Crystal Lake Management Plan and Diagnostic Assessment

FINAL REPORT

January 2021

for the

Town of Orleans

Prepared by:

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

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Town of Orleans
Marine and Fresh Water Quality Committee

Prepared By

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Cover photo: Crystal Lake (10/12/17)

Acknowledgements

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

The authors also specifically recognize and applaud the generosity of time and effort spent by the Orleans Marine and Fresh Water Quality Committee, Orleans Water Quality Advisory Panel and Orleans Pond and Lake Stewards (PALS), both past and present members. The individuals in these groups are advocates for sustainable pond ecosystems and gave of their time to collect or support collection of needed water quality information, which made the development of this management plan possible. Among these groups particular thanks go to Carolyn Kennedy, Judy Scanlon, Betsy Furtney, Carol Etzold, Judith Bruce, Ed Hafner, Lara Slifka, and Cecil Newcomb. The authors thank all involved for their support and advocacy for Orleans ponds.

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Executive Summary

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Crystal Lake is one of three freshwater ponds within the Town of Orleans that are classified as Great Ponds under Massachusetts law.[1] As a Great Pond, Crystal Lake is publicly owned and management of its water quality has to address local concerns, as well as regulatory requirements of the Massachusetts Department of Environmental Protection (MassDEP) in its implementation of the federal Clean Water Act.

The Town of Orleans has more than 50 freshwater ponds of various sizes and depths.[2] These ponds and lakes are important recreational areas for swimming, fishing, and boating. Their ecosystems also provide important ecological and commercial services for cranberry bogs, herring runs, and natural nitrogen attenuation that protects downgradient estuaries. Orleans citizens have long recognized that ponds and lakes are important community resources. In 1999, citizens began collecting water quality data to ensure that these resources were better understood. These efforts have expanded and become more robust as they have continued through both town and regional efforts like the Cape Cod Pond and Lake Stewards (PALS) program.[3] Crystal Lake was among the first ponds sampled by Orleans citizen monitors and the long history of collected data was organized and reviewed in 2017.[4] The present Crystal Lake diagnostic assessment and management plan includes an updated and refined review of citizen water quality data, as well as data collected during 2019 as part of the assessment to address data gaps identified in 2017. These data gaps needed to be addressed for development of reliable and scientifically defensible water quality management strategies.

During the discussions of the results of the 2017 review of citizen-collected pond water column data, the Town Marine and Fresh Water Quality Committee (MFWQC) and project staff from the Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) discussed strategies to build on Orleans Water Quality Advisory Panel (OWQAP) efforts to implement comprehensive water quality management throughout the town. Just as the OWQAP efforts benefited from the insights provided by volunteer pond water quality monitoring, the MFWQC thought that the collected data could be used as springboard to refined, pond-specific management strategies that would allow the Town to have

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

[2] Eichner, E.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.

[3] The Cape Cod PALS program began collecting annual late summer water quality samples in 2001 from nearly 200 lakes and pond through a collaboration between the Towns/citizen volunteers, the Cape Cod Commission and donated analytical services from the CSP/SMAST.

[4] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database: Development and Review. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 217 pp.

comprehensive water quality management of all its water resources. The 2017 pond data review provided initial assessments of the water quality status of all monitored ponds and identified data gaps that needed to be addressed in order to develop and assess pond water quality management options. Using the data review findings, local knowledge and MFWQC insights, an initial prioritization was developed to complete a series of individual pond assessments and management plans. These plans would include coordinated public input to select management strategies tailored to address water quality impairments and restoration of acceptable water quality in each of the individual prioritized ponds. These discussions resulted in the initial prioritization of the following ponds: Uncle Harvey's Pond, Pilgrim Lake, Crystal Lake, and Bakers Pond.

Crystal Lake was prioritized as the third Orleans freshwater pond for completion of a management and remediation plan after Uncle Harvey's Pond[5] and Pilgrim Lake.[6] Among the initial resource issues identified for Crystal Lake during the 2017 review of citizen-collected water column data was persistent bottom hypoxia during the summer (and occasionally in the spring) and a trend of decreasing water clarity between 2000 and 2016. The 2017 review also identified a series of potential data gaps that should be addressed as part of developing a management plan and CSP/SMAST staff refined them in discussions with Town staff and the MFWQC. Data gap surveys included: a) collection of phytoplankton samples and associated water quality data to understand predominant species, proportion of blue-green algae, and factors causing changes throughout the summer, b) collection of sediment cores to understand the triggers for phosphorus regeneration from sediments to the water column and how much additional potential release was available if the area of bottom anoxia expanded during the summer, c) measurement and chemical analysis of stream inflow from the historic cranberry bog north of the lake and stream outflow to the active cranberry bog south of the lake, and d) measurement and chemical analysis of stormwater runoff from Route 28 near the Town boat ramp. This Crystal Lake Management Plan and Diagnostic Assessment summarizes the review of all available data including data gap surveys completed in 2019, as well as reviewing management options to restore water quality and pond health.

Crystal Lake is a 39-acre pond located between Route 28 and Monument Road and to the northwest of Lonnie's (aka Kescayogansett) Pond estuary. It is the second largest pond in Orleans after Pilgrim Lake and has a municipal swimming beach, a boat ramp, and a surface water connection to Lonnie's Pond through an adjacent cranberry bog. Bathymetric data collected during the 2019 data gap surveys found that the lake has a maximum depth of 17 m, a total volume of 951,844 cubic meters, and a 122 hectare watershed that includes portions of the watersheds to Baker Pond and Cliff Pond, among others. Average residence time of water in Crystal Lake is 0.88 years. Review of historic maps show 10 buildings around the lake nearly 80 years ago and connections to two cranberry bogs.

Review of historic and 2019 data gap water quality data shows that Crystal Lake regularly has impaired conditions with anoxia in its deeper waters and high phosphorus and chlorophyll levels. Dissolved oxygen concentrations in the lake water column are regularly less than the MassDEP

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

[6] Eichner, E., B. Howes, and D. Schlezinger. 2019. Pilgrim Lake Management Plan and Diagnostic Assessment. Town of Orleans, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 114 pp.

regulatory minimum (*e.g.,* 100% of deep summer readings were less than the MassDEP minimum) and phosphorus and chlorophyll concentrations regularly exceed Cape Cod ecoregion thresholds for healthy ponds and lakes. Comparison of water quality concentrations showed that phosphorus reductions are the key to removing the water quality impairments and restoring pond health. The data also shows that while these impaired conditions were persistent throughout most summers, the extent of these impairments varies from year to year and also varies within the summer season with the worst conditions typically occurring in late summer. This review also indicated that acceptable water quality existed when total phosphorus in the water column was less than or equal to 9.9 kg. This TP mass is recommended as a Crystal Lake target restoration threshold and a potential TMDL.

In order to provide a context for restoration of acceptable water quality, project staff developed a phosphorus budget to compare the magnitude of all the various phosphorus sources and provide a reliable basis for discussions of which phosphorus managements strategies would be the most beneficial. This review showed that 66% of the current annual external/watershed phosphorus load to pond waters (12.4 kg) was from septic system effluent from 18 of the 23 properties in the Crystal Lake watershed and within 100 m of the lake. This load was also more than half of the average total summer phosphorus load to the water column when internal TP additions from the sediments were also added. During the summer, watershed septic system effluent accounted for 50% to 57% of the TP water column mass, sediment regeneration was 17% to 28% depending on the month, and road runoff from Route 28 was 17% to 19%. Other sources were generally relatively small and together comprise <1% of the average annual total phosphorus load.

Review of phosphorus management options to restore water quality in Crystal Lake found that all potential strategies will require some reduction in watershed phosphorus inputs. This review also found that some options were more sustainable and reliable than others. Given that septic system effluent was the largest source of watershed phosphorus inputs to Crystal Lake, project staff found that permanently removing wastewater phosphorus from 13 of the 18 septic systems currently adding TP to the lake could attain the recommended restoration TP threshold without any management of internal sediment regeneration. One watershed property is already included in the planned Meetinghouse Pond sewer collection area developed for the Town's Amended CWMP.[7] Another wastewater TP alternative that also attained the TP threshold was the installation of experimental phosphorus-reducing septic systems[8] on all 18 septic systems with an additional 0.65 kg TP removal from another watershed source. Both of these approaches would require additional TP reductions to address the 5 existing houses with septic systems that were constructed too recently for their effluent phosphorus plumes to be reaching the lake at this time.

Review of in-lake treatments to address summer sediment TP regeneration could also attain the TP restoration threshold, but only if accompanied by reductions in watershed phosphorus additions. Applicable in-lake treatment options were hypolimnetic aeration, alum treatment, and dredging. Each of these in-lake options would reduce sediment TP regeneration, but would require additional reductions in watershed P loads (2 to 2.5 kg/yr) to attain the TP restoration threshold. In addition, these options would require either permanent commitment to operation (hypolimnetic

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[7] AECOM Technical Services, Inc. 2016. Amended Comprehensive Wastewater Management Plan. Town of Orleans, MA.

[8] MassDEP has given "piloting" approval to two types of phosphorus reducing septic systems. Under MassDEP regulations, only 15 systems may be installed state-wide under the piloting approval. Each piloted system is required to have monitoring designed to document the treatment goals/levels in the approval permit.

aeration) or regular repeating of procedures (alum treatment or dredging) every 5 to 10 years since watershed loads will remain the largest source of TP to Crystal Lake.

Project staff recommend that the Town consider reduction of wastewater TP as the most reliable approach to attain restoration of water quality in Crystal Lake. Given that development and implementation of a reliable wastewater TP reduction strategy will likely require some time, it is further recommended that the town consider implementation of an interim in-lake treatment (hypolimnetic aeration or alum treatment) to reduce internal sediment regeneration of TP. Implementation of such a treatment would provide improvement in water quality and allow time for implementation of a watershed wastewater solution. Planning level costs are provided for wastewater and in-lake management options.

Recommendations Summary:

1. Utilize a target restoration threshold of 9.9 kg total phosphorus (TP) in the water column as a preliminary water quality target for pond restoration, but avoid a TMDL designation until attainment of satisfactory water quality. Review of past water quality shows that acceptable water quality generally exists when the TP mass in the water column is at this level.
2. Develop and implement a watershed-wide strategy for reducing phosphorus discharges from residential septic systems to a loading level sufficient to restore water quality in Crystal Lake.
3. Develop and implement an interim in-lake treatment (hypolimnetic aeration or alum treatment) to reduce internal sediment regeneration of TP and provide acceptable water quality until implementation of a wastewater phosphorus reduction strategy occurs.
4. Develop and implement a streamlined adaptive management monitoring program to assess progress toward attaining the restoration TP threshold, assess the performance of the in-lake treatment, and the performance of the selected wastewater TP reductions. Part of the monitoring program should be regular review of collected data and whether management approaches should be altered.

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. CSP/SMAST staff are available to further assist the town with implementation, adaptive monitoring, and regulatory activities.

Following review of the draft Management Plan, the MFWQC summarized in a January 29, 2021 Memo to the Town of Orleans Select Board that the MFWQC "strongly support sewering of selected properties adjacent to the pond as the preferred water quality management solution for both Pilgrim Lake and Crystal Lake." The MFWQC further recommended development of a potential timeline for "extending the connection of the selected watershed properties to the municipal sewer system as part of Phase 2" and that the "Select Board support either alum treatments or aeration systems in both lakes" if the potential "timeline for reviewing sewering options and connecting these properties is more than 5 years." The MFWQC memo is appended to this Management Plan.

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APPENDED:
January 29, 2021 Memo regarding Crystal Lake and Pilgrim Lake Management Plans from Marine and Fresh Water Quality Committee (Judy Scanlon, Chair) to Orleans Board of Selectmen and Town Administrator, John Kelly. 3 pp.

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I. Introduction

The Town of Orleans has more than 50 ponds and lakes of various sizes and depths. These ponds and lakes are important recreational areas for swimming, fishing, and boating. Their natural habitats provide important ecological and commercial services, including use for cranberry bogs, herring runs, and natural nitrogen attenuation that protects estuaries. Orleans citizens have long recognized that ponds and lakes are important community resources and concern over water quality declines led to citizen-based water quality monitoring beginning in 1999. These efforts have expanded and become more robust as they have continued to the present, including town participation in regional efforts like the Cape Cod Pond and Lake Stewards (PALS) program.

The goal of PALS is to encourage development of basic, often initial, pond water quality data collected using consistent, scientifically-based, protocols and proper QA/QC. The resulting data can then support Town efforts to prioritize ponds for additional analysis and collection of more refined data, such as sediment nutrient regeneration, stream inputs and/or outputs, and watershed analysis. More refined targeted data collection can then be combined with the initial, citizen-collected water column data to develop active, appropriate, and pond-specific management strategies to ensure long-term sustainable high quality waters and aquatic habitats. The PALS program began by recruiting, training, and assisting Cape citizens to gather regular, long-term water column samples once a year during the critical late summer period. The PALS program was initiated as a partnership between the Cape Cod Commission and the Coastal Systems Program at the School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) with in-kind support from most of the Cape towns and environmental organizations.

Some towns, including Orleans, used PALS to create more focus and attention on ponds and lakes and gradually pursue more refined data collection and management. As the Town is now in the midst of initiating comprehensive water quality management actions, the Town is benefiting from over 15 years' worth of volunteer pond water quality monitoring data collected through PALS and other local efforts. This data was recently organized and reviewed by CSP/SMAST to develop a comprehensive water quality monitoring database for the 18 ponds that Orleans volunteers have regularly sampled.[9] This review also provided initial assessments of water quality conditions for each of the monitored ponds and identified data gaps that would need to be addressed in order to develop pond-specific management plans and restoration options.

Using the findings from the 2017 data review and other characteristics of the various ponds (*e.g.*, size, beaches, regulatory status, etc.), the Orleans Marine and Fresh Water Quality Committee (MFWQC) developed an initial prioritization of fresh water ponds needing restoration and selected Crystal Lake as the third fresh water pond in Orleans for completion of a management and remediation plan.[10] During 2018/2019, CSP/SMAST staff worked with the MFWQC to develop a series of Crystal Lake-specific tasks to: a) collect targeted, refined data to address identified existing data gaps, b) synthesize targeted and historic data to complete a comprehensive

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[9] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database: Development and Review. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 217 pp.

[10] Ponds were prioritized by the MFWQC through the overall Town wastewater planning effort in the following order: Uncle Harvey's Pond, Pilgrim Lake, Crystal Lake, and Baker Pond. Pond management plans have been completed and approved by the MFWQC for Uncle Harvey's Pond and Pilgrim Lake.

assessment of the water quality in Crystal Lake, and c) develop and evaluate specific management strategies to address ecosystem nutrient-related impairments. The present Crystal Lake Management Plan and Diagnostic Assessment reviews and summarizes all available lake ecosystem data, including 2019 data gap surveys, proposes water quality goals, and recommends a set of pond-specific strategies for the management and restoration of this impaired Great Pond.

The present Management Plan is primarily composed of two sections: 1) a Diagnostic Summary of how Crystal Lake generally functions based on the available historic water column data and data developed in the data gap investigations and 2) Management Options Summary, which reviews applicable and best options, estimated costs, 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 Crystal Lake water quality.

II. Crystal Lake Background and Previous Evaluations

Crystal Lake is a 39-acre pond located between Route 28 and Monument Road and to the northwest of Lonnie's (aka Kescayogansett) Pond (Figure II-1). It is the second largest pond in Orleans after Pilgrim Lake and has a municipal swimming beach, a boat ramp, and a surface water connection to Lonnie's Pond through an adjacent cranberry bog. The 1944 USGS quad map also shows it had a historic hydroconnection to another cranberry bog along its northeast side in approximately the same location as a current small, intermittent stream (Figure II-2). This 1944 quad, which is the first detailed USGS map of the area, shows 10 buildings around the lake. Review of 1938 and 1947 historic aerial photos also show both cranberry bogs.[11]

Crystal Lake is listed in the Cape Cod Pond and Lake Atlas[12] as pond number OR-153 and has had regular citizen water quality monitoring according to PALS sampling protocols since 2001.[13] Crystal Lake is located within the Pleasant Bay watershed and has a separate subwatershed delineated as part of the Pleasant Bay Massachusetts Estuaries Project (MEP) assessment.[14] The MEP assessment included a review of nitrogen loading to the pond and assignment of a standard MEP 50% nitrogen attenuation rate due to insufficient water quality data outside of the standard PALS sampling period. Crystal Lake citizen water quality data was also reviewed in 2007 and that review found that: 1) it had impaired conditions due to regular summer hypoxia in deeper waters and anoxia in waters deeper than 6 m, 2) the water column had significant fluctuations in dissolved oxygen conditions, 3) water column data suggested sediments were contributing a large portion of the summer water column phosphorus, but the variability in water column concentrations made definitive statements difficult based on water column data alone, and 4) phosphorus concentrations were likely to increase since all the impacts from houses around the pond had not reached pond waters.[15]

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[11] Historic aerial photographs supplied by George Meservey.

[12] 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.

[13] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database report. pp. 24-28.

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

[15] Eichner, E. 2007. Review and Interpretation of Orleans Freshwater Ponds Volunteer Monitoring Data. Cape Cod Commission. Barnstable, MA. 80 pp.

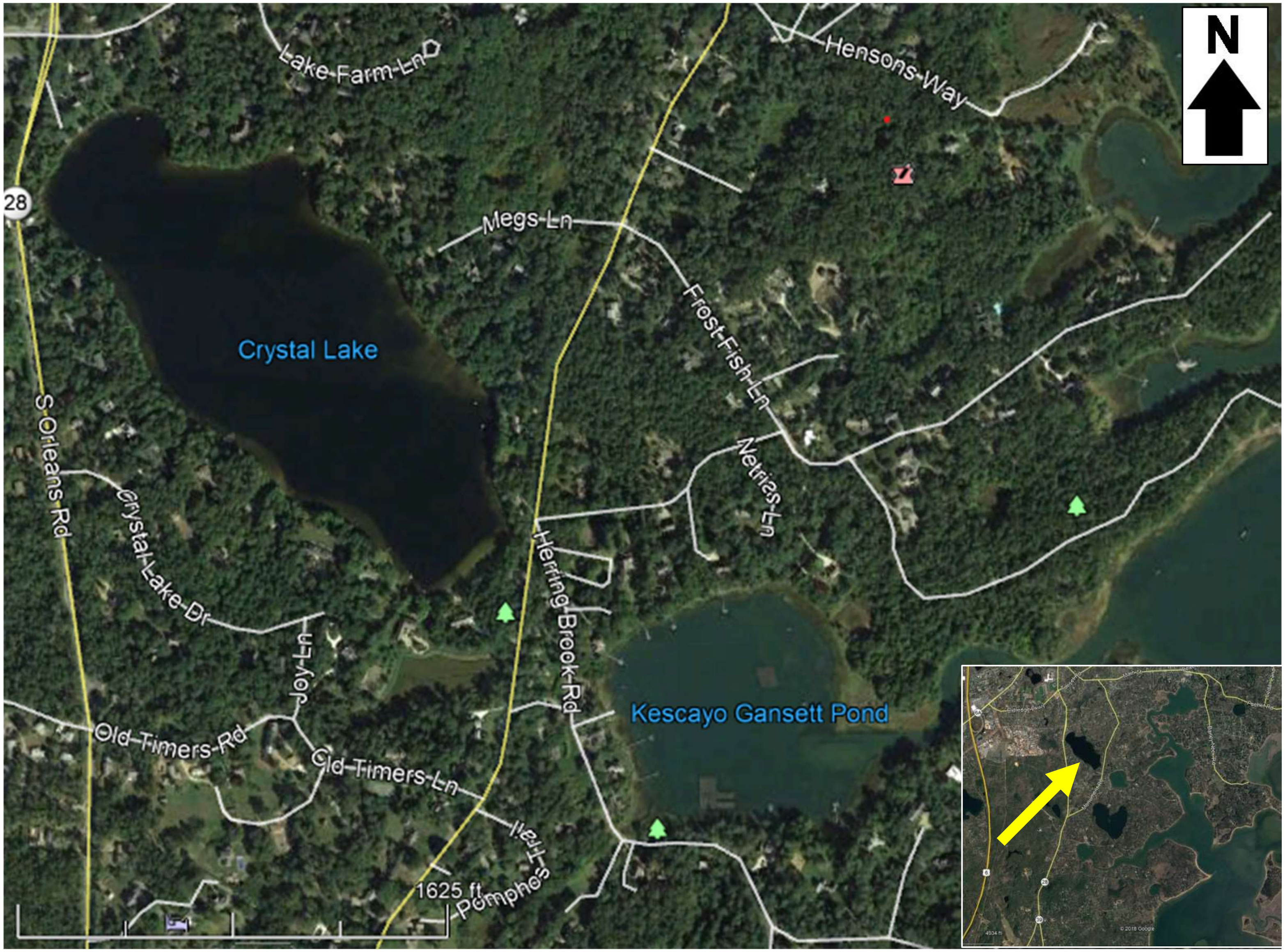

Figure II-1. Crystal Lake Locus. Crystal Lake is a 39-acre pond located in Orleans, MA between Route 28 and Monument Road and to the northwest of Lonnie's (aka Kescayogansett) Pond, which is part of the Pleasant Bay estuary.

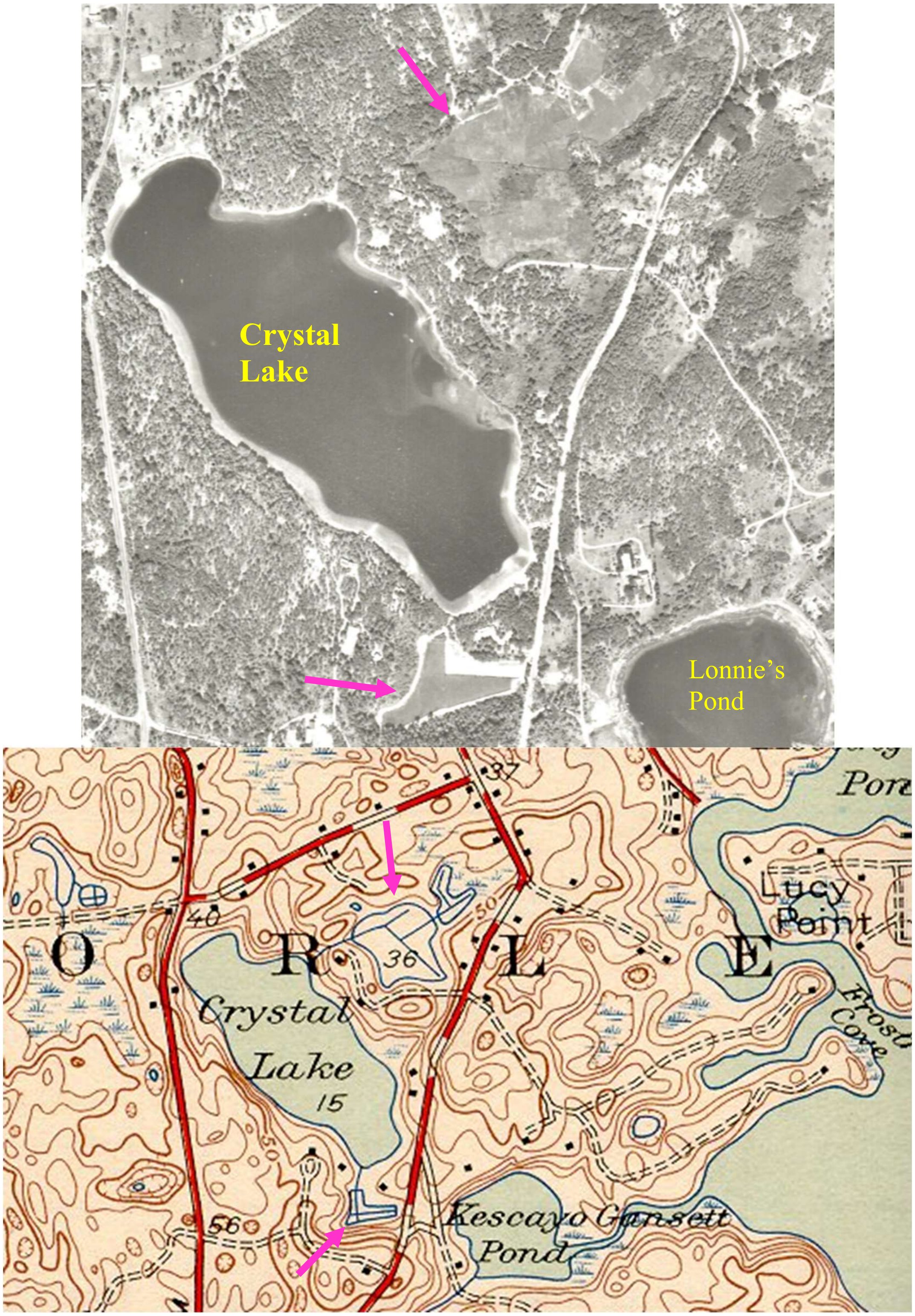

Figure II-2. Crystal Lake area: 1947 aerial ortho-photograph and 1946 US Geological Survey quadrangle. Both figures show approximately 8 buildings near the lake and adjacent cranberry bogs (indicated by pink arrows). The southernmost bog is still in operation today and receives outflow from Crystal Lake. The northernmost bog has not been used in decades and has largely been reclaimed by nature, but still has a small inflow into Crystal Lake.

Given that its surface area is greater than 10 acres, Crystal Lake is considered a Great Pond under Massachusetts law.[16] In the most recent draft of the Massachusetts Department of Environmental Protection (MassDEP) Integrated List, Crystal Lake is listed as Segment#MA96050 and classified as a Category 5 water based on impaired dissolved oxygen concentrations.[17] Because Crystal Lake is identified as being impaired, it is required to have a TMDL prepared under the federal Clean Water Act to determine the appropriate level of pollutant(s) needed to remove the impairment.

The 2017 CSP/SMAST review of Town citizen pond water quality monitoring results concluded that Crystal Lake was impaired based on a comparison to both MassDEP surface water regulatory standards and Cape Cod Ecoregion water quality thresholds.[18] MassDEP regulations classify Crystal Lake as a warm water body[19], though the deepest portions of the water column consistently remain below the regulatory cold water temperature maximum (20°C). Comparison of available data to MassDEP numeric standards for dissolved oxygen (DO) and pH show that shallow DO concentrations were generally greater than the MassDEP warm water threshold (5 mg/L), but deep waters were consistently impaired (<5 mg/L DO) during the summer and in 38% of the spring readings. Crystal Lake, like all Cape Cod ponds and lakes, is naturally acidic (*i.e.*, pH<7). A majority (76%) of shallow summer chlorophyll readings, which are a proxy for phytoplankton biomass, were above the Cape Cod Ecoregion threshold consistent with nutrient enrichment. Deep summer nutrient concentrations (phosphorus and nitrogen) indicated significant sediment nutrient regeneration as seen in average deep concentrations approximately 2X shallow concentrations. Comparison of average ratios between nitrogen and phosphorus concentrations showed that phosphorus is the primary nutrient controlling phytoplankton blooms and, thus, is the key nutrient to manage in order to restore the water and habitat quality within Crystal Lake.

The 2017 review of historic Crystal Lake water quality data also identified some key data gaps that needed to be addressed in order to determine what is controlling phosphorus levels and ecological health of the lake and which management strategies would work best to address its impairments. Surveys to address these data gaps were completed by CSP/SMAST in 2018 and 2019. Data gaps included:

a) stormwater monitoring of the identified discharges and any other direct discharges,
b) collection and incubation of sediment cores to measure both summer nutrient regeneration rates and conditions that trigger enhanced nutrient regeneration,
c) a survey of plant communities (both rooted macrophytes and phytoplankton) to determine the extent of their role in creating the measured water quality,
d) measurement of surface water flows and associated nutrient loads both into and out of the pond,
e) a freshwater mussel survey given previous reviews indicating that sediment treatment is a likely management strategy to be considered and that certain freshwater mussels are designated as threatened or endangered species, and
f) installation of a number of continuous recording devices to evaluate conditions that create occasional exceptionally high DO concentrations near 9 m depth, the frequency of deep hypoxic conditions, as well as relationships to plant community findings.

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

[17] Massachusetts Department of Environmental Protection. June 2017. Massachusetts Year 2016 Integrated List of Waters, Draft Listing. CN 470.0. Worcester, MA. 357 pp.

[18] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database report. pp. 24-28.

[19] 314 CMR 4.06, Table 26.

III. Crystal Lake 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. Crystal Lake has a surface greater than 10 acres, which means that it is a Great Pond under Massachusetts Law[20] and subject to Massachusetts regulations. As such, local Town decisions regarding management may be subject to state review. Massachusetts maintains regulatory standards for all its surface waters.[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. For example, Class A freshwaters are used for drinking water and have a descriptive standard that reads, in part, that these waters "are designated as excellent habitat for fish, other aquatic life and wildlife, including for their reproduction, migration, growth and other critical functions, and for primary and secondary contact recreation, even if not allowed. These waters shall have excellent aesthetic value."[22] Additional distinctions are made between warm and cold water fisheries.

Under these state Surface Water Regulations, which are administered by MassDEP, Crystal Lake is classified as a Class B water, warm water fishery, and Outstanding Resource Water. As noted above, deeper portions of the water column meet the definition of a cold water fishery (temperatures regularly below 20°C). The primary distinction between the warm and cold water fisheries as specified in the regulations is the difference between <u>minimum</u> dissolved oxygen (DO) concentrations: 6 mg/L for cold water fisheries and 5 mg/L for warm water fisheries. In Crystal Lake, deeper portions of the Lake regularly have DO concentrations below both minima, so the distinction is not relevant for its water quality management discussions. As such, for the purposes of the Crystal Lake diagnostic review and water quality management planning to address state regulatory standards, we have focused on the warm water regulatory standards, which means that the following numeric standards apply:

a) dissolved oxygen shall not be less than 5.0 mg/L,
b) temperature shall not exceed 83°F (28.3°C),
c) pH shall be in the range of 6.5 to 8.3, and
d) bacteria (*Enterococci*) shall not exceed 61 colonies per 100 ml at bathing beaches (with variations available for multiple samples or use of different indicator species).

These numeric standards are accompanied by descriptive standards, which state the following are required for Class B waters: "designated as a habitat for fish, other aquatic life, and wildlife, including for their reproduction, migration, growth and other critical functions, and for primary and secondary contact recreation. Where designated in 314 CMR 4.06, they shall be suitable as a source of public water supply with appropriate treatment ("Treated Water Supply"). Class B waters shall be suitable for irrigation and other agricultural uses and for compatible industrial cooling and process uses. These waters shall have "consistently good aesthetic value."[23]

Under the federal Clean Water Act, MassDEP is required to provide a listing of the status of all surface waters compared to the state regulatory standards. This "Integrated List" has waters

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[20] MGL c. 91 § 35
[21] 314 CMR 4.00
[22] 314 CMR 4.05(3)(a)
[23] 314 CMR 4.05(3)(b)

assigned to five categories including Class 5 impaired waters failing to attain state standards. Class 5 waters are required to have a maximum concentration or load limit (also known as a TMDL) defined for the contaminant causing the impairment.[24] The Massachusetts Integrated List is updated every two years and submitted to and approved by the Environmental Protection Agency (EPA). As previously mentioned, Crystal Lake is listed in the 2016 Massachusetts Integrated List as a Category 5 (impaired) water[25] and has been listed in this category since at least 2004 when MassDEP began following current EPA integrated list guidance.

Though a number of Cape Cod ponds have been identified as being impaired, no Cape Cod pond or lake nutrient TMDLs have been developed or approved by MassDEP. In an effort to begin to define regionally-specific pond and lake nutrient standards, the Cape Cod Commission used the 2001 sampling results from over 190 ponds and lakes during the first PALS Snapshot to develop potential Cape Cod-specific nutrient thresholds.[26] This effort used a recommended EPA method that relies on a statistical review of the available data within an ecoregion to develop nutrient thresholds.[27] This review suggested a target TP concentration range of 7.5 to 10 µg/L for sustaining unimpaired conditions in Cape Cod ponds. Potential target threshold ranges were also developed for total nitrogen (0.16 to 0.31 mg/L), chlorophyll-a (1.0 to 1.7 µg/L), and pH (5.19 to 5.62). These concentrations closely approximated the EPA reference criteria at the time for the east coast region that includes Cape Cod.[28] These Cape Cod-specific thresholds are guidance targets and have not been formally adopted as regulatory standards by MassDEP, the Cape Cod Commission, or any of the towns on the Cape.

Additional Crystal Lake management issues to consider are: a) Crystal Lake is within Pleasant Bay MEP watershed, b) the stream outlet from Crystal Lake flows into Lonnie's Pond, and c) Crystal Lake is within the Pleasant Bay Area of Critical Environmental Concern (ACEC). Given that portions of the Pleasant Bay estuary, including Lonnie's Pond are impaired by excessive watershed nitrogen inputs, water quality management actions to restore Crystal Lake should also include consideration of how activities may also impact nitrogen management in saltwater Lonnie's Pond. Finally, the Pleasant Bay ACEC was designated in 1987.[29] Functionally, this designation means that any management activities in Crystal Lake may require additional state review. Each of these issues is incorporated into the discussions below.

