobic events. During aerobic conditions, which are usually present in the pond, the sediments throughout the pond either release or uptake a small amount phosphorus with shallow sediments removing phosphorus and deep sediments adding phosphorus. If anaerobic conditions occur, they must be sustained for at least 8 days before the iron-bound phosphorus is released from the sediments. However, the rate of iron-bound P release varies with depth and the rate of release from the deep sediments only increases slightly from the aerobic conditions rate, while the shallow sediments have a substantially higher rate. Therefore, the amount of sediment P released during anaerobic events must 1) be sustained for more than 8 days and 2) must occur in shallower waters (<2 m). Based on the core results, the estimated sediment P addition from the 16 day anaerobic period measured in 2016 was only 0.3 kg. If anaerobic conditions were sustained at throughout the water column for the 16 days, phosphorus sediment release would be up to approximately 1 kg. Since these additions would rapid and would occur when high P concentrations would already be present due to the seasonal increase residence time, these events would help to explain the algal blooms experienced in Savery Pond. Nitrogen release from the sediments was relatively consistent with depth and did not change significantly in the transition from aerobic to anaerobic conditions, suggesting that denitrification within the surficial sediments is generally low.

Review of the watershed sources of phosphorus found that the two primary sources were septic system leachfields on properties adjacent to the pond and the cranberry bog to the west of the pond. Comparison of water column phosphorus and nitrogen mass generally indicated that

changes in the water column concentrations were caused by seasonal changes in the residence time of water within the pond. Loads from the watershed sources were relatively constant.

Overall, Savery Pond periodically shows impaired water quality. Specific impairments include high phosphorus concentrations, low DO, diminished clarity and cyanobacteria blooms. These impairments do not occur every summer and seem to be enhanced by the combined impact of low groundwater levels, low summer precipitation, and high pumping of the nearby public supply well.

V. Savery Pond Management Plan: Goals and Options

Savery Pond is periodically impaired based on comparison of water quality monitoring results to both ecological and regulatory measures, as noted in the Diagnostic Summary above. These impairments include: a) high water column phosphorus and chlorophyll concentrations b) occasional deep dissolved oxygen concentrations less than the Massachusetts regulatory minimum, c) diminished clarity, and d) algal bloom closures. Review of available water quality data clearly identifies phosphorus as the key nutrient determining water quality conditions in Savery Pond, but variations in the groundwater inflow, caused by water level fluctuations, precipitation changes, and water supply withdrawals at a nearby well, determines the magnitude of the phosphorus concentrations in pond water.

It is clear from the diagnostic review that the watershed phosphorus loading from the watershed would result in acceptable water quality conditions if the residence time of the pond did not substantially increase during the summer. Estimated residence time increased from 48 days determined from USGS regional groundwater modeling to 145 days on average during the summer and to over 200 days during years when increased water supply pumping is also accompanied by low summer precipitation and low groundwater levels. The increase in residence time generally matched the increasing phosphorus concentrations in the pond suggesting the watershed loading is relatively constant.

The increase in the residence time is due to seasonal changes in groundwater elevations but mainly increased summer water withdrawal from the John Holmes water supply well, which is located approximately 1 km to the northwest of Savery Pond. This well is the primary source of public water to Cedarville and pumping generally increases from 0.2 to 0.3 MGD in the spring to 0.7 to 0.8 MGD in July. Although updated groundwater modeling would be necessary to confirm the impacts of the pumping, past modeling suggests that the seasonal increase in pumping expands the capture area of the well into the winter/spring Savery Pond watershed. The transfer of this water to the well reduces the groundwater flowing through the pond and results in increases in the pond water residence time, which, in turn, results in increased phosphorus concentrations in the pond. Because each public water supply well represents a substantial public infrastructure investment, it raises the question of whether and how phosphorus concentrations could be reduced to acceptable levels without altering the pumping schedule of the well during periods where water supply demand is greatest, such as low rainfall years.

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. The pond generally attains MassDEP minimum conditions for the available numeric standards in the state water quality regulations, but does not attain some of the descriptive standards and Savery Pond is on MassDEP's most recent list of waters in the Impaired Waters/Waters requiring a TMDL because of past harmful algal blooms. Since the pond is in the impaired waters list, the Town has some obligation to address the water quality impairments in the pond.

It is recommended that the Town implement management option(s) before approaching MassDEP to address TMDL requirements. The Town should review the potential options and the recommended option discussed below. If monitoring completed after the Town's

implementation of the preferred management strategy demonstrates that the state water quality standards are attained and avoids additional harmful algal blooms, then the Town should approach MassDEP with the solution and a draft TMDL for MassDEP approval. Development of a TMDL would remove Savery Pond from the MassDEP Impaired Waters List.

Since this is a draft management plan, TMDL Solutions and CSP/SMASST staff will review potential options that apply to the impairments in Savery Pond with the Town and its various Savery Pond stakeholders. Final recommended options will be developed and incorporated into a final version of this plan through these discussions before moving forward to implementation.

The following discussion lists potential management options based on the consideration of the pond functions reviewed in the Diagnostic Summary and discusses the most applicable management options that will restore appropriate water quality conditions in Savery Pond and allow the Town to attain regulatory compliance.

V.A. Savery Pond TMDL and Water Quality Goals

Nutrient TMDL development is generally based on a set of water quality and ecosystem conditions developed by comparisons to either similar water bodies or acceptable characteristics within the impaired water body. Most of the EPA-approved TMDLs in southeastern Massachusetts are nitrogen TMDLs based on the Massachusetts Estuaries Project (MEP) assessments and this process provides some insights about TMDL development in Massachusetts. The MEP team utilized a multiple parameter approach to the assessments that included measurement and review of a) historic and current eelgrass coverage (eelgrass functions as a keystone species in southeastern Massachusetts estuaries), b) benthic communities (invertebrates living in estuaries provide the primary food source for most of the secondary consumers⁸³), c) water quality conditions, including nitrogen concentrations (nitrogen is the generally the nutrient controlling water quality conditions in estuaries), dissolved oxygen, and chlorophyll, 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 the available data and system modeling. It was recognized that this relatively simple regulatory approach would require confirmatory direct assessments of key ecological components (eelgrass and benthic communities), but this approach provided a short-hand regulatory goal that could be used by towns and regulators for assessing progress toward restoring water and habitat quality.

Freshwater pond TMDLs are relatively limited in Massachusetts with only one completed within the Plymouth/Cape Cod Ecoregion over the past 10 years.⁸⁴ During the initial development of the Cape Cod PALS program in 2001, the initial PALS Snapshot data were used with a USEPA nutrient criteria method to determine that an appropriate total phosphorus concentration for Cape Cod ponds was between 7.5 to 10 µg/L.^{85,86} As with the MEP assessments, it was recognized

⁸³ Fish and birds

⁸⁴ White Island Pond phosphorus TMDL was approved in 2010.

⁸⁵ Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas.

