Mill Ponds Management Plan
Walkers Pond, Upper Mill Pond, and Lower Mill Pond

FINAL REPORT
November 2014

for the

Town of Brewster

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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Prepared for

Town of Brewster
Comprehensive Water Planning Committee

and

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Cover photo: Upper Mill Boat Ramp (6/21/14)

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Executive Summary

Mill Ponds Management Report
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Walkers Pond, Upper Mill Pond and Lower Mill Pond are a series of relatively large ponds located in the western portion of the Town of Brewster. Water flows through a series of hydroconnections between the ponds, flowing from Walkers Pond to Upper Mill and then from Upper Mill to Lower Mill. Water flows out of Lower Mill Pond into Stony Brook and then into Cape Cod Bay. The connection between Lower Mill Pond and Stony Brook includes the Stony Brook Grist Mill and its associated structures, which are located along Stony Brook Road. The brook includes one of the more productive herring runs on Cape Cod.

All three ponds are publicly owned and their water quality is subject to the Massachusetts and federal clean water regulations. Since the areas of all three pond are greater than 10 acres, Walkers Pond (103 ac), Upper Mill Pond (257 ac) and Lower Mill Pond (50 ac) are "Great Ponds" under Massachusetts law. As such, they are required to attain water quality standards in Massachusetts surface water regulations (314 CMR 4.00). The most recent Massachusetts Department of Environmental Protection (MassDEP) surface water list includes Walkers Pond and Lower Mill Pond as impaired waters, while Upper Mill Pond is listed as having an incomplete assessment.[1] Under federal Clean Water Act requirements, any impaired waters are required to have a limit (or TMDL[2]) for the contaminant causing impairment. Based on state listings, Walkers Pond and Lower Mill Pond are required to have TMDLs developed, while data reviewed in this management plan supports listing Upper Mill Pond as impaired.[3]

Water quality data has been collected in Walkers Pond, Upper Mill Pond and Lower Mill Pond approximately 40 times since 2001, although the data collected in each sampling runs was sometimes inconsistent. In 2009, available data was reviewed and a series of recommendations for targeted data collection focused on development of a future management plan were suggested to the Town.[4] In 2011, Coastal Systems Program at the School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) completed a number of these targeted data collection efforts for the three ponds to: a) identify and quantify direct road runoff phosphorus loads, b) determine sediment nutrient loads released under aerobic, hypoxic, and anaerobic conditions in each pond through the collection of sediment cores, c) measure water and nutrient transfers via the hydroconnections between the ponds, and d) collect continuous measures within the pond watercolumns of dissolved oxygen, chlorophyll, and

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[1] Massachusetts Department of Environmental Protection. March, 2013. Massachusetts Year 2012 Integrated List of Waters, Final Listing of the Condition of Massachusetts' Waters Pursuant to Sections 305(b), 314 and 303(d) of the Clean Water Act. MassDEP, Division of Watershed Management, Watershed Planning Program. Worcester, MA.

[2] TMDL = Total Maximum Daily Load

[3] TMDLs are developed through a public process involving a draft proposed TMDL, a public hearing, and a final TMDL that is submitted by MassDEP to EPA for approval.

[4] Eichner, E. 2009. Brewster Freshwater Ponds: Water Quality Status and Recommendations for Future Activities. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth and Cape Cod Commission. New Bedford and Barnstable, MA. 117 pp.

temperature in order to see if short-term events were significantly impacting water quality in the ponds.[5] Based on these results and further discussions with the Town of Brewster Comprehensive Water Planning Committee (CWPC), CSP/SMAST staff recommended some additional targeted data collection as part of development of a pond system management plan. This additional targeted data collection included updated bathymetric maps to allow accurate determination of pond volumes and nutrient balance and a combined survey of aquatic plant and freshwater mussel distribution. These efforts were completed and are documented in this report. Collectively, all of these efforts were directed toward preparing adequate information to develop management strategies to restore water quality in Walkers Pond, Upper Mill Pond and Lower Mill Pond.

In 2009, the Town began working on a town-wide Integrated Water Resource Management Plan (IWRMP), which is coordinated through the CWPC. The IWRMP is designed to comprehensively review the current status of all of Brewster's water resources (*e.g.*, ponds, estuaries, drinking water), review options for their restoration and management, and develop an integrated plan that will comprehensively sustain acceptable water quality in all these resources. The Phase I comprehensive status review was completed in 2011[6] and a Phase II report on some management options for drinking water, wastewater, stormwater, and emergency preparedness was completed in 2013.[7] This report, the Mill Ponds Management Plan, is part of Phase III of the IWRMP, which is being completed by Horsley Witten Group.

This Mill Ponds Management Plan relies on available water quality data collected by Brewster volunteers and staff since 2001 and targeted data collected in 2011 and 2012 by CSP/SMAST. The water quality data were reviewed to assess the status of the water quality in each of the ponds. This data was then combined with other information, such as watershed delineations and land use data, to develop a linked conceptual model of water quality and the factors that influence water quality in Upper Mill Pond, Lower Mill Pond, and Walkers Pond. This empirical model was then used to evaluate potential options to restore water quality conditions in the ponds.

Review of water quality conditions in Upper Mill Pond, Lower Mill Pond, and Walkers Pond showed all three ponds are impaired with high concentrations of phosphorus, chlorophyll, and nitrogen. Each pond is also showing diminished water clarity. Review of dissolved oxygen (DO) concentrations show that Upper Mill Pond and Lower Mill Pond regularly had DO concentrations less than the state regulatory standard (5 mg/L). In fact, the continuous DO record found 85% and 91% of the Lower Mill Pond and Upper Mill Pond DO readings to be less than 5 mg/L. Review of total phosphorus concentrations showed that average total phosphorus concentrations in all three ponds exceeded the Cape Cod-specific regional threshold of 10 µg/L, with average surface water TP concentrations in Walkers Pond, Upper Mill Pond, and Lower Mill Pond being 49 µg/L, 22 µg/L, and 32 µg/L, respectively. Chlorophyll and total nitrogen average concentrations also exceeded their respective Cape Cod-specific regional thresholds.

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[5] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013. From Ed Eichner and Brian Howes, CSP/SMAST. To Lem Skidmore, Brewster CWPC Chair and Sue Leven, Brewster Town Planner.

[6] CDM, 2011. Town of Brewster, Massachusetts Integrated Water Resource Management Plan, Phase 1 - Needs Assessment Final Report. CDM-Smith, Cambridge, MA.

[7] Horsley Witten Group, 2013. Town of Brewster, Massachusetts Integrated Water Resource Management Plan, Phase II - Needs Assessment Final Report. Horsley Witten Group, Sandwich, MA.

Review of phosphorus to nitrogen ratios show that phosphorus is the key management nutrient for determining water quality conditions in all three ponds.

Review of the watersheds, bathymetry, and flows between the ponds showed that there are significant physical differences among the ponds. Walkers Pond has a volume of 730,603 m^3 and an average depth of 1.9 m with groundwater inflow from its watershed and seasonal surface water inflow from a cranberry bog off Cranview Road; it has an average residence time of 154 days. Upper Mill Pond receives groundwater inflow from its watershed and surface water inflow from Walkers Pond. It also has surface water outflow to Lower Mill Pond. Upper Mill Pond has an average depth of 5.8 m, is nearly 8X the volume of Walkers Pond (5,708,219 m^3) and has an average residence time of nearly 15 months (441 days). Lower Mill Pond, on the other hand, has an average residence time of just over one month (38 days) with a volume that is 75% of Walkers Pond (550,406 m3), but an average depth of 2.9 m. Lower Mill Pond receives groundwater inflow from its watershed and surface water inflow from Upper Mill Pond. Lower Mill Pond discharges surface water flow to Stony Brook, although the measured water flux accounts for only ~50% of the collective inflow. This finding is common in ponds with control structures where pond water discharges to both an outlet and the downgradient aquifer along the downgradient shoreline. Water table readings in the area near Lower Mill Pond have gradients that are consistent with discharge to the surrounding groundwater.[8] Review of measured seasonal hydroconnection inflows/outflows between the ponds is highest in the colder months and declines 33-36% during the summer.

The phosphorus budget for each pond showed that the primary source of phosphorus to support plant and algae growth is within the ponds themselves: 90% of the load to Walkers Pond, 65% of the load to Upper Mill Pond, and 55% of the load to Lower Mill Pond. This evaluation uses the measured data from the hydroconnections and the mass within each pond, as well as source-specific estimates for various land uses within the watersheds. Within each pond, the internal source differs in magnitude. The predominant source in Walkers Pond is the extensive macrophyte stands in the shallow areas that ring the pond, while the primary P source in Upper Mill Pond is regenerated P from its deep sediments. In Lower Mill Pond, the review of the data suggests a complex mix of sediments and macrophytes with the balance shifting rapidly because of the short residence time. After these internal sources, the hydroconnection inputs are the next largest contributor to the phosphorus budgets for Upper Mill Pond (24%) and Lower Mill Pond (39%), while watershed inputs (6%) are the next largest to Walkers Pond. Because of these relationships, reducing the internal phosphorus loads in the upgradient/upstream ponds will provide water quality benefits to the downgradient/downstream ponds by reducing the phosphorus transfers downstream.