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[24] 40 CFR 130.7 (CFR = Code of Federal Regulations)

[25] Massachusetts Department of Environmental Protection. June 2017. Massachusetts Year 2016 Integrated List of Waters, Draft Listing. CN 470.0. Worcester, MA. 357 pp.

[26] 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.

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

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

[29] https://www.mass.gov/service-details/pleasant-bay-acec (accessed 2/21/18)

IV. Diagnostic Review: Crystal Lake

The Crystal Lake diagnostic summary reviews the 19 years (2001-2019) of citizen-collected water column data and the supplemental data gap information collected by CSP/SMAST in 2018/2019. The data gap information includes sediment nutrient regeneration, bathymetric, rooted plant, and freshwater mussel surveys, plankton tows, and complementary water column data. Data gap information was collected to develop a better understanding of the causes of measured water column conditions, as well as a more comprehensive understanding of the Lake ecosystem functions important for proper water quality management. Collectively, interpretation of the available data provided a reliable baseline for the development of water and habitat quality management strategies.

Water column data provides an understanding of the conditions in the water column, but additional types of information are needed to provide an understanding of the causes of measured chemical concentrations and any identified impaired conditions. Citizen-based water column sampling in Crystal Lake has been completed more than 70 times since the start of the PALS program in 2001. The available data was compiled and reviewed in the 2017 Database Project and was updated with an additional 11 sampling events to fill identified data gaps and support development of this Management Plan. Details on laboratory assay procedures for water column samples are discussed in the Database Report.[30] Collectively, these data and the present resulting summary provide the basis for the assessment of impairments within the Crystal Lake ecosystem, as well as the review of management options to address those impairments.

IV.A. Water Column Data Review

IV.A.1. *In Situ* Field Data: Temperature, DO, Secchi

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

Crystal Lake water column data has been collected consistently by citizen volunteers during the PALS Snapshots between 2001 and 2019 with more frequent monitoring (mostly monthly May to November) in various periods: 2000 and 2001[31], summer monitoring in 2002-2005[32], intermittent spring sampling between 2005 and 2019. In addition, CSP/SMAST staff collected water column data during six months in both 2018 and 2019 as complementary data for the various data gap surveys completed for this management plan.

As a result of all these sampling events, there have been a combined total of 87 water column sampling surveys of Crystal Lake with most (>70%) following PALS protocols. Project staff reviewed all data to address reliability and consistency. Profiles of temperature and dissolved

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[30] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database report.

[31] Scanlon, J. and G. Meservey. 2001. 3 Ponds Study, Orleans, MA. Crystal Lake, Pilgrim Lake, Baker's Pond.

[32] Summer-long sampling during 2003 -2005 was supported by a grant through Cape Cod National Seashore/National Park Service. PALS Snapshot samples were also collected during these years.

oxygen and Secchi disk depth readings were collected during 83 sampling surveys, while water samples were collected for laboratory analysis in approximately 40 to 60 events depending on the constituent.[33]

Mean depth at the deepest location where PALS samples are collected across all surveys was 13.5 m with a range of 11.9 to 15 m. Mean average Secchi transparency depth was 4.45 m (n=81) and averaged 31% of the total depth. Minimum and maximum recorded Secchi measurements were 13% and 56% of the total depth of the pond (July 2003 and September 2004, respectively). Overall, average August/September Secchi depth (4.81 m) was significantly greater ($\rho<0.05$) than April/May average (3.61 m) (Table IV-1). The late summer average Secchi depth, however, was approximately 1 m less than the single August 1948 reading[34] that is available. Trend analysis of water clarity (*i.e.*, Secchi depth) showed that clarity has significantly decreased ($\rho<0.05$) between 2000 and 2019 (Figure IV-1). Seasonal breakdown of the trend shows that late summer (August/September) trend was greater (-0.15 m/yr) than the spring (April/May) trend (-0.06 m/yr).

Average late summer temperature profiles showed average stratification or temperature layering with a warmer upper layer between the surface and 4 m depth, a transition zone between 5 and 7 m depth, and a cooler lower layer between 8 m and the bottom (Figure IV-2). This layering usually did not occur during the spring; on average, spring temperatures were sufficiently similar to allow the whole water column to mix. It was also notable that average water temperatures 6 m or deeper (approximately 30% of the pond volume) remain below the 20°C maximum that MassDEP has specified for cold water fisheries; this suggests that MassDEP should consider listing Crystal Lake as a cold water fishery rather than the its current listing as a warm water fishery. Temperature profiles collected in 2019 showed no stratification in April, a transition zone beginning at 3 to 5 m depth during the summer, and a slight stratification at 10 m depth in October, indicating that consistent water temperatures throughout the water column was likely in November (Figure IV-3).

Average late summer dissolved oxygen (DO) profiles showed that concentrations at 6 m and deeper were below the MassDEP minimum concentration of 5 mg/L (Figure IV-4). This depth was consistent with the average summer temperature profile, where waters deeper than 5 to 7 m were isolated from the upper portions of the water column. DO concentrations in the isolated, deeper layer would then be decreased by sediment oxygen demand and the thermal layering would prevent any atmospheric replenishment of the DO loss. Overall, 85% of average late summer DO readings ≥6 m deep were less than 5 mg/L DO. The average spring DO profile showed some loss of DO in the deepest waters (32% of readings at ≥12 m deep were less than 5 mg/L DO), showing sediment oxygen demand was prevalent even when the water column is not thermally layered.

DO profiles in 2019 showed the impact of significant sediment oxygen demand in all profiles, but the greatest DO losses late in the summer (see Figure IV-3). In April 2019, DO throughout the water column was acceptable with concentrations >10 mg/L and some slight losses due to sediment oxygen demand in the deepest readings. The June 2019 profile continued to have acceptable concentrations (*i.e.*, ≥5 mg/L) throughout the water column, but showed the initial impacts of

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[33] through October 2019

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

Table IV-1. Crystal Lake Water Column Averages. Averages were based on 2000 to 2019 data. Statistically significant differences in averages at corresponding depths are shaded blue. Statistics are based on database with outliers removed. Deep readings are from depths ≥12 m.

	All	Apr/May				Aug/Sept			
	data	shallow	3 m	9 m	deep	shallow	3 m	9 m	deep
Total Depth									
Average (m)	13.47	13.79				13.42			
N	70	11				29			
Max	15.00	15.00				14.50			
Min	11.86	12.00				11.86			
Secchi Depth									
Average (m)	4.45	3.61				4.81			
N	81	13				32			
Max	8.48	5.38				8.48			
Min	1.82	2.75				2.75			
Temperature: MassDEP Cold Water Maximum = 20°C									
Average (°C)	14.08	15.95	14.47	8.03	7.29	23.62	23.38	9.56	8.35
N	1,097	13	16	16	30	33	32	32	57
Max	27.70	22.10	18.80	10.20	8.70	26.90	26.70	12.80	10.40
Min	5.60	8.40	7.60	6.00	6.10	19.10	19.10	7.60	6.70
Dissolved Oxygen: MassDEP Regulatory Minimum = 5 mg/L (temp data suggest should be 6 mg/L)									
Average (mg/L)	6.48	10.14	10.36	9.62	6.82	7.90	7.79	1.67	0.61
N	1,096	13	16	16	31	33	32	34	57
Max	13.10	12.03	11.90	11.53	10.85	9.96	9.95	6.53	2.80
Min	0.04	8.59	8.88	6.49	0.36	5.71	5.92	0.16	0.07
% <MassDEP min	31%	0%	0%	0%	32%	0%	0%	97%	100%
pH: MassDEP Regulatory Minimum = 6.5									
Average (stnd)	6.18	6.44	6.46	6.21	6.29	6.43	6.46	5.78	6.15
N	159	2	2	2	1	25	25	21	24
% <MassDEP min	85%	50%	100%	100%	100%	60%	61%	100%	100%
Chlorophyll: Cape Cod Ecoregion Threshold = 1.7 µg/L									
Average (µg/L)	2.06	1.47	1.33	1.80	0.62	2.68	2.59	2.16	1.44
N	148	2	2	2	1	24	22	22	20
Max	8.38	1.65	1.37	2.32	-	5.14	6.11	6.59	7.40
Min	0.00	1.28	1.29	1.28	-	1.04	0.01	0.03	0.03
% >Ecoregion	45%	0%	0%	50%	0%	75%	68%	45%	25%
Total Phosphorus: Cape Cod Ecoregion Threshold = 10 µg/L									
Average (µg/L)	17.44	16.80	13.93	10.90	21.79	8.98	8.03	15.79	45.41
N	262	7	7	7	8	31	25	27	31
Max	155.00	42.50	24.96	41.80	62.00	25.00	18.37	38.58	155.00
Min	0.50	3.54	4.45	2.00	3.79	0.50	1.55	2.75	0.50
% >Ecoregion	57%	57%	71%	14%	75%	35%	32%	67%	81%
Total Nitrogen: Cape Cod Ecoregion Threshold = 0.31 mg/L									
Average (mg/L)	0.37	0.34	0.34	0.33	0.45	0.32	0.31	0.30	0.61
N	247	8	9	9	8	31	25	27	30
Max	1.00	0.50	0.45	0.47	0.95	0.52	0.44	0.48	1.00
Min	0.13	0.17	0.17	0.20	0.22	0.16	0.16	0.14	0.28
% >Ecoregion	60%	50%	56%	56%	75%	48%	52%	48%	93%

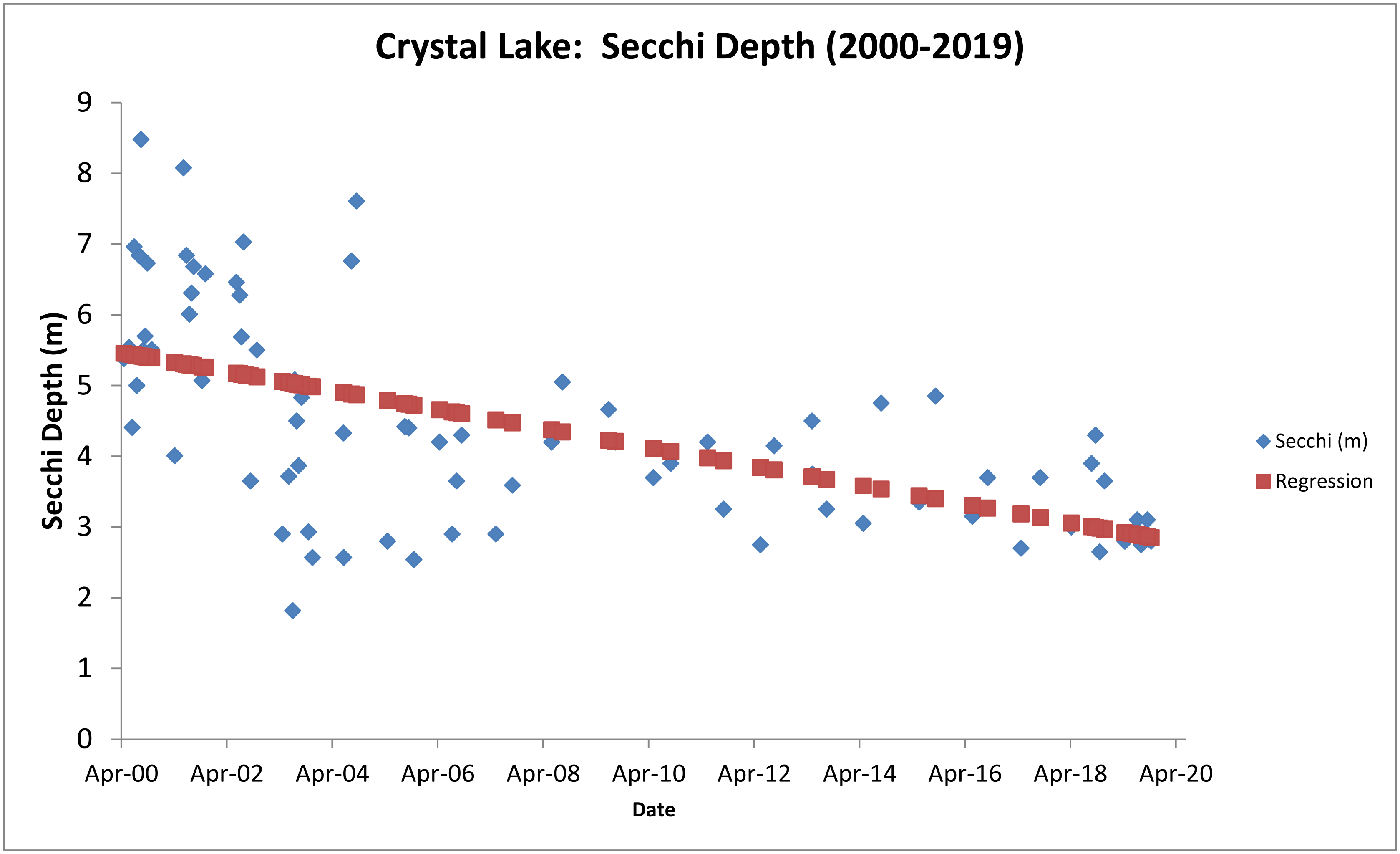

Figure IV-1. Crystal Lake Secchi Measurements 2000-2019. Trend analysis of Secchi depth (*i.e.*, water clarity) showed a significant ($\rho<0.05$) decreasing trend between 2000 and 2019. The overall trend was -0.1 m per year (-5 in/yr) with slightly lower rate in the spring (April/May) and slightly higher rate in the late summer (August/September). Decreased clarity in Cape Cod ponds tends to be exclusively related to increased phytoplankton growth.

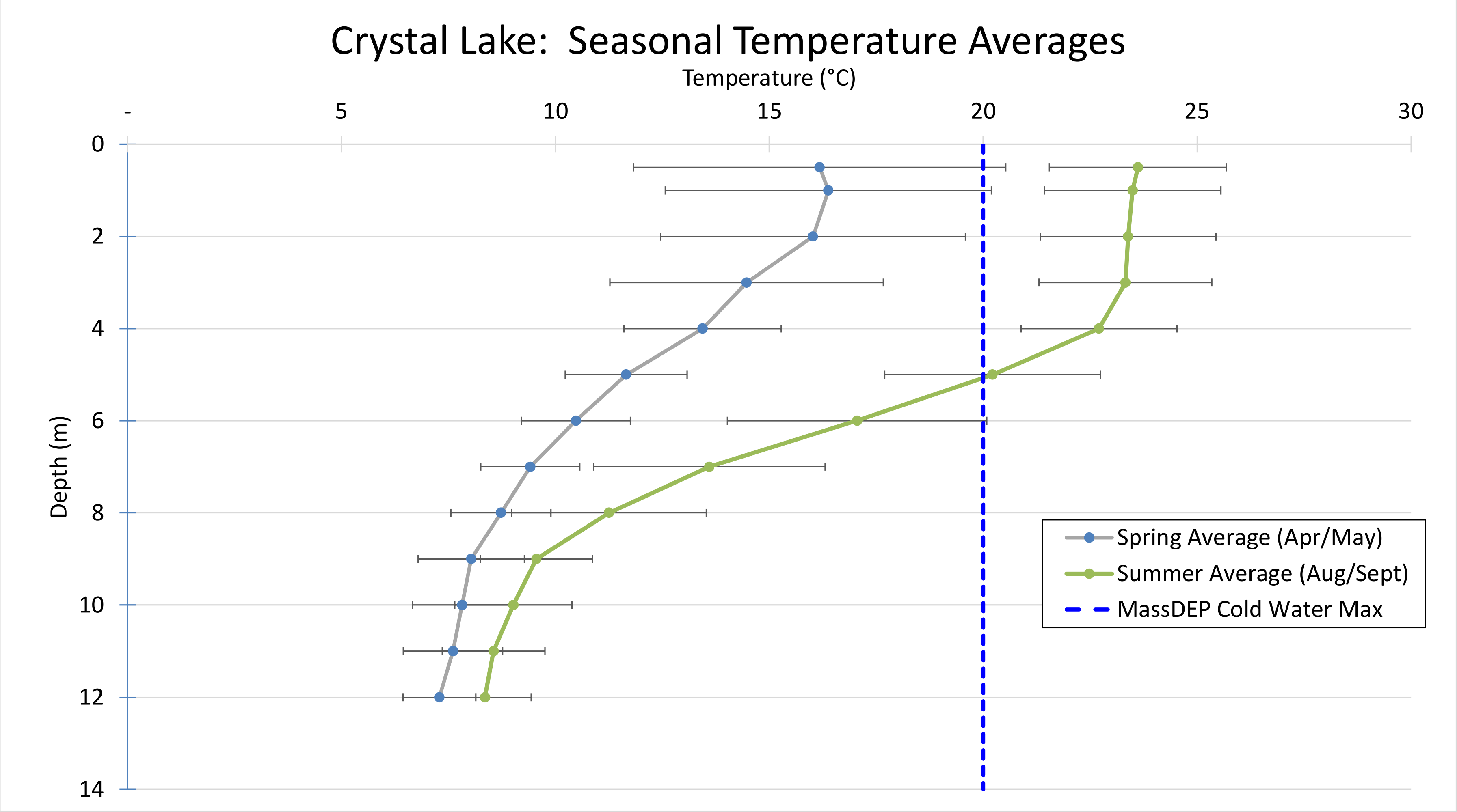

Figure IV-2. Crystal Lake Seasonal Temperature Averages 2000-2019. Average temperature profiles in spring (April/May readings) and late summer (August/September readings) are shown with error bars of one standard deviation. Spring readings show the greatest variation in the shallowest portions of the water column, while late summer readings have the greatest variation at the depths where the stratification boundary occurs (*i.e.*, 6 to 8 m depth). Late summer readings also showed that temperatures deeper than 7 m remain well below the MassDEP maximum reading (20°C) for defining a cold water fishery. Based on these readings, MassDEP should consider changing the classification of Crystal Lake from a warm water fishery to a cold water fishery.

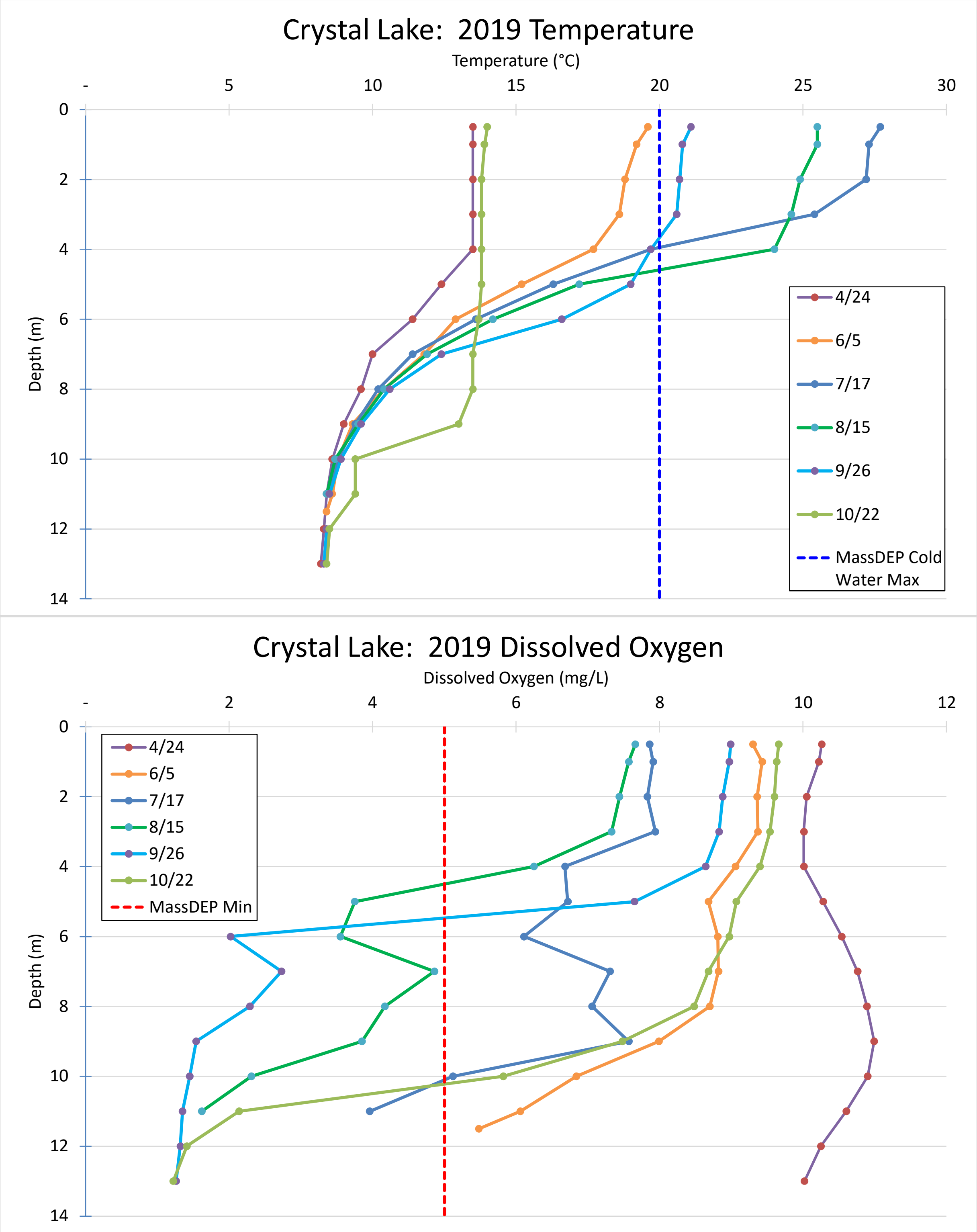

Figure IV-3. Crystal Lake 2019 Temperature and Dissolved Oxygen Profiles. Temperature profiles show strong stratification began between April and June, strengthened throughout the summer, and began to breakdown during October. Sediment oxygen uptake occurred in all DO profiles, but had the most impact once strong stratification occurred in June. In August and September, 30% or more of the pond volume had DO concentrations less than the MassDEP minimum.

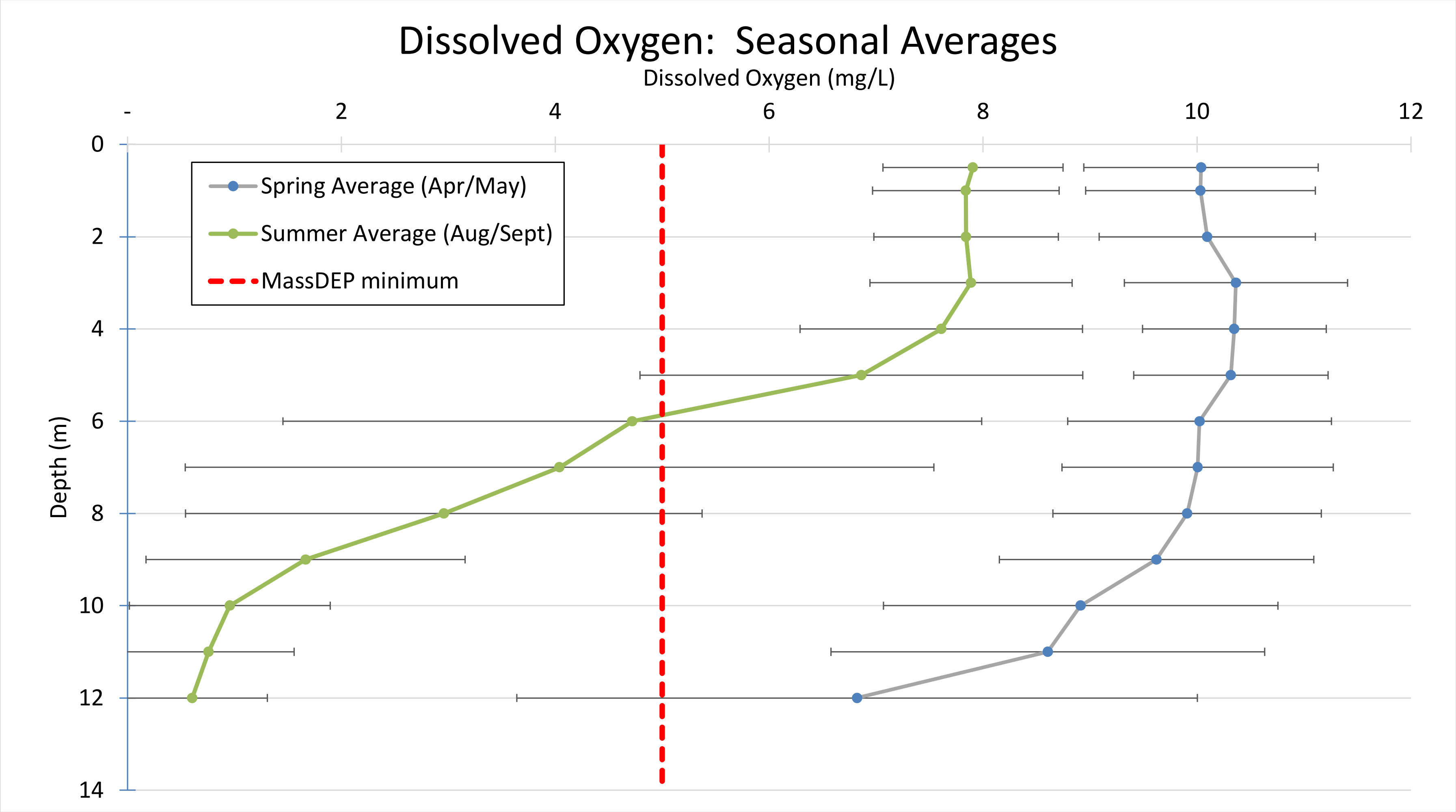

Figure IV-4. Crystal Lake Seasonal Dissolved Oxygen Averages 2000-2019. Average DO profiles in spring (April/May readings) and late summer (August/September readings) are shown with error bars of one standard deviation. Average spring readings were greater than the MassDEP minimum of 5 mg/L DO, but show the greatest variation in the deepest readings (*i.e.*, closest to the sediments). Late summer readings were less than the MassDEP minimum at 6 m and deeper, but had high variation between 5 and 8 m, which brackets the depths where maximum temperature changes have historically occurred and transition between the warm and cold stratification layer occurs.

temperature layering with DO losses beginning at 5 m and gradually increasing with deeper depths. In the July 2019 profile, a sharp drop in DO concentrations occurred between 9 and 10 m with the 11 m reading below the MassDEP warm water DO minimum of 5 mg/L. By the August 2019 profile, the water column deeper than 4 m (or 42% of the pond volume) was less than the 5 mg/L DO minimum. The September 2019 profile showed a sharper distinction between the two layers with near atmospheric saturation in the warmer upper layer and more DO losses in the deeper colder layer (*e.g.*, all DO concentrations ≥6 m depth were 2.7 mg/L or less). In the October 2019 profile, the water column temperatures were relatively consistent to 9 m depth and DO concentrations at 11 m and deeper were significantly impacted by sediment oxygen demand (*i.e.*, all <2.1 mg/L DO) and shallower portions of the water column with DO concentrations above the MassDEP minimum of 5 mg/L.

Collectively, the DO and temperature profiles and Secchi readings show that Crystal Lake regularly has impaired water quality. The decreasing trend in the Secchi readings over the past two decades shows that the impairments have increased over the period that regular water quality monitoring has occurred. Complementary profile and clarity data collected in 2019 generally confirmed the impairments noted in the long-term record.

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

Among the 87 sampling surveys of Crystal Lake completed between 2000 and 2019 there were approximately 70 surveys that included the collection of water quality samples. The samples were not consistently assayed at the same labs or using the same laboratory techniques or for all the same parameters, but the dataset was more extensive than is generally available for lake diagnostic reviews. Compilation and analysis of these assay results through 2016 was summarized in the 2017 Pond Monitoring Database report, which also details the labs used and the assay procedures that were followed.[35] The findings in the Database report were also used to identify data gaps that needed to be addressed for the preparation of reliable water quality management strategies for Crystal Lake. The summary below updates the data analysis in the Pond Monitoring Database report by including the results from the sampling events in 2017 and 2018, as well as from the 2019 data gap surveys.

Review of 2000 to 2019 nutrient data showed that most of the individual readings were above Cape Cod Ecoregion thresholds (57% of total phosphorus readings and 60% of total nitrogen readings), which is consistent with impaired conditions (see Table IV-1). Average shallow N:P ratios were 93.5, which indicates that phosphorus is the key nutrient directing plant growth in the lake and, thus, is the primary focus for managing its water quality. Average shallow and deep TP concentrations were 12.7 µg/L and 31.1 µg/L, respectively, while corresponding TN concentrations were 0.33 mg/L and 0.50 mg/L, respectively. Closer review of the nutrient data showed that deep TP and TN readings during the summer were significantly higher ($\rho<0.05$) than shallow concentrations, but they were not significantly different during the spring when the water column was not strongly stratified; these comparisons are also consistent with enhanced summer sediment nutrient regeneration and bottom water hypoxia.

Deep summer average TP concentrations were also significantly higher than deep spring average TP concentrations; this difference is consistent with summer nutrient additions due to anoxia

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[35] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database report.

enhanced sediment regeneration. Deep TN concentrations were not significantly different, which suggests that summer low DO conditions were generally not low enough or prolonged enough to trigger complete release of sediment bound nitrogen. Mid-depth (both 3 and 9 m) TP and TN concentrations were not significantly different from surface concentrations during both the spring and summer, which means that on average TP and TN sediment regeneration primarily impacted water column depths of 10 m and deeper and only during the summer. Deep summer average TP concentrations were >4X surface TP concentrations. Elevated bottom water concentrations show the regular enhanced sediment nutrient regeneration during the summer, which is also consistent with the temperature stratification and lower deep DO concentrations discussed above.

Review of the most recent data collected to complement the data gap surveys showed that most of the TP and TN water column concentrations collected between April and October 2019 were above their respective Cape Cod Ecoregion thresholds (Figure IV-5). TP showed increases in water column concentrations beginning in July with the largest increases at depths greater than 9 m due to bottom water anoxia. TP concentrations shallower than 9 m generally varied between 10 and 20 µg/L TP in the July, August, September, and October samplings, but concentrations deeper than 9 m increased in July, August, and September and remained at September levels in October (>70 µg/L TP) consistent with sustained temperature stratification, low oxygen conditions, and sediment TP regeneration. TN concentrations showed a decrease from April in the shallower portions of the water column (<9 m) in both June and July, followed by a return to April levels in August, a significant decrease in September, then a slight increase in October at the mid-depths and a significant increase at the shallowest depth (0.5 m). Deeper TN concentrations also varied, but were generally higher than surface concentrations reflecting sediment TN regeneration.

This complex pattern suggests occasional near surface discharges of TN and high internal uptake and transfer out of the water column in early summer. In all six of the 2019 samplings, all surface N:P ratios were greater than the Redfield ratio limit indicating phosphorus control of phytoplankton growth. Close to the sediments, where phytoplankton would not grow due to low light, high TP regeneration rates lowered the N/P ratio to near balance between N and P limitation of plant growth. N and P concentrations in July were closer to the N:P limit than other months largely due to the higher TP concentrations in the shallow water column (<9 m).

Chlorophyll concentrations in the water column <9 m in all 2019 samplings after April were well above the Cape Cod Ecoregion threshold of 1.7 µg/L; April concentrations were less than the threshold. The depth of maximum chlorophyll concentration in each of the 2019 profiles shifted up and down within the water column, but tended to be at the bottom of the upper well mixed layer as defined by temperature (*i.e.*, the top of the transition zone). Higher concentrations of phosphorus diffusing upward from the lower, colder layer would be most available to phytoplankton in this portion of the water column while also having sufficient light for photosynthesis. TP concentrations generally seem to follow this pattern, but there were enough differences to suggest other factors were also involved in these interactions.