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

that selection of this criteria would also require consideration of other measures such as dissolved oxygen concentrations, the physical characteristics and setting of each pond, and the role of sediment nutrient regeneration. Subsequent review of more comprehensive pond-specific monitoring data has shown that some ponds in the ecoregion may be more sensitive to phosphorus additions and impaired conditions may exist at TP concentrations lower than this initial range.⁸⁷

Project staff reviewed Savery Pond phosphorus concentrations and other water quality parameters, such as bottom water DO concentrations, and found, as expected, that April/May conditions generally represented the highest levels of water quality during a given year with lowest water column DO depletion and lowest TP concentrations in both surface and bottom waters. Closer review of this data showed that none of the April or May profiles (n=6) had DO concentrations less than the MassDEP regulatory minimum (5 mg/L). Average clarity in April/May readings was 87% of the water column. Maximum water column phosphorus mass during these samplings was 5.7 kg. Average surface TP concentrations among these April and May readings was 23 µg/L (n=6),⁸⁸ which would result in a water column TP mass of 4.4 kg. Looking at individual sampling dates in the summer months (June to September) generally showed that dates with surface TP concentrations of 26 µg/L or less had DO concentrations above 5 mg/L throughout the water column and clarity of at least 50% of the water column. Based on this review, project staff recommend 26 µg/L TP as the upper limit to sustain acceptable water quality in Savery Pond and as a preliminary TMDL target. This concentration throughout the water column would result in a pond-wide TP water column mass of 5 kg.

Review of the available samplings (n=14) show that the proposed 26 µg/L TP limit was occasionally attained during the summer, but not consistently. All of the September samplings (n=4) had surface TP concentrations were less than 26 µg/L. Only two of the June to August samplings were less than 26 µg/L (and both of these were in 2020). Chronological review of the samplings showed that in 2016, surface TP concentrations were greater than 26 µg/L in all June, July, and August samplings (n=5), while in 2020, only the May and July exceeded 26 µg/L TP.

Based the review in the diagnostic assessment, consistently attaining 26 µg/L TP during the summer in Savery Pond is dependent on maintaining a relatively short residence and/or reducing the TP input from the watershed. Also as summarized in the above Diagnostic Assessment, the residence time is dependent on both the pumping at the John Holmes well, the aquifer groundwater elevations, and the amount of precipitation during the summer. Review of the nitrogen loads resulted in an estimated pond water residence time of 62 to 67 days in May; average surface TP in May was 26 µg/L TP (n=3). Pumping at the John Holmes well in May averages 0.41 MGD (range = 0.28 to 0.62 MGD). Average pumping at this well was greater than 0.41 MGD from June to August, but September pumping averaged 0.41 MGD. Monthly minimum pumping was below 0.41 MGD in all months except July and August, while maximum pumping was above 0.41 MGD in 8 of 12 months. If the pumping cannot be limited in order to maintain a shorter water residence time in the pond, then the other option is to reduce the phosphorus contributions from the watershed and sediments.

⁸⁷ e.g., the Orleans Freshwater Database (Eichner, *et al.*, 2017) shows that Bakers Pond has an average summer, surface TP concentration of 5.6 µg/L and regular DO loss in most of its cold water habitat/hypolimnion.

⁸⁸ April shallow concentrations averaged 20 µg/L TP (n=3), while May shallow concentrations averaged 26 µg/L TP (n=3).

Review of the watershed and sediment information in the Diagnostic Assessment show that watershed phosphorus inputs are generally much larger than summer sediment inputs with the exception of extended periods of anoxic bottom waters. The primary sources of watershed phosphorus are septic system leachfields and the cranberry bog adjacent the pond. Based on the sediment core incubations, the maximum potential anaerobic phosphorus release from the whole pond would be 2 kg, which would require the highly unlikely event of anaerobic conditions throughout the water column for 41 days. This release would be approximately half of either the annual watershed wastewater load or cranberry bog load, both of which are assumed to be adding phosphorus consistently throughout the year.

Given the variability in Savery Pond, both natural and controllable, developing a reliable management strategy may require some adjustments as conditions change. Because of these variabilities, it is recommended that monitoring of the pond continue throughout implementation of phosphorus management actions to gauge the response in pond water and habitat quality and to potentially refine the target threshold as appropriate. When acceptable conditions have been regularly achieved that attain MassDEP regulatory minimums, it is recommended that the Town then provide MassDEP with a recommended TP TMDL to prevent future impairment of the pond.

V.B. Review of Management Options

The TP mass in the water column of Savery Pond has been documented as varying between 3.4 and 7.8 kg based on measured water column concentrations. Much of this variability is related to changes in water residence time with relatively stable inputs from adjacent properties within the pond watershed, as well as relatively small internal loads from the sediments. Preliminary review in this Management Plan suggests that management of water withdrawals from the John Holmes wells is the key to managing water quality within Savery Pond. However, more in-depth review of groundwater changes due to pumping are required to confirm. Given the importance of pond water residence time to the management of the pond, it is recommended that evaluation of groundwater flow, including well pumping, precipitation and groundwater elevations be more thoroughly reviewed. Watershed and in-pond controls should only be approached if water residence time cannot be efficiently managed.

A comprehensive list of potential lake management options is provided in Table V-1. Among the applicable options, management of the pond water residence time, reduction in watershed phosphorus loads, and regular water column alum treatments are the options most likely to attain acceptable water quality in Savery Pond. Management of internal phosphorus loads (*i.e.*, preventing sediment regeneration) may lessen the likelihood of worst case conditions (*i.e.*, algal blooms), but the regular internal sediment loads are relatively small load compared to watershed sources and worst case sediment releases are infrequent and still relatively small compared to watershed sources. Some combination of the most applicable options may also attain the water management goals, but staff will review these options if discussions with the Town and Savery Pond stakeholders indicate that they are worth pursuing. Staff reviewed all potentially applicable options for Savery Pond.

Based on the Diagnostic Summary, the following techniques were the most applicable to water and habitat quality management in Savory Pond:

- a) Residence Time Management/Dilution: keeping the pond water residence time at less than approximately 120 days should maintain acceptable water quality without watershed phosphorus management.
- b) Watershed Wastewater P reductions: septic system wastewater is the second largest source of watershed P contributions to Savory Pond.
- c) Watershed Fertilizer P reductions/controls: cranberry bog fertilizers are identified as the largest watershed source based on regional studies, but part of this source may be residual release from past fertilizer applications even if no new fertilizers are currently being added; lawn fertilizers additions are negligible.
- d) In-pond P water column alum treatments: removal of a portion of the water column P mass by regular annual alum treatment (this would also reduce the sediment P regeneration at the same time).

There are a number of more experimental techniques that were also reviewed (*i.e.*, phosphorus reducing septic systems). Some of these were considered potentially applicable, but are considered experimental due to few or no field studies evaluating: a) their efficiency of lowering P levels, b) their ecosystem impacts, c) their regulatory standing with MassDEP and/or d) their general lack of use in New England and Massachusetts conditions.

The following section reviews applicable options using the information in the Diagnostic Summary, provides estimated costs for implementation, potential regulatory requirements that would need to be addressed for implementation, and prospective timelines.