Using the Cape Cod-specific regional TP threshold for restoration of 10 µg/L, CSP/SMAST staff reviewed potential management options to reduce the internal phosphorus loads within each pond. In order to maximize benefits to downstream ponds, this review began by reviewing options for Walkers Pond. Review of the phosphorus balances show that slightly more than a 90% removal of internal P alone would be required to meet a 10 µg/L threshold if no other actions were taken. A number of macrophyte control options were reviewed and annual late summer harvesting with collection of clippings is the initial recommended approach with a

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[8] Localized water table readings collected during the assessment of the Brewster Landfill (Cambareri and Eichner, 1993) suggest this is reasonable.

targeting of 50% of the dense macrophyte areas (16.5 acres of the >80% density areas). The goal of this approach is to move the macrophyte population to a growth-oriented condition that stimulates phosphorus removal. It is anticipated that this approach will require regular monitoring to assess and adapt the frequency, area, and optimal timing of harvesting. These details could be organized in a macrophyte monitoring plan. Estimated cost is $15,000 to $52,000 for harvester rental for each harvesting run with additional costs for disposal. It is further recommended that the town consider purchase of a harvester that could be used on other town or nearby town ponds.

Review of Upper Mill Pond inputs showed that even if Walkers Pond attains a 10 µg/L TP threshold, sediment inputs in Upper Mill Pond will need to be reduced by 60% in order to attain a 10 µg/L TP threshold. Based on this assessment, CSP/SMAST staff reviewed dredging, aeration, and application of aluminum salts for Upper Mill Pond to reduce its sediment P regeneration. The preliminary low cost estimate for dredging was $10.9 million and also presented a number of logistical hurdles, so this was not pursued further. Upper Mill Pond has a slight resistance to mixing for waters deeper than 7 m and has regular anoxia events (23% of continuous readings were below 1 mg/L DO). For these reasons, project staff reviewed aeration as an option to reduce internal P additions from the sediments in Upper Mill Pond. Estimated cost of aeration including capital equipment and 10 years of operation and maintenance was $432,600 for conventional aeration and $250,000 to $1.45 million for updraft pumping. The wide range of costs for the updraft pumping is based on the questions about the expected efficiency. Estimated cost of an application of aluminum salts was $158,300. This comparison of cost estimates favors the aluminum salt application. A series of recommendations regarding monitoring and management adjustments were also made for Upper Mill Pond following the application; these will have to occur for at least two years because of the pond's long residence time. The efficacy of sediment P reduction in Upper Mill Pond is somewhat dependent on the performance attained in Walkers Pond, so monitoring at the hydroconnection is also recommended.

Lower Mill Pond is the most downstream of the three ponds and, as such, is influenced by the water quality conditions in the other two ponds. Review of the phosphorus budget for Lower Mill Pond showed that internal sources of P were also the predominant source, but the review of sediment incubation, dissolved oxygen concentrations, and research on potential macrophyte and mussel contributions showed that this internal contribution is multifaceted with many sources contributing and potentially varying by season and, perhaps, month to month because of the pond's short residence time. Lower Mill Pond has ecosystem characteristics that must be considered in development of management strategies: it has a macrophyte population that is greater than the sparse Upper Mill Pond populations, but less than the extremely dense Walkers Pond communities (i.e., densities ~40% in littoral zone). Its mussel population is similar to Walkers Pond, but more spatially extensive. Both macrophytes and mussels are mostly associated with shallow sediments in a narrow strip along the shoreline; macrophytes are generally are confined to depths of 1.25 m and less due to light penetration, while mussels are confined to depths of 2 m and less most likely due to dissolved oxygen limitations. Given that the full impact of the recommended aluminum salt application in Upper Mill Pond is unlikely to be clear for two years, CSP/SMAST staff recommends that the Town avoid significant expenditures to further resolve the internal P sources in Lower Mill Pond until monitoring of the Upper Mill impacts is complete.

After the completion of the recommended two years of monitoring in Upper Mill Pond, it is recommended that the collected water quality data from all three ponds be reviewed. If water quality conditions in Lower Mill Pond are judged to be adequately resolved or have attained an average TP concentration of 10 µg/L, then no further restoration activity in Lower Mill Pond is recommended. If further P reductions are recommended, further evaluation of alternatives based on the review in this report is suggested.

Additional management plan recommendations for all three ponds include: a) implementation of a landowner education program, b) a stormwater infiltration program, and c) regular monitoring and review of pond water quality data. The landowner education program is proposed to assist and educate homeowners with clear understanding of setbacks, buffer designs, alternative groundcover options, and other activities that will minimize nearshore stormwater and fertilizer phosphorus loading to the ponds. The stormwater infiltration program is proposed to prevent direct stormwater discharges to the pond surface from identified sources by encouraging subsurface infiltration. This program should begin with elevation surveys in the six source areas with direct discharges. Another part of this program would be regular (1-2 year) visual inspection of steeper slopes along the pond shorelines to look for and repair any stormwater scour channels. Regular monitoring is the key to provide on-going feedback on any restoration steps taken for these ponds. It is recommended that the town continue its current April and August/September sampling using PALS sampling protocols, publicly present the data results annually, much like drinking water consumer confidence reports, and more extensively review the data every five years for trends and comparison to past data.

The overall strategy of the management plan is adaptive management with sequential implementation, monitoring, and review of monitoring data to make adjustments. This strategy addresses the uncertainty in the performance of the restoration strategies, as well as variability in the underlying water quality data. It incorporates the concept that improvements in the upgradient ponds will also impact the lower ponds. Implementation of alternatives can be phased in an adaptive management approach which prevents overmanagement and is timed with the observed changes through time.

Implementation of these recommendations will require funding sources and close coordination among local project planners, local regulatory boards, and state and regional regulators. 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 is available to further assist the town with implementation and regulatory activities.

Table EX-1. Summary of Recommended Management Plan Actions

Action	Description	Pond	Estimated Cost	Issues to Resolve
1	Macrophyte Harvesting	Walkers	$15,000 to $52,000	All costs and implementation details including optimal plant disposal, permitting, timing of harvesting, monitoring, and regular adaptation based on monitoring results; renting vs. buying harvester
2	Alum application	Upper Mill Pond	$158,300	All costs and implementation details including mussel accommodations, permitting, monitoring (for at least two years), and regular adaptation based on monitoring results
3	Await results of management activities in other ponds	Lower Mill Pond	To be determined	Monitoring and adaptation based on transferred results from other two ponds; monitoring for at least two years
4	Shoreline Landowner Education Program	All ponds	To be determined	Best form of accessibility (website, pamphlets, etc.) for clear homeowner understanding of issues to reduce or eliminate phosphorus contributions to ponds including setbacks, buffer designs, alternative groundcover options, and stormwater design
5	Implement Stormwater Infiltration Program	All ponds	To be determined	Redesign six (6) identified areas that have direct stormwater discharges to pond surfaces. Initial step: complete elevation surveys in the areas and review design options to encourage infiltration. Program should also include regular (1-2 year) visual inspection of steeper slopes along the pond shorelines for stormwater scour channels and development of strategies to mitigate any identified channels.
6	Pond Monitoring Program	All ponds	To be determined	Program to monitor and regularly review benefits of management activities and adjust as indicated. Issues to resolve include components to be monitored (*e.g.*, water, plant height, etc.), monitoring schedule, schedule for data review, and action thresholds for changes/adjustments.

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I. Introduction

The Town of Brewster has over 70 freshwater ponds 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 for cranberry bogs, herring runs, and nitrogen attenuation protecting estuaries. Brewster citizens have long recognized that ponds are important community resources and, in 1999, helped to initiate the Cape Cod Pond and Lake Stewards (PALS) program to encourage development of basic knowledge about these resources in order to develop active, appropriate, and pond-specific management strategies to ensure long-term sustainable water quality.

The Cape Cod PALS program began with annual citizen water quality monitoring snapshots, but expanded into more extensive town-wide and pond-specific assessments with future plans to develop pond management plans. As part of this expanded effort, staff from the Coastal Systems Program at the School for Marine Science and Technology, University of Massachusetts Dartmouth (CSP/SMAST) completed a 2009 review of citizen-collected water quality data from 29 ponds in the Town of Brewster (Figure I-1).[9] This review identified water quality problems in a number of the ponds and included recommendations to complete basic assessment data collection in order to establish a solid basis for development and implementation of future management plans. The Brewster Comprehensive Water Planning Committee (CWPC) initiated an effort to address these recommendations and focus initial work on selected ponds within the Mill Ponds Complex: Upper Mill Pond, Lower Mill Pond, and Walkers Pond.

The 2009 review of citizen-collected water quality data included more detailed interpretation and context for the water quality data for the following ponds: Blueberry, Seymour, Canoe, Walkers, Upper Mill, and Lower Mill. These detailed reviews included watershed delineations and development of preliminary water and phosphorus budgets. These reviews also recommended a number of pond-specific targeted data collection needed to develop reliable water and habitat quality management strategies. Among the recommended targeted data collection for Upper Mill Pond, Lower Mill Pond, and Walkers Pond were activities to quantify phosphorus loading to the pond watercolumns from four sources: 1) road runoff, 2) birds, 3) pond sediments, and 4) the transfer of water and nutrients through the connections between the ponds.

During 2012, CSP/SMAST staff, working with the CWPC, developed a series of specific tasks to address this targeted data collection. Working with Town Natural Resources staff, CSP/SMAST project staff initiated efforts to quantify the four targeted sources of phosphorus loads. Initial field observations of road runoff during storm events indicated a positive result: there were fewer direct stormwater discharge sites than originally estimated. On the other hand, town and project staffs were unsuccessful in recruiting volunteers to be bird counters in order to estimate phosphorus input from avian fauna. In addition, during the early portion of the project data collection, Walkers Pond, which was considered the least phosphorus impacted of the three ponds[10], experienced an extensive blue-green algae bloom in August 2011.