Review of trends in shallow water nutrient concentrations (TP and TN) showed that nutrient levels have significantly increased between 2000 and 2019. Shallow nutrient levels should be the least impacted of the water column TP and TN concentrations by sediment nutrient regeneration. Trend analysis of shallow TN concentrations from 2000 to 2019 show a statistically significant increasing

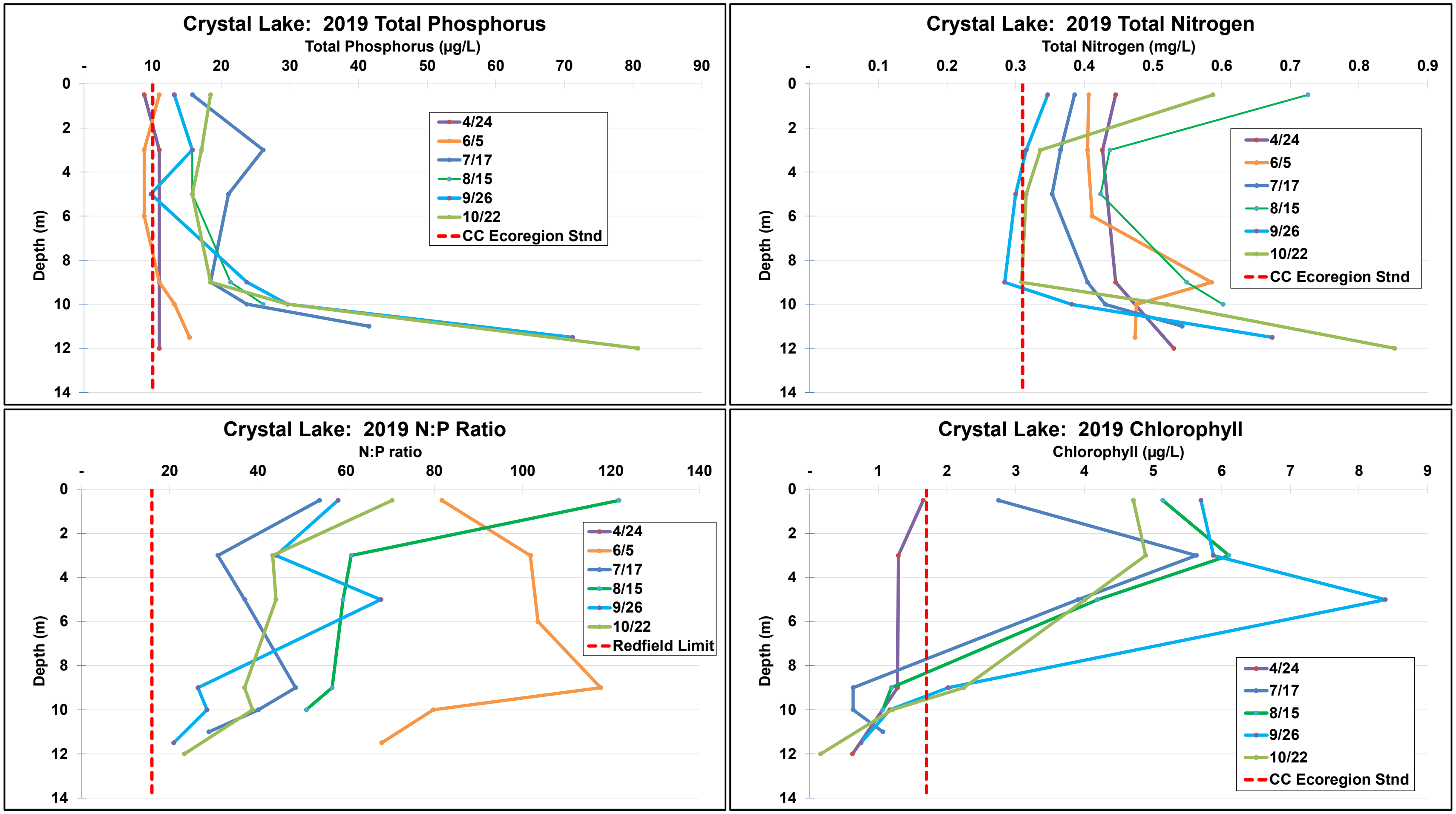

Figure IV-5. 2019 Nutrient and Chlorophyll Profiles. TP profiles show that all concentrations after June exceeded the Cape Cod Ecoregion threshold (10 µg/L TP) and also had deep concentrations that increased each subsequent month. TN profiles also showed that concentrations generally exceed the 0.31 mg/L Ecoregion threshold and had sediment regeneration, but also had notable near-surface summer increases, which suggests short term, high concentration inputs. All April chlorophyll concentrations were less than the 1.7 µg/L Ecoregion threshold, but all subsequent concentrations measured <8 m depths were above the threshold. Chlorophyll maximums tended to be at the top of the temperature transition zone suggesting phytoplankton utilizing TP diffusing upward from the higher TP concentration in the lower colder layer.

trend ($\rho<0.05$) of +0.007 mg/L per year or a predicted +0.14 mg/L increase between 2000 and 2019 (Figure IV-6). A rise in TN concentrations in freshwater ponds is usually due to additional septic systems added to the watershed or increase in housing occupancy. Shallow TP concentrations also increased between 2000 and 2019, though just short of the typical statistically significant threshold ($\rho=0.065$). Shallow TP concentrations increased +0.35 µg/L per year or a predicted +6.6 µg/L increase between 2000 and 2019. Since TP typically moves much slower than TN within the groundwater, increases in TP concentrations are usually due to increased watershed additions within ~100 m of the pond shoreline. The increasing TP trend was consistent with the decreasing Secchi clarity trend that was noted above. Deep TP and TN concentrations did not have significant trends between 2000 and 2019.

Using the updated bathymetric volumes (discussed in Section IV.B.3.), conversion of available water column concentrations to water column TP and TN mass showed how both have increased over time. TN mass at various depths approximates the decrease in water volume with increasing depth in Crystal Lake, whereas TP mass was more balanced throughout the water column reflecting the higher concentrations caused by low DO in the deepest waters. Since the TN concentrations are largely unimpacted by internal lake processes, water column TN mass would reflect changes in amount of TN added from the watershed over time. Review of available water column TN between 2001 and 2019 showed that the water column mass increased by approximately 7 kg annually, which is approximately the N load from two septic systems (Figure IV-7). Average water column TN mass between 2001 and 2005 was 276 kg (n=19), while average water column TN mass between 2015 and 2019 was 368 kg (n=13). TP water column mass also showed an increase with time between 2001 and 2019 (0.3 kg/yr), but there was more scatter in the data due to the impact of variable seasonal inputs from the sediments. Average water column TP mass between 2001 and 2005 was 10 kg (n=21), while average water column TP mass between 2015 and 2019 was 15 kg (n=13). Review of seasonal water column mass (April to June vs. August/September) had approximately the same long term increase suggesting that the increase is largely due to watershed additions.

It should also be noted that pH readings were generally less than the stated MassDEP regulatory range (6.5 to 8.3), but this was consistent with the naturally acidic levels found in most Cape Cod groundwater and ponds and is, therefore, acceptable under the natural conditions provision of the regulations. Cape Cod ponds tend to be naturally acidic (pH<7) because of the lack of carbonate materials in the surrounding sandy aquifer.[36] Increases in pH in Cape Cod ponds are generally measured in nutrient-enriched settings; photosynthesis from extensive phytoplankton populations consumes hydrogen ions.[37] During the 2001 PALS Snapshot, the average pH of the 193 Cape Cod ponds and lakes sampled was 6.16.[38] Average pH of all the water column readings in Crystal Lake was 6.18. However, there were significantly higher pH readings in shallow waters (6.40) and mid/3 m depth water (6.43), than in 9 m or deep waters (5.82 and 6.12, respectively). Most of the pH readings were collected in summer, so seasonal comparisons were not possible; readings have only been collected twice in April or May. The higher pH in shallow waters would be consistent with higher phytoplankton populations.

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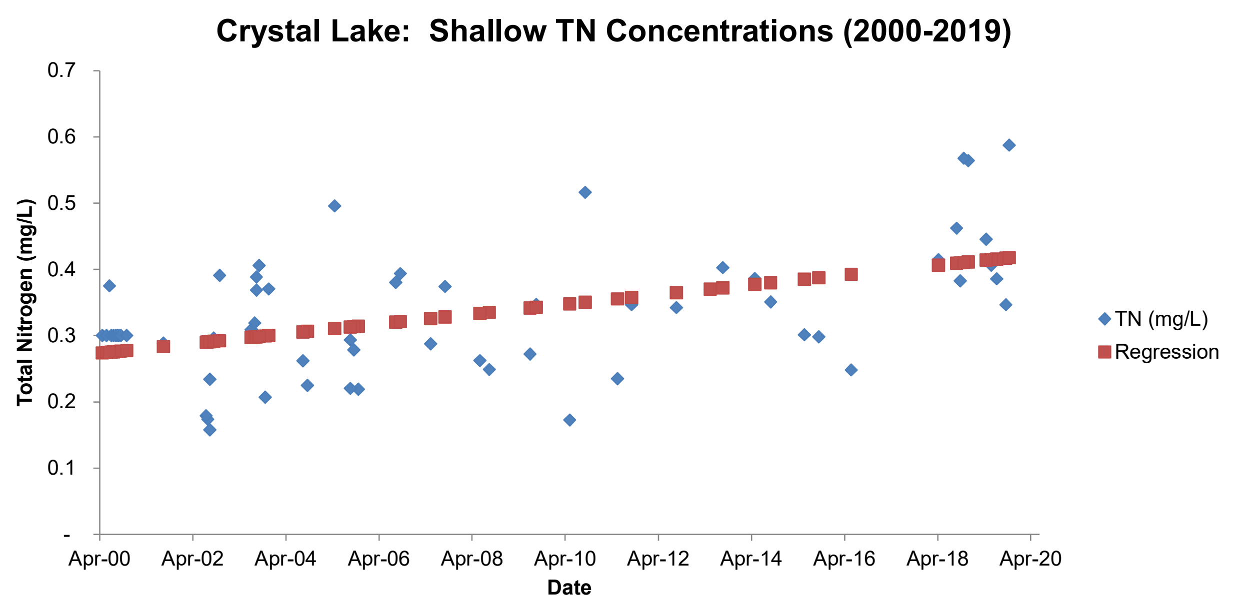
[36] Recommended Cape Cod Ecoregion threshold for pH is 5.62 (Eichner, E.M., T.C. Cambareri, G. Belfit, D. McCaffery, S. Michaud, and B. Smith. 2003. Cape Cod Pond and Lake Atlas.)

[37] pH is the negative log of the hydrogen ion concentration.

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



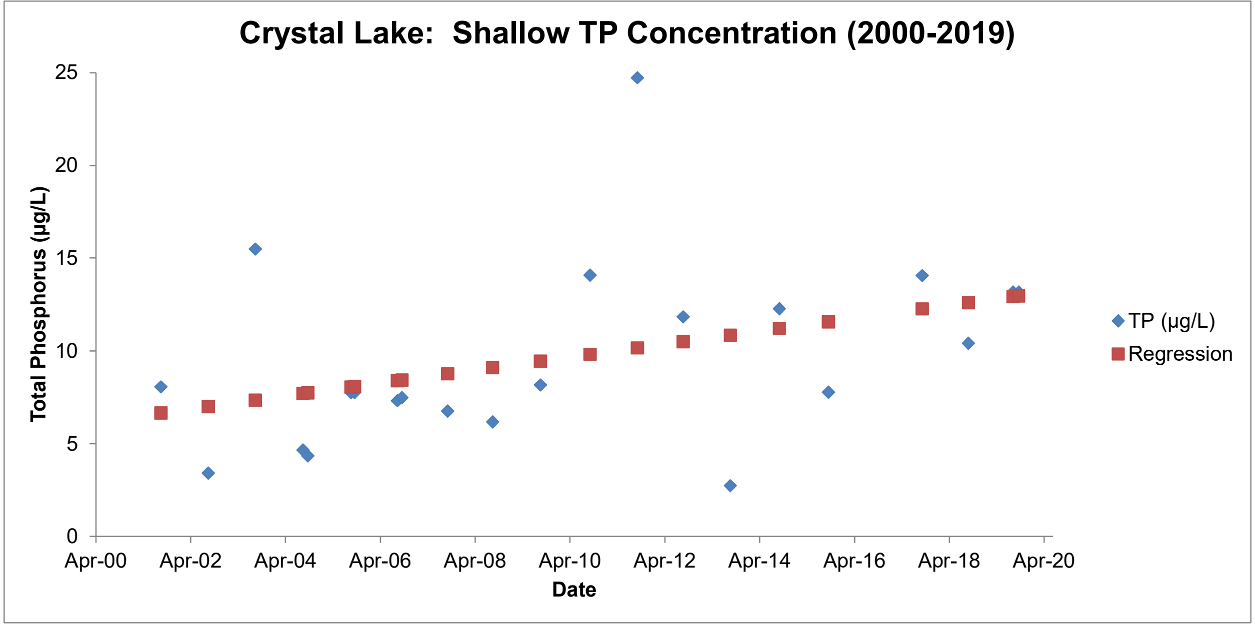
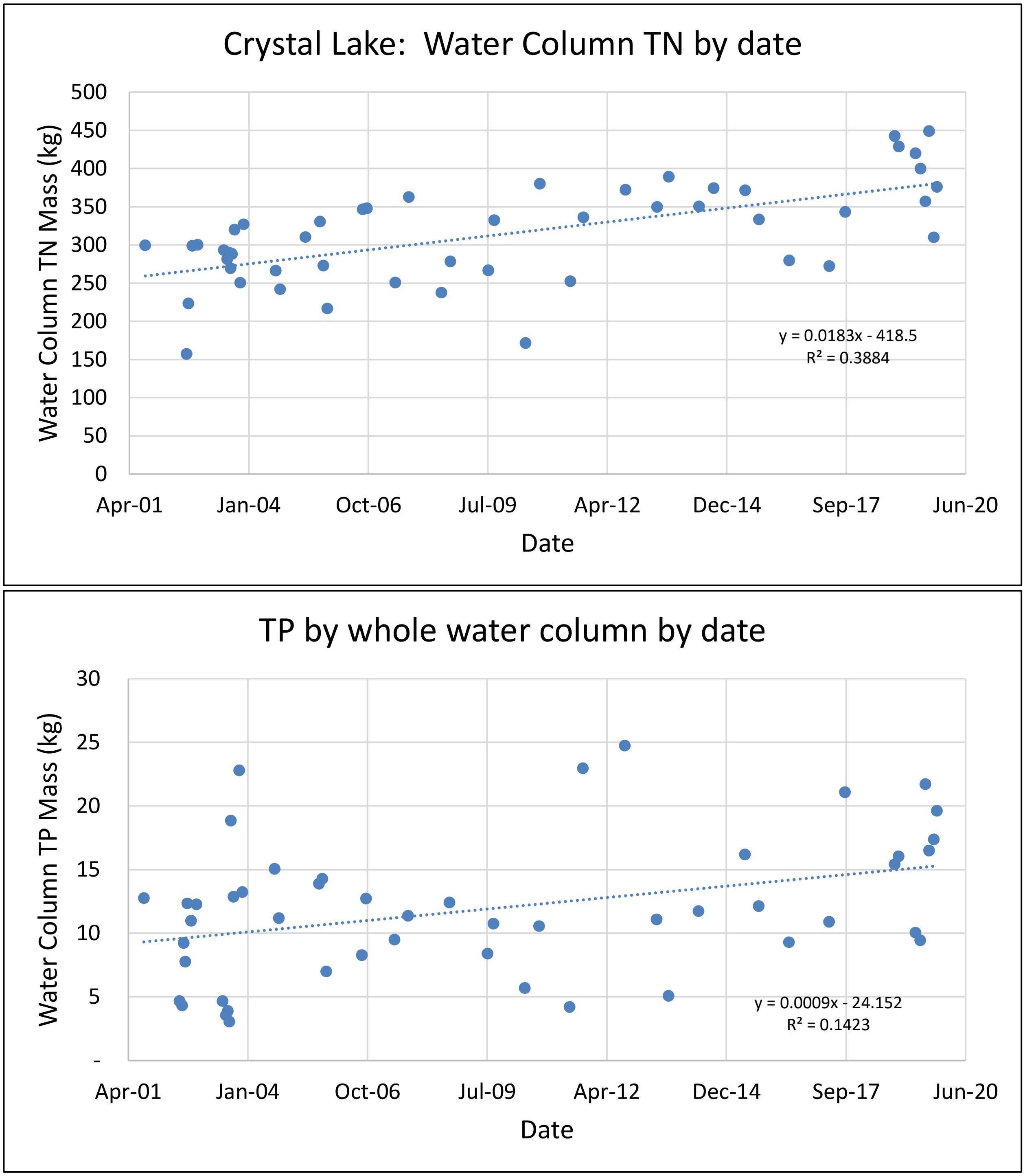


Figure IV-6. Trend Analysis: Shallow Total Nitrogen and Total Phosphorus (2000-2019). Shallow TP and TN concentrations have significantly increased between 2000 and 2019. Shallow TN concentrations have a significantly increased trend of +0.007 mg/L per year or a predicted +0.14 mg/L increase between 2000 and 2019, while shallow TP concentrations have increased +0.35 µg/L per year or a predicted +6.6 µg/L increase between 2000 and 2019. The TN trend was statistically significant at the $\rho<0.05$ level, while the TP was significant at the $\rho<0.065$ level.



Crystal Lake: Water Column TN by date

TP by whole water column by date

Figure IV-7. Crystal Lake: Water Column TN and TP Mass (2000 to 2019). TN and TP mass were determined by reviewing respective water column concentrations and water volume at corresponding depths. This estimate was determined for each sampling run between 2000 and 2019. Water column TN mass increased relatively consistently approximately 7 kg annually, while TP mass increased approximately 0.3 kg annually, but had more data scatter, likely due to summer sediment regeneration fluctuations.

IV.B. Crystal Lake Data Gap Surveys

As a result of the review of Town of Orleans volunteer-collected water column data completed in 2017[39], project staff identified a number of data gaps that would need to be addressed in order to understand the sources of the nutrient levels in Crystal Lake, the processes that cause ecosystem changes seasonally and year-to-year, and to provide a more complete understanding of the system in order to select management strategies that will reliably address the identified water quality impairments. These data gaps included: a) measuring the nutrient loads from stormwater runoff discharge into the lake, b) measuring surface water inflows and outflows and their associated nutrient loads, c) surveying the bathymetry, rooted plant community, and freshwater mussel populations, d) measuring the changes in the phytoplankton community, and e) continuously measuring the changes in water column water quality conditions. Results from each of these data gap surveys are summarized in this section.

IV.B.1. Phytoplankton Community

Since Crystal Lake has a long history of high phosphorus and chlorophyll concentrations, CSP/SMAST recommended that the town include regular monthly sampling of the phytoplankton community as a 2019 data gap tasks to evaluate how the population changes and what species dominate during different portions of the spring and summer. Assessment of phytoplankton community composition along with associated measurements of chlorophyll and DO concentrations through continuously recording sensors, as well as the other 2019 data, was sought to gain a better understanding of the role the phytoplankton community plays in the water column measurements collected in Crystal Lake.

CSP/SMAST staff collected phytoplankton samples through vertical net tows monthly between June and October 2019. Tows were conducted through the photic zone, as determined by a Secchi reading at the lake'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 for cell counts per milliliter and biovolume per milliliter.

The phytoplankton tow results generally showed relatively low cell counts and biomass levels. Figure IV-8 shows how the cell counts and biomass levels of the plankton community changed throughout the summer. Given the low cell counts and relatively high TP levels, project staff confirmed the results twice with Phytotech. The cell counts were confirmed, but low levels suggest that a portion of the phytoplankton population was not included in the tows, perhaps blue-greens, which can control their buoyancy were dropping just below the Secchi depth to take advantage of the higher TP concentrations in the deeper portions of the water column. Sufficient light is usually present for photosynthesis beyond the Secchi depth with the euphotic zone often interpreted as up to 45% greater than the Secchi depth depending on other factors such as water color, suspended solids, etc.[40] It was thought that this may account for the low cell counts and biomass levels. Community breakdown likely is reasonably representative of the lake's photosynthetic community, but should be regarded as qualitative because of the biomass and cell count results.

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[39] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database report

[40] Brown, R. 1984. Relationships Between Suspended Solids, Turbidity, Light Attenuation, and Algal Productivity. *Lake and Reservoir Management*. 1:1, 198-205, DOI: 10.1080/07438148409354510

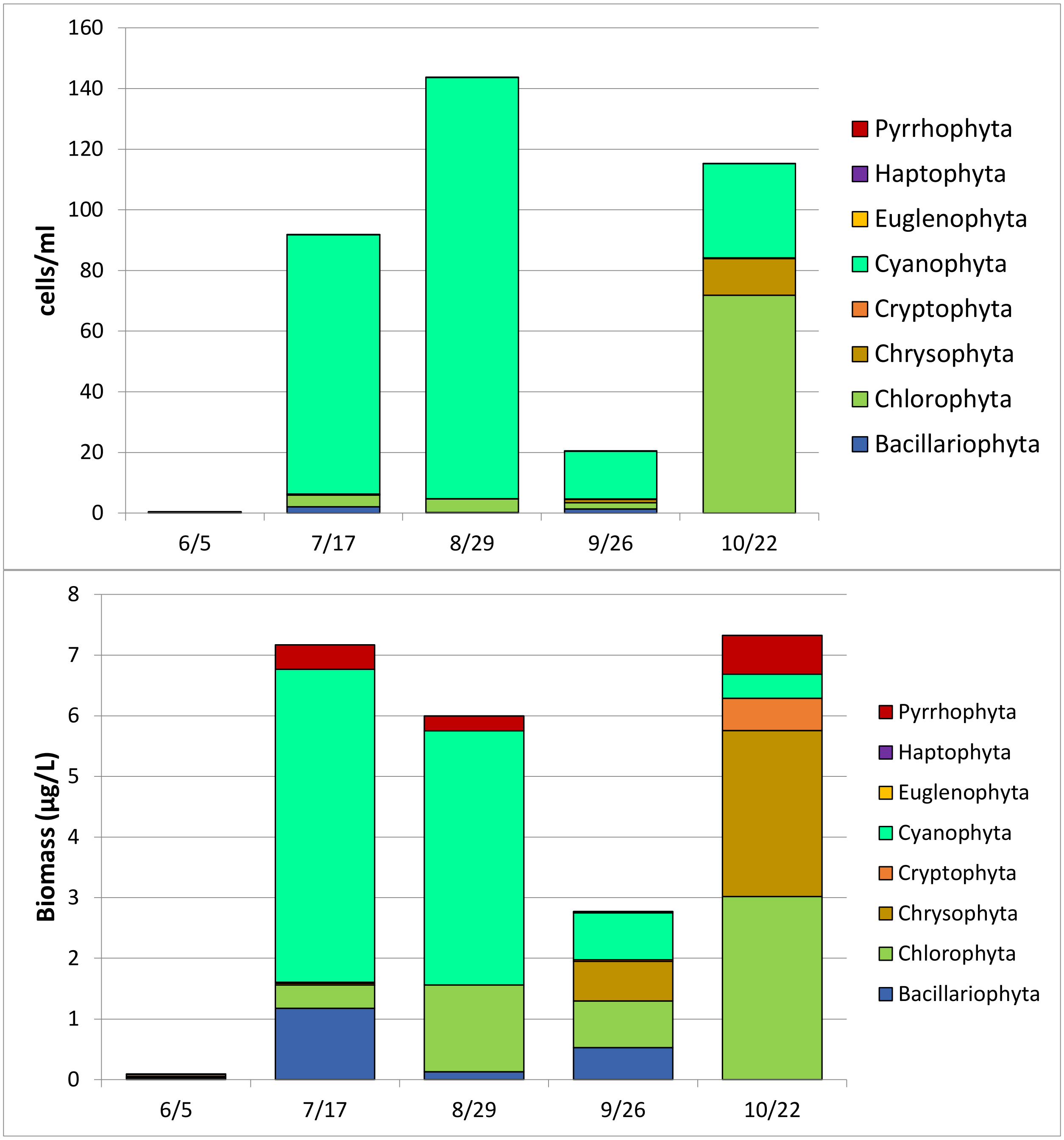

Figure IV-8. Crystal Lake 2019 Phytoplankton Cell Count and Biomass. Crystal Lake plankton tows were conducted monthly between June and October 2019. Cell counts in July, August, and September (top) were dominated by blue-green/cyanophytes with the highest overall count in August; all counts were well below the MassDPH advisory threshold for contact recreation. In October, chlorophyta (green algae) had the highest cell count. Biomass (bottom) was predominantly blue-greens in July and August, split between four taxa in September, and then primarily chlorophyta and chrysophyta (golden algae) in October.

In June, the phytoplankton biomass[41] and cell counts were extremely low.[42] Only six species were present in June with *Chrysochromulina parva* as the dominant cell type. It is worth noting that most of the euphotic zone in June had TP concentrations between 9 and 11 µg/L (10 µg/L TP is the Cape Cod Ecoregion goal). In the July tow, cell counts and biomass increased, but remained relatively low. The species count increased to 16. Blue-green algae (*i.e.*, cyanophytes or cyanobacteria) became the predominant cell type and accounted for most of the biomass in July. The blue-greens were approximately evenly divided between *Microcystis aeruginosa* and *Dolichospermum lemmermannii*. Both of these species are known to produce toxins, but the cell counts and biomass levels in the pond were well below public health levels. It is notable that the maximum 2019 TP concentration at 3 m was also measured in July. In the August tow, the biomass level was approximately the same as July, but blue-greens became more dominant in the cell count with *Microcystis aeruginosa* becoming the dominant species in both biomass concentration and cell count. Species count in August increased to 20. In September, the biomass concentration decreased by approximately 50% and was split approximately evenly between four divisions. Blue greens remained the dominant cell types, evenly divided among *Microcystis aeruginosa* and *Dolichospermum circinale.* Species count in September increased to 24 and, though toxic blue-greens were dominant, cell counts and biomass levels in the lake were well below public health levels. Comparison of the September chlorophyll readings illustrated the issues with the tows and the Secchi readings; the water column chlorophyll maximum was at 5 m and the tow began at 3 m (roughly the Secchi depth). The two blue-green species in September both have gas vesicles, which allow them to control their buoyancy. Since the upper layer of the pond was relatively isothermic, these species could drop down to the lower level of the euphotic zone (where light was likely less than 5% of surface light) and then use the vesicles and natural mixing to return to shallower depth with higher light levels. In October, cell counts and biomass concentrations returned to July/August levels, but blue-greens were less prevalent and chlorophyta (*i.e.*, green algae) became the dominant cell type and the predominant portion of the biomass. Chlorophyll levels at 3 m in October were slightly less than in July. Overall, the maximum cell count in Crystal Lake was measured in August (143 cells/mL) and the maximum phytoplankton biomass was in October (7.3 µg/L).

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

Characterization of the 2019 phytoplankton community also included the installation of a moored autonomous sensor array to evaluate short-term changes in key water-column parameters and their relationship to changes in the phytoplankton community. The instruments were installed on June 5 at the monthly water column profile sampling site and were removed October 22. The instruments recorded depth, chlorophyll-*a*, dissolved oxygen, and temperature every 15 minutes. Water quality samples were collected on five occasions during the deployment period as part of QA/QC of sensor readings; parallel mooring and laboratory chlorophyll readings generally differed by <5%.

The instrument had an average depth of 9.5 m, but the mooring was occasionally moved so there was a generalized range of 1.5 m around the average (Figure IV-9). Temperature readings were relatively constant (average = 8.5°C), but also had fluctuations that mostly appear to be related to the mooring being moved (see Figure IV-9). The relatively constant temperatures at this depth

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[41] weight per volume of water

[42] June cell count was 0.4% of June 2017 cell count in Pilgrim Lake

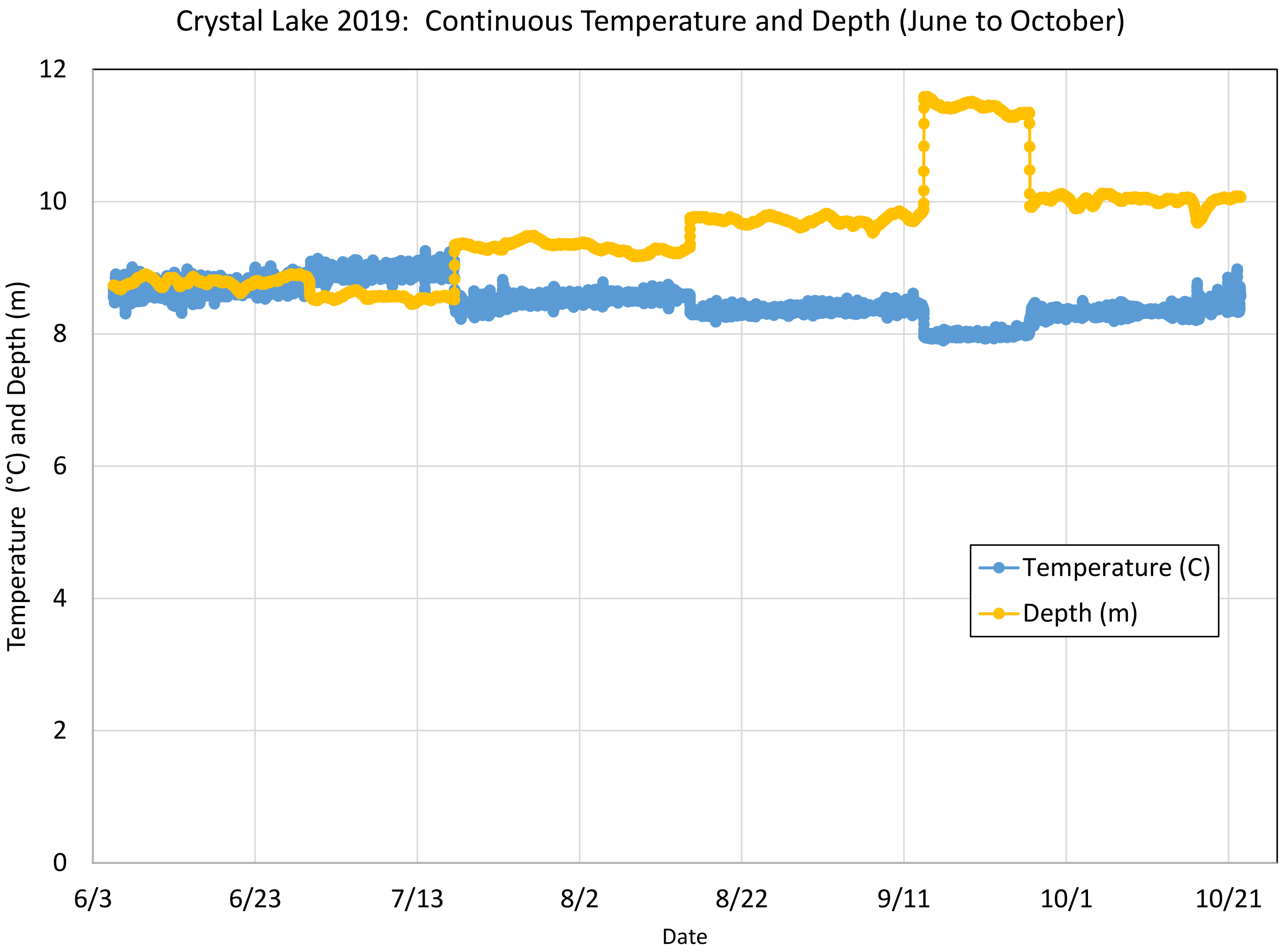

Figure IV-9. Crystal Lake Continuous Temperature and Depth Readings, Summer 2019. A sensor array was deployed to collect temperature and depth readings every 15 minutes between June 3 and October 22. Average depth of the array was 9.5 m, although it was occasionally moved at various points during its deployment. Temperature readings were relatively steady and averaged 8.5°C. Since this temperature was consistently less than the MassDEP 20°C upper limit for cold water fisheries, it is recommended that the current classification of Crystal Lake in the MassDEP regulations should be revisited.

throughout the summer and below the MassDEP 20°C cold water fisheries limit reinforce that the MassDEP warm water classification should be reconsidered.

Continuous chlorophyll pigment concentrations were consistent with the increasing phytoplankton concentrations measured throughout the summer in the water column measurements. Pigment concentrations were approximately 0.5 µg/L in early June, increased to approximately 3.0 µg/L during the second week of August, and began to slightly decrease until the mooring was moved on 9/13 (Figure IV-10). Pigments increased approximately 0.04 µg/L daily between early June and mid-August; this rate was similar to what was observed in Pilgrim Lake albeit at lower concentrations due to the depth of the sensor. Since the sensor depth was mostly at 9.5 m, which was deeper than the bottom of the euphotic zone, the increases in the pigment readings reflect increased chlorophyll concentrations in the water column above the sensor. Based on water column samples, 60 to 70% of the sensor signal was composed of pheophytin, which is a breakdown pigment of chlorophyll.

The dissolved oxygen sensor on the array measured decreasing DO concentrations throughout the deployment. At the time of the June 5 installation of the sensor array, DO concentrations at 9.5 m depth were around 7 mg/L, which is similar to the water column profile concentration (see Figure IV-3). DO concentrations decreased at a rate of approximately 0.08 mg/L per day before reaching <0.1 mg/L at the end of August (Figure IV-11). This gradual decrease in DO concentration at this depth indicates a gradual loss of oxygen deeper in the water column and low DO concentrations that would trigger release of sediment-bound phosphorus reaching shallower in the pond as summer proceeded.