Table V-1a. WATERSHED PHOSPHORUS LOADING CONTROLS: Address watershed sources of P entering the pond, typically: a) road runoff from stormwater, b) septic system P discharges from properties adjacent the pond, and c) excess fertilizers from lawn or turf applications. Other additions can occur from pond-specific sources, such as ditches/pipe connections to areas outside of the watershed. Since P is typically bound to iron rich, sandy aquifer soils in Plymouth, P movement in groundwater tends to be very slow (est. 20-30 yrs to travel 100 m), so watershed controls in these settings typically focus on sources within 100 m of the pond shoreline.

OPTION	Option Variations	Advantages	Disadvantages	Examples of uses	Applicability to Savery Pond
Wastewater P reductions	• Sewering • Alternative Septic Systems • Septic Leachfield Setbacks • Septic Leachfield Replacement or Movement • PRBs	• Addresses watershed wastewater P source • Range of costs to homeowners and can be implemented 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 benefits to be realized due to groundwater flow rates • May not solve all WQ impairments • PRBs will involve shoreline habitat disruptions	• Brewster BOH septic leachfield setback regulation • Preliminary sewer plans in some towns include properties around ponds	<u>Applicable</u> ; wastewater is second largest P source in watershed and overall lake P budgets; 34% of watershed load
Fertilizer P reductions	• Restrict lawn areas, restrict P in lawn fertilizers (done under Mass law) • Require natural buffers near pond with limited paths/use of non-fertilized landscape • Cranberry bogs: treatment of outflow, reduction of P applications	• Relatively straightforward • Can be simple as adjusting landscaping • Requires no infrastructure funding • Low P fertilizer maintains cranberry yield, lowers P loss at no additional cost	• 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</u> ; Cranberry bog estimated as 41% of watershed load; lawn fertilizer P additions addressed through state limitations (<0.1% of watershed load)
Stormwater P reductions	• Remove or infiltrate direct discharge • Recharge outside of watershed, 300 ft buffer • Runoff treatment using BMPs	• Rerouting discharge or infiltration straightforward • Town DPWs usually have stormwater funding • Removes other contaminants e.g., Bacteria, TSS, metals	• Likely insufficient to solve all water quality impairments	• Not specifically done for ponds in the past, but is now being discussed in many towns	<u>Not Applicable</u> ; no identified direct discharge; all current runoff infiltrated in watershed; 12% of watershed P load

Table V-1b. IN-LAKE PHYSICAL CONTROLS: Address internal P or plant growth by changing water or sediment conditions within the pond. These types of *in situ* treatments typically move large volumes of pond water (adding or subtracting) to change concentrations, removing sediments to create greater volume and remove the sediment P source or physical removal/limitation for plant growth. Some of these techniques are difficult to implement in Plymouth-type settings due to hydrogeology.

OPTION	Option Variations	Advantages	Disadvantages	Examples of uses	Applicability to Savery Pond
Enhanced Circulation (shallow ponds), Destratification (deeper ponds)	• Use of water or air to keep water column vertically well mixed • typically used in shallow ponds with weak stratification	• Uses mixing of atmospheric source of oxygen to address sediment oxygen demand • Additional oxygen reduces sediment P release • Prevents oxygen stratification • May disturb blue-green growth	• May spread high nutrients and oxygen demand to rest of water column with improper design • Will destroy cold water habitat in deep ponds; may not be permissible for deep ponds • Varying results • Needs power	• Santuit Pond, Mashpee & Skinequit Pond, Harwich (Solar Bees) • Flax Pond, Harwich (Living Machine) • Varying results	<u>Not Applicable:</u> would maintain acceptable DO year-round; but sediments are only 5% of water column P load and seem to no more than double in worst cases
Aeration (shallow and deep 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	<u>Not Applicable:</u> would disrupt occasional notable SOD during summer, but summer P sediment load is relatively low
Decreased residence time, dilution	• Add water to pond • Restrict watershed water withdrawals	• Increased flushing • Can add treatment additives	• Additional water: need to find source outside of watershed • May create undesirable ecosystem impacts on plankton	• Mostly a hard geology/stream fed solution; need water source	<u>Applicable:</u> analysis shows nearby public water supply reducing groundwater watershed inflow
Drawdown	• Lower water level increases water column atmospheric mixing • Oxidation of exposed sediments	• May provide rooted plant control • May reduce nutrient availability • Opportunity for shoreline cleaning	• Negative impact on desirable species (can affect fish spawning areas) • Difficult or impossible in sandy aquifer settings	• Mostly a hard geology/stream fed solution (limited dewatering at Ashumet Pond was very difficult)	<u>Not applicable</u>

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

OPTION	Option Variations	Advantages	Disadvantages	Examples of uses	Applicability to Savery Pond
Dredging of sediments	• Removal of P with sediments • Wet or dry excavation • Hydraulic dredging (all require dewatering area)	• 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 • Typically expensive • Limited benefit if watershed is primary P source	• Usually reviewed but not implemented due to high cost • Current discussion for Mill Pond, Barnstable in order to deepen filled basin	Not Applicable: sediments not a significant P source
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 sediment oxygen demand and may increase demand and P availability 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)	Not applicable; primary P source are watershed sources

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

OPTION	Option Variations	Advantages	Disadvantages	Examples of uses	Applicability to Savery Pond
Selective Withdrawal	- Remove deep, near-sediment water - Generally done for deep thermally stratified ponds	- Removes impaired waters and nutrients - 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)	none	<u>Not applicable:</u> because of relative shallowness, variability of bottom, and only temporary stratification
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 controlled studies)	<u>Not applicable</u> experimental; would likely have significant regulatory hurdles

Table V-1c. IN-LAKE CHEMICAL CONTROLS: Address P 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	Applicability to Savery Pond
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 • Could result in super-saturation, which may harm sustainable fish population • May have to be used every year	• none	<u>Not applicable</u> : no stable hypolimnion, complex bottom,
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 sediment oxygen demand and may increase available P in the pond

Table V-1c (continued). IN-LAKE CHEMICAL CONTROLS: Address P 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	Applicability to Savery Pond
Phosphorus inactivation	• Addition of aluminum, iron, calcium or other salts or lanthanum clay to bind phosphorus and remove its biological availability from 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)	• 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	• 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 in paired with watershed P source reduction	Alum applications: • Hamblin Pond, Barnstable: 1995, 2015 • Mystic Lake, Barnstable: 2010 • Lovers Lake, Chatham: 2010 • Stillwater Pond, Chatham: 2010 • Long Pond, Harwich/Brewster: 2007 • Lovell's Pond, Barnstable: 2014 • Ashumet Pond, Mashpee/Falmouth: 2011 • Herring Pond, Eastham: 2012 • Great Pond, Eastham: 2013 • Cliff Pond, Brewster: 2016	<u>Not applicable:</u> sediments not a significant P source

Table V-1c (continued). IN-LAKE CHEMICAL CONTROLS: Address P 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	Applicability to Savery Pond
Sediment oxidation (generally regarded as experimental in region)	• Addition of oxidants, binders and pH adjustors to oxidize sediment • 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	• none	<u>Not applicable:</u> town may consider if it chooses to evaluate experimental options in other ponds
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	<u>Applicable;</u> Would require regular, annual treatment; uncertainty regarding floc management (buildup in pond)
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	<u>Not applicable:</u> high nutrient levels already exist; may create non-blue green algal blooms; permitting issues (no track record in MA)

Table V-1d. IN-LAKE BIOLOGICAL CONTROLS: Address P 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 Plymouth settings.