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[9] Eichner, E. 2009. Brewster Freshwater Ponds: Water Quality Status and Recommendations for Future Activities. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth and Cape Cod Commission. New Bedford and Barnstable, MA. 117 pp.

[10] Eichner, E. 2009. Brewster Freshwater Ponds

Based on these events, CSP/SMAST staff recommended some repurposing of project resources in order to install continuous sampling devices in each of the three ponds during July and August 2012. It was thought that the placement of these devices, known as sondes, would provide insights into the potential cause of the bloom in Walkers Pond, as well as complementing the other pond-specific targeted data collection. These time-series measurements of key water quality parameters also provided information that can later be used to provide robust water quality management strategies for the each of the ponds and the overall pond complex. Results from all this series of data collection activities were summarized in a 2013 CSP/SMAST Technical Memorandum[11] and were presented and discussed at a CWPC meeting.

In 2009, the Town began the working on a town-wide Integrated Water Resource Management Plan (IWRMP), which is coordinated through the CWPC. The IWRMP is designed to comprehensively review the current status of all of Brewster's water resources (*e.g.*, ponds, estuaries, drinking water), review options for restoration and management, and develop an integrated plan that will comprehensively sustain acceptable water quality in all these resources. The Phase I comprehensive status review was completed in 2011[12] and a Phase II report on some management options for drinking water, wastewater, stormwater, and emergency preparedness was completed in 2013.[13] The Mill Ponds Management Plan is part of Phase III of the IWRMP, which is being completed by Horsley Witten Group.

The Mill Ponds Management Plan relies on available water quality data collected by Brewster volunteers and staff since 2001 and targeted data collected in 2011 and 2012 by CSP/SMAST for the purposes of creating a pond management plan. These datasets are combined with other information, such as land use data, to develop an empirical model of Upper Mill Pond, Lower Mill Pond, and Walkers Pond. This model and the collected data are then used to review water quality management options. This report details the development of the model and review of selected options.

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[11] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013. From Ed Eichner and Brian Howes, CSP/SMAST. To Lem Skidmore, Brewster CWPC Chair and Sue Leven, Brewster Town Planner.

[12] CDM, 2011. Town of Brewster, Massachusetts Integrated Water Resource Management Plan, Phase 1 - Needs Assessment Final Report. CDM-Smith, Cambridge, MA.

[13] Horsley Witten Group, 2013. Town of Brewster, Massachusetts Integrated Water Resource Management Plan, Phase II - Needs Assessment Final Report. Horsley Witten Group, Sandwich, MA.

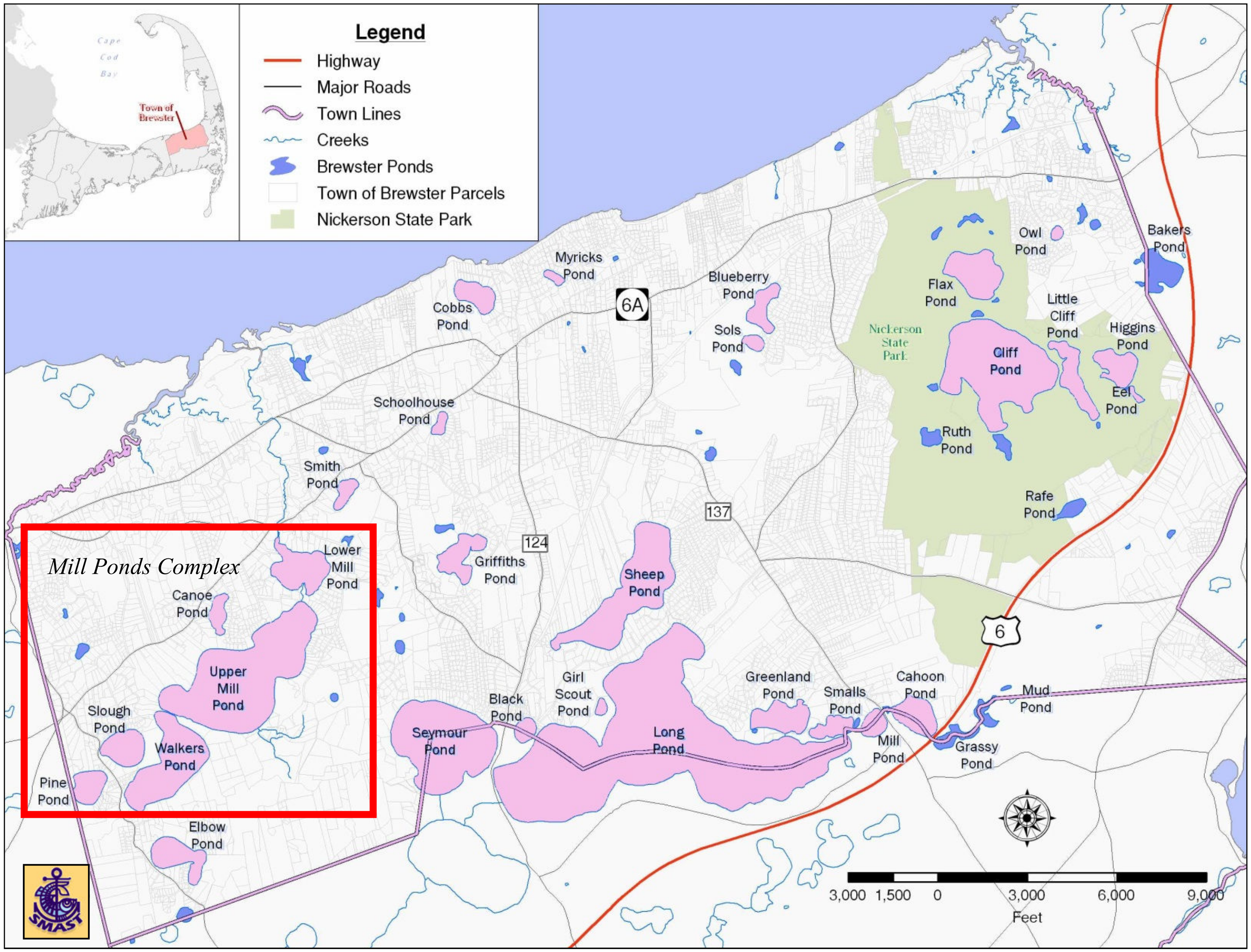

Figure I-1. Brewster Ponds and Mill Ponds Complex.

The Town of Brewster volunteers have sampled 29 freshwater ponds (shown in pink). This Management Plan focusses on the largest ponds in the Mill Ponds Complex (in the red box). The Town of Brewster has a total of 76 freshwater ponds (Eichner and others, 2003). Figure is modified from Figure I-1 in Eichner (2009).

II. Regulatory and Ecological Standards

The surface areas of Walkers Pond, Upper Mill Pond and Lower Mill Pond are 103 acres, 257 acres, and 50 acres, respectively. Since the areas of all three of the ponds are greater than 10 acres, they are classified as Great Ponds, which are publicly owned, "waters of the Commonwealth" under Massachusetts law.[14] Massachusetts maintains regulatory standards for all of its surface waters.[15] These regulations include descriptive standards for various classes of waters based largely on how waters are used plus an accompanying set of numeric standards for each class for dissolved oxygen, pH, temperature, and bacteria. For example, Class A waters are used for drinking water and "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."[16] Further distinctions are made between warm and cold water fisheries.

Under these state regulations, Walkers Pond, Upper Mill Pond, and Lower Mill Pond would be classified as Class B waters. Review of the temperature profile data would classify all of the ponds as warm water fisheries. As such, the following numeric standards would apply: a) dissolved oxygen shall not be less than 5.0 mg/L, b) temperature shall not exceed 83°F (28.3°C), c) pH shall be in the range of 6.5 to 8.3, and d) bacteria shall not exceed 235 colonies per 100 ml at bathing beaches (with variations available for multiple samples). The descriptive standards for Class B waters are "designated as a habitat for fish, other aquatic life, and wildlife, including for their reproduction, migration, growth and other critical functions, and for primary and secondary contact recreation. Where designated in 314 CMR 4.06, they shall be suitable as a source of public water supply with appropriate treatment ("Treated Water Supply"). Class B waters shall be suitable for irrigation and other agricultural uses and for compatible industrial cooling and process uses. These waters shall have consistently good aesthetic value."[17]

Under the federal Clean Water Act, surface waters failing to attain state surface water standards are considered impaired. Impaired waters are required under the Clean Water Act to have a maximum concentration or load limit defined for the contaminant causing the impairment.[18] This limit is labeled as a Total Maximum Daily Load or TMDL. States are required to list all waters that are impaired as part of an Integrated List of Waters, which must be submitted and approved by the Environmental Protection Agency (EPA) ever two years. This list includes a listing of all waters in the state and their status, including whether their water quality has been assessed and whether it has been judged impaired. The latest list from Massachusetts was the 2012 list.[19] On this list, Walkers Pond and Lower Mill Pond are Category 5 (Impaired) waters, while Upper Mill Pond is a Category 2 water (Attaining some uses; other uses not assessed). According to the list, Lower Mill Pond is impaired based on the following causes: a) Chlorophyll-a, b) Excess Algal Growth, c) Phosphorus (Total), d) Secchi disk transparency, and e) Turbidity. Walkers Pond is impaired for the same causes except chlorophyll-*a* is not included. Based on these listings, Walkers Pond and Lower Mill Pond are

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[14] Massachusetts General Law, Ch. 131, sec. 1 specifies all ponds greater than 10 acres are "Great Ponds" and all Great Ponds are "waters of the Commonwealth" and, as such, are publicly owned.