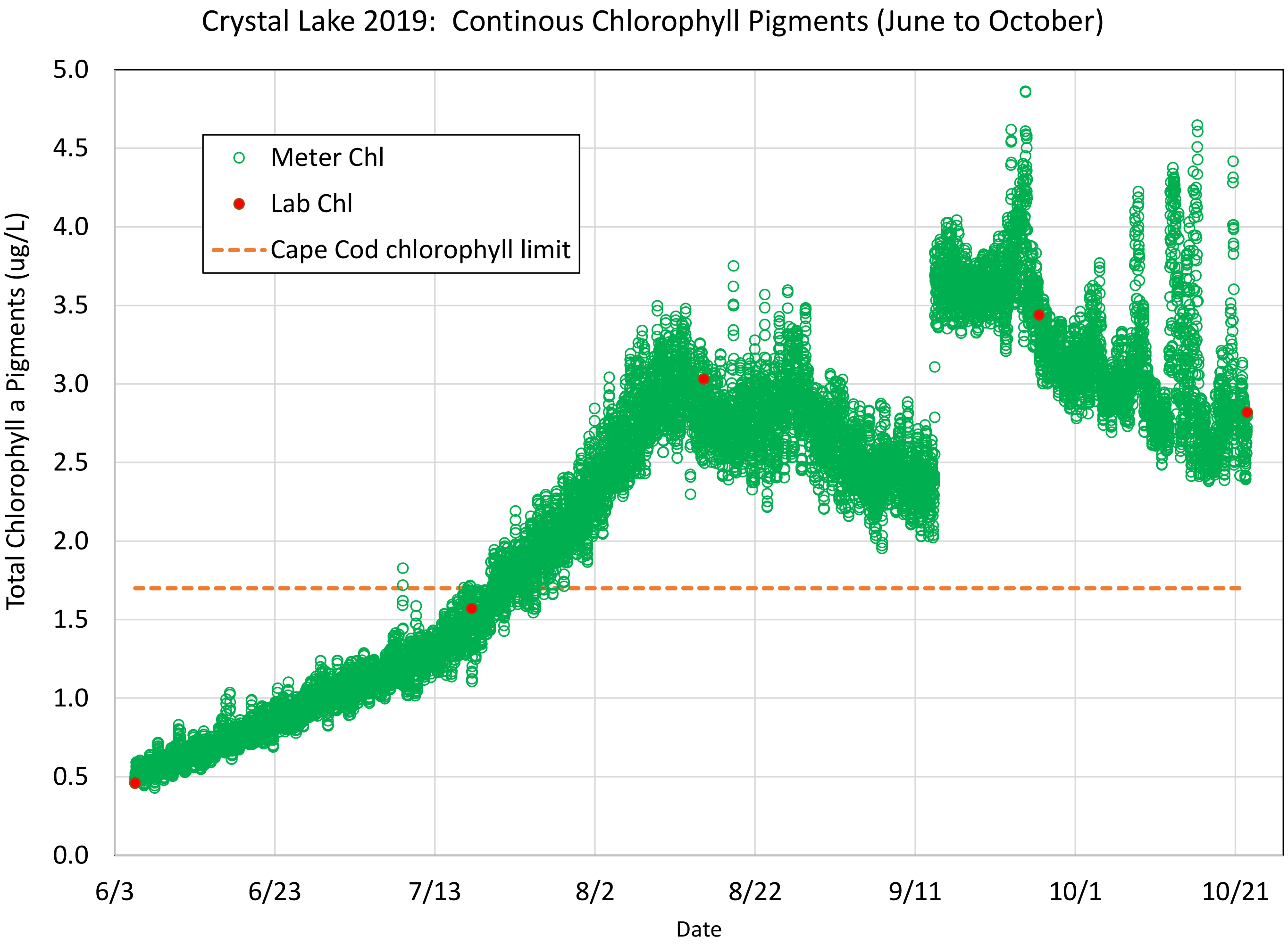

Figure IV-10. Crystal Lake Continuous Chlorophyll Readings, Summer 2019. A sensor array was deployed to collect chlorophyll pigment (chlorophyll a + pheophytin) readings every 15 minutes between June 3 and October 22. Average depth of the array was 9.5 m. Pigment concentrations increased 0.04 µg/L per day between June 3 and mid-August before slowly decreasing. Movement of the array on September 13 placed it at a slightly deeper location. Given the depth of the array, pigments were approximately 30 to 40% chlorophyll a. Red dots indicate the laboratory assay results from water quality samples collected for quality assurance. Temporal pattern generally reflects the biomass and cell counts of the phytoplankton community.

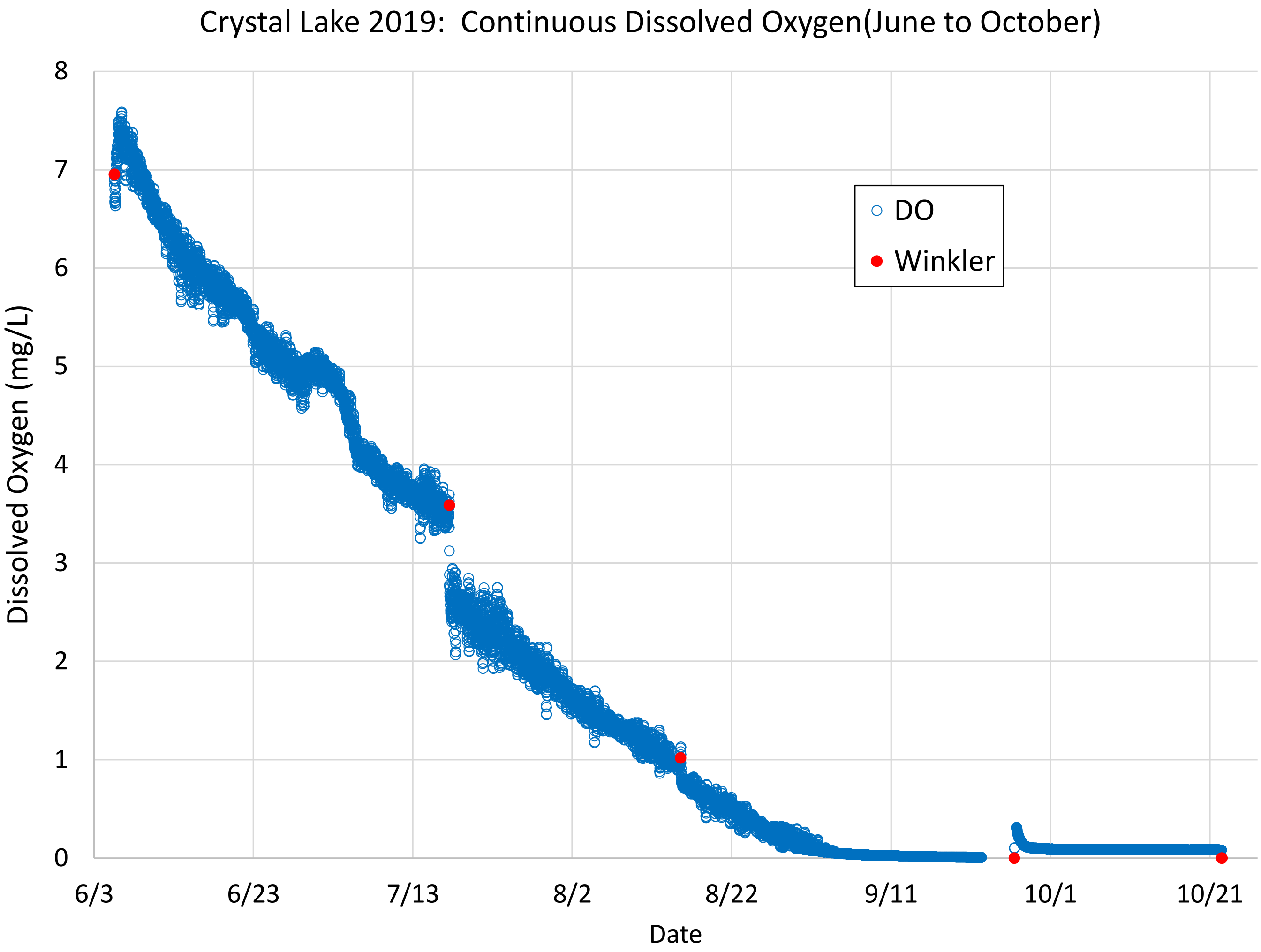

Figure IV-11. Crystal Lake Continuous Dissolved Oxygen Readings, Summer 2019. A sensor array was deployed to collect dissolved oxygen readings every 15 minutes between June 3 and October 22. Average depth of the array was 9.5 m. DO concentrations decreased at a rate of approximately 0.08 mg/L per day from initial deployment to the end of August. DO concentrations throughout September and October until array removal were less than 0.1 mg/L (anoxic). Red dots indicate the laboratory assay results from water quality samples collected for quality assurance.

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

Extensive populations of freshwater mussels and macrophytes (aquatic rooted plants) have the potential to alter nutrient cycling and can complicate development of pond management strategies, especially those that involve treatment of the sediments. Bathymetric information is key for understanding the volume and depth of a pond, which are important for determining the extent and overall impact of water quality change, the relationship between the pond and its watershed, and how biota in the pond are distributed. During the initial review of available Crystal Lake water column sampling results,[43] these issues were identified as potential data gaps and were incorporated into the 2019 data gap surveys.

CSP/SMAST staff completed bathymetry, rooted plant, and freshwater mussel surveys on April 4, 2019 using a differential GPS mounted on a boat for positioning coupled to a survey-grade fathometer and submerged video camera. This approach provided thousands of depth readings throughout the pond, which is a significant data density increase over previous bathymetric mapping. This data collection determined the total volume of Crystal Lake was 951,844 cubic meters with a maximum depth of 17 m (Figure IV-12). This volume was 2.5% less than previous estimate developed by the Cape Cod Commission based on tens of depth readings collected by local volunteers.[44]

The underwater video survey completed at the same time as the bathymetric survey determined the distribution of freshwater mussels and macrophytes (or rooted plants) in Crystal Lake. 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 m^2 of pond bottom and the video record was reviewed frame-by-frame for mussel valves and plant density.

The mussel survey was completed because many of the freshwater mussel species on Cape Cod are listed by the Massachusetts Natural Heritage Program as threatened or endangered species or species of special concern, including the Tidewater Mucket (*Leptodea ochracea*) and Eastern Pondmussel (*Ligumia nasuta*).[45] Surveys completed by CSP/SMAST in other Cape Cod ponds have shown some ponds to have extensive mussel populations, while others have no mussels present.[46] Reviews of available studies suggest mussels have complex responses to nutrient enrichment with both positive and negative impacts due to high or low loads.[47] Generally, freshwater mussels are restricted to areas that do not experience regular hypoxia.[48] A visual survey was recommended for Crystal Lake as a relatively low cost approach to assess whether special consideration would be needed to protect mussels as management strategies are developed.

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[43] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database report.

[44] Eichner, E. 2007. Review and Interpretation of Orleans Freshwater Ponds Volunteer Monitoring Data. Cape Cod Commission. Barnstable, MA. 80 pp.

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

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

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

[48] Eichner, E., B. Howes, D. Schlezinger, and M. Bartlett. 2014. Mill Ponds Management Report.

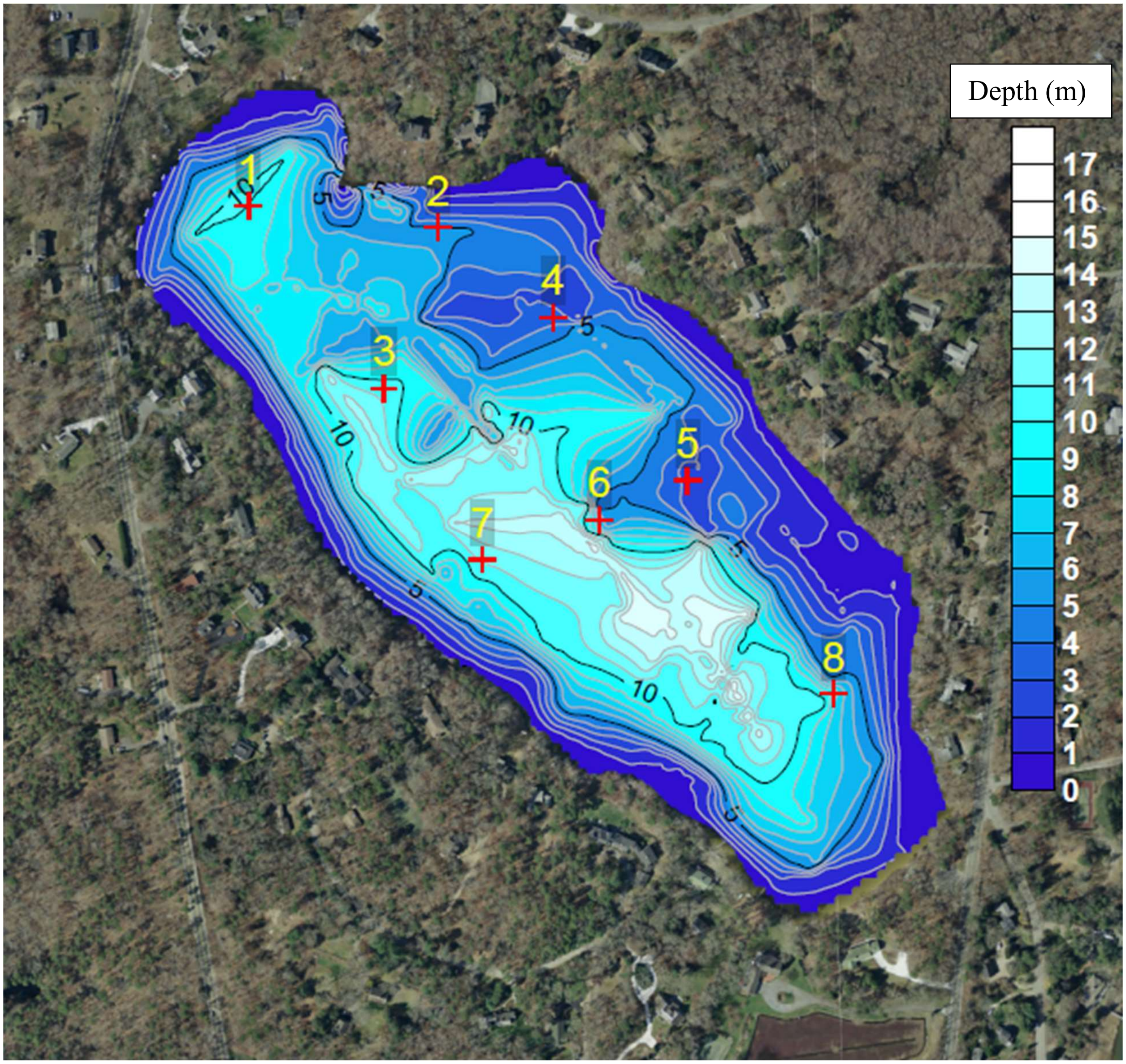

Figure IV-12. Crystal Lake 2019 Bathymetry. CSP/SMAST staff completed a bathymetric survey on April 4, 2019 using a differential GPS mounted on a boat for positioning coupled to a survey-grade fathometer. This approach provided thousands of depth readings throughout the pond. Based on this survey, the total volume of Crystal Lake was 951,844 cubic meters with a maximum depth of 17 m.

The freshwater mussel survey did document the presence of mussels in Crystal Lake, but they were relatively sparse (Figure IV-13). Approximately 10 individuals were noted during the review of the lake bottom; all were located north of the long axis of the lake and all were at depths <6m in regions that remains oxic in summer. It was also noted that the area on the south side of the long axis had an extensive coverage of leaf litter. The litter was dense and any mussels under this cover would have been smothered. Given the sparsity of the mussels, it is likely that current conditions in the lake are not conducive for their growth.

During the review of the video recordings, CSP/SMAST staff also gathered data on rooted plant (macrophyte) density and benthic algae coverage. Macrophytes are typically sparse in Cape Cod ponds, but some eutrophic ponds can have extensive plant populations if there is sufficient water column light penetration.[49] Benthic algae are also generally sparse, but can be extensive in the shallow areas of highly eutrophic ponds.[50] Macrophyte abundance is a complex interaction of a number of factors, including sediment characteristics, nutrient and light availability and pond depth.[51] Extensive macrophyte populations can alter nutrient cycling by favoring settling of suspended particles within colonized areas, but also can increase transfer of buried phosphorus to aboveground plant parts, which during senescence and decay release nutrients to pond waters.[52] The plant survey was completed to provide insights into the influence of macrophytes on the overall Crystal Lake phosphorus balance and effects on water quality management.

Macrophyte coverage in Crystal Lake was variable with approximately 70% of lake bottom supporting macrophytes (Figure IV-14). Filamentous algae were noted in some deeper areas, while emergent grasses (sedges and rush) were found in the shallower portions along both the eastern and western shorelines. Most of the northwesternmost portion of the pond had no macrophytes and, similarly, no macrophytes were noted in the western areas where leaf litter accumulations were extensive and dense. The areas with the densest growth of macrophytes were in the shallower areas (generally <4 m deep) in the northeastern quadrant of the lake and a relatively deep area in the southernmost portion of the lake. This southernmost area is relatively deep (beyond average Secchi depth). Further review of available video did not clarify which species were present, but light penetration of even 1% of surface intensity can be sufficient to allow plant growth and this can be attained at between 2 and 3 times the Secchi depth.[53] Since the average Secchi depth in Crystal Lake was 4.45 m, light penetration of slightly more than two times this depth could regularly reach these areas.

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[49] Roman, C.T., N.E. Barrett, and J.W. Portnoy. 2001. Aquatic vegetation and trophic condition of Cape Cod (Massachusetts) kettle ponds. *Hydrobiologia*. 443(1-3): 31-42.

[50] see Figure IV-19 in Eichner, E., B. Howes, and D. Schlezinger. 2018. Uncle Harvey's Pond Management Plan and Diagnostic Assessment.

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

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

[53] Brown, R. 1984. Relationships Between Suspended Solids, Turbidity, Light Attenuation, and Algal Productivity. *Lake and Reservoir Management*. 1(1): 198-205. DOI: 10.1080/07438148409354510

Figure IV-13. Crystal Lake 2019 Mussel Survey. CSP/SMAST staff completed an underwater video survey on April 4, 2019, to determine the distribution of freshwater mussels in Crystal Lake. Cameras were synced with dGPS and recorded at five frames per second. Staff reviewed each video frame (approximately 0.25 m^2 of pond bottom) to determine the presence of mussels; each video frame with mussels is noted with a red cross. A total of approximately 10 individual mussels were noted.

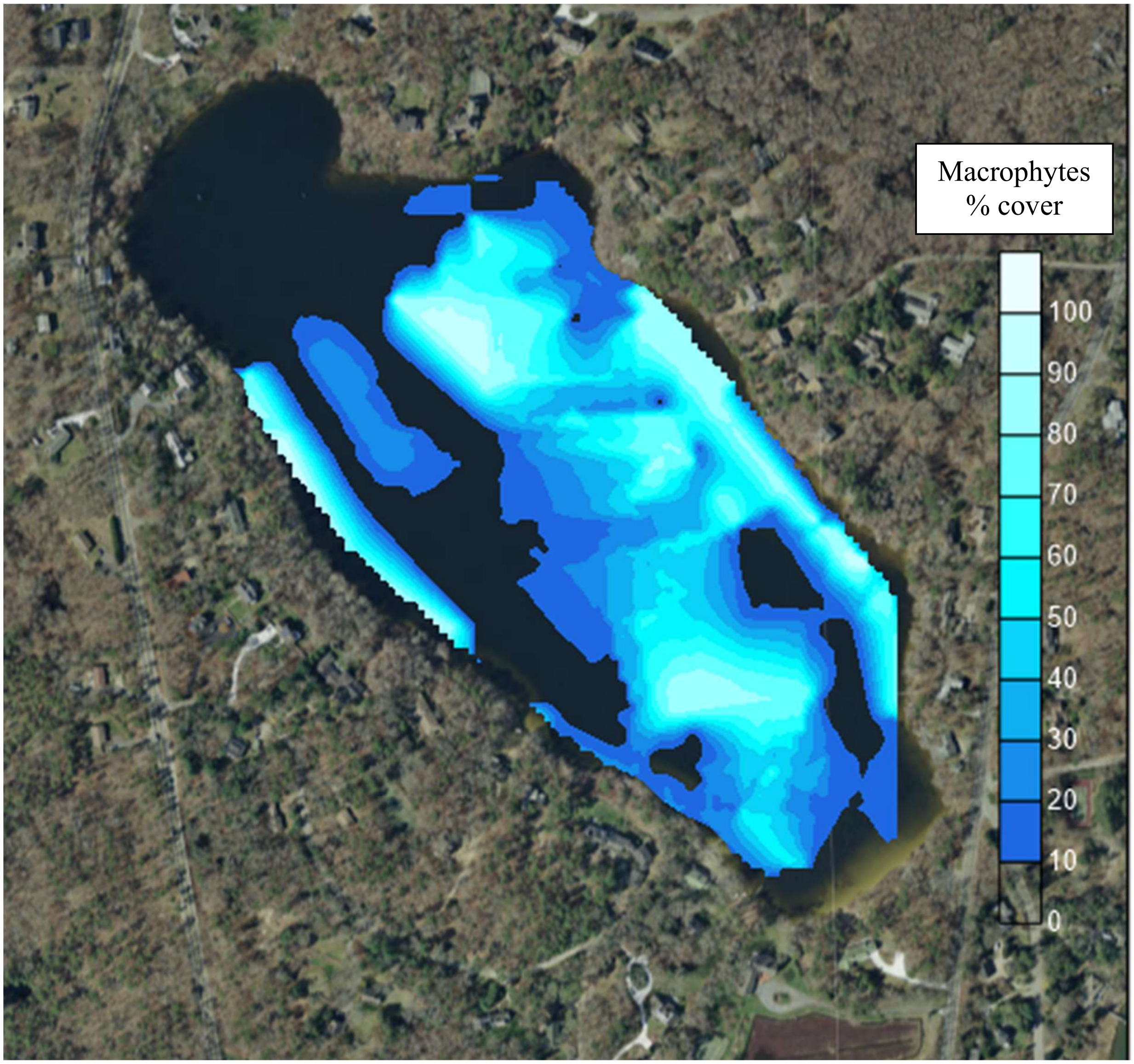

Figure IV-14. Crystal Lake 2019 Macrophyte Survey. CSP/SMAST staff completed an underwater video survey on April 4, 2019, to determine the distribution of submerged aquatic vegetation (*i.e.*, rooted macrophytes and macroalgae). Cameras were synced with dGPS and recorded at five frames per second. Staff reviewed each video frame (approximately 0.25 m^2 of lake bottom) to determine the density and type of macrophytes (% cover). Macrophytes tended to have the highest densities in shallower areas, but there were deeper areas in the easternmost portion of the lake with high densities. Northwesternmost portion of the lake had insignificant macrophyte coverage, as did area along the western portion where the bottom was covered by thick leaf litter.

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

During the initial CSP/SMAST review of historic Crystal Lake water column data[54], it was clear that the sediment oxygen demand and resulting hypoxia was causing an increase in bottom water nutrient concentrations during summer. However, the amount of the potential nutrient release was not clear, nor was the relationship between dissolved oxygen conditions and nutrient release. Because resolving these issues was important to developing restoration and management strategies for Crystal Lake, measurement of sediment nutrient release was identified as an important data gap that needed to be addressed during the diagnostic evaluation of Crystal Lake.

Sediment regeneration of nutrients regularly occurs in ponds and begins as organic detritus (such as phytoplankton, aquatic plant material or fish) settles to the bottom and is decomposed by sediment bacteria (*i.e.*, biodegradation). This bacterially-mediated decomposition of the detrital material breaks it down into its constituent chemicals, including inorganic nutrients. 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.

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

These relationships can be further complicated by rooted aquatic plants/macrophytes and mussels. Extensive macrophyte populations can alter nutrient cycling by favoring settling of suspended particles within plant beds, but also can increase the transfer of otherwise buried sediment phosphorus to the above-ground plant shoots and to the water column during growth, senescence and decay.[55] Some research has also found that macrophyte beds can be net sources of phosphorus to the water column even in aerobic conditions.[56] The role of freshwater mussels on phosphorus cycling is not well studied, but water filtering by extensive populations of bivalves has been shown to increase the amount of deposition and decrease the amount of phosphorus available to phytoplankton.[57] Determining the net phosphorus contribution from sediments should account for the potential role of macrophytes and mussels, if their population or densities are large.

In order to measure potential sediment nutrient regeneration within Crystal Lake, CSP/SMAST staff collected and incubated eight intact sediment cores collected from various locations (Figure IV-15). These undisturbed sediment cores were collected by SCUBA diver on April 17, 2019, while the bottom waters were fully oxygenated and before strong thermal stratification was established. The sediment cores were incubated at *in situ* temperatures and nutrient regeneration from the sediments was measured under oxic and anoxic conditions.

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[54] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database report.

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

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

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

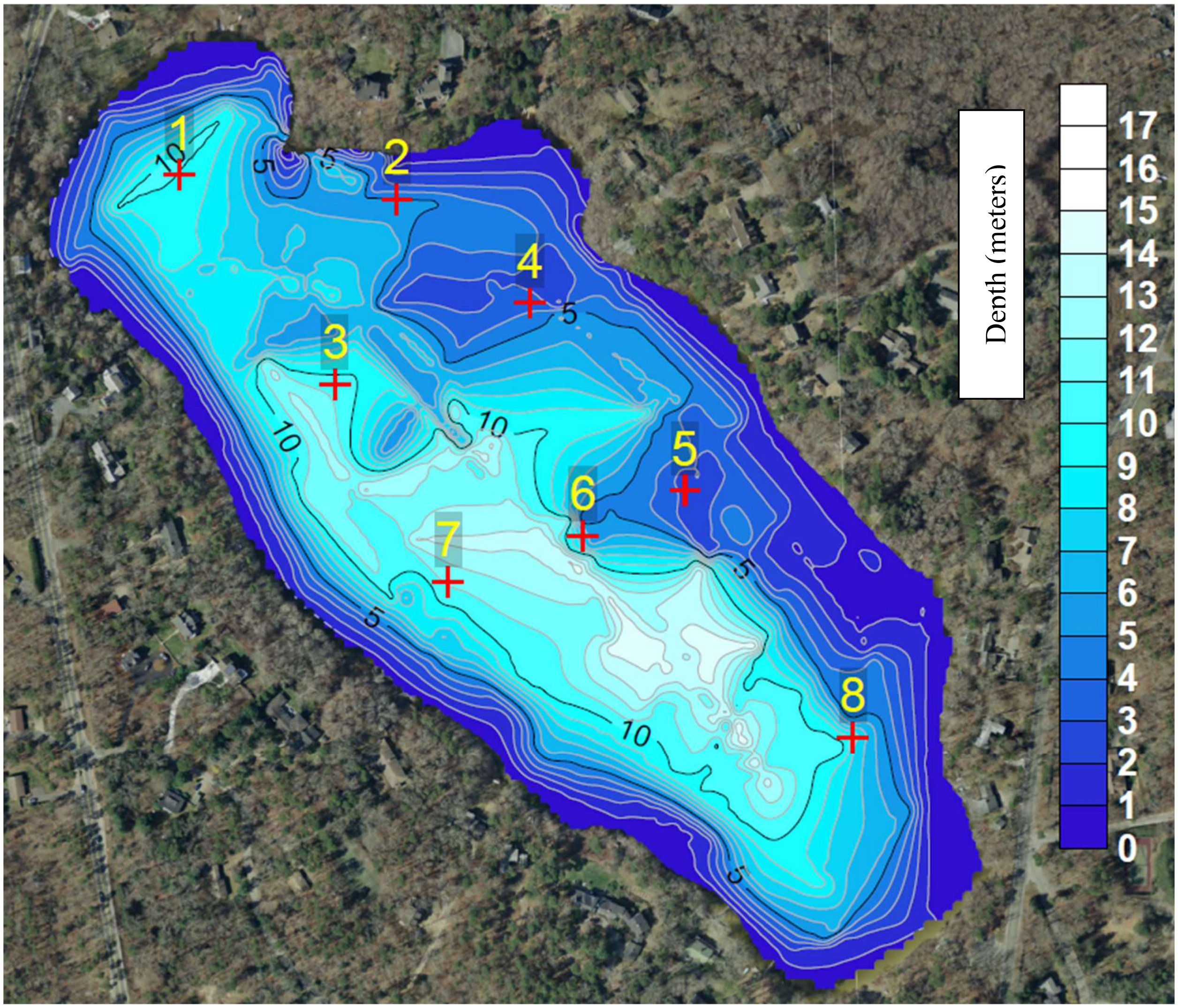

Figure IV-15. Crystal Lake 2019 Sediment Core locations. Red crosses show the locations of eight sediment cores collected in Crystal Lake on April 17, 2019. Base map is the bathymetric map that was developed based on CSP/SMAST readings also collected in April 2019.

During the collection of sediment cores, standard handling, incubation, and sampling procedures were followed based on the methods of Jorgensen (1977), Klump and Martens (1983), and Howes (1998). During the core incubations, water samples were withdrawn periodically and chemical constituents were assayed. Rates of sediment nutrient release were determined from linear regression of analyte concentrations through time. Cores were incubated to first sustain aerobic conditions, matching environmental conditions in Crystal Lake when dissolved oxygen in lake 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 (severing of weak chemical bonds) and continues with phosphorus release through anaerobic respiration alone. This latter process is the same as experienced in the Crystal Lake water column when dissolved oxygen concentrations drop to less than 1 mg/L (conditions that regularly occur in the deepest depths in summer/early fall). Anaerobic conditions were maintained and measured for 40 days after the onset of the anoxic chemical release phase. The laboratory followed standard methods for analysis as currently used by the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

Review of the incubation results showed that sediment phosphorus regeneration rates varied depending on oxygen conditions (aerobic vs. anaerobic), collection depth of the core, and location in the lake. Under aerobic conditions (those typically encountered during the winter and into April/May), all but one of the eight cores indicated that sediments were removing P from the water column. Removal rates were generally relatively low, except for C2 and C5, which were from the northern edge of the lake at depths that are always aerobic (Figure IV-16). Since these depths have always been aerobic, they will always be removing P, even during the summer when anaerobic conditions were impacting deeper portion of the lake. During the rapid chemical release phase of the core incubations, all cores released P, but cores collected deeper in the pond (>7.3 m, *i.e.*, cores C1, C6, C7, and C8) had rates that were generally 3X the rates of cores from shallower areas. Among all the July and August water column readings, anaerobic conditions were measured in 34% of the 7 m readings. Once the chemical release phase was complete, the anaerobic P release continued at lower rates with similar rates at most of the depths except for the deepest core (C6), which had a rate ~2X higher than the others. This difference suggests that the deeper portions of the pond (>11 m) may be collecting settling particles from a greater area and therefore are a disproportionately larger and prolonged source of P to the water column after low DO conditions are sustained during the summer.

Using the core results and the areas determined from the CSP/SMAST updated pond bathymetry, the whole pond sediment P regeneration rates can be estimated for various oxygen conditions and seasons. During the spring or when the water column is largely well-oxygenated, the sediments throughout the pond would generally remove P from the water column. Based on the core incubation results, the shallow sediments (between 0 and 4 m depth) remove approximately 4.5 kg of P when the water column is well-oxygenated (approximately November to April). Sediments at deeper depths remove less than 1 kg of P during the same period. Comparison of spring and summer water column TP mass, when hypoxic ortho-phosphate release from sediments occurs, showed that the water column TP mass generally increased between 4 and 5 kg each summer. Review of the chemical release and anaerobic release rates measured from the sediment core incubations generally agreed with this rate, adding between 3.5 and 4.1 kg, depending on the timing and depth of initial anaerobic conditions. As anaerobic conditions rose higher in the water column, more sediment bottom area became overlain with anoxic water triggering rapid chemical P release and greater TP mass in the water column. The sediment incubation results also showed that during the well-oxygenated, winter conditions the sediments are generally storing TP, while under the warm weather anaerobic conditions, sediments are releasing close to an equivalent TP mass as is stored in the winter.