OPTION	Option Variations	Advantages	Disadvantages	Examples of uses	Applicability to Savery 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 evaluation of impact on resident fish populations Given its lack of use in Plymouth region 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 Savery Pond impairments

Table V-1d. IN-LAKE BIOLOGICAL CONTROLS: Address P 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 Plymouth settings.

OPTION	Option Variations	Advantages	Disadvantages	Examples of uses	Applicability to Savery 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	<u>Not applicable:</u> theoretically may be able to reduce sediment levels with accompanying oxygenation system Given its lack of use in Plymouth region ecosystems and lack of peer reviewed studies should be considered experimental and would likely have significant regulatory hurdles
Pathogen addition	• Addition of microbes that will kill algae • May involve fungi, bacteria or viruses	• May cause lakewide reduction in algal biomass • Depending on competition, impacts may be sustained through number of pond years • May be tailored to address specific algae	• Limited scientific evaluation • May cause release of cytotoxins • May cause sediment nutrient additions and increased sediment oxygen demand • May favor growth of resistant nuisance forms of algae • Unknown impacts on rest of ecosystem species • Time between applications unclear	• none	<u>Not applicable:</u> does not address cause of high TP and may increase available P in the pond Given its lack of use in Plymouth region ecosystems and lack of peer reviewed studies should be considered experimental and would likely have significant regulatory hurdles

Table V-1d. IN-LAKE BIOLOGICAL CONTROLS: Address P 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 Plymouth settings.

OPTION	Option Variations	Advantages	Disadvantages	Examples of uses	Applicability to Savery Pond
Competitive addition of plants	• Addition/encouragement of rooted plants to competitively reduce availability of nutrients to phytoplankton/algae through additional growth • Addition of plant pods, floating islands, etc., for removable addition • Plants may create light limiting conditions for algal growth	• May shift nutrient use from phytoplankton/algae to rooted plants and reduce algal biomass • Uses natural processes • May provide prolonged control	• May add additional nutrients to overloaded ponds • May lead to excessive growth of rooted plants • May add additional organic matter to sediments and increase oxygen demand and phosphorus availability	• none, although natural competition in some regional ponds may offer some examples of impacts	<u>Not applicable</u> ; implementation has significant potential downsides and implementation issues; would likely reduce open area of pond available for use; uncertain impact on extensive existing plant population
Barley straw addition	• Addition of barley straw might release toxins that can set off a series of chemical reactions which limit algal growth • Straw might release humic substances 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 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	<u>Not applicable</u> ; may cause increased SOD; generally regarded as unregistered herbicide and cannot be officially permitted or applied by licensed applicator in MA

V.C. Applicable Management Options

V.C.1. Residence Time Management

As discussed in the Diagnostic Summary, changes in pond water residence time appears to be the key factor for determining water quality in Savery Pond. Review of the USGS regional groundwater modeling showed a relatively short residence time of 48 days, but review of groundwater elevations and precipitation shows this varies significantly, is likely longer than 48 days throughout the year, and is notably increased during the summer by water supply withdrawals at the nearby John Holmes well.

The annual average pumping at the John Holmes well between 2010 and 2020 was 52% higher than the rates the USGS included in the groundwater modeling that was the basis for the watershed delineation and the 48 days residence time. If 48 days was the base residence time, then summer pumping at the well would notably increase the pond residence time by reducing groundwater inflow. However, review of winter (October to March) pumping also showed it was 62% higher than the USGS monthly winter pumping data incorporated into the model. Collectively, these higher 2010 to 2020 rates suggest that the current residence time is longer than 48 days throughout the year and tends to be even longer when summer peak pumping occurs.

Review of water quality can provide some guidance about potentially acceptable range of pumping and accompanying residence times. Even with higher than modeled pumping rates and accompanying longer pond water residence times, pond water quality during the April/May period is generally acceptable. Review of the water quality data adjusted to account for an April baseline above the USGS modeling suggests that the April residence time is approximately 90 days. Average pumping in April between 2010 and 2020 was 0.29 MGD with a range of 0.03 to 0.47 MGD, while average pumping in May was 0.41 MGD with a range of 0.28 to 0.62 MGD. Review of groundwater levels and summer precipitation rates were consistent with this estimate.

In contrast, similar review estimated that residence time increases to approximately 220 days on average during the summer. Review of fluctuating groundwater levels were generally consistent and showed that estimated summer residence times could reach 213 days when groundwater levels and summer precipitation are high (*e.g.*, 2019), but increase to 827 days when groundwater levels are low (*e.g.*, 2016). Review of the phosphorus loading analysis shows that a 220 day residence time would result in a water column mass of 7.8 kg, which would match the maximum mass in the water quality datasets and occurred in 2016 with accompanying impaired conditions.

Based on these comparisons, if 0.41 MGD were selected as the upper bound of pumping at the John Holmes well to maintain acceptable water quality in Savery Pond, review of the current pumping rates suggests that this would not require any change in winter pumping strategies, but summer pumping would need to be reduced. Review of 2010 to 2020 monthly pumping rates showed that most (97%) of the monthly pumping rates between October and March were less than 0.41 MGD and 9 of 11 April readings were less than 0.41 MGD. However, in May, only 45% of the monthly rates were less than 0.41 MGD and this percentage decreased throughout the summer until returning to winter levels in October. Pumping rates were less than 0.41 MGD for 18% of June rates, 9% of rates in July and August (*i.e.*, 1 of 11 monthly rates), and 36% in

September. Average monthly pumping rates between May and September was 0.54 MGD with a peak of 0.68 MGD in July. However, the maximum pumping rates between May and September were 44% higher and had a maximum monthly rate of 0.95 MGD (July 2010). Based on this review, an average of 0.27 MGD additional flow would be necessary if the John Holmes well pumping was limited to 0.41 MGD and an additional 0.54 MGD would be required to address maximum monthly pumping of 0.95 MGD.

Implementation of a managed pumping management program at the John Holmes well could attain acceptable water quality in Savery Pond on average without any reductions in current watershed phosphorus loads or treatment of pond water column P. Project staff recognize that this sort of pumping limitation is likely unattainable in the short-term and the Town would benefit from additional confirmation of appropriate pumping volumes through groundwater modeling. Even if this approach was selected immediately, time would be required to develop, plan, fund, and implement this strategy. Development of the potential cost of installation of a new public supply well in a location that did not impact Savery Pond (or other Great Ponds) while fitting it within the existing public water supply well network would require additional tasks outside of the scope of this project.