[15] 314 CMR 4.00 (CMR = Code of Massachusetts Regulations)

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

[17] 314 CMR 4.05(3)(b)

[18] 40 CFR 130.7 (CFR = Code of Federal Regulations)

[19] Massachusetts Department of Environmental Protection. March, 2013. Massachusetts Year 2012 Integrated List of Waters, Final Listing of the Condition of Massachusetts' Waters Pursuant to Sections 305(b), 314 and 303(d) of the Clean Water Act. MassDEP, Division of Watershed Management, Watershed Planning Program. Worcester, MA.

required to have TMDLs developed. TMDLs are developed through a public process involving a draft proposed TMDL, a public hearing, and a final TMDL that is submitted by MassDEP to EPA for approval.

Upper Mill Pond was listed as a Category 5 water in the 2010 list, but had the following listing factors removed based on "new assessment" and was reclassified in 2012 as a Category 2 water: "Phosphorus (Total)", "Oxygen, Dissolved", "Excess Algal Growth" and "Turbidity." According to the 2012 list, Upper Mill Pond is attaining the following uses: "Aesthetic", "Fish, other Aquatic Life and Wildlife," and "Secondary Contact Recreation." It has not been assessed for "Primary Contact Recreation" or "Shellfish Harvesting." It is not clear what the "new assessment" was, but the use attainments match a listing for Upper Mill Pond in the MassDEP's most recent Water Quality Assessment Report.[20] The attainments in this report appear to rely on a single DO profile collected in August 2004 and three water quality sampling runs during the 2004 summer. The discussion of Upper Mill Pond in the MassDEP report does not mention the data in the Brewster Ponds Report, the Cape Cod Ponds Atlas, or the ten years of PALS data that would have been available at the time.

In recent years, most of MassDEP TMDL development efforts have been focused on either estuaries (through the MEP assessments) or on large-scale targeting of contaminants, such as pathogens for regions or whole watersheds.[21] Since 2003, only one nutrient TMDL has been developed in Massachusetts for a pond or lake: White Island Pond in Plymouth/Wareham.[22] This approved TMDL established 19 µg/L total phosphorus concentration as the target restoration goal for the pond. White Island Pond has a very complex shoreline with depths of 3.4 m and 3.5 m in its two basins.[23] In this pond, comparison of sediment core incubation, flow from cranberry bogs, and watercolumn data indicated that internal cycling was the dominant source of phosphorus to the watercolumn.

No pond or lake nutrient TMDLs have been developed on Cape Cod, but the Cape Cod Commission used the regional 2001 PALS Snapshot data from over 190 ponds and lakes to develop potential Cape Cod-specific nutrient thresholds.[24] This review used an EPA method that relies on a statistical review of the available data.[25] This review suggested a target TP concentration range for Cape Cod ponds between 7.5 and 10 µg/L. 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 Ecoregion reference criteria available at the time for the region that includes Cape Cod.[26] These thresholds

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[20] MassDEP. 2011. Cape Cod Coastal Drainage Areas 2004-2008 Surface Water Quality Assessment Report. Report Number: 96-AC-2. DWM Control Number: CN 171.0. Worcester, MA.

[21] *e.g.*, MassDEP. 2009. Pathogen Total Maximum Daily Load for Cape Cod Watershed (CN 252.0)

[22] MassDEP. 2010. Final Total Maximum Daily Load for Phosphorus for White Island Pond, Plymouth/Wareham, MA. (CN 330.2)

[23] Eichner, E., B. Howes, and C. DeMoranville. 2012. White Island Pond Water Quality and Management Options Assessment. Completed for the Cape Cod Cranberry Growers Association. Coastal Systems Program, School of Marine Science and Technology, University of Massachusetts Dartmouth. 108 pp.

[24] 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.

[25] 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.

[26] 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-

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.

III. Water Quality Review: Walkers Pond, Upper Mill Pond, and Lower Mill Pond

As mentioned in Section I, basic water quality sampling in Brewster ponds has been completed numerous times over the past decade or so. Walkers Pond, Upper Mill Pond and Lower Mill Pond have generally been sampled approximately 40 times since 2001, although many of the sampling runs have been primarily focused on dissolved oxygen/temperature profiles and water clarity readings (Table III-1). Sampling in 2001 was completed through the Cape Cod Pond and Lake Stewards (PALS) program water quality snapshot and Brewster volunteers and town staff have consistently utilized the PALS Snapshot sampling protocol for most sampling runs. This consistency generally allows comparison of data collected at similar depths and at similar times of year. Water quality data has been collected from 29 Brewster ponds, including Walkers Pond, Upper Mill Pond, and Lower Mill Pond.[27] This section reviews this data and the continuous monitoring conducted during the 2012 targeted data collection.[28]

The PALS pond water sampling protocol calls for a shallow (0.5 m) sample and then generally a deep sample 1 m off the bottom for all ponds of 9 m total depth or less; ponds less than 1.5 m should have two samples from the surface collected. Ponds that are deeper than 5 m will have a third sample collected at 3 m (*i.e.*, 0.5 m, 3 m, and one meter off the bottom) and ponds greater than 10 m will have a fourth sample collected at 9 m (*i.e.*, 0.5 m, 3 m, 9 m, and one meter off the bottom). Samples are collected as whole water, stored at 4°C, and transferred to the SMAST Analytical Facility within 24 hours. The PALS Snapshot field sampling procedures include water column profile measurements (every meter) of dissolved oxygen and temperature, water clarity (Secchi disk), and a measure of station depth. PALS Snapshots have been supported by free laboratory analyses from the SMAST Coastal Systems Analytical Facility Laboratory for 13 years and are coordinated in conjunction with the Cape Cod Commission.

The SMAST lab analysis and sample handling procedures are described in the SMAST Coastal Systems Analytical Facility Laboratory Quality Assurance Plan (2003), which is approved by the Massachusetts Department of Environmental Protection (MassDEP). These procedures, which are used for all PALS Snapshot samples and Brewster pond samples analyzed at the SMAST Analytical Facility, include analysis of the following parameters: total nitrogen, total phosphorus, chlorophyll-a, pheophytin-a, pH, and alkalinity. Detection limits for SMAST laboratory analytes and field data collection are listed in Table III-2. In 2002 and 2003, samples were collected in a number of ponds throughout the summer and these samples were analyzed at the North Atlantic Coastal Laboratory at Cape Cod National Seashore (CCNS); CCNS lab procedures are listed in Table III-3. Samples collected by CSP/SMAST staff in the hydroconnections between the ponds during 2011 and 2012 and the multiple sampling runs in 2011 associated with the sediment core collections were analyzed at the SMAST Coastal Systems Analytical Facility. The 2011 CSP/SMAST sampling runs also followed the PALS Snapshot protocols.

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

[27] Eichner, E. 2009. Brewster Freshwater Ponds

[28] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013.

Table III-1. Water Quality Data collection in Mill Ponds (2001-2013)

A. Walkers Pond												
Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2001									1			
2002						2	2	3	2			
2003					2	3	1	2	2	1		
2004				1	2	2	2	1				
2005					2	3	2		2			
2006					1	2	2	2	2			
2007					2	2	2	3	2			
2008								1				
2009								1				
2010									1			
2011								3	1			
2012									1			
2013									1			
B. Upper Mill Pond												
2001									1			
2002									2			
2003					1	2	2	2	2	1		
2004					1	1	2	1	1	1		
2005					1	2	1	3	2			
2006						3	2	2	2			
2007					1	1	1					
2008								1				
2009								1				
2010									1			
2011								3	1			
2012									1			
2013									1			
C. Lower Mill Pond												
2001									1			
2002						2	2	2	2			
2003					1	2	1	1	2			
2004					1	1			1			
2005					2	2	1	2	1			
2006						1	1	1	1			
2007									1			
2008								1				
2009								1				
2010									1			
2011								3	2			
2012									1			
2013									1			

Notes: a) Numbers indicate number of sampling runs that month, b) PALS sampling protocols followed at least once every year, c) Not all parameters measured or analyzed during each sampling event

Table III-2. Field and laboratory reporting units and detection limits for water samples analyzed at the SMAST Coastal Systems Analytical Facility Laboratory and field data parameters for PALS Snapshots

Parameter	**Reporting Units**	**Detection Limit**	**Accuracy (+\-)**	**Measurement Range**
PALS Field Measurements				
Temperature	ºC	0.5°C	± 0.3 ºC	-5 to 45
Dissolved Oxygen	mg/l	0.5	± 0.3 mg/l or ± 2% of reading, whichever is greater	0 – 20
Secchi Disk Water Clarity	meters	NA	20 cm	Disappearance
Laboratory Measurements – School of Marine Science and Technology, University of Massachusetts Dartmouth				
Alkalinity	mg/l as $CaCO_3$	0.5	80-120% Std. Value	NA
Chlorophyll-*a*	µg/l	0.05	80-120% Std. Value	0-145
Nitrogen, Total	µM	0.05	80-120% Std. Value	NA
pH	Standard Units	NA	80-120% Std. Value	0 - 14
Phosphorus, Total	µM	0.1	80-120% Std. Value	NA

Note: All laboratory measurement information from SMAST Coastal Systems Analytical Facility Laboratory Quality Assurance Plan (January, 2003)

Table III-3. Laboratory methods and detection limits for pond water samples analyzed by the Cape Cod National Seashore lab.