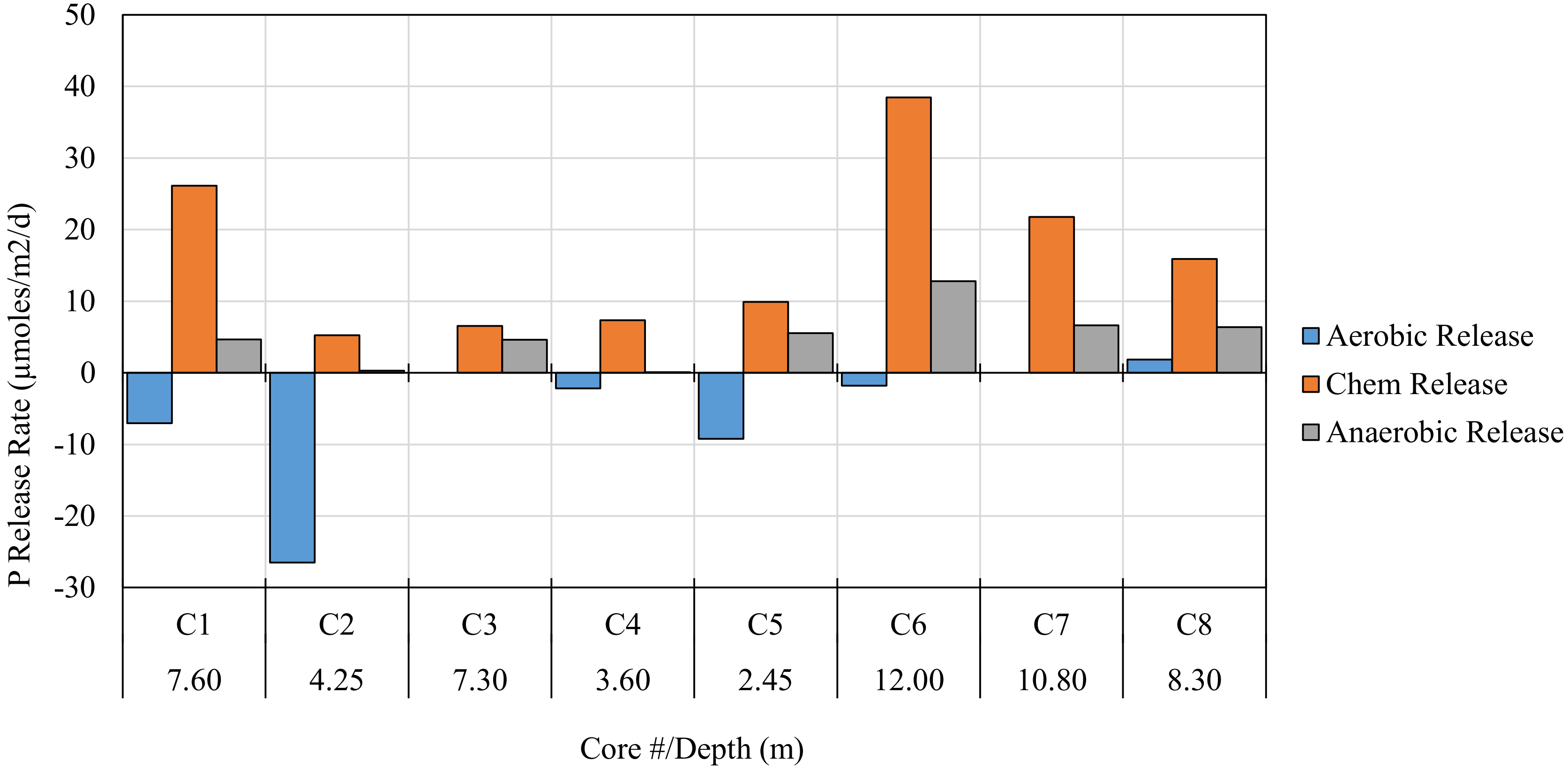

Figure IV-16. Crystal Lake Phosphorus Release from 2019 Collected Sediment Cores. Graph shows average P release measured during incubation of the cores collected at Crystal Lake on April 17, 2019. Aerobic incubation showed that most sediments were retaining phosphorus; estimated P retention using water column conditions between November and April was between 4 and 5 kg removed. Chemical release rates were rapid release, typically occurring in less than a day, and were generally higher than long-term anaerobic release, which can occur over a month or more. This difference would allow the release of TP from the sediments at the initial onset of anaerobic conditions, followed by anaerobic release only if anaerobic conditions were sustained. Comparison of water column TP mass in spring (April/May) and late summer, on average, showed a 4 to 5 kg increase. The sediment core incubation results were generally consistent with this increase. General congruence between these two approaches indicate that the depth of anaerobic conditions and their persistence will largely determine the summer TP additions from the sediments to water column.

IV.B.5 Direct Stormwater Runoff Discharge to Crystal Lake

During the review of water column data and potential management issues for Crystal Lake[58], direct stormwater runoff from Route 28 and Monument Road was identified as a data gap based largely on the Town's stormwater structure survey.[59] Project staff completed site surveys for each site during an initial storm to gauge potential monitoring details and then collected runoff flow and water quality samples during three storms: 9/25/18, 1/24/19, and 12/9/19. Monitoring was conducted using standard stormwater measurement techniques, including collection of first flush runoff, replicates of flow readings, and collection of runoff samples for constituent analysis. All runoff samples were assayed at the Coastal Systems Analytical Facility at SMAST for phosphorus and nitrogen components using the same assay protocols as used for the lake water samples.

The Monument Road site is on the downgradient side of the lake and has a parking area for the Dickinson Conservation Area and a small beach. This site was identified as a potential stormwater discharge site in the 2013 stormwater survey, which showed it had two discharge pipes just off the road which were connected to an undetermined number of upstream stormdrains. When staff initially reviewed the site in 2018, it was clear that upgrades had been made to both the road and the runoff system. There are now two pipes that discharge into a swale area that is north of the parking area and west of the road; no discharge to the swale was noted during the three monitored storms, so there must be leaching basins upstream of the swale. Observations at the site also noted that there may be occasional overland flow down the hill to the north side of the beach. No direct stormwater discharge to Crystal Lake was noted at either the swale area or down the hill during any of the three monitored storms.

The Route 28 stormwater site has a 24 inch diameter pipe that discharges stormwater runoff from an undetermined portion of Route 28 (Figure IV-17). The runoff discharges from the pipe into a small basin (~0.7 m^3 capacity). Once the basin is filled runoff flows down approximately 15 m rip-rap path to directly discharge into Crystal Lake. From observations at the site, the basin is filled with fines that have settled, so it probably does not provide much infiltration, but it is likely infiltration occurs along the rip-rap path. It should be noted, however, that all infiltration would occur adjacent to the lake and most phosphorus would likely reach the lake whether it infiltrates or directly discharges.

The three storms had total precipitation amounts that were reasonably representative of the majority of rainstorms that occurred in Orleans in 2018 and 2019. The September 25 and January 24 storms had total precipitation of 0.53 and 0.5 inches (in), while the December 9 storm had 2.76 in.[60] Project staff coordinated with the local Cocorahs precipitation monitor to track precipitation during the period runoff sampling occurred. Precipitation during the runoff sampling on the respective dates were 0.11 in, 0.5 in, and 0.16 in. Based complete-year 2018 and 2019 precipitation records, rainfall of 0.11 in or more was measured on approximately half of all the dates where precipitation was recorded.[61]

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[58] Eichner, E and B. Howes. 2017. Town of Orleans Freshwater Ponds, Water Quality Monitoring Database report.

[59] GHD, Inc. 2013. Orleans Town-Wide Preliminary Stormwater Assessment. 159 pp.

[60] https://www.cocorahs.org/ViewData/StationPrecipSummary.aspx (accessed 1/8/20)

[61] The remainder of 2018 and 2019 storms in Orleans had precipitation amounts less than 0.11 in.

Figure IV-17. Route 28 Stormwater Runoff Pipe to Crystal Lake. A 24 inch pipe (A) collects stormwater runoff from an undetermined portion of Route 28 and discharges the runoff first to a small basin (~0.7 m3) then down a ~15 m rip-rap path (B) to the lake.

The three storms had different runoff and precipitation patterns. The September 25 storm had relatively slow runoff flow for two hours, peaked after 3 hours of runoff and then began to decrease (Figure IV-18); an additional 0.42 in of rain fell after runoff monitoring was stopped. Noteworthy during this storm was the strong hydrogen sulfide smell from the Route 28 pipe approximately 4 hours after the first flush, perhaps indicative of runoff flow from the wetland west of Route 28 being added to the stormwater collection system. The January 24 storm had a rapid increase in runoff flow, peaking 1.5 hours after the first flush sample at a flow rate approximately 3X the September 25 storm. No additional rain fell after monitoring was stopped on January 24. The December 9 storm had a slow, but relatively steady, rate of runoff (comparable to the first two hours of the September 25 storm) and precipitation during the runoff monitoring period. An additional 2.6 in of rain fell after the runoff monitoring was stopped.

Based on comparison of measured runoff rates at the various precipitation rates for the monitored storms and the count of individual storms with similar precipitation rates during 2018 and 2019, staff estimated that the annual stormwater runoff to Crystal Lake from the Route 28 pipe was approximately 3,500 m^3. Using the TN and TP loads for each of the measured storms and the same approach to the individual storms in 2018 and 2019, staff estimated the annual TN and TP loads from the Route 28 pipe: 10.5 kg TN and 1.7 kg TP.

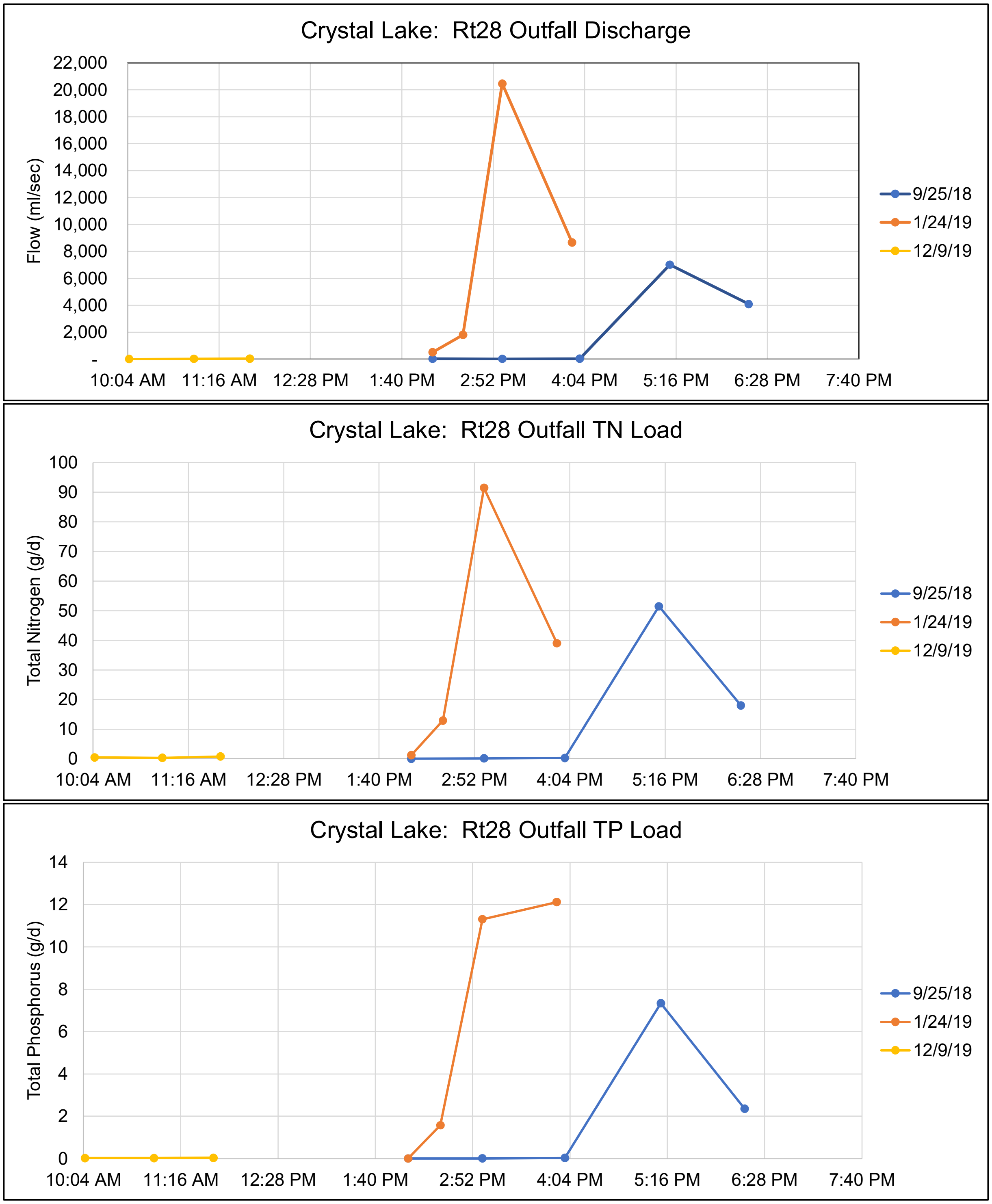

Figure IV-18. Route 28 Stormwater Runoff: Flow and Nutrient Loads. Runoff flow readings and water quality samples were collected at the Route 28 outfall adjacent to Crystal Lake during three storms: 9/25/18, 1/24/19, and 12/9/19. These storms were representative of approximately half of the precipitation events in Orleans in 2018 and 2019. Based on these results it was estimated that 3,500 m3/yr of runoff is discharged through this outfall with an annual TN and TP loads of 10.5 kg and 1.7 kg, respectively.

IV.C. Crystal Lake Watershed Review and Physical Characteristics

Crystal Lake is located approximately 180 m northwest of Lonnie's Pond between Route 28 and Monument Road. Measured groundwater elevations in the area were generally between 12 and 16 ft NGVD with Crystal Lake at 14.8 ft; projected groundwater flow into the lake was from the west and flow out of the lake to groundwater was projected to the east and south toward Lonnie's Pond.[62] Massachusetts Estuaries Project (MEP) watershed delineations completed by the United States Geological Survey for Pleasant Bay showed the Crystal Lake watershed included portions of the Town of Orleans "watershed" properties for public water supply wells and portions of downgradient flow from Baker Pond (Figure IV-19).[63] Crystal Lake has a surface water outflow to a cranberry bog south of the lake that then flows into Lonnie's Pond, as well as an intermittent surface water inflow from a historic, but now abandoned, cranberry bog system located to the northeast of the lake.

Revised Crystal Lake bathymetry was collected as part of the macrophyte and mussel data gap surveys and this was used to determine a total lake volume of 951,844 cubic meters (see Figure IV-12). The CSP/SMAST survey was completed 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, which is a significant data density increase over the previous bathymetric mapping. The updated lake volume is 2.5% less than the volume previously determined by the Cape Cod Commission from citizen collected soundings.[64]

IV.C.1. Crystal Lake Water Budget

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

The primary water input source to kettle ponds on Cape Cod is typically groundwater discharge from their watershed. Additional water input sources to consider would be imported drinking water recharged through septic systems, direct stormwater runoff outfalls, and precipitation on the pond surface. Water movement out of 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, this usually becomes the primary exit pathway for water out of the pond. Crystal Lake has five inputs of water and three outputs for water. The water budget balancing these inputs and outputs for Crystal Lake is represented in the following equation:

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

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[62] Leab, M.P., T.C. Cambareri, D.J. McCaffery, E.M. Eichner, and G. Belfit. 1995. Orleans Water Table Mapping Project. Cape Cod Commission. Barnstable, MA.

[63] Howes B., S.W. Kelley, J.S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner. 2006. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Pleasant Bay, Chatham, Massachusetts.

[64] Eichner, E. 2007. Review and Interpretation of Orleans Freshwater Ponds Volunteer Monitoring Data.

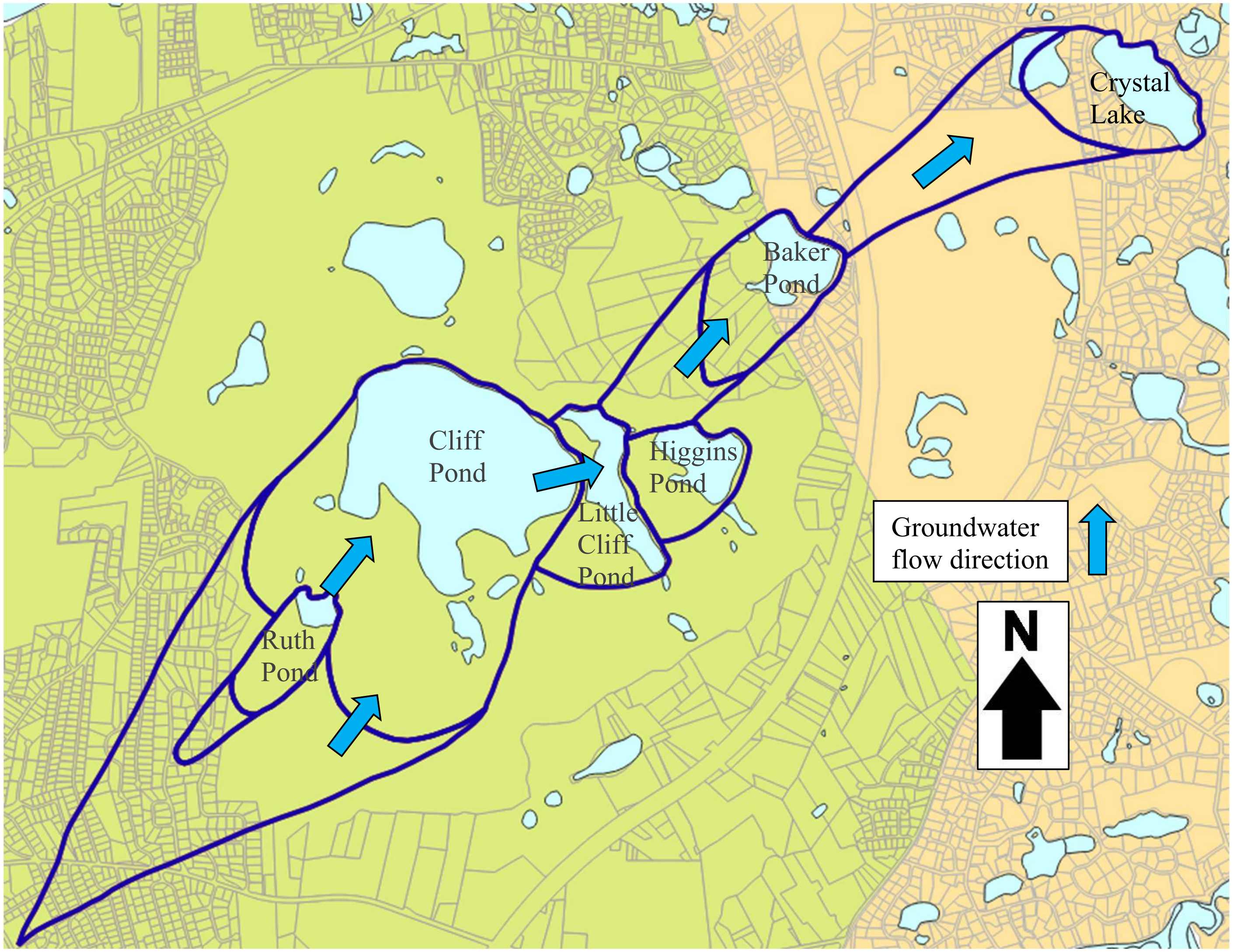

Figure IV-19. Watershed to Crystal Lake. The watershed to Crystal Lake includes portions of watersheds to five other ponds and extends into Brewster. This watershed was delineated by the US Geological Survey as part of the MEP Pleasant Bay watershed delineation and the development of the regional groundwater model (Walter and Whealan, 2005).

Among these pathways, stream inflow, 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 by calculation based upon temperature, wind and other factors and previous regional measurements. Groundwater$_{out}$ is usually estimated by difference.

IV.C.1.a Streamflow into and out of Crystal Lake

As mentioned in Section II, Crystal Lake has two surface water connections: 1) inflow from an historic cranberry bog system northeast of the pond and 2) outflow to an existing cranberry bog that discharges to Lonnie's Pond (see Figure II-2). Both streams had continuous stream gauges installed in April 2018 with at least monthly stream velocity measurements to July 2019, but both had periods where no flow occurred (Figure IV-20). Average stream inflow was 74 cubic meters per day (m3/d), while average stream outflow was 625 m3/d. Flow varied with season (*e.g.*, higher flows in spring and winter) and related natural fluctuations in groundwater/pond water levels, as well as occasional use of pond water for irrigation of the southern cranberry bog. Comparison of flow during 2018 and 2019 also showed that flow was different in the two years; only low or no inflows and outflows between June and October 2018, while there were measurable flows from June to August 2019 (when recording stopped).

Review of local groundwater levels suggest that the stream inflows and outflows during 2018 and 2019 were higher than usual. Spring 2018 groundwater levels were exceptionally high with new maximum levels in March, April, May, and December (Figure IV-21**)**. Groundwater levels remained above average throughout both 2018 and 2019. These high levels suggest that inflow and outflows were likely higher than usual during 2018 and 2019. Higher groundwater levels would also mean shorter residence time for water in the pond.

IV.C.1.b Groundwater flow and Precipitation

Groundwater flows into ponds on Cape Cod along an upgradient shoreline margin and then pond water flows back into the groundwater along the downgradient shoreline margin as the groundwater follows a path to the downgradient ocean or estuary shoreline. The water level of a pond is typically an exposed portion of groundwater system that has filled a depression in the land surface. The pond surface and surrounding groundwater are at approximately the same elevation. The watershed to freshwater ponds is defined by upgradient groundwater flowpaths. As mentioned, streams can serve to collect groundwater, but they can also serve as rapid drains, especially on the downgradient sides of ponds, to redirect groundwater flow to different flowpaths. Downgradient streams tend to function as "release valves" because water flowing out through a stream has less resistance than pond water returning to groundwater. Groundwater levels fluctuate with precipitation with levels determined by how much precipitation is not utilized by plants or evaporated to the atmosphere and infiltrates through the sandy soils to recharge the groundwater system.

Recharge is a portion of precipitation; it is the amount that is not captured by the root zone of plants and slowly percolates down to the top of the saturated sediments (*i.e.*, the water table). Recharge will vary seasonally with greater recharge occurring during the winter and less occurring during the summer. Precipitation on pond surfaces is also subject to evapotranspiration.

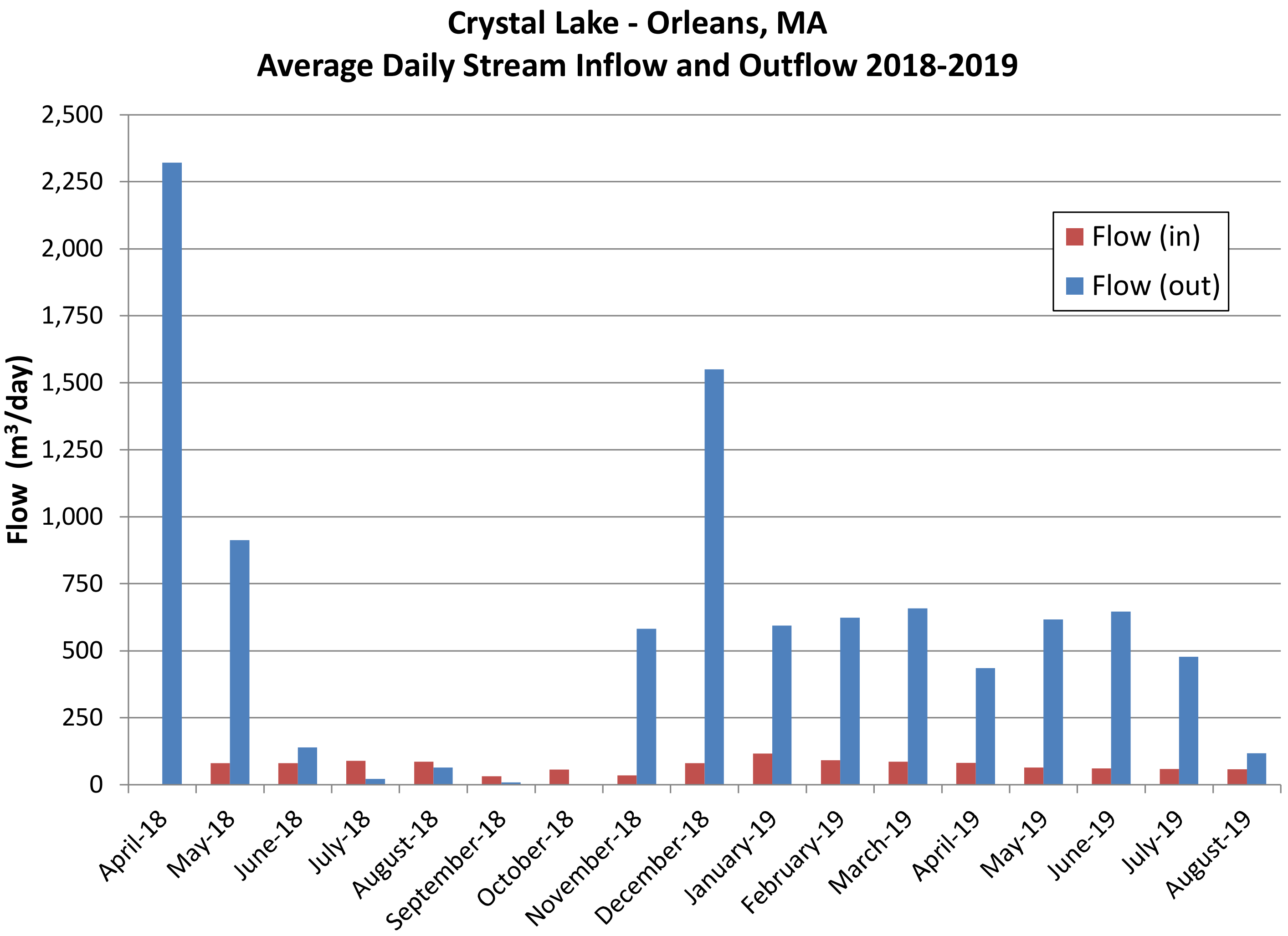

Figure IV-20. Average Monthly Streamflow Into and Out of Crystal Lake (2018 to 2019). Stream inflow was from a historic abandoned cranberry bog system north of the lake and had an average flow of 74 m3/d. Stream outflow was to the adjacent active cranberry bog south of the lake and had an average flow of 625 m3/d. Flow varied with season (e.g., higher in the spring and winter) and from year to year. Average flows were based on continuous gauge readings and instantaneous measurements collected 1 to 2 times per month.

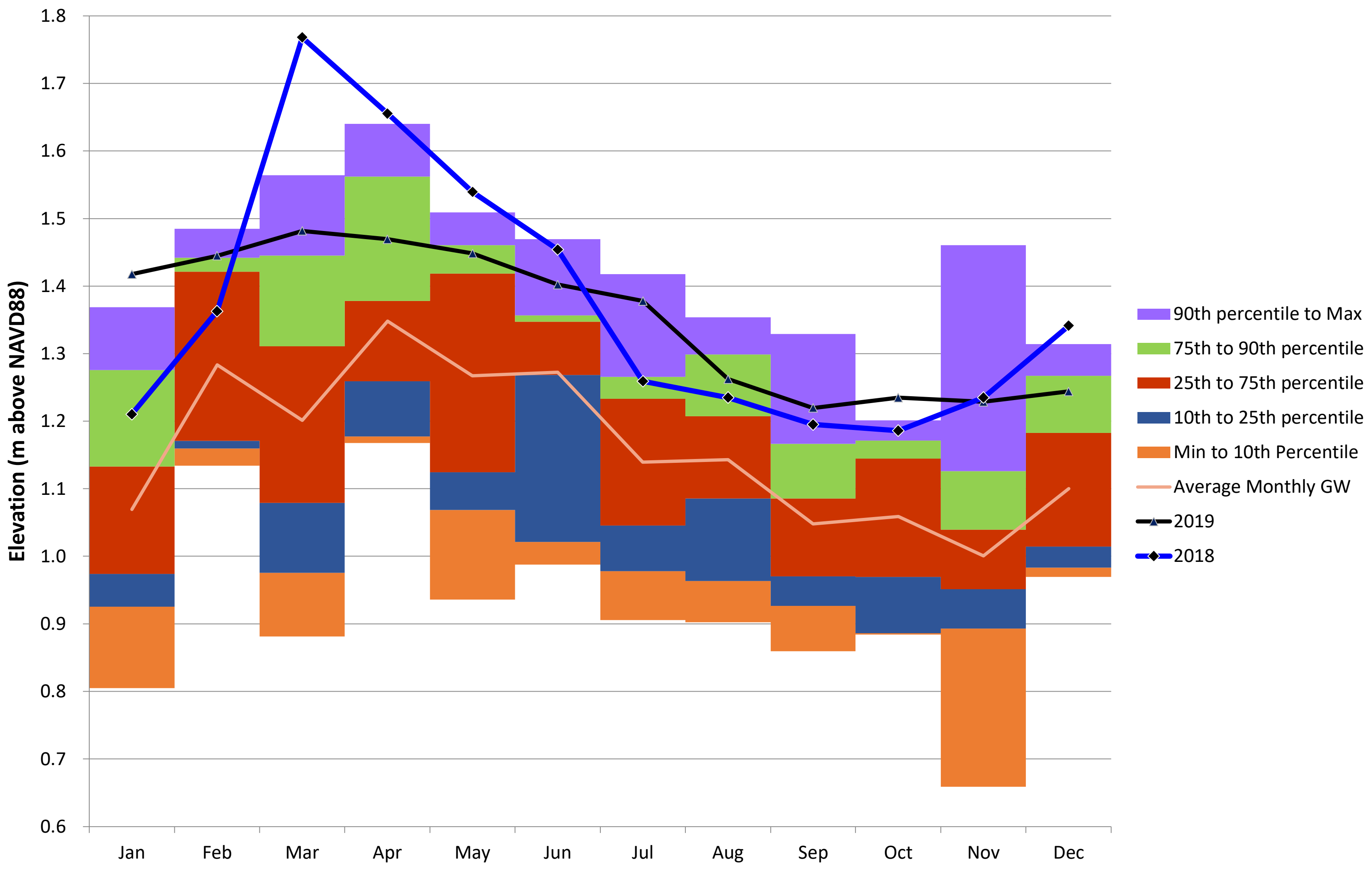

Figure IV-21. Orleans Groundwater Levels (OSW-22). Percentile groupings of historic groundwater elevations at OSW-22, which is located near Town Cove and has been measured since 1975, are shown along with levels during 2018 and 2019. During 2018, new historic groundwater high levels were established in March, April, May, and December and were above average throughout both 2018 and 2019. This comparison suggests that Crystal Lake stream inflows and outflows in 2018 and 2019 were higher than average.

The watershed to Crystal Lake was delineated by the US Geological Survey as part of the Massachusetts Estuaries Project (MEP) assessment of Pleasant Bay (see Figure IV-19).[65] The delineation was based on results of a regional groundwater model[66] that included a recharge rate of 27.25 inches per year. It is notable that the Crystal Lake watershed includes portions of downgradient flow from a number of ponds, including Baker Pond, Higgins Pond, and Cliff Pond. The overall watershed to Crystal Lake was based on the area of the Crystal Lake watershed plus the portions of the upgradient pond watersheds that have groundwater flowpaths that reach Crystal Lake. Annual groundwater flow to Crystal Lake based on this watershed area and a 27.25 in/yr recharge rate was 846,981 m3/yr.

Precipitation in Orleans has been collected daily since 2011 at a site east of Town Cove.[67] Annual precipitation at the local site between 2012 and 2017 averaged 46.35 inches per year. Precipitation in 2018 and 2019 totaled 56.5 inches and 53.7 inches, respectively. The recent rates were much higher than the 45 inches per year used in the USGS groundwater modeling effort and suggest that if the watershed delineations remain the same, the amount of groundwater flowing through Crystal Lake was much higher than average in 2018 and 2019. There was also a seasonal pattern to the precipitation with more occurring between January and April and September to December than during the summer (May to August). Average annual precipitation on the surface of Crystal Lake was 186,824 m3/yr based on USGS assumptions, but would be a 227,760 m3/yr based on the 2018 precipitation rate. Evapotranspiration off the surface of Crystal Lake was assumed to equal the difference between average precipitation and the annual recharge rate (27.25 inches per year). Based on these assumptions, 76,975 m3/yr was estimated to be returned to the atmosphere from the lake surface.

IV.C.1.c Crystal Lake Water Budget Summary

The overall annual water budget for Crystal Lake is shown in Table IV-2. Groundwater was the predominant water pathway in and out of the lake, accounting for 79% of the inflow and 72% of the outflow. Stream outflow is approximately 8X the stream inflow. Collectively and given the volume of the pond, water has an average residence time in the lake of 0.88 year or 323 days.

This residence time will vary depending on precipitation and flow fluctuations, but was likely reflective of high groundwater conditions (see Figure IV-21**)**. In periods of low groundwater elevations (*e.g.*, decreased by 0.5 m), the level of the pond would also decrease, stream inflow would likely disappear, stormwater runoff and pond surface precipitation would diminish. During these periods, the residence time would increase, but only by approximately 2%. This fluctuation already likely occurs seasonally, as precipitation, groundwater levels, and stream inflow decrease during the summer. Given greater fluctuations have been measured in water levels in ponds across the Cape[68], it is likely that the pond ecosystem has developed some resiliency for these regular changes.

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

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

[67] Readings at station MA-BA-12; https://www.cocorahs.org/; readings recorded since 2011

[68] McHorney, R.P. 1998. Final report — Phase II. Hyannis Pond Biohydrology Project. The Nature Conservancy, Boston, MA, USA.

Table IV-2. Crystal Lake Water Budget. Water budget was based on annual water flows; there are seasonal variations in flows that will slightly alter residence time. The water budget accounts for flows of water into and out of the pond. Groundwater inflow and pond surface precipitation are based on USGS groundwater modeling (average regional recharge at the time) and recent Orleans precipitation records (higher than USGS used), respectively. Stream inflow and outflow rates are based on data collected for this assessment and discussed above. Wastewater inputs are based on average 2011 to 2015 measured water use for parcels within the watershed and represent imported water from outside the watershed. Groundwater is the primary component of the water budget. Annual average residence time of Crystal Lake based on these flows is 0.88 years.