V.C.2. Watershed Phosphorus Controls

If the residence time cannot be managed or if the full John Holmes well pumping target cannot be met, another applicable approach to ensure acceptable water quality in Savery Pond is to reduce watershed phosphorus inputs. As noted in the water quality review, these inputs are relatively constant throughout the year, so reductions would be required to eliminate or significantly reduce specific categories of loads.

As shown in Figure IV-22, septic system leachfield wastewater and the cranberry bog at the western end of pond were the primary watershed phosphorus sources (each is 38% of the annual load). The other watershed P sources were: road runoff (12%), atmospheric load on the pond surface (7%), pond sediments (5%), and roof runoff (1%). Total average phosphorus load to the water column during the summer is 13 kg, which was consistent with water column measurements.

Watershed P loads would need to be reduced in order to maintain acceptable TP water column concentrations throughout the summer. Attaining the acceptable TP water column concentration of <26 µg/L needs to consider the higher residence times during the summer (average of ~220 days) when the watershed is reduced by higher water withdrawals at the John Holmes well. If watershed phosphorus load reductions are the only management action implemented, the watershed load would need to be reduced by approximately 5 kg from the present 13 kg during the summer to keep water column TP levels below 26 µg/L. A 5 kg phosphorus mass reduction is approximately equal to the entire estimated septic system wastewater P load or the estimated annual P load from the cranberry bog at the western end of the pond. Elimination of controllable loads from road runoff, roof runoff, and sediment contributions combined would be insufficient to attain a 5 kg TP reduction.

V.C.2.a. Wastewater

Removal of all of the wastewater phosphorus from the properties contributing to Savery Pond would require construction of a wastewater collection system (*i.e.*, a sewer system) and treatment and discharge of the collected treated wastewater at a location outside of the Savery Pond watershed. The closest portion of the existing town sewer collection system is approximately 12 km to the north and development of a plan to extend piping to Savery Pond would likely require extensive discussion about a number of issues, including funding, potential connection of properties in between the current system and Savery Pond, 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.

Use of alternative septic systems designed to remove phosphorus at all of the developed properties would be insufficient to attain a 5 kg TP reduction on their own. Either of the currently available MassDEP-permitted, alternative septic systems that remove phosphorus would remove approximate half of the wastewater P load, so another 2.5 kg watershed P would need to be removed to attain the 5 kg removal target if watershed P reductions were the only management approach. This approach would also have to include provisions to address the experimental nature of the two technologies. No phosphorus removal technologies for innovative/alternative (I/A) septic systems are currently approved for general use in Massachusetts.⁸⁹

The two phosphorus removal septic system technologies that are approved for piloting use (no more than 15 installations with monitoring to field test their performance) are: a) PhosRID Phosphorus Removal System and b) Waterloo EC-P for Phosphorus Reduction. 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.

Since both of these on-site systems are approved for piloting/experimental use, average costs for installation and maintenance in Massachusetts (including potential monitoring) are difficult to estimate and would likely change if these technologies are approved for general use. A 2010 proposal to the Town of Mashpee estimated that the individual PhosRID system costs were \$8,364 per unit with an annual operation and maintenance cost of \$574.⁹⁰ Applying inflation adjustments and assuming a 20 year annual cost life cycle, these costs applied to the eight

⁸⁹ MassDEP Title 5 Innovative/Alternative Technology Approval Letters website (accessed 3/2/21).
<http://www.mass.gov/eea/agencies/massdep/water/wastewater/title-5-innovative-alternative-technology-approvals.html>.

⁹⁰ Lombardo Associates, Inc. 2010. Town of Mashpee, Popponesset Bay, & Waquoit Bay East Watersheds. Nitrex Technology Scenario Plan. Submitted to Town of Mashpee. Newton, MA.

properties currently estimated to be contributing wastewater phosphorus to the Lake would result in a current estimated cost of approximately \$191,000. If these technologies reduce effluent TP to the estimated 1 mg/L TP, the wastewater load to Savery Pond would eventually be reduced by approximately 50% (given groundwater flow and phosphorus travel time). Given that the necessary reduction is the equivalent of complete removal of wastewater P loading, additional reductions in watershed P loading would be necessary to attain the target and the only source with sufficient P load to address the 2.5 kg difference would be the P loading from the cranberry bog.

V.C.2.b. Cranberry Bog

The estimated cranberry bog P load is equivalent to the septic system wastewater load in the overall pond P loading estimate. As mentioned above, this estimated load is based on refined measurements of the average P output at three bogs in southeastern Massachusetts.⁹¹ These three bogs had P export rates between 1.46 and 1.74 kg/acre. For the Savery Pond P loading, staff estimated that the bog exported 5 kg/yr based on a rate of 1.6 kg/ac and the bog area based on MassDEP Water Management Act permitting.⁹²

Reviews of other bogs have found a wide variety of P export rates that are dependent on a number of factors, including fertilizer application rates, historic application rates and residual bog P, bog connections to the surround aquifer, and bog position within the aquifer (*i.e.*, including a stream or near a discharge boundary). Characterization of the bog adjacent to Savery Pond by FOEM said that it is “no longer irrigated, applied with fertilizers or pesticides, or commercially harvested; however, it is sometimes flooded during winter/spring months. The bog is also reported to be fairly “leaky” due to high permeability soils.”⁹³ Refined understanding of the P export from this cranberry bog to refine its actual P export to the pond is important, since the bog is no longer fertilized. However, this would require a detailed evaluation of water flow associated with the bog and its transport of P to the pond. This type of evaluation may be warranted depending on the water quality management strategy adopted for Savery Pond. However, it is anticipated that this effort is unlikely to achieve complete removal of the required 5 kg P reduction required; P reductions from other sources or some well pumping reduction or some combination of both would be required.

V.C.2.c. Other Watershed P Sources

The total of all the other watershed phosphorus sources to Savery Pond is 3 kg/yr and they are either not locally controllable, dispersed throughout the watershed, and/or a relatively small portion of the overall load. Among these atmospheric deposition on the pond surface impervious surface (7% of the annual load) is largely uncontrollable. Road and roof runoff is a bit more controllable, but are relatively dispersed. Road runoff is 11% of the total load, but most of the road areas within 100 m of the pond are unpaved, so treatment of runoff at key selected points would be difficult. Sediments are assumed to contribute 0.6 kg P/yr based on review of average water conditions and sediment incubation measurements. Most treatment would not completely remove this source and any sort of treatment would require other management activities to reduce the total load to the 5 kg/yr reduction target.

⁹¹ Demoranville, C. and B. Howes. 2005.

⁹² MassDEP Water Management Act cranberry bog GIS layer. From J. McLaughlin, MassDEP SERO.

⁹³ Friends of Ellenville Marsh. 2019. Savery Pond 2018 Water Levels and Streamflow. 39 pp.

V.C.3. In-Pond P Management: Addition of Settling Agent (Alum)

Another alternative water quality management technique applicable to Savery Pond is regular, annual addition of a settling agent (likely alum) to strip phosphorus out of the water column. This approach would apply the agent during the summer to prevent phosphorus concentrations from increasing to levels that would impair water quality.