Parameter	Units	Detection Limit	Method
Ammonium	µg/l	4	Lachat QC FIA+ 8000 Method #10-107-06-1-C (Diamond and Switala, 10/9/00 Revision)
Orthophosphate	µg/l	0.62	Lachat QC FIA+ 8000 Method #31-115-01-1-G (Diamond, 12/30/98 Revision)
Nitrogen, nitrate-N	µg/l	1.68	Lachat QC FIA+ 8000 Method #31-107-04-1-C (Diamond, 6/27/00 Revision)
Phosphorus, Total	µg/l	1	Persulfate digestion Lachat QC FIA+ 8000 Method #10-115-01-1-F (Diamond, 10/14/94 Revision)
Phosphorus, Total Nitrogen Total	µg/l µg/l	0.62 1.68	Simultaneous persulfate digestion Lachat QC FIA+ 8000 Method #31-115-01-1-G Lachat QC FIA+ 8000 Method #31-107-04-1-C
Carbon/Nitrogen, particulate	µg/l		CarloErba CH N S Elemental Analyzer (Beach, R., MERL Manual, 1986)
Pigments, Chlorophyll-a & Pheopigments	µg/l		90% Acetone Extraction (Godfrey, P., *et al.*, 1999)

Note: All laboratory measurement information provided by Krista Lee, CCNS (personal communication, 2002).

III.A. Continuous Time-Series Water Quality Monitoring - July/August 2012

In addition to discrete, snapshot water quality sampling throughout the years, continuous sampling devices were installed in Walkers Pond, Upper Mill Pond, and Lower Mill Pond by CSP/SMAST as part of the targeted data collection during July and August 2012.[29] These devices were placed in the ponds to gain information on rapid temporal changes in key water-column parameters during summer and to address concerns that short-term events were impacting the overall water quality of the ponds and snapshot data was only intermittently capturing these events because of their short duration. The instruments recorded depth, chlorophyll-*a*, temperature, and dissolved oxygen every 15 minutes between July 2 and September 6, 2012; more than 6,300 readings were collected by each sonde during the mooring period. The sondes were moored at 30 cm off the bottom in each pond at depths at the edge of previously measured hypoxia[30]. Average depths at the sonde placements were 1.4 m, 6.3 m, and 2.6 m in Walkers Pond, Upper Mill Pond, and Lower Mill Pond, respectively. Water quality samples were collected on four occasions during measurement period as part of QA checks on sonde readings; dissolved oxygen and chlorophyll readings were generally within 95% of laboratory results.

Upper Mill Pond and Lower Mill Pond dissolved oxygen (DO) concentrations were consistently below the MassDEP 5 mg/L water quality limit for surface waters[31] with 85% and 91% of the Lower Mill Pond and Upper Mill Pond record being below 5 mg/L DO, respectively (Figure III-1). These concentrations are lower than the averages based on the citizen-collected data between 2001 and 2013 and suggest that either conditions have worsened or 2012 was an exceptionally poor water quality year. This finding also underscores the need for time-series measurements in a variable environment.

Walkers Pond, on the other hand, presented a different type of dissolved oxygen concern. Only 2% of Walkers Pond readings were below 5 mg/L DO but readings also showed a large portion (38%) of the readings above atmospheric equilibration (100% saturation). These readings mostly occurred in July. The elevated oxygen levels in Walkers Pond are consistent with a prolonged phytoplankton bloom in July followed by a population crash with transfer of organic matter and nutrients to the sediments in August. Both depressed and elevated DO are indicative of phosphorus overloading and eutrophication.

Temperature readings largely reflect the depths of the ponds. The two shallow ponds (Walkers and Lower Mill) had temperature readings that generally trended together, although Walkers Pond tended to show higher daily ranges in temperature (Figure III-2) likely due to its greater surface to depth ratio. Lower Mill Pond temperatures were also likely somewhat buffered by the entry of lower temperature water from Upper Mill Pond. Upper Mill Pond began July at a lower temperature than the other two ponds, but warmed over the mid-late summer. The temperatures of the three ponds were generally the same in late July, but Upper Mill returned to colder temperatures in early August before coming back to congruence in later August. The temperature consistency in late July suggest that a significant windy period mixed

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[29] *Ibid*.

[30] CSP/SMAST staff reviewed the datasets from the 2009 Brewster Ponds report, as well as collecting field profile data at the time of sonde installation.

[31] Massachusetts Surface Water Quality Standards: 310 CMR 4.05. www.mass.gov/dep/service/regulations/314cmr04.pdf

the water column in Upper Mill down to the depth of the sonde sensor, then returned to a pattern of gradual warming of the deeper waters that again attained consistency in late August. The down-mix warm surface waters containing oxygen can also be seen in the brief rise in bottom water dissolved oxygen (compare Figures III-1 and III-2).

Chlorophyll-*a* concentrations, much like the dissolved oxygen readings, reflect the differences among the ponds. Walkers Pond, the uppermost pond in the complex, showed an extended phytoplankton bloom beginning in mid-July and extending to mid-August (Figure III-3). Concentrations before and after the bloom generally were in the same range (10 to 20 µg/L) as Upper Mill, the adjacent downstream pond. Upper Mill Pond generally remained in this concentration range, although it went through periods where it appears that the retention of nutrients in Walkers Pond, during the bloom period, diminishes its chlorophyll concentrations. Once the bloom in Walkers Pond subsides, Upper Mill Pond went through a two week period of elevated chlorophyll concentrations (20 to 30 µg/L) with a return to more usual concentrations by the end of August. Lower Mill generally had the largest bloom with highest concentrations and multiple very high peaks above 70 µg/L.

Average chlorophyll-*a* concentrations in the ponds are well above recommended Cape Cod limits.[32] Average concentrations during the mooring periods were 23.3 µg/L, 10.9 µg/L, and 26.9 µg/L in Walkers Pond, Upper Mill Pond, and Lower Mill Pond, respectively. These concentrations are very close to the averages developed for 2001-2007 data reviewed in the Brewster Ponds report of 22.0 µg/L, 10.2 µg/L, and 18.1 µg/L in Walkers Pond, Upper Mill Pond, and Lower Mill Pond, respectively.[33] All of these concentrations are an order of magnitude higher than the 1.7 µg/L recommended as a management target concentration for Cape Cod ponds.

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[32] Based on the 2001 PALS sampling of 195 Cape Cod ponds, Eichner and others (2003) recommended a 1.7 µg/L limit for chlorophyll-*a*.