IN		**OUT**	
Source	**m3/yr**	**Sink**	**m3/yr**
Groundwater	846,981	Groundwater	772,115
Pond Surface Precipitation	186,824	Pond Evapotranspiration	76,975
Stream Inflow	27,156	Stream Outflow	227,980
Wastewater (imported water)	12,609		
Stormwater	3,500		
TOTAL	1,077,070	TOTAL	1,077,070

IV.C.2. Crystal Lake Phosphorus Budget

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

External phosphorus loads to Crystal Lake vary depend on the pathway of entry. Phosphorus travels slowly (*e.g.*, 0.01-0.02 ft/d[69]) within the upgradient aquifer relative to groundwater flow (*e.g.*, 1 ft/d[70]). This is rate of travel is different than nitrogen, which is also a key, but not controlling, nutrient; nitrogen (as nitrate) tends to travel at the same rate as the groundwater, so nitrogen from throughout the watershed can impact Crystal Lake. Since phosphorus movement in the aquifer is relatively slower, management of phosphorus inputs to ponds generally focuses on properties within 250 to 300 ft of the pond shoreline except where there are direct surface water inputs from streams, pipes, or stormwater runoff. Shoreline properties generally have phosphorus impacts on pond water quality within typical wastewater management planning horizons (*i.e.*, 20 to 30 years) whereas the impact from direct surface water inflows is immediate.

The steady-state watershed nitrogen load to Crystal Lake was previously estimated in the Pleasant Bay MEP assessment as 674 kg N/yr[71] and a recently completed draft update[72] found a nearly identical loading rate (644 kg N/yr). Both of these loads were based on approved MEP practices albeit with site-specific data collected 15 years apart. MEP practices focus on obtaining parcel-specific information for each parcel in the watershed,[73] including water use, building footprint areas, and road surface areas, and combining these with MEP nitrogen loading factors (Table IV-3).[74] Comparison of these watershed loads to the estimates of water column nitrogen mass indicate attenuation rates of 35% to 53% with an apparent decrease in attenuation over the 2001 to 2019 timeframe. Data collected in 2018/2019 showed that approximately 100 kg of the average 385 kg of TN in the water column (26%) left the pond through the stream outflow; the remainder would leave the pond via groundwater.

In order to complete a similar review of phosphorus loading to the Crystal Lake, staff had to go through the same land use analysis steps, but with a focus on phosphorus instead of nitrogen. In order to develop the watershed inputs, staff began by reviewing the likely travel time for phosphorus in groundwater on the upgradient side of the lake. Review of groundwater contours in the Crystal Lake area, suggest an approximate groundwater travel time of 1.0 ft/d on the

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

[70] 1 ft/d is typically used as a planning number on Cape Cod. Site-specific flow rates vary depending on sub-surface materials and location in the aquifer.

[71] Howes B., S.W. Kelley, J.S. Ramsey, R. Samimy, D. Schlezinger, E. Eichner. 2006. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Pleasant Bay, Chatham, Massachusetts.

[72] CSP/SMAST Technical Memorandum. April 18, 2020. Task 3 Ecosystem Monitoring and Modeling for Implementation. From: E. Eichner, TMDL Solutions and B. Howes, CSP/SMAST. To: Pleasant Bay SNEP Working Group. 18 pp.

[73] 75 parcels were identified in the Crystal Lake LT10 and GT10 subwatersheds during the MEP; 81 parcels were identified in the 2020 update.

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

Table IV-3. Phosphorus and Nitrogen Loading Factors for Crystal Lake Watershed Estimates. Listed below are factors used in the development of the watershed phosphorus and nitrogen loading estimates for Crystal Lake. Nitrogen loading factors are the same as those utilized in Massachusetts Estuaries Project assessments in Orleans. Listed sources are the primary basis, but most have been confirmed by other sources and/or modified to better reflect conditions in Orleans.

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	measured		Summarized in this report
Roof surface P load	0.23	kg/ha/yr	Waschbusch, *et al.*, 1999 modified by P leaching through lawns
Atmospheric P deposition on pond surface	5 to 8	mg/m2/yr	Reinfelder, *et al.*, 2004.
Lawn: Fertilizer load	0.02 to 0.3	lb P/ac/yr	Literature review
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
Road surface direct runoff N load	Measured	kg/yr	Summarized in this report
Atmospheric N deposition on pond surface	1.09	mg/L	MEP; MassDEP-approved
Common Factors			
Watershed Recharge Rate	27.25	in/yr	Walter and Whealan, 2005
Precipitation Rate	44.8	in/yr	Walter and Whealan, 2005
Building Area	Actual	ft2	MassGIS aerial photo review
Road Area	Actual	ft2	Mass. DOT records
Lawn: Area	measured	ft2	Aerial photo review

upgradient side of the lake.[75] Measurements of phosphorus movement in septic system plumes in sandy soils have estimated it is slowed by factors of 25 to 37 compared to the groundwater flow rate.[76] Using these endpoints with the groundwater travel time resulted in estimated phosphorus movement of 0.03 to 0.04 ft/d[77] on the upgradient, watershed side of Crystal Lake. Project staff then reviewed the watershed boundaries and looked at parcels on both the upgradient and downgradient sides to assess their potential phosphorus loads; downgradient properties were reviewed for potential direct (or overland) discharges. The refined parcel review included reviewing Town Board of Health records for the location and age of each septic system leachfield/leaching pit, reviewing Town Assessor records for the age of each house or building, and determining road, lawn and building areas based on a review of aerial photographs.

Staff initially identified 25 parcels that were completely or partially within the Crystal Lake watershed and had the potential to contribute phosphorus to the lake (Figure IV-22). Two of these parcels were undeveloped based on Town Assessor data and Town Board of Health septic system records. Land use around the lake also included a number of areas that are part of the road parcels, as well as the boat ramp parcel off Route 28. For the 23 developed parcels, the buildings on these lots averaged 52 years old and their septic system leachfields averaged 28 years old. Most of the parcels (16 of 23) were single-family residences with multi-family residences on six of the parcels.

Aside from the age of septic system and its components (*i.e.*, leachfield vs. leaching pits), project staff also reviewed Town Board Health records to determine the distance between the leaching component and the Crystal Lake shoreline.[78] Using the leaching component age and estimated phosphorus travel time in sandy aquifers, staff determined which properties had wastewater phosphorus that was likely reaching Crystal Lake in 2019, the year of the data gap surveys completed for the current project. Based on this review, 18 of the leachfields were discharging into the lake.[79] Based on the age of the houses, 22 of the 23 developed parcels had phosphorus reaching the pond from other sources, such as lawn and impervious surface runoff. Average lawn area of parcels with lawns was 9,662 square feet and the median building area on each lot was 2,761 square feet. The Route 28 runoff pipe near the town landing was identified as the only direct stormwater discharge to the lake.

Once the land use information was adequately developed, staff used phosphorus loading factors based on Cape Cod-specific and literature values to develop phosphorus loads to the lake from each source. Previous Cape Cod pond phosphorus budgets 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 (see Table IV-3). Available studies have generally confirmed that this is a reasonable factor. Review of published phosphorus loading factors have shown that annual *per capita* phosphorus loads range from 1.1 to 1.8 pounds, while sandy soil retention factors range between 0.5 and 0.9.

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[75] Based on both Leab, M.P., T.C. Cambareri, D.J. McCaffery, E.M. Eichner, and G. Belfit. 1995. Orleans Water Table Mapping Project and the USGS regional groundwater parameters

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

[77] This is slower than at Pilgrim Lake because of the slower groundwater travel rate.

[78] Board of Health records were reviewed on January 10, 2020 (assistance provided by Bob Canning and BOH staff).

[79] Given the age and distance of leachfields, the houses contributing P to the pond did not differ based on varying groundwater P travel times.

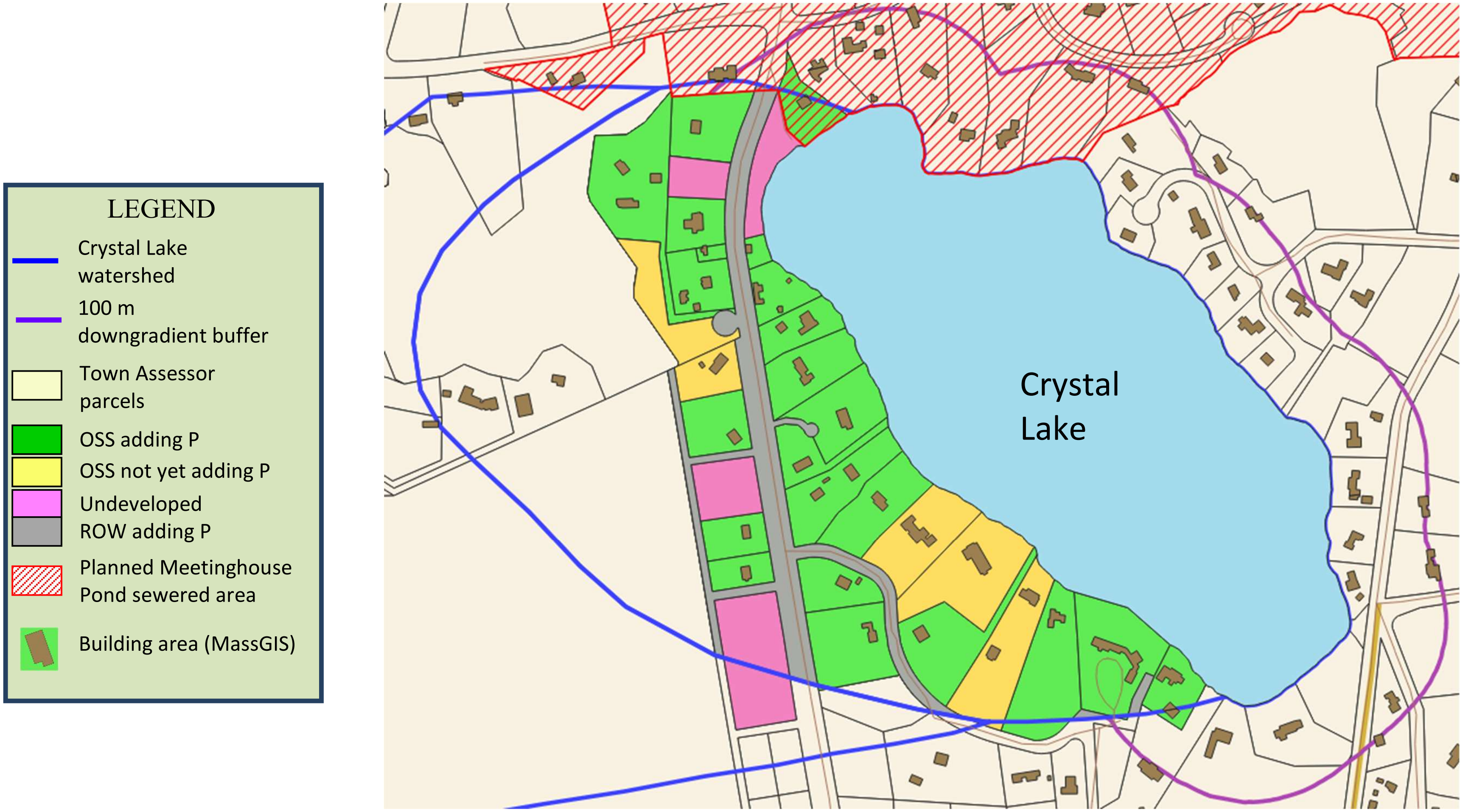

Figure IV-22. Crystal Lake Watershed Parcels Reviewed for Phosphorus Loading Budget. Parcels upgradient of the lake and downgradient of the lake but within 100 m (purple line) were reviewed for potential phosphorus additions to the lake. Ages of each upgradient building and the on-site septic system (OSS) leachfield were determined from Town Board of Health and Assessor's data and compared to likely phosphorus travel time to the lake based on their ages. Parcels shaded green were contributing P loads to the lake from both OSS and lawns. Parcels shaded yellow have newer leachfields that are too young be contributing phosphorus to the lake, but generally have buildings that have existed long enough for lawn P loads to reach the lake. Parcels shaded pink currently do not have buildings on them. Also noted is the Meetinghouse Pond sewer area (red pattern) planned under the current Town wastewater management plan; one house in the Crystal Lake watershed that is currently contributing P to the lake would be included in this area.

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 uses the Orleans average annual occupancy during the 2010 Census (2.0 people per house), the *per capita* range results in an average individual septic system load range 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 Crystal Lake resulted in an estimated 2019 wastewater phosphorus load to Crystal Lake of 8.2 kg/yr, while completing a similar estimate based on the age of the house/building resulted in a wastewater P load of 10.4 kg/yr. Given the ages of the upgradient houses, the wastewater P load would likely to be between 8.2 and 10.4 kg/yr.

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.[80] The Town approved a similar local regulation in 2013.[81] Past reviews of Orleans homeowner fertilizer practices 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.[82,83] 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. As with the septic systems, phosphorus travel time is also an important consideration; even though not all of the septic systems were old enough to contribute wastewater P to Crystal Lake, all 22 of the residences are old enough to contribute lawn fertilizer P to the lake. Given the restrictions on P fertilizers and P travel in sandy aquifers, it is not clear whether historic fertilizer loading is still moving toward the lake or whether new P is still being added. Based on a reasonable range of factors, the estimated lawn fertilizer P load to Crystal was between 0.04 and 0.47 kg.

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.[84] However, the primary airflow over Cape Cod during the summer is from the southeast, which is air that was last over land in New Jersey. The New Jersey Department of Environmental Protection maintained phosphorus measurement through the New Jersey Atmospheric Deposition Network from 1999

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[80] 330 CMR 31.00 (http://www.mass.gov/eea/docs/agr/pesticides/docs/plant-nutrient-regulations.pdf)

[81] Chapter 103 of Town bylaws

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

[83] 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.

[84] 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.

through 2003.[85] 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 monitoring network was relatively consistent, varying between 5 and 8 mg/m^2/yr. Review of other northeastern datasets suggests that these rates are reasonable.[86] Application of these factors to Crystal Lake resulted in estimated atmospheric phosphorus loads of 0.8 to 1.3 kg/yr.

Stormwater runoff is the final component to be considered in the watershed portion of the Crystal Lake phosphorus loading budget. Runoff is the result of precipitation on impervious surfaces, such as roofs or roads. Since roof runoff within the Crystal Lake 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 within 100 m of the pond, 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 these buildings. Based on the range of phosphorus groundwater travel time, roof loading varied between 0.13 and 0.32 kg/yr.

Road runoff would be based on two different sources: Route 28 and Crystal Lake Drive. Route 28 runoff was measured at the stormwater outfall (see Section IV.B.5 above), but it is unclear how much of the Route 28 road surface is captured by the outfall flow and there is some indication that the runoff may occasionally include nutrients from overflow from the wetland system to the west of Route 28. The area of Route 28 within the Crystal Lake watershed is 37,800 sqft with 29,500 sqft north of Crystal Lake Drive and 8,300 sqft south of Crystal Lake Drive. The area of Crystal Lake Drive in the watershed is 9,273 sqft. Runoff measurements based on water quality samples collected at the outfall yielded an estimated annual phosphorus load of 1.7 kg. If the source of this load was assumed to only be the portion of Route 28 north of Crystal Lake Drive and the remaining road areas had the same phosphorus runoff characteristics, an additional 1.0 kg/yr of TP would be added from road runoff from Crystal Lake Drive and the portion of Route 28 south of Crystal Lake Drive. This load may be somewhat tempered by the infiltration characteristics of the road runoff. Collectively, runoff loads varied between 16% and 18% of the summer TP loading to the lake.

The other phosphorus source to be considered was the streamflow input from the historic cranberry bog system north of the lake. As noted in the water budget section above, a continuous stream gauge was placed near the discharge point to the lake and instantaneous flow readings were collected monthly. The stage-discharge relationship between these readings indicated that the average annual daily flow was 74 m3/d and it was noted that the daily flows were extremely variable. During each site visit when instantaneous measurements were collected, water quality samples were also collected and assayed for various water quality parameters, including TP, at the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth. Using the stage-discharge relationship to properly weight the resulting TP concentrations, project staff determined that the annual TP load from the stream inflow was 0.56 kg (3% to 4% of the overall TP loading to the lake).

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[85] 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.

[86] 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.

Calculation of the annual TP watershed budget includes the sum of all the inputs from wastewater, lawn fertilizers, roof runoff, road runoff, stream inflow and atmospheric deposition to the pond surface. Using the best estimates of these loading components, the total annual external phosphorus input into the lake each year is 12.4 kg (Figure IV-23). This estimate used wastewater phosphorus loads based on the age and location of septic system leachfields, age of houses for loads from roof runoff and lawns. This load is consistent with spring water column phosphorus mass after accounting for the lake residence time and net TP addition and removal from the prior summer and winter, respectively. Average water column TP mass in the spring equals 9.9 kg, while the corrected estimate of annual P loading based on spring conditions equals 9.8 kg. Based on the total watershed TP load, wastewater was the predominant source (66%) of watershed TP inputs to Crystal Lake.

Based on the sediment core incubation results and the water column data, the lake sediments retain phosphorus during the winter and early spring and then deeper sediments become an internal source of TP during the summer as hypoxic/anaerobic conditions develop. Based on monthly average water column readings, sediments add between 2.5 and 4.4 kg P during summer with higher cumulative loads occurring later in the summer. As discussed above the sediment core incubation results coupled with deep water dissolved oxygen fluctuations yielded a similar range with an estimated 3.5 to 4.1 kg P added to the water column during the summer. Including these loads into the overall lake P load results in sediments being between 17% and 27% of the summer Crystal Lake phosphorus budget. Wastewater continued to be the predominant phosphorus source (48% to 55%) during the summer.

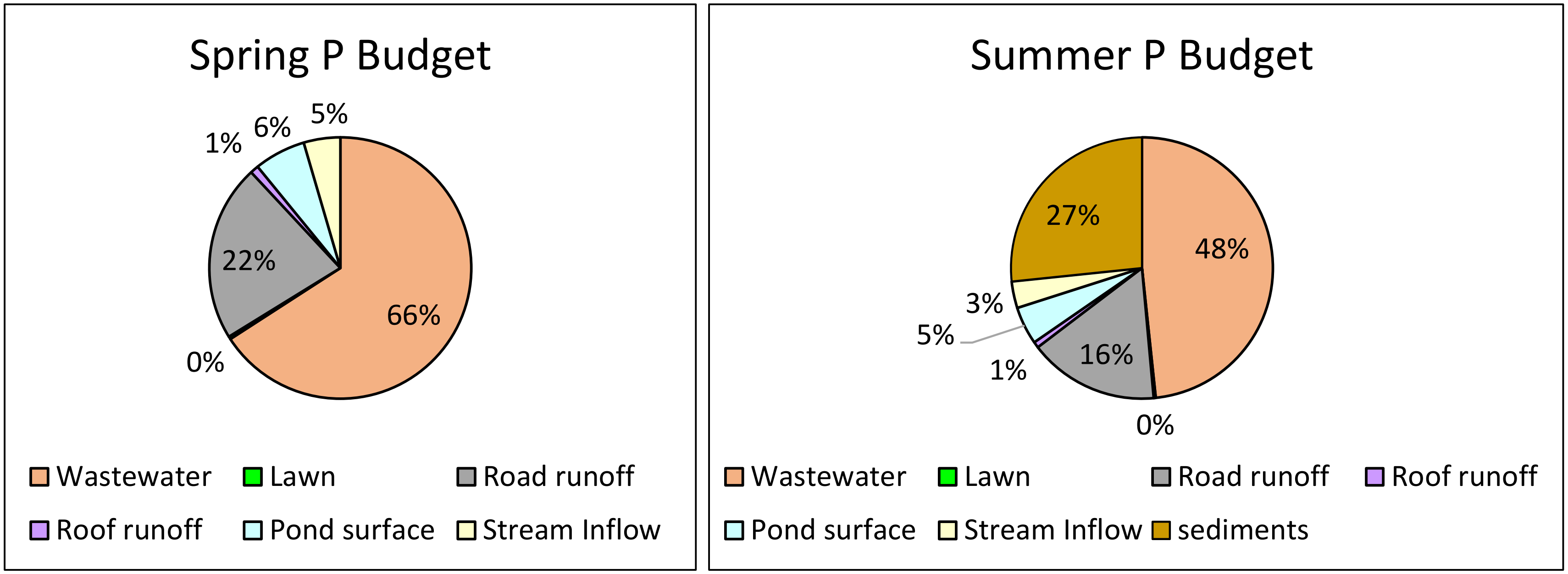

Figure IV-23. Comparison of Phosphorus Sources to Crystal Lake. Spring TP loads to Crystal Lake were determined by estimated watershed/groundwater inputs from: septic systems/wastewater, lawn fertilizers and stormwater runoff from nearby roofs and roads (roads were based on measurements collected at Route 28 outfall), as well as measured streamwater inflow and direct deposition on the pond surface through precipitation and dry fall. Loading factors were based on review of literature values, as well as Crystal Lake and Orleans-specific factors. Key factors, such as phosphorus groundwater travel time and age of houses vs. age of septic system leachfields were also determined and reviewed to assess the variability of loading estimates. Spring loading estimates were comparable to average May TP water column loads; overall spring watershed TP load was estimated as 12.4 kg/yr. After correcting for lake residence time and winter sediment TP uptake, this estimate reasonably matched average spring water TP mass. Summer TP loads were based on spring watershed loads plus estimates of internal sediment regeneration additions. Sediment loads varied between 17 and 27% of the overall summer phosphorus budget and were based on similar estimates from both a) summer increases in water column TP mass and b) sediment core incubation measurements and fluctuations in the area of the pond bottom exposed to anaerobic conditions. Overall summer TP load ranged between 14.9 kg/yr and 16.9 kg/yr. In both spring and summer, wastewater P was the primary phosphorus source to the Crystal Lake.

IV.D. Crystal Lake Diagnostic Summary

Crystal Lake is a 39-acre Great Pond located between Route 28 and Monument Road and to the northwest of Lonnie's (aka Kescayogansett) Pond estuary and fully within the Town of Orleans. There have been 83 temperature and dissolved oxygen (DO) profiles collected since 2000. Most of these have followed PALS sampling protocols and have included Secchi readings and collection of water quality samples. CSP/SMAST completed a review of available water column data in 2017 and recommended a number of surveys for Crystal Lake to address identified data gaps including stream monitoring, measurement of sediment nutrient regeneration, characterization of the phytoplankton population, measurement of short-term conditions that might be missed by snapshot sampling and profiles, and review of the watershed and development of phosphorus and water budgets. These surveys were completed in 2019. Review of all the collected data, both historic and 2019 data gap surveys results, had the following key conclusions:

- The 2019 surveys found that the lake has a maximum depth of 17 m, a total volume of 951,844 cubic meters, and a 122 hectare watershed that includes portions of the watersheds to Baker Pond and Cliff Pond, among others.

- The water budget for the lake showed that direct groundwater discharge is the primary source of both incoming water (79%) and outgoing water (72%). The 2019 streamflow survey indicated that the small intermittent stream from a historic cranberry bog system north of the lake was <3% of the water input to the lake and the controlled outflow to an active cranberry bog south of the lake was 21% of the outflow from the lake. The average residence time of water in the lake is 0.88 years.

- Review of temperature profiles showed that the lake typically begins to thermally stratify during May or June. The warm upper layer is typically 4 to 5 m and overlies a 4 m thick temperature transition zone, which, in turn, overlies a cold layer that extends from approximately 8 m depth to the bottom. The depths of these layers, the process of stratification, and when it occurs during the summer can vary from year to year; available profiles also showed that the transition zone may move up and down within a given summer (typically within a 1 to 2 m range).

- MassDEP currently classifies Crystal Lake as a warm water fishery (*i.e.,* water temperatures greater than 20°C throughout the year). Average water temperatures 6 m or deeper (approximately 30% of the pond volume) remained below the 20°C in all the 2019 profiles between April and October. Continuous temperature readings between June and October 2019 at ~9.5 m were also less than 10°C. Collectively, these datasets suggest that MassDEP should consider listing Crystal Lake as a cold water fishery.

- Review of dissolved oxygen profiles showed that concentrations at 6 m and deeper were consistently below the MassDEP minimum DO concentration during the summer. Failure to attain state regulatory minimums means Crystal Lake meets this criterion to be classified as impaired.

- Clarity, as measured by Secchi depth, averaged 4.45 m, but had a significant long-term decreasing trend (-0.1 m per year) between 2000 and 2019. Decreased clarity in Cape Cod ponds tends to be exclusively related to increased phytoplankton growth, which is prompted by increasing phosphorus additions.

- Comparison of nitrogen and phosphorus water column concentrations showed that phosphorus is the key nutrient directing phytoplankton and macrophyte growth in the lake and, thus, the primary focus of control for managing its water quality. Average shallow and deep TP concentrations were 12.7 µg/L and 31.1 µg/L, respectively. Deep summer average TP concentrations were >4X surface TP concentrations, due to buildup of P from sediment regeneration during stratification. 10 µg/L TP is the Cape Cod Ecoregion threshold. Shallow TP and TN concentrations showed increasing trends between 2000 and 2019.

- Cyanophytes (aka blue green algae or cyanobacteria) were the largest component of the phytoplankton population in July, August, and September 2019, but cell counts were not high enough to warrant public health contact advisories. However, movement of blue-greens out of the photic zone to utilize high TP concentrations deeper in the pond may have reduced biomass levels and cell counts.

- Comparison of water quality data and sediment core incubation measurements showed that shallow sediments in the lake remove approximately 4.5 kg of P during the well-oxygenated winter (November to April), but deep anaerobic conditions during the summer release 4 to 5 kg of P to the water column.

- Wastewater was the primary source of year-round phosphorus inputs to Crystal Lake (66% of the watershed total). Road runoff from Route 28 was the second largest source (14% of the total). Development of a P budget based on Cape Cod-specific factors and Crystal Lake-specific measurements was in balance by average spring water column TP mass. Wastewater was also the primary P source (48%) in the late summer P budget, but sediments were also a significant source (27%).

V. Crystal Lake Water Quality Management Goals and Options

Crystal Lake is 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) regular dissolved oxygen concentrations less than the Massachusetts regulatory minimum, b) enhanced sediment phosphorus regeneration with bottom water anoxia during the summer, and c) high water column phosphorus and chlorophyll concentrations. Review of available water quality data clearly identifies phosphorus control as the primary path to improving water and habitat quality throughout Crystal Lake.

Review completed through the Diagnostic Summary showed that wastewater phosphorus from the lake watershed is the largest source of phosphorus to Crystal Lake. Secondary and seasonal sources of phosphorus were stormwater runoff from Route 28 and summer sediment regeneration of phosphorus. Potential management actions and goals need to effectively address the phosphorus sources from the watershed and/or in the pond to eliminate the water quality impairments in Crystal Lake.

Management actions to restore water quality generally have two components: 1) identification of target water quality conditions in the pond that need to be attained to remove impairments and 2) implementation of management actions to attain the water quality targets. As discussed above, MassDEP surface water regulations generally rely on descriptive standards as water quality targets, although there are a limited set of numeric standards for four factors: dissolved oxygen, temperature, pH, and indicator bacteria.[87] These regulations work in tandem with the TMDL provisions of the federal Clean Water Act, which requires states to identify impaired waters (*i.e.*, water bodies failing to attain state water quality standards) and develop water body-specific targets to restore them to acceptable conditions. Since Crystal Lake is on MassDEP's most recent list of waters in the "Waters requiring a TMDL" category (based on dissolved oxygen), the Town has the opportunity to define the TMDL and set the management goals that will attain the TMDL.

Since this is a draft management plan, CSP/SMAST staff reviewed potential options that apply to the impairments in Crystal Lake, but will help select a final strategy following public feedback. This draft plan will be publicly reviewed with the Marine and Fresh Water Quality Committee and Town consultants. Final recommended options will be developed and incorporated into a final plan through public discussions and with input from appropriate committees before moving forward to implementation.

The following lists potential management options based on the consideration of the data discussed in the Diagnostic Summary and puts forward the most applicable management options that will restore appropriate water quality conditions in Crystal Lake and allow the Town to attain regulatory compliance.

V.A. Crystal Lake TMDL and Water Quality Goals

As documented above, dissolved oxygen concentrations in Crystal Lake were regularly less than the MassDEP regulatory threshold of 5 mg/L.[88] Low dissolved oxygen concentration in surface waters are generally due to excessive plant/phytoplankton growth prompting sediment oxygen

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[87] 314 CMR 4.00 (CMR = Code of Massachusetts Regulations)

[88] The threshold would be 6 mg/L if Crystal Lake were classified as a cold water fishery.

demand greater than the combined DO additions from atmospheric resupply from water column mixing and photosynthesis DO production. The excessive plant/phytoplankton growth is prompted by nutrient additions. Thus, low dissolved oxygen is usually an expression of elevated plant nutrients. Effectively reducing excess nutrients addresses low dissolved oxygen concentrations while also increasing water clarity.

Nutrient TMDL development is generally based on a set of water quality and ecosystem conditions developed by reviewing data from either similar water bodies or acceptable characteristics within the impaired water body. The largest set of Cape Cod TMDLs are those based on the Massachusetts Estuaries Project (MEP) assessments and the MEP assessment process provides some insights into TMDL development in Massachusetts. The MEP technical 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 Cape Cod estuaries), b) benthic communities (invertebrates living in estuaries provide the primary food source for most of the secondary consumers[89]), c) water quality conditions, including nitrogen concentrations (nitrogen is the generally the nutrient controlling water quality conditions in estuaries), dissolved oxygen, and chlorophyll (*e.g.,* phytoplankton biomass), and d) macroalgal accumulations that impair benthic habitat. For regulatory purposes, the MEP team generally selected a monitoring location (or locations) within each estuary where attaining a selected nitrogen concentration should restore water conditions throughout the system based on a review of all the collected 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 Cape Cod Ecoregion over the past 10 years and none completed on Cape Cod. During the initial development of the Cape Cod PALS program, 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.[90,91] As with the MEP assessments, it was recognized that selection of this criteria would also require consideration of other measures such as dissolved oxygen and chlorophyll concentrations, the physical characteristics and setting of each individual pond, and the role of sediment nutrient regeneration. Subsequent review of Cape Cod monitoring data has shown that some ponds may be more sensitive to phosphorus additions and become impaired at TP concentrations lower than this initial range.[92]

Project staff reviewed Crystal Lake 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 level of water quality during a given year, with lowest water

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[89] Fish and birds

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

[91] 10 µg/L was also a reasonable TP criterion based on Ecoregion data gathered by USEPA (limited data was available on Cape Cod prior to PALS sampling snapshots)

[92] *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.

column DO depletion and TP concentrations in both surface and bottom waters. By late summer, the Lake has shifted to its worst condition with highest TP concentrations and water column DO depletion, including anoxia in bottom waters. As noted above, however, past monitoring has shown that there has been variability in DO and TP concentrations from year-to-year and even within individual years. This variability is likely related to the variability in factors that influence TP and DO concentrations in Crystal Lake, including fluctuations in groundwater elevations and temperature variations.

Combining the findings of the overall data review and the goals of effectively addressing impaired conditions in Crystal Lake through reducing TP concentrations and DO depletion, CSP/SMAST staff selected 9.9 kg TP as an appropriate initial water column mass goal for achieving restoration and potential phosphorus TMDL for Crystal Lake. This mass matches the average May water column mass (n=7) in the available historic profiles. All of these profiles have at least 5 mg/L DO in the deepest profile reading. This mass also generally approximates the regional 10 µg/L TP threshold concentration developed for Cape Cod ponds and lakes. Since 2012, Crystal Lake water column TP mass has been determined 17 times and three of those were less than 9.9 kg.[93] These various analyses indicate that attaining this level of TP mass and concentration will be sufficient to restore acceptable water quality conditions in Crystal Lake and attain TMDL compliance.

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

The TP mass in the water column of Crystal Lake has ranged from as high as 24.8 kg to less than 10 kg based on measured water column concentrations. As noted above in the phosphorus budget, wastewater from septic systems is the largest and most constant source of TP to the Lake. The other major sources are summer regeneration from the pond sediments and road runoff from Route 28. Sediments provide variable TP contributions and TP removals depending on the time of year and location in the pond, while precipitation and runoff is reduced during the summer.

CSP/SMAST staff discussed issues associated with various lake management options at a number of 2017 meetings with the Marine and Fresh Water Quality Committee and the Town's consultants (Table V-1). These discussions were conducted to generally familiarize the committee and the public with potential options for lake water quality management and in what circumstances each of the options might be applicable. At the time, it was also noted that diagnostic information developed for each individual pond would determine which lake management options would apply. This type of review would be included in a management plan and would be accompanied by potential costs for implementing each option for each individual pond. This approach was used in the development of the pond management plans for Uncle Harvey's Pond[94] and Pilgrim Lake.[95] This same approach is utilized to develop management strategies for Crystal Lake that are discussed in this section.

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[93] Recent readings were reviewed since TP concentrations have an increasing trend between 2000 and 2019.

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

[95] Eichner, E., B. Howes, and D. Schlezinger. 2019. Pilgrim Lake Management Plan and Diagnostic Assessment. Town of Orleans, Massachusetts. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 114 pp.