Alum applications are typically used in ponds where summer sediment regeneration of phosphorus is the primary water column P source and the Massachusetts Lake Management GEIR prefers the use of alum applications in these circumstances.⁹⁴ But the same chemical interactions (*i.e.*, binding of phosphorus) could be used to remove P from the Savery Pond water column and time the application to address the summer increase in residence time due to the increase in the John Holmes well pumping to ensure that impaired conditions do not occur. Addition of aluminum salts or alum has a long track record in both pond applications⁹⁵ and in drinking water treatment.⁹⁶ Alum binds inorganic phosphorus and creates precipitates/solids that are not sensitive to redox conditions, so aluminum additions can be used in anoxic settings. All of the alum applications in southeastern Massachusetts ponds and lakes have been in ponds where sediments were the primary source of summer water column phosphorus.⁹⁷

Aluminum salts are used to treat phosphorus because aluminum binds phosphorus and creates insoluble solids (“floc”) that are stable under conditions typically found in Plymouth-ecoregion ponds and lakes. This floc tends to bind inorganic phosphorus, but alum treatments have often been used to remove suspended solids in settings where drinking water is obtained from lakes or rivers. Factors that generally influence the variability of aluminum application performance include the application process, dose, and the area of treatment. Aluminum sulfate and sodium aluminate are generally used in a 2:1 mix to buffer pH reductions that would occur if only aluminum sulfate was used. At low pH’s (<6), aluminum tends to become soluble and unbound; Al(III) is toxic to fish at high enough concentrations.⁹⁸ For this reason, buffering is especially important in the naturally low pH Plymouth-ecoregion ponds and lakes and is achieved through balancing the mix of aluminum salts.

In Savery Pond, a whole water column alum application would be recommended in May. Average water column P mass in May was 4.6 kg. Alum applications in Cape Cod ponds have a median P reduction of 59% (range 35% to 80%).⁹⁹ If an alum application removed 59% of the P in the average May water column, the remaining P in the water column would be 1.9 kg. If the

⁹⁴ Massachusetts Department of Environmental Protection and Department of Conservation and Recreation. 2004. Eutrophication and Aquatic Plant Management in Massachusetts, Final Generic Environmental Impact Report. Executive Office of Environmental Affairs, Commonwealth of Massachusetts. 514 pp.

⁹⁵ Huser, B.J., S. Egemose, H. Harper, M. Hupfer, H. Jensen, K.M. Pilgrim, K. Reitzel, E. Rydin, and M. Futter. Longevity and effectiveness of aluminum addition to reduce sediment phosphorus release and restore lake water quality. *Water Research*. 97: 122-132.

⁹⁶ U.S. Environmental Protection Agency. 1999. 25 Years of the Safe Drinking Water Act: History and Trends. United States Environmental Protection Agency, Office of Water. EPA 816-R-99-007. 57 pp.

⁹⁷ *e.g.*, Wagner, K.J., D. Meringolo, D.F. Mitchell, E. Moran, and S. Smith. 2017. Aluminum treatments to control internal phosphorus loading in lakes on Cape Cod, Massachusetts. *Lake and Reservoir Management*. 33: 171-186.

⁹⁸ Cooke, G.D., Welch, E.B., Peterson, S.A, Nichols, S.A. 2005. *Restoration and Management of Lakes and Reservoirs*. Third Edition. CRC Press. Boca Raton, FL.

⁹⁹ Wagner, K.J., D. Meringolo, D.F. Mitchell, E. Moran, and S. Smith. 2017.

application was on May 15, constant watershed P additions until September 15 would add 4.3 kg P to the water column resulting in a water column mass of 6.2 kg P. This mass is at the low end of the June water column P range, but the actual P mass in the water column would be less than 6.2 kg because pumping rates and the pond residence time typically decrease in September. Available September water column TP mass estimates average 4.7 kg, maximum September shallow TP concentration was 26 µg/L (n=4), and all but one of the deep September DO concentrations were above the MassDEP minimum. On average, a May water column alum application should maintain acceptable water quality in Savery Pond throughout most summers if this was the only management option pursued.

Uncertainties for this approach include the dosing, impacts on the biota, and projected long-term buildup of alum in the sediments. Dosing, in particular, has uncertainties because much of the water column P in May will be in the form of organic phosphorus rather than inorganic (*i.e.*, ortho-P). Applications of alum in settings with high organic P components may require twice as much alum as discussed below. It is likely that it may take a number of years to determine optimal dosing and this may be complicated by the high vs low groundwater and precipitation issues discussed above. Impacts on the biota may also be notable. The proposed alum application would occur in depths greater than 1 m, which should provide some sanctuary for phytoplankton, zooplankton, and fish, but the floc is designed to remove particles, including the plankton, from the water column. Finally, long-term buildup of alum in the bottom sediments is likely to occur, but initial calculations indicate that the addition will be approximately 0.5 mm per year at the application rate discussed below. Depending on how the dosing is adjusted, the actual rate might be slightly higher.

Estimated annual cost of an alum treatment would be \$15,134 per year with additional costs for permitting and monitoring (Table V-2). This amount is a planning cost that will need to be refined through a procurement process and further discussions about dosing. If the dose needed to be twice as large, the chemical cost would increase to approximately \$12,000 and the overall annual cost would increase to approximately \$21,000. These estimates do not include pre- and post-application monitoring (\$5,000 to \$10,000 per year depending on details required during permitting) or monitoring during the application to ensure that pH is relatively stable. The cost estimate also does not include permitting costs, which, at a minimum, will include an initial permit from the town Conservation Commission (\$5,000 to \$10,000). The Order of Conditions from the Conservation Commission will approve the details associated with application timing, monitoring, and any reporting, as well as any permitting requirements for each future annual application. The estimated cost includes a mix of aluminum sulfate and sodium aluminate to try to attain a neutral pH application; actual balance will be determined by the pH and alkalinity on the date of application.

Table V-2. Phosphorus Settling/Aluminum Treatment Cost Estimates for Savery Pond for Reducing Water Column P. Costs for an aluminum treatment of the water column over portions of the pond deeper than 1 m. Assumptions for costs include: a) application in mid-May, b) 4.6 kg P in water column, and c) treatment at the surface to allow alum floc to settle through the water column. Costs do not include provisions for permitting (est \$5,000 to \$10,000) or post-implementation monitoring (est \$5,000 to \$10,000 depending on details). It is anticipated that the Town will have to secure a Conservation Commission permit during the initial application, but not subsequent applications. It is also anticipated that regular monitoring will be required just prior to the application (e.g., baseline Al concentrations), during the application (e.g., pH monitoring), and post-application (e.g., return of Al to pre-application levels). This treatment would be required annually if no changes are implemented in either watershed P loading or pumping of the John Holmes public supply well. Based on these calculations, 686 kg of aluminum will be added to the sediments annually, so sediment accumulation will also have to be part of the regular monitoring with longer-term contingency to remove aluminum buildup if volume loss becomes a concern.