[33] Eichner, E. 2009. Brewster Freshwater Ponds

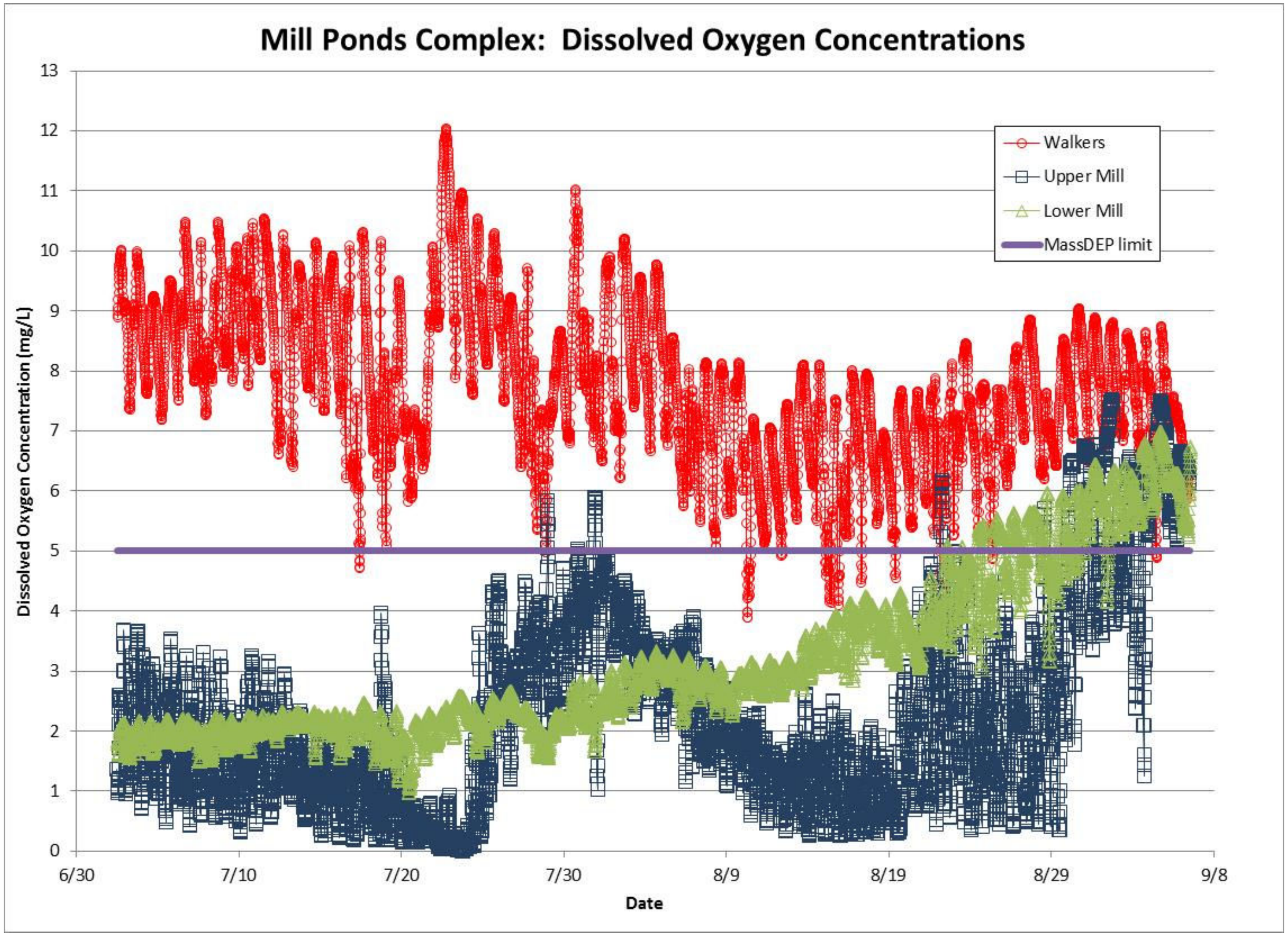

Figure III-1. DO Concentrations in Walkers, Upper Mill, and Lower Mill ponds (July 2 to September 6, 2012). Dissolved Oxygen (DO) concentrations collected by sondes every 15 minutes. Sondes were placed 30 cm off the bottom at average depths of 1.4 m, 6.3 m, and 2.6 m in Walkers, Upper Mill, and Lower Mill, respectively. Concentrations in Lower Mill and Upper Mill were generally below the MassDEP 5 mg/L limit (purple line) during the mooring period, while Walkers were generally above the limit. More than 60% of July concentrations in Walkers were supersaturated (>100%), which is consistent with a large phytoplankton population, while 23% of Upper Mill were anoxic (<1 mg/L DO). Modified from Figure 5 in 2013 CSP/SMAST Technical Memorandum.

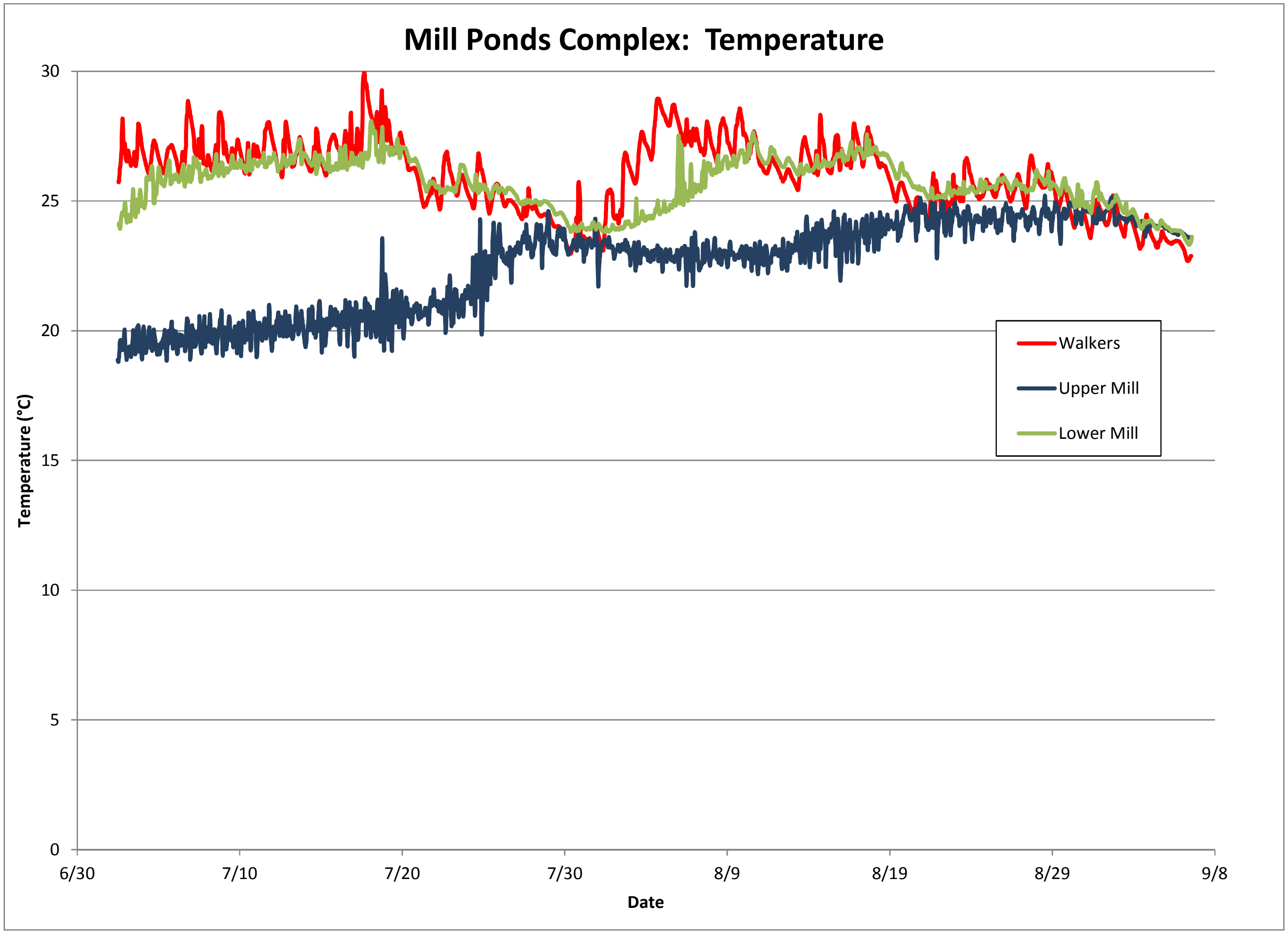

Figure III-2. Temperature in Walkers, Upper Mill, and Lower Mill ponds (July 2 to September 6, 2012). Temperature (ºC) readings were collected by sondes every 15 minutes. Sondes were placed 30 cm off the bottom at average depths of 1.4 m, 6.3 m, and 2.6 m in Walkers, Upper Mill, and Lower Mill, respectively. The two shallow ponds (Walkers and Lower Mill) have temperature readings that generally trend together. Upper Mill temperatures begin July at a lower temperature than the other two ponds, but warm as the mooring period proceeds. Lower Mill temperatures are likely somewhat buffered by the lower temperature water passing into the pond from Upper Mill. Modified from Figure 6 in 2013 CSP/SMAST Technical Memorandum.