The review of management options in Table V-1 incorporated the results from the Crystal Lake Diagnostic Summary above and, based on the lake-specific characteristics, this review found that the following techniques were applicable to water and habitat quality management in Crystal Lake:

a) Watershed Wastewater P reductions: septic system wastewater is the largest source of watershed P contributions to Crystal Lake
b) Watershed Fertilizer P reductions: largely addressed through state regulatory P limitations
c) In-pond P control: Enhanced Circulation/Aeration (addition of air/oxygen) to create sufficient bottom water oxygen concentrations to favor chemical binding of sediment P within surficial sediments and reduce sediment P regeneration
d) In-pond P control: Dredging of sediments to remove sediment P regeneration source from the lake
e) In-pond P control: Phosphorus Inactivation/Alum Treatment (addition of aluminum salt mix) to permanently bind available P within the sediments, reducing regeneration to the water column.

The efficacy of these various management options varies depending on the relative magnitude of the individual phosphorus sources to Crystal Lake. So, for example, complete removal of wastewater P through sewering of properties within the watershed would remove more than twice as much P from the Crystal Lake water column than any of the in-pond sediment or watershed stormwater controls (see Figure IV-23). Approaches can be used in tandem to attain desired P reductions or they could be use sequentially to provide temporary reductions (*e.g.*, using aeration until dredging funds could be secured).

There are a number of more experimental techniques that were also reviewed (*i.e.*, microbial competition with aeration, P-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 general lack of use under New England and Massachusetts conditions, and/or d) regulatory hurdles to be overcome for their implementation.

The following section reviews applicable options using all 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 phosphorus entering the pond, typically: a) road runoff from stormwater, b) septic system phosphorus 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 streams, connections to other ponds or ditches/pipe connections to areas outside of the watershed. Since phosphorus is typically bound to iron rich, sandy aquifer soils on Cape Cod, phosphorus movement through groundwater tends to be very slow (estimated 20-30 yrs to travel 300 ft), so watershed controls in these settings typically focus on sources within 300 ft of the pond shoreline or a stream discharging to the pond.

OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Crystal Lake
Wastewater P reductions	• Sewering • Alternative Septic Systems • Septic Leachfield Setbacks • Septic Leachfield Replacement or Movement • PRBs	• Addresses watershed wastewater P source • Can be implemented with a range of costs to homeowners and at time of property transfer • Can control other wastewater contaminants	• May have high individual property cost and/or community cost • May involve lag time for 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	Applicable: wastewater is largest P source in overall lake P budget; 69% of watershed P load; 1 shed house already included in planned Meetinghouse Pond sewer area
Fertilizer P reductions	• Restrict P in lawn fertilizers (done under Mass law) • Restrict lawn areas • Require natural buffers near pond with limited paths/use of non-fertilized landscaping	• Relatively straightforward • Can be simple as adjusting landscaping • Requires no infrastructure funding	• Changing the landscaping paradigm can be difficult • May involve lag time for benefits to be realized due to groundwater flow • May not solve all water quality impairments	• State P fertilizer regulations (330 CMR 31): use of P only for turf establishment; 10-20 ft setback	Applicable: Addressed through state limitations; <0.5% of watershed P load
Stormwater P reductions	• Remove or infiltrate direct discharge • Recharge outside of watershed, 300 ft buffer • Runoff treatment using BMPs	• Rerouting discharge or infiltration usually relatively straightforward • Removes P source • DPWs usually have stormwater repair funding on hand • Removes other contaminants *e.g.*, Bacteria, TSS, metals	• Likely does not solve all water quality impairments	• Not specifically done for ponds in the past, but is now being discussed in many towns	Applicable: Rt28 discharge was 23% of existing P watershed load

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

OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Crystal Lake
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 permittable for deep ponds • Varying success • Needs power	• Santuit Pond, Mashpee & Skinequit Pond, Harwich (Solar Bees) • Flax Pond, Harwich (Living Machine) • Varying success	<u>Not Applicable</u>: disrupting stratification would eliminate cold water fishery
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 • Mill Pond, Falmouth	<u>Applicable</u>: Significant SOD during summer; deep sediments could be P sink; short-term solution, sediments not primary P source
Dilution, Decreased residence time	• Add water to pond	• Increased flushing • Can add treatment additives	• Need to find source outside of watershed • May create undesirable ecosystem impacts on plankton	• Mostly a hard geology/stream fed solution; need water source	<u>Not applicable</u>
Drawdown	• Lower water level increases water column atmospheric mixing • Oxidation of exposed sediments	• May provide rooted plant control • May reduce nutrient availability • Opportunity for shoreline cleaning	• Negative impact on desirable species (can affect fish spawning areas) • Difficult or impossible in sandy aquifer settings	• Mostly a hard geology/stream fed solution (limited dewatering at Ashumet Pond was very difficult)	<u>Not applicable</u>

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

OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Crystal Lake
Dredging of sediments	• Removal of P with sediments • Wet or dry excavation • Hydraulic dredging (all require dewatering area and disposal site)	• Reset/renovation of ecosystem through removal of accumulated nutrients • Increases water depth • Reduces sediment oxygen demand • Reduces sediment nutrient regeneration	• Disturbs benthic community • Dry excavation (draining pond) removes fish population • Downstream impacts of dewatering area • Disposal of sediments • Typically expensive	• Usually reviewed but not implemented due to high cost • Current discussion for Mill Pond, Barnstable in order to deepen filled basin (not P control)	Applicable: but number of issues to resolve if pursued (*e.g.*, mussels, add'l sediment characterization, selection of dewatering/ disposal areas, relative benefit based on P budget, etc.)
Dyes and surface covers to restrict plant growth	• Create light limitation to restrict phytoplankton or rooted plant growth through physical means (surface cover) or light absorption (dyes)	• Opaque surface covers may be removed or reset • Dyes may produce some control of rooted plants depending on concentration	• May exacerbate anoxia (limits plant oxygen production) • Dye may not adequately address surface phytoplankton	• Mystic Lake, Barnstable (benthic barriers use part of strategy to control hydrilla)	Not applicable; does not address 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) • Mill Pond Falmouth	Not applicable (primary P source are watershed sources)

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

Table V-1c. IN-LAKE CHEMICAL CONTROLS: Address phosphorus or low oxygen by addition of chemical(s) that alter water conditions to either provide oxygen and/or bind phosphorus. These types of *in situ* treatments typically require some sort of delivery system into the pond water column and generally include pond water quality management techniques that have been used most frequently.

OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Crystal Lake
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 • Likely to require use every year	• none	Applicable: Hypolimnion is small, but relatively stable
Algaecides	• Add herbicide to kill phytoplankton • Can be applied in targeted area (use of booms/curtains) • Types include: copper, peroxides, synthetic organics	• Removal of phytoplankton from water column will improve clarity • Dying, settling phytoplankton may transfer large portion of nutrients to sediments	• Restricted use of water during summer • Potential impact on non-target species and accumulation concerns for copper/ organics • Increased oxygen demand from settling phytoplankton; greater release of sediment nutrients • May have to be used each year or multiple times during summer season • Synthetic organics may have daughter compounds with persistent toxicity	• none	Not applicable; does not address sediment oxygen demand and may increase available P in the pond

Table V-1c (continued). IN-LAKE CHEMICAL CONTROLS: Address phosphorus or low oxygen by addition of chemical that alter water conditions to either provide oxygen and/or bind phosphorus. These types of *in situ* treatments typically require some sort of delivery system into the pond water column and generally include pond water quality management techniques that have been used most frequently.

OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Crystal Lake
Phosphorus inactivation	• Addition of aluminum, iron, calcium or other salts or lanthanum clay to bind phosphorus and remove its biological availability to phytoplankton (choice depends on pond water chemical characteristics) • Bound P complexes settle to sediments • Can be added as liquid or powder • Can be applied in targeted area (use of booms/ curtains or careful application)	• Can reduce water column P concentrations and phytoplankton population • Can minimize future sediment P regeneration • Single application can be effective for 10-20 years • Removal of phytoplankton from water column will improve clarity • Can minimize regeneration of other sediment constituents • Variety of application approaches both in timing, dosing, areal distribution, and depth • Can reduce sediment oxygen demand and low water column DO • No maintenance	• Persistent anoxia may reduce P binding for some additions (*e.g.*, Fe) • pH must be carefully monitored during aluminum application; mix of alum salts addresses potential low pH toxicity during application • Cape Cod ponds already have low pH; potential toxicity for fish and invertebrates, related to low pH • Possible resuspension of floc in shallow areas in areas with high use • May need to be repeated in 10 to 20 years if not paired with watershed P source reduction	Alum applications: • Hamblin Pond, Barnstable: 1995, 2015 • 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	Alum application: applicable: limited freshwater mussels found, short-term (~10 yr) solution since sediments not primary P source Iron application: not applicable: sufficient iron generally exists, low DO negates use Calcium application: not applicable: generally used in waters where pH ≥ 8 Lanthanum application: not applicable: concerns about biotoxicity, bioaccumulation, especially in low pH settings

Table V-1c (continued). IN-LAKE CHEMICAL CONTROLS: Address phosphorus or low oxygen by addition of chemical that alter water conditions to either provide oxygen and/or bind phosphorus. These types of *in situ* treatments typically require some sort of delivery system into the pond water column and generally include pond water quality management techniques that have been used most frequently.

OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Crystal Lake
Sediment oxidation (generally regarded as experimental in region)	• Addition of oxidants, binders, and pH adjustors to oxidize sediments • Binding of phosphorus is enhanced • Denitrification may be stimulated	• May reduce phosphorus sediment regeneration • May decrease sediment oxygen demand	• Potential impacts on benthic biota • Duration of impacts not well characterized • Increased N:P ratio may increase sensitivity to watershed inputs • Duration unknown	• none	Not applicable; town may consider if it chooses to evaluate experimental options in other ponds
Settling agents (akin to P binding, but primarily targets the water column)	• Creation of a floc through the application of lime, alum, or polymers, usually as a liquid or slurry • Floc strips particles, including algae, from the water column • Floc settles to bottom of pond	• Cleaning of water column removes algae and accompanying nutrients and transfers them to sediments • May reduce nutrient recycling depending on dose	• Potential impacts on benthic biota, zooplankton, other aquatic fauna • May require multiple or regular treatments • Adds to sediment accumulation • Potential resuspension of floc in shallow ponds	• none	Not applicable; will not substantially address sediment oxygen demand or nutrient regeneration; town may consider if it chooses to evaluate experimental options in other ponds; herring impacts?
Selective nutrient addition	• Add nutrients to change relative ratios to favor different components of plankton community • Favor settling and grazing to transport nutrients to sediments and avoid HABs	• May reduce algal levels where control of limiting nutrient not feasible • May promote non-nuisance forms of algae • May rebalance productivity of system without increasing algae component	• May increase algae in water column • May require frequent additions to maintain nutrient balances • May be incompatible with water quality in downstream waters	• none	Not applicable; will not substantially address sediment oxygen demand or nutrient regeneration; may create non-blue green algal blooms

Table V-1d. IN-LAKE BIOLOGICAL CONTROLS: Address phosphorus by altering the composition or relationships between the plants and animals in the pond, typically through shifting nutrients from plants/algae to other organisms (e.g., fish or zooplankton). Usually requires accompanying in-lake chemical controls to enhance oxygen levels. Generally have not been used on Cape Cod.

OPTION	Option Variations	Advantages	Disadvantages	Examples of Cape Cod uses	Applicability to Crystal Lake
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: • other controls to address low DO; • more extensive evaluation of impact resident fish populations Given its lack of use in Cape Cod ecosystems, should be considered experimental and would likely have significant regulatory hurdles
Bottom-feeding fish removal	• Remove agitation, resuspension, and reworking of sediments by bottom-fish	• May reduce turbidity and nutrient conversion by these fish • May shift more of the pond biomass indirectly to other fish	• May be difficult to achieve complete removal of this population • Effects may not be tunable • May be a favored species for other biota and/or humans	• none	Not applicable, bottom fish are not cause of Crystal Lake impairments

Table V-1d. IN-LAKE BIOLOGICAL CONTROLS: Address phosphorus by altering the composition or relationships between the plants and animals in the pond, typically through shifting nutrients to other organisms (e.g., fish or zooplankton). Usually requires accompanying in-lake chemical controls to enhance oxygen levels. Generally have not been used on Cape Cod.

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

Table V-1d. IN-LAKE BIOLOGICAL CONTROLS: Address phosphorus by altering the composition or relationships between the plants and animals in the pond, typically through shifting nutrients to other organisms (e.g., fish or zooplankton). Usually requires accompanying in-lake chemical controls to enhance oxygen levels. Generally have not been used on Cape Cod.

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

V.C. Applicable Management Options

V.C.1. Watershed Phosphorus Management

Watershed phosphorus inputs to Crystal Lake are the largest annual source of phosphorus to the lake waters. Among these watershed sources, wastewater treated in septic systems is the largest component (66% of the total annual watershed load, see Figure IV-23). Review of the overall phosphorus budget, including both watershed additions and internal additions from sediment regeneration, shows that wastewater is also the largest overall component of the comprehensive phosphorus budget (see Figure IV-23). The estimated wastewater phosphorus load to Crystal Lake is 8.2 kg per year.

Project staff looked at a variety of wastewater phosphorus reduction strategies that could be applied within the Crystal Lake watershed ranging from complete removal (*i.e.*, sewering of identified properties) to partial removal (*i.e.*, installation of alternative septic systems designed to remove phosphorus). The current amended town draft Comprehensive Wastewater Management Plan focusses mostly on nitrogen issues and estuary water quality impairments and has targeted a downtown area and an area near Meetinghouse Pond for sewer connections (Figure V-1).

Complete removal of wastewater phosphorus additions from 13 of the 18 watershed houses currently adding wastewater would reduce the water column TP mass below the 9.9 kg threshold goal during the highest water column load during late summer. Summer sediment TP regeneration water column additions typically range between 2.5 kg and 4.5 kg (see Section IV.D.2.). Complete removal of wastewater TP loads from 13 properties would attain the 9.9 kg water column TP threshold mass at the high end of the sediment regeneration range without any in-lake restoration activities (Figure V-2). The wastewater loads from the 5 existing houses that have not reached the lake would also need to be completely removed to sustain the threshold load in the future. One (1) of the Crystal Lake watershed properties is included in the planned Meetinghouse Pond area (see Figure IV-22), but most of the Crystal Lake properties are not currently targeted for sewering.

The range of costs of a sewer connection for the typical house in the 2016 Amended CWMP was estimated as $7,800 to $12,000 depending on the technology choice with offsets to be determined by how sewer funding is apportioned (*e.g.*, property taxes vs. use assessments vs. mix).[96] Applying these costs to 13 properties currently estimated to be contributing wastewater phosphorus to the Lake, the total capital cost would range from $97,500 to $156,000 with additional costs for installing collection pipes, annual usage and long-term maintenance.

There are currently no phosphorus removal technologies for innovative/alternative (I/A) septic systems approved for general use in Massachusetts.[97] There are two phosphorus removal technologies that are approved for piloting use (*i.e.*, no more than 15 installations with monitoring to field test their performance): a) PhosRID Phosphorus Removal System and b) Waterloo EC-P for Phosphorus Reduction. MassDEP piloting approval "is intended to provide field-testing and technical demonstration to determine if the technology can or cannot function effectively."[98]

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[96] AECOM Technical Services, Inc. 2016. Amended Comprehensive Wastewater Management Plan. Town of Orleans, MA. Appendix I. Technical Memo – Collection System Technologies (GS, LPS, STEG, STEP, and VS) (May 21, 2016).

[97] MassDEP Title 5 Innovative/Alternative Technology Approval Letters website (accessed 6/10/20). http://www.mass.gov/eea/agencies/massdep/water/wastewater/title-5-innovative-alternative-technology-approvals.html.

[98] Ibid.

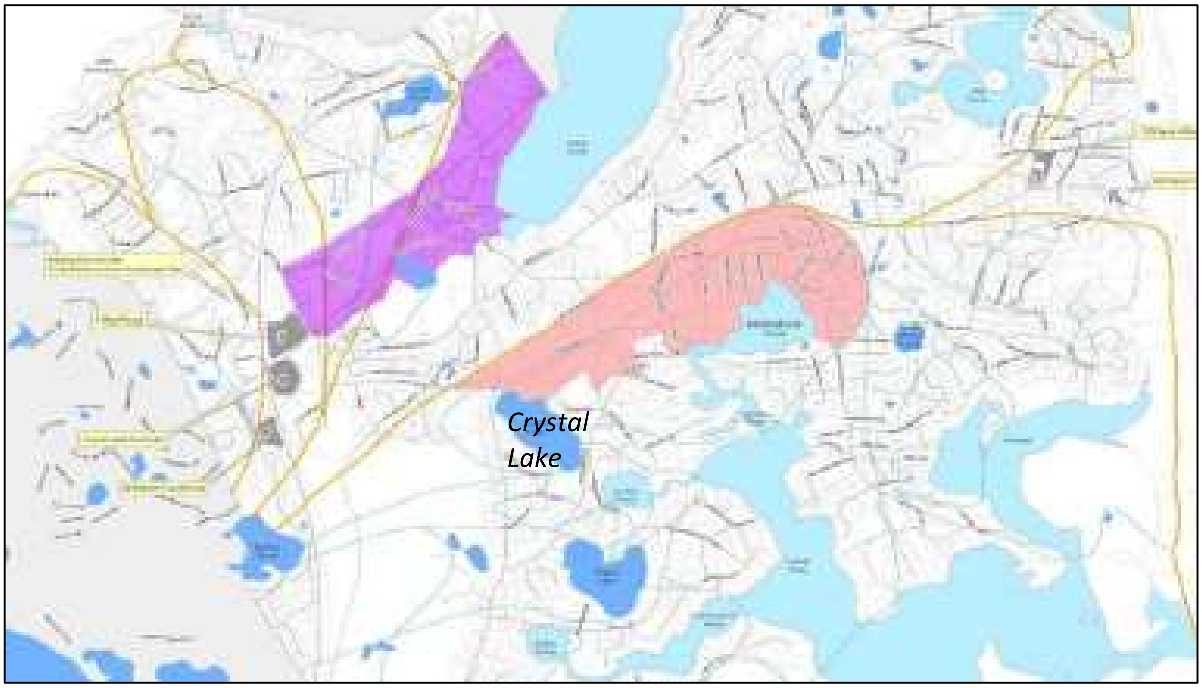

Figure V-1. 2016 Amended Draft CWMP Orleans Sewer Areas. Draft Amended Orleans Comprehensive Wastewater Management Plan (CWMP) shows sewering planned for downtown area (purple) and within a portion of the Meetinghouse Pond watershed (pink). One (1) planned sewered property within the Meetinghouse Pond area is also within the watershed to Crystal Lake (see Figure IV-22). Modified from draft Figure 5-1 in AECOM Technical Services, Inc. (2016).

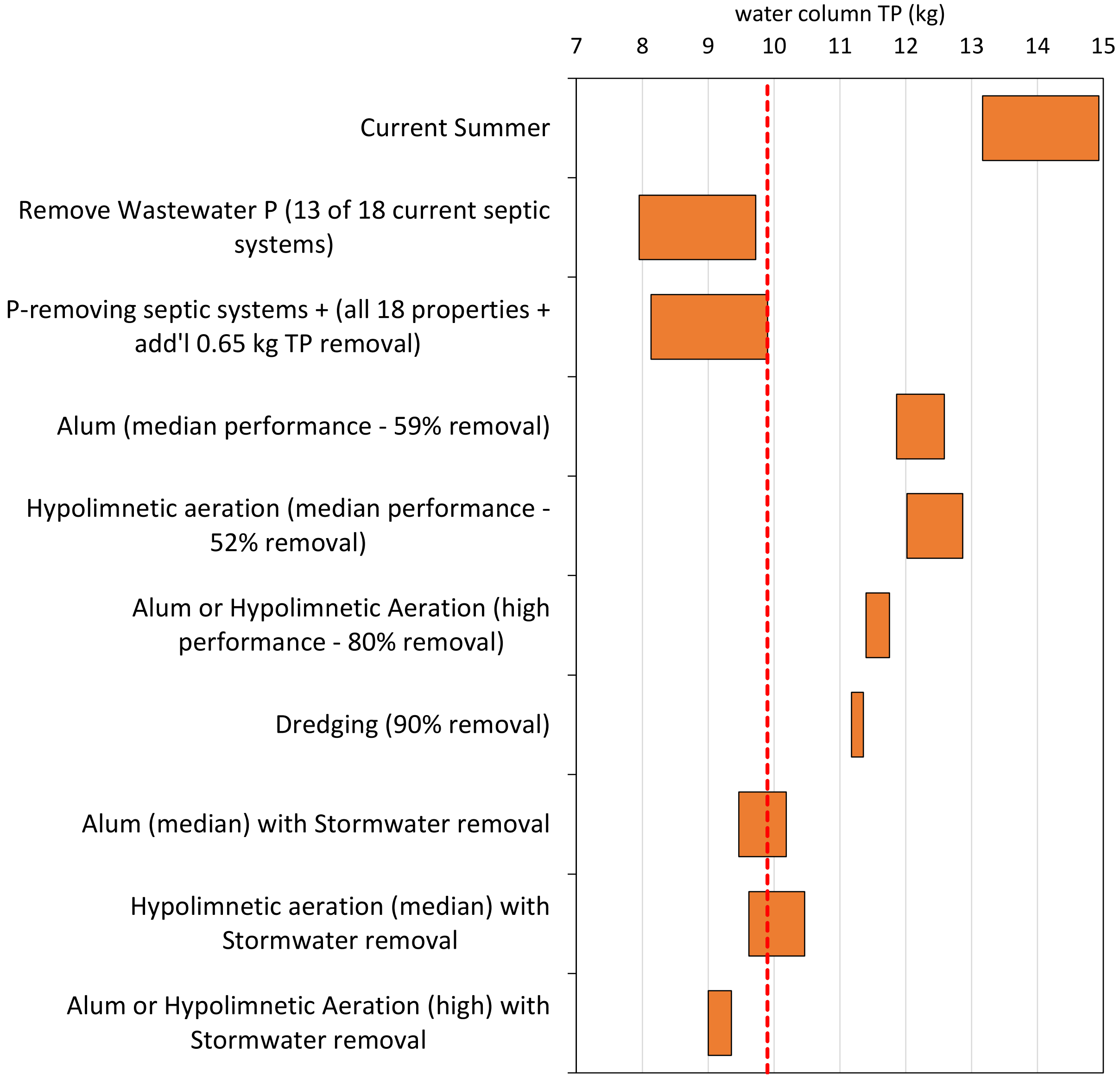

Figure V-2. Crystal Lake: Comparison of Selected Phosphorus Management Options to Attain TP Water Column Threshold. Project staff compared the potential performance ranges for applicable phosphorus management options to the recommended 9.9 kg TP water column threshold mass. Ranges were based on both associated performances, as well as measured fluctuations in sediment TP regeneration. Wastewater achieved the threshold load, while in-lake options could attain the threshold provided sufficient watershed P inputs were removed. Given that wastewater was the predominant P source even during the summer when sediment regeneration was at its maximum, it should not be surprising that treatment of in-lake sediment regeneration alone was insufficient to attain the TP threshold. Given these results, key considerations for selecting a preferred management options will include cost, longevity, management responsibilities, and community acceptance. Since wastewater was the predominant source of water column TP, it was recommended that addressing watershed wastewater P is the best long-term solution. Shorter term internal P loading management could be implemented to provide sufficient time to work out the best long-term solution.

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 have target TP effluent concentrations of 1 mg/L, the use of these types of systems on all the currently developed properties would result in an annual wastewater TP load of 3.7 kg/yr. This load is greater than the equivalent load for complete TP removal scenario and would require an additional 0.65 kg/yr removal to attain the 9.9 kg TP restoration threshold. Any future wastewater TP loads from existing septic systems that have not reached the lake would also need to be removed in order to continue to the attain the TP threshold. One option to attain the additional TP removal would be to combine the use of phosphorus-removing septic systems on all presently contributing properties with the increased 40% removal of the stormwater runoff input from the section of Route 28 that discharges to the lake. Each of these options would have significant regulatory and coordination hurdles.

Retrofitting phosphorus removal on the septic systems for all 18 houses currently contributing wastewater phosphorus to Crystal Lake (plus the 5 additional for future TP loading) would need some sort of waiver from MassDEP if one technology is used since this count is greater than the allowable limit for the currently-approved piloting septic systems. Using both technologies might create issues regarding their future management if monitoring does not attain the target TP goal in the MassDEP permit. Since both systems are approved only for piloting/experimental use, average costs for installation and maintenance in Massachusetts (including potential monitoring) are limited and would likely be lowered if these technologies are approved for general use. In order to provide some idea of potential costs, project staff reviewed a 2010 proposal to the Town of Mashpee that estimated that the individual PhosRID system costs were $8,364 per unit with an annual operation and maintenance cost of $574.[99] Applying inflation adjustments and assuming a 20 year annual cost life cycle, these costs applied to the 23 properties currently estimated to be contributing wastewater phosphorus to the Lake would result in a current estimated cost of approximately $469,000. Additional costs would be incurred for designing a revised stormwater system on Route 28 that did not discharge to Crystal Lake.

Aside from wastewater, the Route 28 stormwater runoff discharge is the other watershed phosphorus load of significance. Removal of this load alone would not be sufficient to attain the target TP water column mass, but removal of this load could reduce the number of houses where wastewater TP reductions would be required. The Route 28 runoff outfall load was 1.7 kg/yr or 14% of the overall annual watershed TP load. Since the outfall is approximately 100 m downhill from the edge of the watershed, complete removal of the runoff flow from the watershed would likely require extensive regrading of a state highway to raise the road elevation relative to the Findlay Road intersection. A wet garden or series of settling pools would likely remove some of the phosphorus load to the pond, but the area between the outfall and the pond is limited (~20 m) and has a relatively steep slope. In addition, any sort of treatment would likely require regular

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

reconditioning or replenishment in order to maintain new phosphorus binding sites. The estimated cost for removing approximately the same TP via sewering would be approximately $270,000.

TP loads from other watershed sources were either not locally controllable, dispersed throughout the watershed, and/or a relatively small portion of the overall load. Atmospheric deposition on the pond surface was 6% of the total annual watershed input (see Figure IV-23). Since atmospheric wet and dry fall tend to be determined by factors outside of the Town boundaries, management strategies should be directed to managing locally controllable loads. Lawn P additions were estimated as <1% of the annual load, but this addition is thought to be legacy loading that will eventually diminish as the impacts of the state fertilizer P ban work their way through the groundwater. It is estimated that this portion of the load will eventually be reduced by approximately 90%. Runoff from roofs was estimated to be 1% of the annual watershed TP load. The annual P contributions from these sources should remain the same unless there are significant changes (*e.g.,* vegetative buffers are removed and lawns are installed to the edge of the pond).

In consideration of the available data and the diagnostic results, the following steps are recommended for watershed management and external phosphorus inputs:

1) the Town should consider incorporating the wastewater phosphorus removal needs into future comprehensive wastewater management discussions and include discussion of whether sewering or enhanced I/A septic systems with TP removal for the identified pond properties could be among pond management options for Crystal Lake (sewering would also remove nitrogen loads),
2) the Town should consider discussing with MassDOT options to treating or remove the Route 28 outfall runoff discharge,
3) the Town should review current Conservation Commission regulations to ensure that natural buffers around Crystal Lake are maintained, and
4) the Town should consider development of a homeowner education package for all pondshore properties that details readily available turf alternatives (including specific plant species), maintenance of natural buffers, and other pond-friendly landscaping, as well as wastewater options. This package could be developed in consultation with landscaping specialists, such as private firms, local golf superintendents, and the county Extension Service.

V.C.2. In-Pond P Management: Aeration/Hypolimnetic Aeration

Once anaerobic conditions occur within the deep portions of the water column, Crystal Lake sediments begin to release phosphorus into the water column and this release persists as long as the anaerobic conditions persist. The amount of TP released varies from year to year depending on the fluctuations and timing of anaerobic conditions, but on average 2.5 to 4.5 kg of TP was released into the water column each summer. During summer, this mass was the second largest TP source to the water column accounting for 17%o 27% of the overall TP loading (see Figure IV-23). Significantly reducing the summer sediment TP regeneration is insufficient to attain the target restoration threshold, but combining an appropriate in-lake treatment with watershed TP reductions could attain the threshold.

Since this phosphorus regeneration is related to the amount of available oxygen, common and applicable in-pond remediation techniques are to a) add oxygen near the sediment/water interface to maintain the chemical bonds that keep the phosphorus in the sediments or b) enhance the circulation of the water column to preventing thermal stratification and provide a regular supply of dissolved oxygen from waters in regular contact with the atmosphere. Since Crystal Lake thermally stratifies, adding oxygen near the deep sediment/water interface without disrupting the stratification is a potential strategy for achieving the TP water column target threshold of 9.9 kg. Maintenance of stratification will preserve a potential cold water fishery.

Addition of oxygen is generally known as aeration and there are a wide variety of aeration techniques and designs, including diffusers for optimal bubbles, pumps for optimal exchange, and various power supplies (conventional, solar, wind). Aeration has generally been approved as an acceptable in-pond lake management technique by MassDEP.[100] Generally, aerators add air or oxygen from shoreline-based pumps to address the sediment oxygen demand. Aeration should generally be considered a permanent solution, requiring annual operation forever since it does not remove the phosphorus source and phosphorus regeneration will return if oxygen levels once again decline. Future monitoring may provide additional insights that may provide a basis for some diminished operation over time, but some substantial level of aeration will need to be maintained to keep sediment phosphorus from being regenerated.

Since aeration has the potential to disrupt thermal stratification and/or eliminate cold water habitat, use of this technique in Crystal Lake should include design considerations to maintain stratification (*i.e.*, hypolimnetic aeration). Review of the temperature profiles showed that the lake regularly stratifies in summer and maintains temperatures low enough to sustain a cold water fishery (see Figure IV-2). MassDEP regulations define cold water fisheries by having temperature consistently less than 20°C. In 2019, Crystal Lake temperature profiles showed waters deeper than 5 m were below 20°C throughout the summer and waters deeper than approximately 8 m were 10°C or less throughout the summer. Based on the bathymetry of the pond, these depths represent 37% and 15%, respectively, of the overall pond volume. If these cold temperatures were sustained and if sufficient oxygen could be maintained, Crystal Lake could provide sustainable habitat for trout and other salmonids.

Review of Crystal Lake DO profile data shows that DO loss occurs most rapidly at the onset of stratification (usually in May or June), but loss continues throughout the summer, often with DO losses due to sediment oxygen demand extending into the water column transition zone between the hypolimnion and the epilimnion. Average June DO loss in the hypolimnion in available profiles was 968 kg (n=5), while both August and September averages were both approximately 2000 kg (n=14 and n=16, respectively). Maximum losses in available profiles were approximately 2,100 kg in June and between approximately 3,000 and 3,100 kg in July, August, and September. Based on the timing of DO loss, operation of an aeration system should begin shortly after stratification occurs in April or May in order to preempt significant DO losses that have generally occurred in June. Given the changeable past measurements of DO loss, it will be important to continue water quality monitoring to ensure that water quality goals are attained if an aeration approach is selected.

Performance reviews of hypolimnetic aeration installations generally show that water column phosphorus levels decline between 33% to 99% (median 52%) compared to baseline conditions,[101] although there has been some evidence of lower performance levels when sediment regeneration

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[100] 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.

[101] Preece, E.P, B.C. Moore, M.M. Skinner, A. Child & S. Dent. 2019. A review of the biological and chemical effects of hypolimnetic oxygenation. *Lake and Reservoir Management*. 229-246. DOI: 10.1080/10402381.2019.1580325

is not the largest P source,[102] as is the case in Crystal Lake. In these cases, hypolimnetic aeration has some benefit in improving water quality until external, watershed sources are adequately addressed. The impact of aeration at a median (52%) or maximum (80%) level of sediment TP reduction would not be sufficient to attain the 9.9 kg water column TP target threshold by itself under current conditions (see Figure V-2). Combining an aeration system with removal of the estimated annual stormwater TP contribution (2.7 kg/yr) would bracket the threshold target at a median performance level and the combined loading range would be under the threshold at maximum performance level.

Details of the design of a hypolimnetic aeration system would depend on the selected technology (*e.g.*, side stream oxygenation, airlift aerator, Speece Cone, bubble-plume diffuser, etc.). Three key factors in designing the system are: avoiding destratification, avoiding hypolimnetic warming, and addressing induced sediment oxygen demand.[103] Destratification by physical mixing of the added gas during hypolimnetic aeration can bring the high phosphorus concentrations in the hypolimnion into the epilimnion and stimulate more phytoplankton growth. Warming of the hypolimnion has occurred in some past hypolimnetic aeration applications.[104] These instances of warming led to the elimination of a cold water habitat and artificially hastened turnover, or mixing of stratified layers. In addition, numerous studies have shown that internal currents created by hypolimnetic aeration prompts additional oxygen demand,[105] which needs to be accommodated in the design.