Pond	Units	Savery Pond >1 m
Treatment Depth	Meters	≥1
Target Area	Acres	19.5
Target Area	square meters	78,923
Available P in water column (May avg)	kg	4.58
Ratio of Al to P		100
Al dose needed	Kilograms	686
Ratio of alum to aluminate		2
Application for Aluminum sulfate	gallon per acre	119
Application for Sodium aluminate	gallon per acre	60
Total applied chemical cost		\$ 5,957
Total mobilization, planning & design		\$ 5,000
Contingency (30%)		\$ 3,493
Total Planning Cost: Alum Treatment		\$ 15,134

VI. Recommended Management Plan and Assessment Summary

Savery Pond has impaired water quality based on both state regulatory standards and guidance developed from reviewing ponds and lakes in the Plymouth ecoregion. Phosphorus and chlorophyll concentrations have been consistently above ecoregion thresholds, but dissolved oxygen (DO) concentrations have generally been above the MassDEP minimum. Review of phosphorus and nitrogen concentrations showed that they regularly increased during the summer (clarity decreased) and that average shallow and deep concentrations were not significantly different in either the spring or the summer. Comparison of phosphorus and nitrogen concentrations showed that phosphorus management is the key to determining water quality in Savery Pond.

DO concentrations in monthly profiles showed that only 6% of available readings were less than the MassDEP minimum, but continuous readings showed that temporary events between monthly readings can have more sustained impaired conditions. Continuous monitoring in 2016 showed that the pond has occasional thermal stratification, but these temporary events are relatively short. These same 2016 readings also showed that deep DO concentrations can become anoxic, but these were also temporary. In this 2016 record, the longest duration of anoxic conditions was 16 days. in 2016. There were a total of 32 anoxic events at the 2.4 m depth of the sensor, but most of these were 58 minutes or less.

Review of phytoplankton populations in 2020 found that blue-green/cyanobacteria were generally a regular part of the phytoplankton population and the predominant phytoplankton during the summer when phosphorus concentrations increased. During 2020, which had higher groundwater conditions than 2016 (the last cyanobacteria bloom), cyanobacteria were the predominant class in July and August, but the maximum cyanobacteria cell count (465 cells/ml in July) was well below the MassDPH 70,000 cells/ml cyanobacteria threshold established as a blue-green direct contact advisory level. The surface TP concentration in July 2020 was 39 µg/L, well above the 26 µg/L TP recommended in this management plan for acceptable water quality.

Review of pond phosphorus sources and watershed interactions found that summer residence time changes were the primary cause of the increased summer phosphorus concentrations and impaired water quality conditions. The pond watershed delineation based on USGS groundwater modeling was completed based on earlier pumping rates at the nearby John Holmes well that were substantially less than average rates between 2010 and 2020. Review of independent groundwater modeling in the same area showed that the capture area for the well expanded into the pond watershed area decreasing groundwater flow to the pond. Review of phosphorus sources found the summer increase in phosphorus concentrations matched the estimated increase in pond residence time due to reduced watershed area. Pond residence time was estimated to increase from approximately 90 days in April to more than 200 days based on average pumping of the well and these changes accounted for the summer increase in water column phosphorus.

Project staff reviewed goals to maintain acceptable water quality in Savery Pond. This review found that April and May water quality conditions are generally acceptable: DO concentrations above the MassDEP minimum and clarity at or near the bottom. April and May chlorophyll and TP concentrations are higher than ecoregion guidelines, but these concentrations are likely acceptable because of the short pond residence time. Based on this review, staff recommended a TP concentration limit of 26 µg/L, which is equivalent to a water column TP mass limit of 5 kg.

Review of available water quality showed that these limits are generally attained in April, May, September, and October.

Management options to attain these water goals focused on three applicable options: a) maintaining a relatively short pond residence time, b) reducing watershed phosphorus inputs, and c) annually removing water column phosphorus. Each of these options has implementation issues that are discussed in detail above and are summarized below:

- a) **Maintaining a short pond residence time.** Project staff review found that April residence time under current average pumping was approximately 90 days and water quality during April were generally acceptable. Average pumping at the John Holmes well in April between 2010 and 2020 was 0.29 MGD with a range of 0.03 to 0.47 MGD. Average pumping in May between 2010 and 2020 was 0.41 MGD with a range of 0.28 to 0.62 MGD and water quality was also generally acceptable though late May readings suggest that this is a transition month to longer residence times. Review of groundwater levels and summer precipitation rates were consistent with this estimated April residence time and showed that estimated summer residence times could increase to 213 days when groundwater levels and summer precipitation are high (*e.g.*, 2019) and increase further to 827 days when groundwater levels are low (*e.g.*, 2016).

If 0.41 MGD were selected as the upper bound of pumping for acceptable water quality in Savery Pond, review of the pumping rates show that this would not require any change in winter pumping strategies, but would require adjustments to summer pumping. Review of 2010 to 2020 monthly pumping rates showed that most (97%) of the monthly pumping rates between October and March were less than 0.41 MGD and 9 of 11 April readings were less than 0.41 MGD. However, in May, only 45% of the monthly rates were less than 0.41 MGD, 18% of June rates, 9% of July and August rates, and 36% of September rates. Average monthly pumping rates between May and September was 0.54 MGD with a peak of 0.68 MGD in July. However, the maximum rates between May and September were 44% higher. Based on this review, 0.27 MGD additional water supply pumping would be necessary, on average, if the John Holmes well was limited to 0.41 MGD and an additional 0.54 MGD would be required to address the maximum water supply demand (0.95 MGD).

Implementation of an approach to manage water withdrawals from the John Holmes well in summer to manage Savery Pond water quality should reduce or eliminate the need for reductions in current watershed phosphorus loads or treatment of pond water column P. Project staff recognize that this sort of pumping limitation is likely unattainable in the short-term and the Town would likely benefit from additional confirmation of appropriate pumping volumes through groundwater modeling. Selecting this approach likely requires time to develop sufficient funding to identify, plan, and implement the additional water supply to address the reduced summer pumping by the John Holmes well. Providing sufficient water supply capacity while reducing pumping from the John Holmes well would require water from existing sources outside of the Savery Pond watershed or even installation of a new public supply well in a location that did not impact Savery Pond (or other Great Ponds) while also fitting within the existing well network and would require additional tasks outside of the scope of this project.

- b) **Reducing watershed P inputs.** If a short residence time cannot be maintained, another applicable water quality management option is to reduce the watershed P inputs. The overall annual P load to the Savery Pond water column was 13 kg P per year. It was determined to achieve the water column P mass goal of 5 kg under average residence times, this annual P load would need to be reduced by 5 kg.

Review of watershed P inputs determined that septic system leachfield wastewater and the cranberry bog at the western end of pond were the primary P sources (each is 38% of the annual load). Pond sediments were generally a small contributor, even during anaerobic conditions (5% of the average load) and most of the other sources were uncontrollable (e.g., pond surface deposition), dispersed and/or small contributors. Total P load from all these smaller sources, including the sediments was 3 kg.