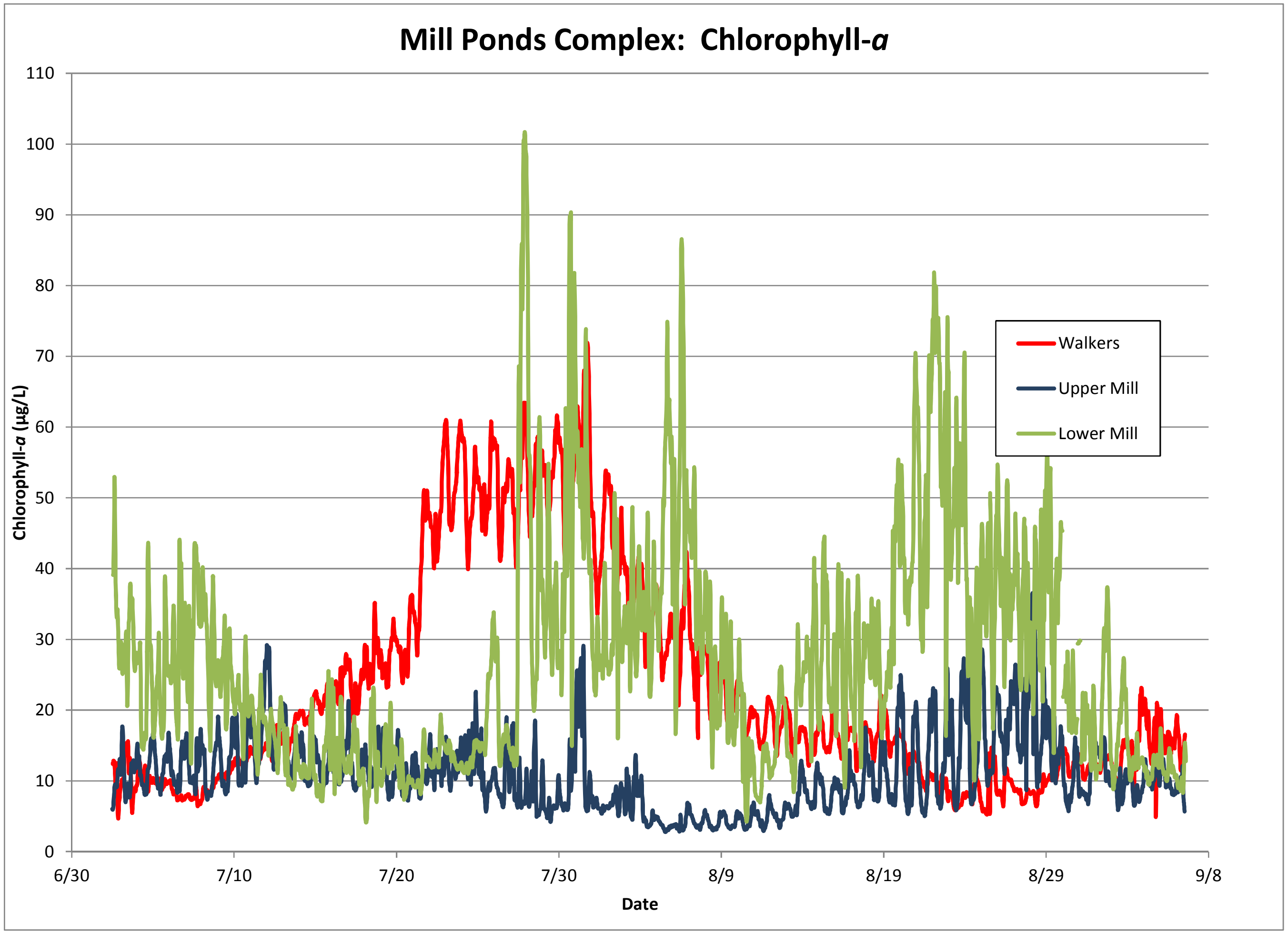

Figure III-3. Chlorophyll-*a* in Walkers, Upper Mill, and Lower Mill ponds (July 2 to September 6, 2012). Chlorophyll-*a* (µg/L) concentrations were collected by sondes recording every 15 minutes. Walkers (red line) shows an extended phytoplankton bloom beginning in mid-July and extending to mid-August. Upper Mill (blue line) shows a decline during this same period, likely due to retention of nutrients in the Walkers phytoplankton. Lower Mill (green line) generally has the highest concentrations with multiple peaks above 70 µg/L. Average chlorophyll-*a* concentrations in the ponds are well above the 1.7 µg/L recommended Cape Cod limit. Average concentrations during the mooring periods were 23.3 µg/L, 10.9 µg/L, and 26.9 µg/L in Walkers, Upper Mill, and Lower Mill, respectively. Modified from Figure 7 in 2013 CSP/SMAST Technical Memorandum.

III.B. Walkers Pond Water Quality Review

Since 2001, water quality data has been collected 57 times from Walkers Pond. The majority of these sampling runs have been for environmental data collection (*e.g.*, temperature and dissolved oxygen profiles); 16 runs have included collection of water samples for laboratory nutrient and chlorophyll *a* analysis. All of the water samples for laboratory analysis have been collected in either August or September, while sampling of environmental data have mostly been between May and September. This data collection was supplemented with the 2012 targeted data collection.[34]

III.B.1. Dissolved Oxygen and Temperature

Dissolved oxygen and temperature profile information show that Walkers Pond is generally vertically well-mixed with temperature and dissolved oxygen concentrations generally the same throughout the water column (Figure III-4). Among the individual sampling runs (and after correcting for outliers), all summer dissolved oxygen concentrations except for one deep readings ($z = 2.5$ m) are above the DEP surface water standard of 5 mg/L.[35] Continuous readings between July 2 to September 6, 2012 generally agreed with the individual snapshot samples, but did show 13 periods where bottom water dissolved oxygen dropped below 5 mg/L (see Figure III-1). Overall, readings <5 mg/L only accounted for 1.5% of the all the continuous readings. The maximum length of time readings were below 5 mg/L continuously was 5.5 hours.

While dissolved oxygen did not regularly drop below regulatory standards in Walkers Pond, readings greater the 100% saturation were a regular occurrence. Readings over 100% dissolved oxygen saturation generally are associated with excessive nutrients because photosynthesis by phytoplankton growing on the nutrients push dissolved oxygen concentrations above the levels that would be expected based on simple mixing of the pond surface with atmospheric oxygen. These elevated readings can help to offset sediment oxygen demand but also indicate nutrient overloading. During July of the continuous readings, 62% of the record exceeded saturation, dropping to 20% in August. Overall, 38% of the continuous readings were above air saturation levels. Individual snapshot samplings generally agree with the continuous readings; summer readings at 0.5 m, 1 m, and 1.5 m depths exceed 100% saturation in at least 35% of the readings (Figure III-5). Review shows that the majority of these >100% saturation events are mixed throughout the water column with >100% at all depths.

Temperature readings exceeded the DEP regulatory limit (28.3ºC) 3% of the time in the continuous readings and none of the readings from the individual samplings exceed this limit once statistical outliers are removed. Temperature readings generally are the same at all depths indicating that the water column is well mixed (Figure III-6).

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[34] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013.

[35] Summer is defined as June through September

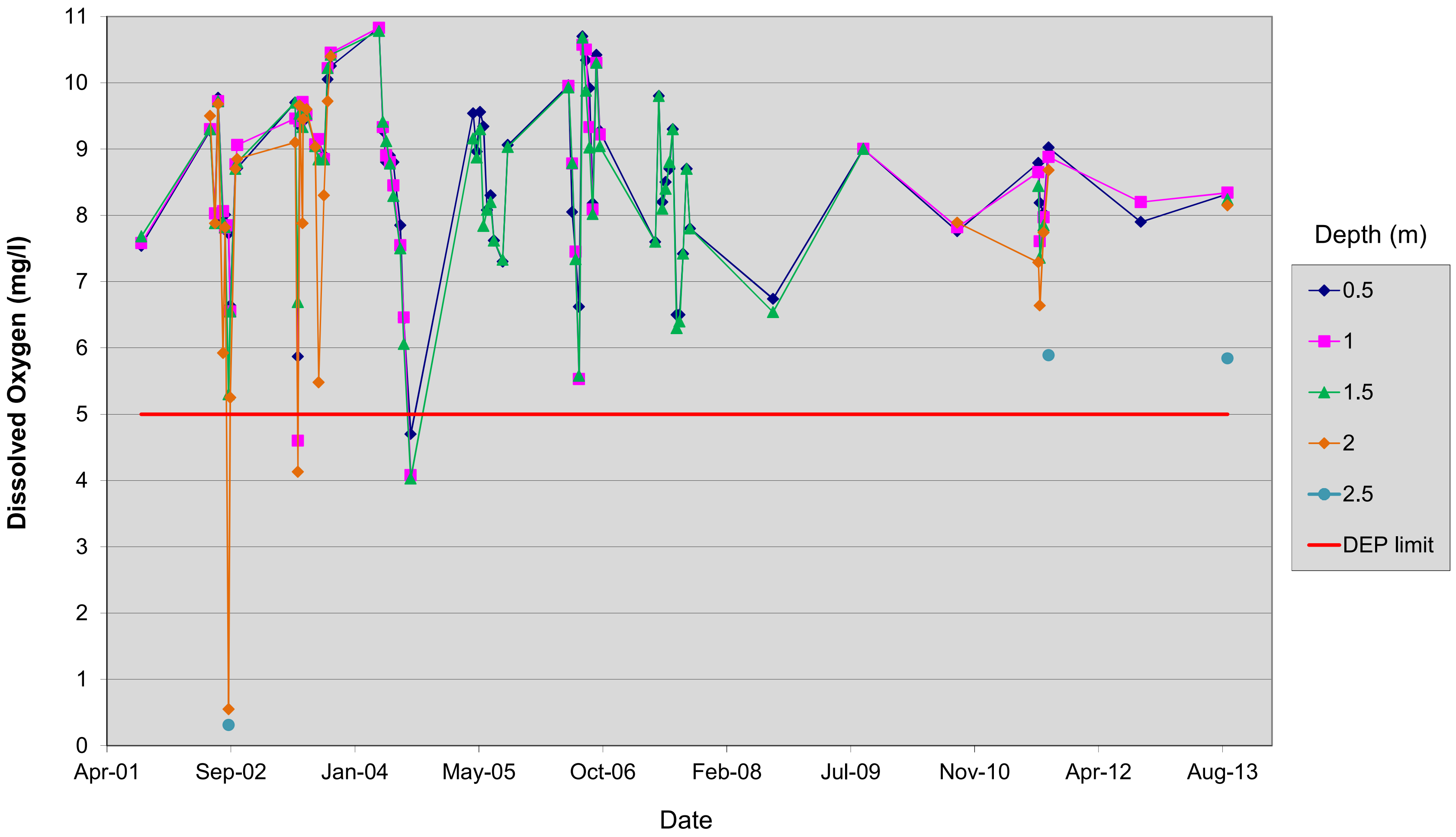

Figure III-4. DO Concentrations in Walkers Pond 2001 - 2013.

Dissolved Oxygen (DO) concentrations collected during individual sampling runs. Almost all readings are above MassDEP 5 mg/L limit regulatory limit (red line). Readings at all depths generally move in tandem indicating a well-mixed water column, but there are occasional periods where deeper samples have lower concentrations. Overall and without correcting for outliers, 3% of the readings are less than 5 mg/L.