Final costs for the hypolimnetic aeration system will be based on a public procurement process and the design details, but staff developed a planning cost estimate based on median FGEIR 2004 cost factors adjusted to 2020 dollars: $2,814/acre for capital costs and $203/acre for annual operational costs. Assuming treatment of the portions of Crystal Lake area deeper than 6 m (approximately 19 acres), the capital cost estimate is $54,275 with a total 20 year cost of $132,673 (Table V-2). Additional costs would also be incurred for permitting and installation. Hypolimnetic aeration is an approved method in the MassGEIR,[106] so the method is unlikely to trigger MEPA review. Based on the historic timing of measured oxygen demand onset and persistence, it is initially recommended that the annual operation of the system would be for six months, April through September. Care would need to be taken to ensure the system operated continuously during the six month period each year; recent experience at Lovell's Pond in Barnstable showed that an intermittent operation resulted in more frequent phytoplankton blooms and greater impairment.[107]

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[102] *Ibid.*

[103] Singleton, V.L. and J.C. Little. 2006. Designing Hypolimnetic Aeration and Oxygenation Systems-A Review. *Environ. Sci. Technol*. 40: 7512-7520.

[104] Toffolon M, Ragazzi M, Righetti M, C.R. Teodoru, M Tubino, C. Defrancesco, and S. Pozzi. 2013. Effects of artificial hypolimnetic oxygenation in a shallow lake. Part 1: phenomenological description and management. *J Environ Management*. 114: 520-529. doi:10.1016/j.jenvman.2012.10.062

[105] e.g., Gantzer, P.A., L.D. Bryant, J.C. Little. 2009. Effect of hypolimnetic oxygenation on oxygen depletion rates in two water-supply reservoirs. *Water Research*. 43(6): 1700-1710. https://doi.org/10.1016/j.watres.2008.12.053.

[106] MassDEP and MassDCR. 2004. Eutrophication and Aquatic Plant Management in Massachusetts, FGEIR.

[107] Water Resource Services, Inc. 2014. Draft Investigation of Algal Blooms and Possible Controls for Lovell's Pond, Barnstable, MA.

Table V-2. Hypolimnetic Aeration Cost Estimates for Crystal Lake for Reducing Sediment P Release. Operation period was assumed to be April through September based on historic monitoring of temperature and dissolved oxygen impacts in Crystal Lake, but could vary from year to year depending on the beginning of stratification. Treatment area was assumed to be portions of the pond deeper than 6 m. 20 years of operation in the cost estimate was based on standard design lifetime, but this system would need to be maintained forever. Costs do not include the costs of installing a separate electrical service, permitting, post-implementation monitoring, or contingencies; it is expected that these costs would be developed during the hiring of an implementation contractor. Watershed P reductions would need to accompany hypolimnetic aeration in order to ensure that the P threshold for acceptable water quality is attained.

Pond	Units	
Total Pond Area	m2	153,766
Treatment Area	m2	78,052
Treatment Area	acres	19
Average Hypolimnion DO loss June	kg	1,171
Average Hypolimnion DO loss August/September	kg	2,006/2,023
Days of Treatment	days	180
Years of operation		20
Aeration		
Treatment Capital Cost	$/ac	$ 2,814
Annual Operational Cost	$/ac/yr	$ 203
TOTAL: Capital Cost		$ 54,275
TOTAL: Operational Cost (20 yrs)		$ 78,398
TOTAL COST Aeration: 20 year		$ 132,673

V.C.3. In-Pond P Management: Sediment Dredging

Another applicable option to address sediment phosphorus regeneration would be to remove the sediments, their associated phosphorus, and much of oxygen demand by dredging the sediments from Crystal Lake. Sediment removal from freshwater ponds has not been used extensively in Massachusetts and does not appear to ever have been used on Cape Cod,[108] though it is now being considered for restoration of a number of man-made mill ponds to increase natural nitrogen attenuation.[109]

Removal of sediments in off-Cape lakes typically is preceded by a drawdown in the water level of the lake, so sediments can be more easily accessed by large equipment. In an unconfined aquifer system like most of Cape Cod, the water level of a pond is typically an expression of the groundwater level, *i.e.* an open, exposed portion of the water table. As such, a drawdown would be technically arduous as the surrounding aquifer groundwater would replenish withdrawn water to maintain the general water level of the aquifer. Dredging could also be accomplished through the use of a diver directed, suction dredge, but would also require consideration/resolution of other factors typically associated with dredging, including securing dewatering and sediment disposal

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[108] MassDEP and MassDCR. 2004. Eutrophication and Aquatic Plant Management in Massachusetts, FGEIR.

[109] Cape Cod Times. October 8, 2017. Restoring a mill pond.

areas, testing of the sediments for metals and hydrocarbons, and, likely, accommodations to protect/restore the freshwater mussel and herring populations.

Because of the technical complications and general lack of its application in the region's freshwater ponds, a dredging effort at Crystal Lake would likely require difficult permitting with both state agencies and local boards. Based on the information discussed in the diagnostic section above, the dissolved oxygen profiles, bathymetric data, core incubations, and water quality data, CSP/SMAST staff estimated that dredging, if pursued, should occur at depths of greater than 6 m in Crystal Lake, based on a conservative estimate of where sediment TP regeneration occurs. Sediment dredging has generally been approved as acceptable in-pond lake management techniques by MassDEP. [110]

For the review of dredging in Crystal Lake, CSP/SMAST staff conservatively assumed that dredging would reduce the average sediment phosphorus regeneration by 90%. Since the largest source of TP to the lake was watershed wastewater, even during the summer when sediment TP regeneration was at its maximum, removal of 90% of the internal sediment TP load is not sufficient to attain the 9.9 kg water column TP target threshold by itself. Combining dredging with the complete removal of wastewater P loading from 4 houses would attain the water column TP target threshold during the late summer. In addition, since this approach would not address the majority of the watershed P load, dredging combined with some wastewater removal would likely need to be repeated every 5 to 10 years.

Based on the factors in Table V-3, the low end cost estimate for sediment dredging in Crystal Lake is approximately $1.5 million without accounting for permitting, monitoring, or additional contingencies. High end cost estimates would double this estimate.

Table V-3. Dredging Cost Estimates for Crystal Lake for Sediment P Reduction. Cost estimates for dredging of the areas deeper than 6 m were developed. Costs do not include provisions for permitting, post-implementation monitoring, or contingencies. It is expected that the final versions of all costs would be developed during the hiring of an implementation contractor. Watershed P reductions would need to accompany dredging in order to ensure that the P threshold for acceptable water quality is attained. In addition, since watershed P loading is the primary source of P to Crystal Lake, dredging would likely need to be repeated every 5 to 10 years without additional watershed P reductions.

Pond	units	Crystal Lake >5 m
Pond Area	m2	153,766
Depth to be dredged	≥ m	6
Dredge Area	m2	78,052
Depth of sediment removal	m assumed	0.5
Dredge material volume	m3	39,026
Low Dredge Cost	$/cubic yd	$ 30
High Dredge Cost	$/cubic yd	$ 60
Low Overall Cost	$	$ 1,531,321
High Overall Cost	$	$ 3,062,642

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[110] MassDEP and MassDCR. 2004. Eutrophication and Aquatic Plant Management in Massachusetts, FGEIR.

V.C.4. In-Pond P Management: Phosphorus Inactivation/Alum Application

Another applicable management technique to address internal sediment phosphorus regeneration is phosphorus inactivation through the application of appropriate compounds that will bind phosphorus in the sediments even if low oxygen conditions occur. Sediment phosphorus inactivation is typically completed by adding salts of aluminum, iron, or calcium that chemically bind with the phosphorus by forming insoluble solids. There are some other, recently developed, treatments that are being evaluated, such as lanthanum[111], but most of these have not seen extensive use in natural systems at this point. In contrast, addition of aluminum salts or alum has a long track record in both pond applications[112] and in drinking water treatment.[113] Alum binds inorganic phosphorus and creates precipitates/solids that are not sensitive to redox conditions, so aluminum additions can be used in anoxic settings. Iron is not added in Cape ponds with periodic anoxia/hypoxia because there is usually already sufficient iron present, but the low oxygen is preventing it from binding with the phosphorus; more iron will not resolve these binding issues.[114] Calcium is similarly not used because the low pHs naturally found in Cape ponds will prevent precipitation of calcium-phosphorus solids; calcium precipitates are more chemically favored at pHs above 8.[115] For these reasons, application of aluminum is typically the favored phosphorus inactivation technique in Cape Cod ponds.

Follow-up monitoring of Cape Cod ponds with aluminum applications has generally showed reduced phosphorus regeneration, reduced sediment oxygen demand, and lower TP concentrations within the surface mixed layer of the water column. The 1995 Hamblin Pond alum treatment was the first on Cape Cod and resulted in restoration of a deep, cold habitat (DO >6 mg/L) and surface TP concentrations in Hamblin Pond were reduced by 85%.[116] Benefits of this treatment were sustained until 2013 *(i.e.*, 18 years of efficacy) and another alum treatment was completed in 2015. In the 12 Cape Cod alum treatments that have been completed, the median post-treatment surface TP concentration was 12 µg/L (range of 5 to 17 µg/L) with a median reduction of 59% (range of 35% to 80%) and a median oxygen demand reduction of 62%.[117]

Factors that influence the variability of aluminum application performance include the features of the pond, the application process, dose, area of treatment, and whether external watershed loads are adequately addressed. 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

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[111] Spears, B.M., E.B. Mackay, S. Yasseri, I.D.M. Gunn, K.E. Waters, C. Andrews, S. Cole, M. DeVille, A. Kelly, S. Meis, A.L. Moore, G.K. Nürnberg, F. van Oosterhout, J. Pitt, G. Madgwick, H.J. Woods, and M. Lürling.. 2016. A meta-analysis of water quality and aquatic macrophyte responses in 18 lakes treated with lanthanum modified bentonite (Phoslock®). *Water Research.* 97: 111-121.

[112] 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.

[113] 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.

[114] Iron has been used along the margins of Ashumet Pond in Mashpee to precipitate phosphorus in the discharge of a historic groundwater plume from the MMR wastewater treatment facility.

[115] Stumm, W. and J.J. Morgan. 1981. Aquatic Chemistry. John Wiley & Sons, Inc., New York, NY. 780 pp.

[116] Eichner, E. 2008. Barnstable Ponds: Current Status, Available Data, and Recommendations for Future Activities.

[117] 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.

(<6), aluminum tends to become soluble and unbound; Al(III) is toxic to fish at high enough concentrations.[118] For this reason, buffering is especially important in the naturally low pH Cape Cod ponds and lakes and is achieved through balancing the mix of aluminum salts.

Since the primary source of phosphorus to Crystal Lake is from watershed wastewater sources and not sediment sources, an alum treatment alone will not adequately restore water in the lake (see Figure V-2). Aluminum applications on Cape Cod have attained sediment TP reductions of 35% to 80% with a median reduction of 59%. An alum treatment combined with a removal of 2.7 kg/yr of watershed P inputs (equivalent to the estimated stormwater input) would bracket the threshold target at a median performance level and the range would be under the threshold at maximum performance level. Just as with aeration, however, the alum application would need to be monitored and, like dredging, likely would require another application in 5 to 10 years if watershed phosphorus sources are not reduced.

Planning an aluminum dose is a combination of determining the proper amount of aluminum to inactivate the available phosphorus and having a proper mix of aluminum salts to keep an acceptable pH level and avoid toxicity effects. As with any treatment, treatment effectiveness is dependent on the dose used and, in this case, the dose is also dependent on the pH and alkalinity conditions at the time of application. Typically, final determination of doses is completed using a test of the pond water completed within a few days of the application (usually called a "jar test"). However, for planning purposes calculations are completed based on available phosphorus and the aluminum necessary to bind (or inactivate) the available phosphorus concentrations.

Development of the estimated aluminum dose varies depending on the source data used. The target area for a Crystal Lake alum treatment would be the bottom area deeper than 6 m; this depth includes the water column and sediment area where anoxic conditions have regularly been measured and, conservatively, where the shallowest stratification boundary has been between June and September. The average summer TP release determined from changes in water column TP was 0.08 g/m^2, while the maximum summer water column TP increase results in a TP release of 0.15 g/m^2. The maximum summer water column release was seen in 2003, which was also the year of maximum water column loss of dissolved oxygen, when low oxygen conditions were measured throughout most of the water column. TP release from the sediment core incubations was slightly lower (0.06 g/m^2) than the water column average, but these values are essentially the same given the spatial variability from the core incubation results. As mentioned above, these rates are low[119] and reflective of the relative low contribution of the sediments to the overall phosphorus mass within the pond water column. Translation of these areal TP releases into necessary aluminum doses requires selecting an appropriate molar ratio; typically, 100 Al added to 1 P removed is used. Use of this ratio results in a range of aluminum doses over the treatment area of between 4.5 g/m^2 and 4.9 g/m^2. Since these doses are similar, project staff conservatively used 4.9 g/m^2 aluminum dose for developing planning estimates of costs.

The key in the review of potential doses is using available information to try to address the uncertainties associated with factors that have not been characterized. Part of resolving these

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[118] 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.

[119] Uncle Harvey's Pond sediment phosphorus availability planning estimate was 0.47 g/m^2.

issues is dose testing on pond water, which was outside of the scope of this management plan, but should be completed in the development of the final aluminum treatment costs if this is the selected in-pond management alternative. This type of testing will resolve *in situ* issues, such as how pH readings will be impacted and better understanding of how other ligands/binding materials in the pond water may compete for aluminum. Generally, these concerns have been addressed by being reasonably conservative in the application rate in order to avoid underdosing and placing an upper limit on aluminum concentrations to avoid any pH issues. For planning purposes, mobilization and planning have been estimated at $10,000 with a 30% contingency fund. With these factors, the estimated planning cost for an aluminum treatment is $10,541 (Table V-5). There are no maintenance or operational costs associated with an aluminum treatment. Additional costs for permitting and post-implementation monitoring would be developed during the hiring of an implementation contractor.

Table V-4. Phosphorus Inactivation/Aluminum Treatment Cost Estimates for Crystal Lake for Reducing Sediment P Release. Costs for an aluminum treatment of the areas deeper than 6 m (the maximum summer anoxic area) were developed. Aluminum dose based on average sediment phosphorus release estimated from water quality data. Treatment does not require maintenance or operational costs. Costs do not include provisions for permitting or post-implementation monitoring; it is expected that these costs would be developed during the hiring of an implementation contractor. Watershed P reductions would need to accompany aluminum treatment in order to ensure that the P threshold for acceptable water quality is attained. In addition, since watershed P loading is the primary source of P to Crystal Lake, aluminum treatment would likely need to be repeated every 5 to 10 years without additional watershed P reductions.

Pond	Units	Crystal Lake >6
Treatment Depth	Meters	≥6
Target Area	Acres	19.3
Target Area	square meters	78,052
Available P in sediments	grams per square meter	0.06
Ratio of Al to P		100
Al dose needed	Kilograms	385
Ratio of alum to aluminate		2
Application for Aluminum sulfate	gallon per acre	39
Application for Sodium aluminate	gallon per acre	20
Total applied chemical cost		$ 3,343
Total mobilization, planning & design		$ 10,000
Contingency (30%)		$ 4,003
Total Planning Cost: Alum Treatment		$ 17,346

VI. Summary and Recommended Plan

Crystal Lake is a Great Pond under Massachusetts law and is currently classified as impaired under the most recent listing of the conditions in Massachusetts waters. Review of historic and 2019 water quality data showed that the lake has impaired water quality based on both state regulatory standards and guidance developed from reviewing ponds and lakes in the Cape Cod ecoregion. Dissolved oxygen concentrations in deep portions of the water column have consistently been below MassDEP minimum concentrations during the summer between 2000 and 2019; all 57 deep DO readings between 2000 and 2019 were less than the MassDEP regulatory minimum and annual anoxia is common. Phosphorus and chlorophyll concentrations have been consistently greater than Cape Cod ecoregion thresholds; 58% and 76% of the August surface water measurements between 2000 and 2019 exceeded the respective thresholds. Comparison of shallow and deep water phosphorus concentrations showed regular summer increases in phosphorus concentration from enhanced sediment regeneration due to the low oxygen in bottom waters.

Review of water quality concentrations showed that phosphorus reductions are the key to removing the water quality impairments and also showed that 9.9 kg TP in the water column is an appropriate threshold target for addressing the impairments and restoring acceptable water quality in Crystal Lake. Historic water quality data, collection of data between April and October 2019, and a review of watershed sources provided insight into how the impaired conditions develop annually and how they varied from year-to-year and throughout given summers. Typically, beginning in April or May, shallower waters warm faster than water column mixing and temperature stratification or thermally layering begins. Once the bottom layer is isolated from the well-mixed upper layer, sediment oxygen and water column uptake reduce dissolved oxygen concentrations in the bottom layer and sediment-bound phosphorus is released. Sediment cores collected and incubated in 2019 and review of historic water column data showed that 2.5 to 4.5 kg of total phosphorus (TP) were typically released from sediments in this bottom layer (below 6 meters) by September. This internal source of phosphorus is combined with an annual wastewater TP load from individual parcels within the Crystal Lake watershed of 8.2 kg. Review of septic system records showed that 18 parcels have septic systems that are both old enough and close enough to the lake to contribute septic system wastewater phosphorus to the water column (another 5 existing septic systems will also eventually add TP to the lake). Measurements of stormwater runoff discharge from Route 28 was the second or third largest TP source to the lake, depending on the time of year. Total phosphorus sources balanced water column TP measurements. Comparison of water quality conditions and water column TP mass showed that 9.9 kg water column TP was generally associated with unimpaired water and habitat quality conditions that met state regulatory standards and Cape Cod ecoregion thresholds. For these reasons, 9.9 kg water column TP mass (equivalent to a 10 ug/L TP concentration) was selected as an initial water quality goal/threshold for restoring water quality in Crystal Lake.

Any solutions to restore acceptable water quality in Crystal Lake will require some reductions in watershed phosphorus loads. Sustainable restored water quality conditions could be attained by reducing wastewater TP loads either through sewering of 13 properties or installation of phosphorus-reducing septic systems on all 18 properties currently adding wastewater effluent TP to the Lake plus 0.65 kg of additional watershed TP removal. Implementation of any internal TP treatment to reduce sediment regeneration would require additional reductions in watershed P loads (2 to 2.5 kg/yr), as well as either permanent commitment to operation (hypolimnetic aeration) or regular repeating of procedures (alum treatment or dredging) every 5 to 10 years.

Based on these considerations and the above review of applicable options, CSP/SMAST staff recommends the following steps for implementation of an adaptive management approach for the restoration of Crystal Lake:

1. **Develop and implement a wastewater phosphorus reduction strategy for the Crystal Lake watershed.**
    - Phosphorous loads are the key to managing Crystal Lake water and habitat quality. Wastewater phosphorus loading was more than half (66%) of the watershed load to the lake and 48 to 55% of the overall summer load with internal sediment regeneration included.
    - Of the more than 50 properties within the Crystal Lake watershed, there are 18 properties that are currently adding wastewater phosphorus to Crystal Lake, 23 current properties that will eventually add phosphorus to the lake once their phosphorus sources reach the lake, and 2 developable properties that will add phosphorus to the lake once they have septic systems.
    - Review of water quality impacts shows that complete removal of the wastewater phosphorus from 13 of the 18 contributing properties today could allow average water column phosphorus levels to attain the Crystal Lake target restoration threshold of 9.9 kg total phosphorus (TP) in the water column without any in-lake restoration activities. One of the watershed properties adjacent to the lake is already included in the planned Meetinghouse Pond wastewater collection area. The septic system phosphorus from the 5 additional properties that will impact Crystal Lake in the future would also need to be addressed if a wastewater solution is selected.
    - An alternative to achieve the Crystal Lake restoration threshold would be to use experimental I/A phosphorus-reducing septic systems on all 18 of the contributing watershed properties and combine this approach with another management activity that would remove an additional 1.7 kg TP (*e.g.*, removal of the Route 28 stormwater runoff discharge). MassDEP has currently approved two TP-reducing septic system technologies for piloting installation. This approach would likely have some regulatory hurdles to overcome with MassDEP limiting the installation of each piloting system to no more than 15 installations.
    - Both of the applicable wastewater TP loading reduction approaches to meet the restorative TP threshold for Crystal Lake would require changes in how watershed wastewater is treated, as well as funding and community discussions. A wastewater solution will likely have the same issues typically found with changes in wastewater treatment (*e.g.*, apportionment of financial responsibilities, homeowner acceptance, regulatory issues); the experimental septic systems would have the additional issues associated with their current MassDEP permitting status.
    - Given that development and implementation of a reliable wastewater TP reduction strategy will likely require some time, it is further recommended that the town consider implementation of an interim in-lake treatment (hypolimnetic aeration or alum treatment) to reduce internal sediment regeneration of TP. Implementation of such a treatment would provide some improvement in water quality and time for working out the particulars associated with implementation of a watershed wastewater solution. Implementation of an in-lake treatment could attain the Crystal Lake restoration goal only if combined with reduction in watershed TP. In

addition, an in-lake treatment would require either permanent commitment to its operation (hypolimnetic aeration) or regular repeating of the treatment every 5 to 10 years (alum treatment or dredging).

2. **Develop and implement an adaptive management monitoring program.**
    - Historical monitoring of Crystal Lake has shown that while it is consistently impaired, water quality conditions vary from year-to-year and from month-to-month. Trend analysis has also indicated that certain measures (*e.g.*, Secchi, TP concentrations) have worsened between 2000 and 2019. Implementation of any of the potential P reduction strategies for Crystal Lake will also be subject to this variability/trends and will create a need to understand how well the strategies work within Crystal Lake and whether strategies will need to be adapted in future years.
    - With this in mind, it is recommended that the town develop an adaptive monitoring program with focus on regular water column monitoring and feedback on water quality changes. Water column sampling should occur monthly (April to October) during at least three summers after the implementation of in-lake treatment. A similar frequency should also be implemented 4 years after the implementation of watershed wastewater reductions.[120] This timing should allow impacts to begin to be seen in Crystal Lake. Sampling should include, at a minimum, temperature and dissolved oxygen profiles, Secchi clarity measurements, and collection of water quality samples at depths of 0.5 m, 3 m, 9 m and 1 m off the bottom. Samples should be analyzed for the same parameters tested for in the PALS Snapshots, at a minimum, with the same or lower detection limits.

3. **Select a target restoration threshold of 9.9 kg TP in the water column as a preliminary water quality target threshold, but avoid a TMDL designation until attainment of satisfactory water quality.**
    - Crystal Lake is currently listed as an impaired water on MassDEP's most recent Integrated List. Under the Clean Water Act, impaired waters are required to have a TMDL for the contaminant causing the impairment.
    - It is recommended that the Town avoid submitting information on a TMDL until after implementation of a wastewater P reduction strategy and subsequent adaptive management monitoring to document improvement and attainment of water quality goals. It is possible that MassDEP (or another party) may cause the Town to expedite a TMDL listing. If this occurs, the information in this Plan should be sufficient to meet the data requirements for a phosphorus TMDL submittal. If the Town pursues the recommended strategy, management of the pond would remain predominantly within local purview.

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,

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[120] Minimum phosphorus travel time for septic systems in the Crystal Lake watershed is estimated to be 5 years. Implementing monitoring at 4 years will allow a recent baseline to be set and account for any variability in travel time.

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

The Town of Orleans Marine and Fresh Water Quality Committee (MFWQC) conducted a number of public meetings to review the draft Crystal Lake Management Plan and discuss the Plan results and preferred management options. As a result, the MFWQC members voted to "strongly support sewering of selected properties adjacent to the pond as the preferred water quality management solution for both Pilgrim Lake and Crystal Lake."[121]

MFWQC further recommended that "the Select Board request a review of potential sewer layout and associated costs from the current CWMP consultants AECOM, and develop a potential timeline for extending the connection of the selected watershed properties to the municipal sewer system as part of Phase 2." The MFWQC further noted that "If the timeline for reviewing sewering options and connecting these properties is more than 5 years, the Committee is further recommending that the Select Board support either alum treatments or aeration systems in both lakes. Given that wastewater phosphorus is the primary source of impairments in both lakes, these in-lake treatments will **not** completely restore their water quality, but these treatments will improve conditions until the more permanent solution is implemented."

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[121] January 29, 2021 Memo from Marine and Fresh Water Quality Committee (Judy Scanlon, Chair) to Orleans Board of Selectmen and Town Administrator, John Kelly. 3 pp. (appended to this Management Plan).

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To: Orleans Board of Selectmen and Town Administrator, John Kelly

Copy To: Board of Water and Sewer Commissioners

From: Orleans Marine and Fresh Water Quality Committee, Judy Scanlon, Chair

Date: January 29, 2021

Subject: Crystal Lake and Pilgrim Lake Management Plans

The citizens of Orleans enjoy and benefit from our many freshwater lakes and ponds. These waters are extremely important ecologically, provide extensive recreational value, and contribute to important town revenue streams. Our waters attract many visitors, and new home buyers seeking to live in close proximity to these natural resources. The Town has recognized the integral importance of these waters through their inclusion in the comprehensive wastewater planning process to address acknowledged water quality impairments, including plans to sewer downtown Orleans, and the watershed around Meetinghouse Pond. Including Uncle Harvey's Pond up-gradient properties is also being considered.

As part of the Comprehensive Wastewater Management Plan process, the Marine and Fresh Water Quality Committee has been working with the staff of the School of Marine Science and Technology at UMass Dartmouth (SMAST) to assess the water quality of key freshwater ponds. To date, these efforts have led to assessments of Uncle Harvey's Pond, Crystal Lake, and Pilgrim Lake. Bakers Pond will be completed later this year.

Unfortunately, these water quality assessments showed impaired conditions, including excessive nutrients and summer anoxia (an absence of oxygen) in all three ponds. These impairments prevent these lakes from meeting state regulatory minimums or Cape Cod Ecoregion guidelines for water quality. Each pond assessment was accompanied by a Management Plan that reviewed the options available to address the impairments and restore the water quality in each pond.

Committee review of the Management Plans for Crystal Lake and Pilgrim Lake showed that the primary source of the water quality impairments was excessive phosphorus, primarily from adjacent septic systems. This contrasts with Uncle Harvey's Pond where the pond sediments were the primary cause of impairment. The SMAST Management Plans showed that 26 residences were contributing phosphorus to Pilgrim Lake and 22 residences were contributing phosphorus to Crystal Lake (Figure 1). Phosphorus was released into the water from the sediments during the summer in both lakes, but septic systems were still the primary phosphorus source.

The Committee discussed options to address the excessive phosphorus, including removing the wastewater phosphorus through sewering, reducing it through experimental septic systems, internal sediment treatments such as alum or aeration, dredging, and various other pond-specific strategies. SMAST review of the results of various options showed that sewering 19 properties within the Pilgrim Lake watershed and 13 properties within Crystal Lake watershed would attain the water quality goals for each lake.

RECOMMENDATIONS:

After deliberations and review of all the options, the Committee has voted 6-0-1 to strongly support sewering of selected properties adjacent to the pond as the preferred water quality management solution for both Pilgrim Lake and Crystal Lake.

The Committee supports, and further recommends, that the Select Board request a review of potential sewer layout and associated costs from the current CWMP consultants AECOM, and develop a potential timeline for extending the connection of the selected watershed properties to the municipal sewer system as part of Phase 2. One property within the Crystal Lake watershed is already included in Phase 2, the Meetinghouse Pond sewered area delineated in the CWMP (Figure 1). Sewering of these properties would also remove nitrogen and provide water quality benefits to Namequoit River, the Upper and Lower River, and Lonnie's Pond.

If the timeline for reviewing sewering options and connecting these properties is more than 5 years, the Committee is further recommending that the Select Board support either alum treatments or aeration systems in both lakes. Given that wastewater phosphorus is the primary source of impairments in both lakes, these in-lake treatments will **not** completely restore their water quality, but these treatments will improve conditions until the more permanent solution is implemented. Preliminary cost estimates without permitting for alum treatments on both ponds is approximately $34,000 and approximately $210,000 for aeration treatment.

The Committee thanks you for your thoughtful consideration.

Respectfully,

Judy Scanlon, Chair-Orleans Marine and Fresh Water Committee

Documents
The Pilgrim Lake Management Plan is available on the town website:
https://www.town.orleans.ma.us/sites/g/files/vyhlif3631/f/uploads/pilgrimlake_managementplan_final.pdf

The Crystal Lake Management Plan and Diagnostic Assessment-Draft Final Report-September, 2020 is not on the website yet.

Executive Summaries for each Management Plan are attached. Ed Eichner, Principal Water Scientist, who worked with SMAST on this project and the Committee are available to meet with you to answer further questions.

Attachments:
Executive Summary, Pilgrim Lake Management Plan
Executive Summary, Crystal Lake draft Management Plan

Links: Water Quality Standards and Ecoregion Guidelines

https://www.mass.gov/regulations/314-CMR-4-the-massachusetts-surface-water-quality-standards
http://www.capecodgroundwater.org/wp-content/uploads/2012/04/PondAtlasExecutiveSummary.pdf

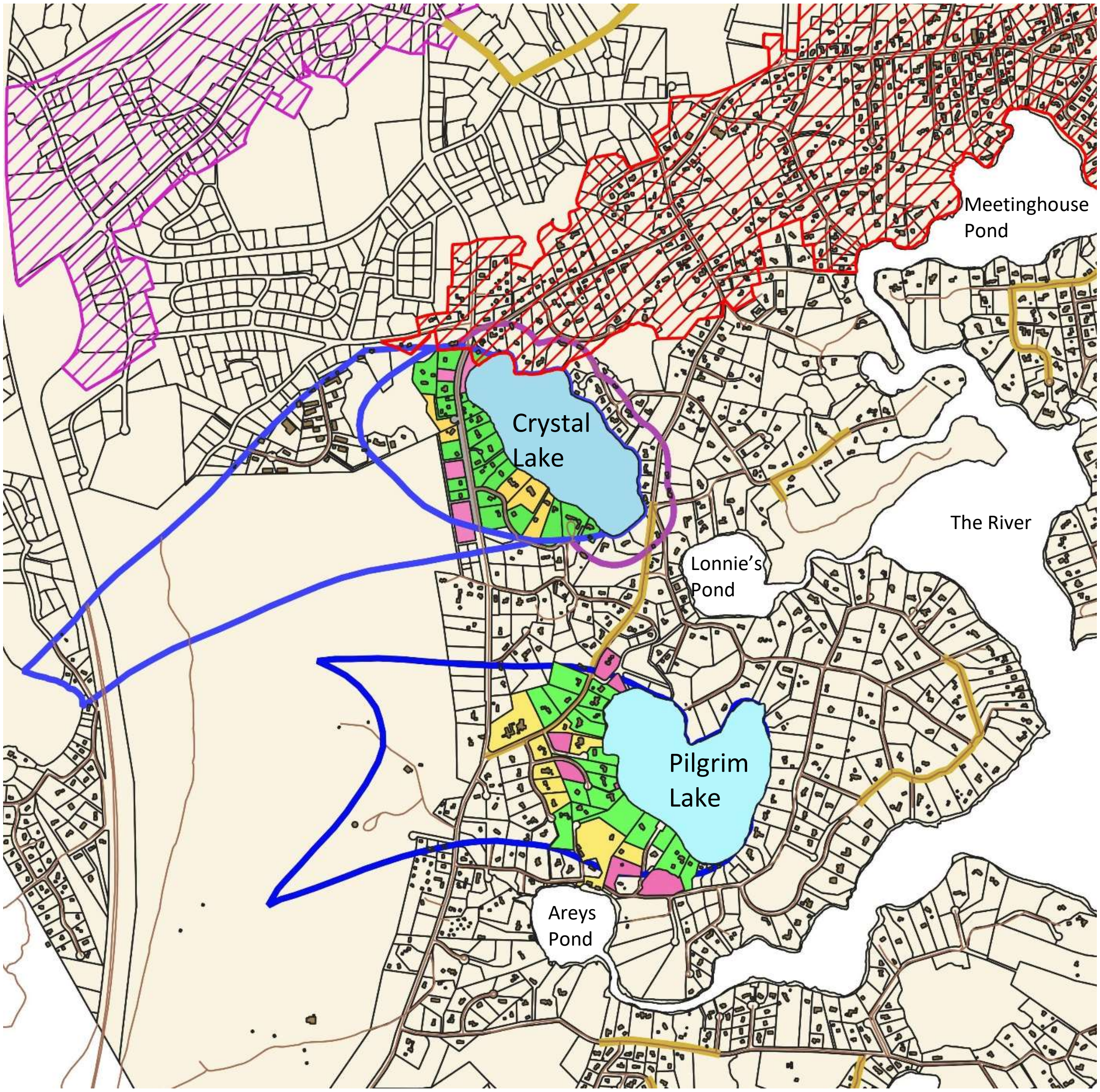

Figure 1. Parcels contributing wastewater phosphorus to Crystal Lake and Pilgrim Lake. Parcels colored green are currently contributing wastewater phosphorus to Crystal Lake and Pilgrim Lake, while those colored yellow have existing buildings that will add wastewater phosphorus in the future. Parcels colored pink are not currently developed. Watersheds to the lakes are outlined in blue. Also shown are the planned Meetinghouse Pond sewer area (red crosshatch) and the planned Downtown sewer area (pink crosshatch).