Complete removal of the septic system leachfield wastewater or the cranberry bog load (or some shared combination) could meet the 5 kg/yr reduction if adequately planned and documented. Complete removal of the wastewater load could be accomplished by collection of all wastewater from watershed properties identified in the P loading and treatment outside of the watershed. Staff identified two options for this complete removal: connection to the existing municipal sewer system or construction of a satellite wastewater treatment facility. Each of these would be relatively expensive (preliminary estimates of several million dollars) and require extensive planning, engineering, and permitting. Project staff also reviewed experimental P removal septic systems that are currently approved under piloting provisions by MassDEP. Use of these at each of the current septic systems would remove half of the wastewater P load, require community acceptance and permitting, and also require reductions from other sources to attain the 5 kg/yr reduction. Removal of the cranberry bog load would require refined evaluation of the bog to understand its use and P export characteristics. Understanding of the P export from this cranberry bog to refine its actual P export to the pond is important, since the bog is no longer fertilized. However, this would require a detailed evaluation of water flow associated with the bog and its transport of P to the pond.

- c) **Adding a P settling agent to the water column.** Another applicable water quality management option is to annual remove P from the water column through the application of a settling option (most common in alum). This settling agent would remove P from the water column prior to the summer increase in residence time. Watershed P inputs would continue through the summer, but the removal would limit the peak summer water column load and maintain acceptable water quality conditions.

Alum applications completed in ponds where sediments are the primary water column source have had median P reductions of 59% (range 35% to 80%). If an alum application was applied to the surface of Savery Pond in May and this median performance was attained, the P remaining in the water column would be 1.9 kg. If this application was on May 15, constant watershed P additions until September 15 would add 4.3 kg P to the water column resulting in a water column mass of 6.2 kg P. However, if the pond residence time was 120 days, estimated average June residence time, then the water column P mass on September 15 would be less than the 5 kg target determined from a review of water quality data.

Uncertainties for this approach include the dosing, impacts on the biota, and projected long-term buildup of alum in the sediments. These issues would need to be addressed during procurement, permitting, and long-term follow-up monitoring.

Estimated annual cost of an alum treatment would be \$15,134 per year with additional costs for permitting and monitoring. This planning cost will need to be refined through a procurement process. Applications of alum in settings with high organic P components may require twice as much alum, which would increase the estimated annual cost to approximately \$21,000. These estimated costs do not include pre- and post-application monitoring or monitoring during the application to ensure that pH is relatively stable (estimated \$5,000 to \$10,000 per year depending on details required during permitting). The cost estimates also do not include permitting costs, which, at a minimum, will include an initial permit and Order of Conditions from the town Conservation Commission (\$5,000 to \$10,000 per year). The Conservation Commission will approve the details associated with application timing, monitoring, and any reporting, as well as any permitting requirements for each future annual application.

The variations of the characteristics of Savery Pond creates challenges for defining appropriate management strategies. Comparisons of the variations in pond water quality and the pumping of the John Holmes well show that low groundwater elevations and low summer precipitation rates cause the most impaired conditions. Review of pumping and groundwater levels showed these conditions occurred in 2016, but 2019 and 2020 water quality monitoring occurred during relatively high groundwater conditions, but differing summer precipitation. Overall, it is recognized that planning for appropriate management may require some adjustments as more monitoring is conducted.

Based on these considerations and the above review of applicable options, TMDL Solutions and CSP/SMASST staff recommend the following steps for implementation of an adaptive management approach for the restoration of Savery Pond:

1. Review options to limit water pumping at the John Holmes well to maintain a Savery Pond residence time of 120 days or less

- Review of estimated residence times based on water quality suggest that residence time in April is 90 days and increases to 220 days on average during the summer. Review of 2016 summer data suggest that residence time increased to 827 days.
- Review of pumping rates suggest this 120 day residence time could be achieved at 0.41 MGD or less. Pumping rates at the well from 2010 to 2020 were generally below this level from October to April. Monthly average pumping from May to September showed this level was exceeded in 55% of the May readings and 91% of the July and August readings.
- Peak pumping rates were up to 0.95 MGD, which would mean an additional 0.54 MGD would be required if the well was limited to 0.41 MGD. Based on average monthly summer readings, 0.27 MGD would be required above 0.41 MGD.
- Project staff recognize that this sort of pumping limitation is likely unattainable in the short-term and the Town would likely benefit from additional confirmation through groundwater modeling.

- Even if this approach was selected, time would be required to develop sufficient funding to identify, plan, and implement sufficient pumping capacity to address the summer pumping currently provided by the John Holmes well. Development of the potential cost of installation of a new public supply well in a location that did not impact Savery Pond (or other Great Ponds) while fitting within the existing well network would require additional tasks outside of the scope of this project.
- 2. If pumping limits cannot be implemented or can only be partially implemented, pursue settling agent addition.**
- Settling agent addition will require annual application of alum, but will not require limitations on pumping or changes in watershed phosphorus sources.
 - Uncertainties for this approach will need to be resolved if selected. These issues include dosing, impacts on the biota, and projected long-term buildup of alum in the sediments.
 - Regular monitoring required to implement settling addition application will help refine interactions between well pumping, water residence time, groundwater elevations, and summer precipitation. Better understanding of these interactions could provide adaptive management options.
- 3. Try to avoid management of watershed phosphorus loads.**
- Watershed phosphorus loads are relatively small compared to the size of the pond and would not need to be managed if the naturally short pond residence time was maintained.
 - Efforts to eliminate the largest sources of watershed phosphorus would either be very costly (*i.e.*, wastewater) or uncertain (*i.e.*, the cranberry bog).
- 4. Maintain regular monitoring of Savery Pond.**
- Annual spring and late summer monitoring of Savery Pond will provide long-term data for the fluctuations seen in the available data. Review of this data on a regular basis (*e.g.*, every 5 years) will provide better insights into future management options.
- 5. Address MassDEP TMDL provision once management approach is implemented and reliable water quality is regularly attained.**
- Savery Pond is currently listed on the latest MassDEP Integrated List as an impaired water body requiring a TMDL. Towns have generally been held responsible by MassDEP for developing strategies to attain acceptable water quality in impaired waters.
 - Diagnostic summary suggests that 26 µg/L TP and 5 kg water column TP are appropriate targets for acceptable water quality in Savery Pond.
 - Once Plymouth and the other Savery Pond stakeholders decide on an acceptable water quality management strategy for Savery Pond, it is recommended that the strategy be implemented, water quality be monitored, and, once acceptable water

quality conditions have been achieved, the Town should approach MassDEP with both the strategy and a proposed TMDL.

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

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

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APPENDIX A. 2017 DO and Temperature Profiles. This FOEM/SPC data was received after the completion of the draft Management Plan. 2017 Secchi readings are included in Figure IV-4. Results are consistent with data reviewed in the diagnostic assessment: DO readings have more frequent anoxia than previously available snapshot profiles in 2016 and 2020, but they also show DO recovery measured in other years and in the 2016 continuous DO dataset (see Figure IV-2).