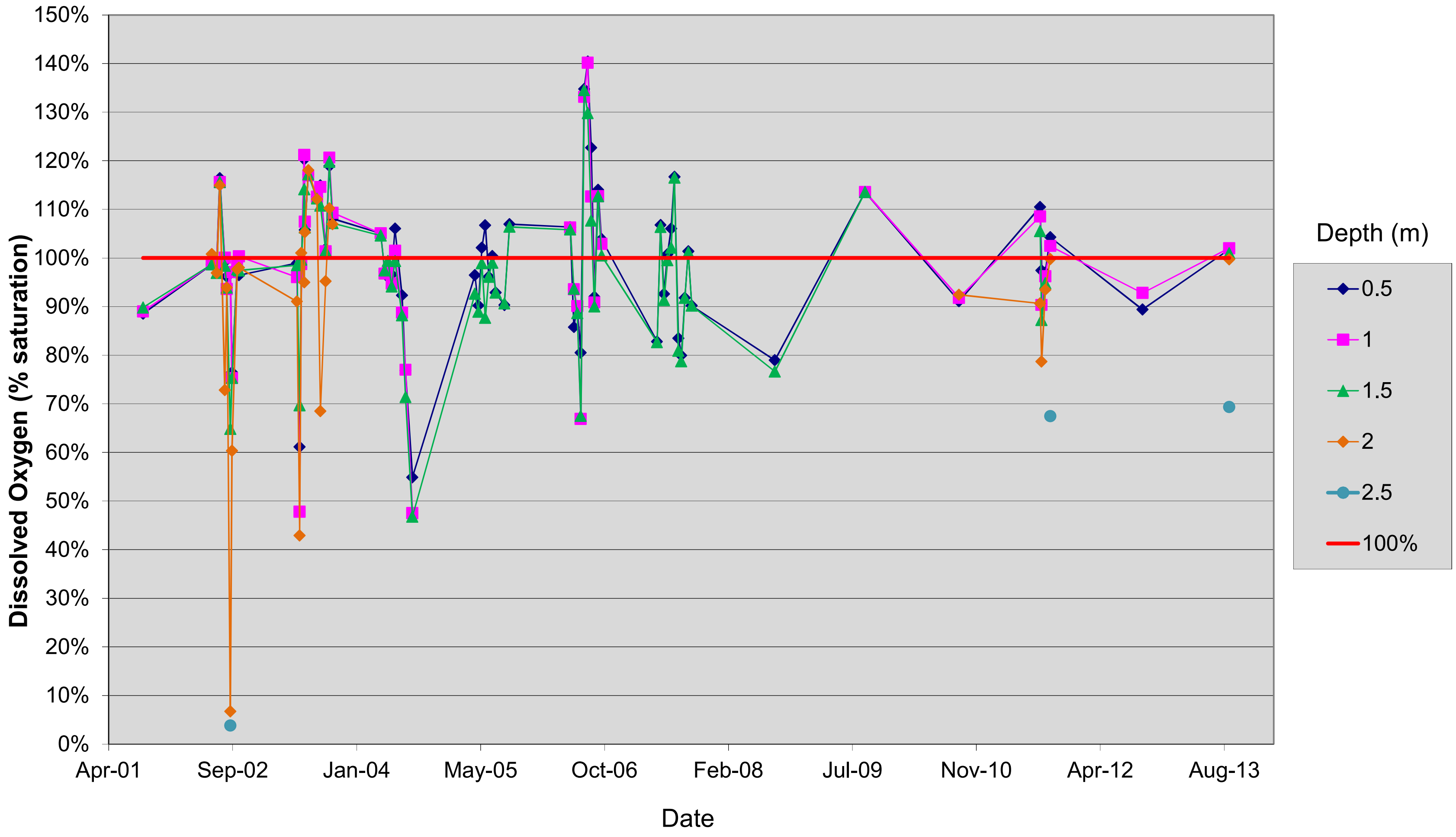

Figure III-5. DO % Saturation in Walkers Pond 2001 - 2013.

Surface (0.5 m) Dissolved Oxygen (DO) % saturation summer average ~100%, but levels >100% occur more than 44% of the time. These occurrences are generally mixed throughout the water column and are most prevalent in August and September.

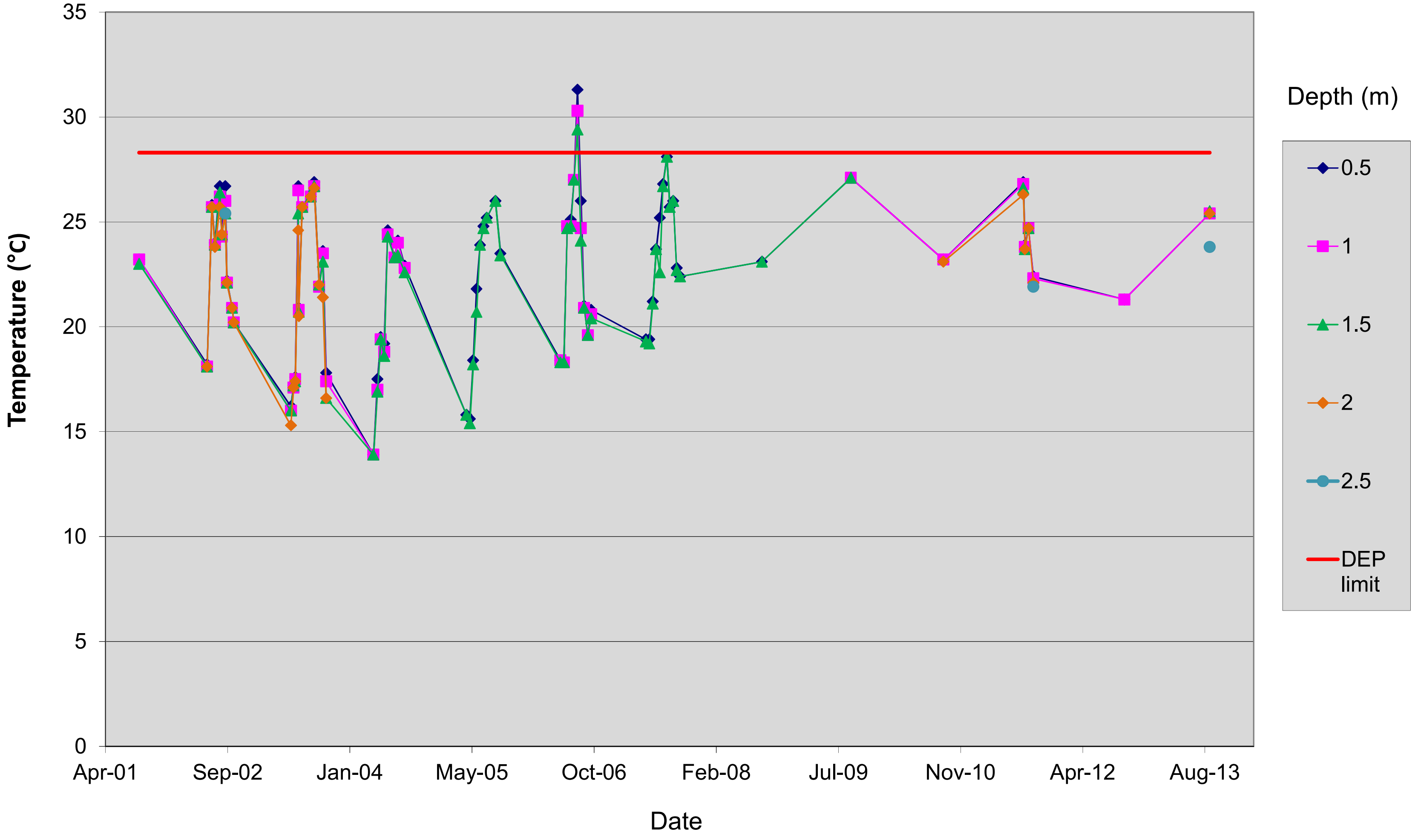

Figure III-6. Temperature in Walkers Pond 2001 - 2013.

Temperatures are generally the same at all depths within Walkers Pond, indicating a well-mixed water column. There is no statistical difference ($\rho<0.05$) between surface and deep temperatures. Temperature fluctuations generally mirror seasonal air temperature changes.

III.B.2. Water Clarity

Water clarity determined by Secchi disk readings averaged 0.73 m for individual summer readings collected between June and September (Figure III-7). Review of monthly readings show that average May readings (n=9) were the highest (1.18 m) with July having the lowest average light penetration depth (0.67 m). The average summer relative clarity reading was 31% of the water column.

Although there is no state regulatory standard for Secchi depth, state regulations do have a clarity limit of 4 feet for safe swimming conditions.[36] All but two of the Secchi readings between June and September in the entire Walkers Pond dataset (3%) are less than the 4 ft limit.

III.B.3. pH and alkalinity

As mentioned in Section II, Massachusetts surface water regulations have numeric standards for pH, which specify that pH should be between 6.5 and 8.3 unless natural conditions cause readings to fall outside of this range. In the Walkers Pond dataset, surface pH readings have only been collected in August and September (n=16) and have an outlier-corrected average of 6.8 with a range of 6.10 to 8.22 (Table III-4). Within this dataset, four of the surface pH readings are less than 6.5 and one is greater than 8.3. Average surface and deep pH readings showed little difference. Similarly, alkalinity averaged 6.64 mg $CaCO_3$/L in surface samples and 6.35 mg $CaCO_3$/L in deep samples.

Surface pH and alkalinity levels in Cape Cod ponds tend to be low unless altered by growth-associated with excessive nutrients. The average surface pH of 193 ponds sampled in the 2001 PALS Snapshot was 6.16 with a range of 4.38 to 8.92, while the average alkalinity was 7.21 mg/L as CaCO3 with a range of 0 to 92.1 mg/L.[37] The lower 25th percentile among pH readings from the 2001 Snapshot, or the least impacted ponds, was 5.62. This lower percentile is consistent with the pH of natural rainwater, which is 5.65. Photosynthesis is one of the primary ways pH increases in surface waters; when aquatic plants photosynthesize they take carbon dioxide and hydrogen ions out of the water causing pH to increase. Thus ponds with higher nutrient levels tend to have higher pH. Alkalinity does not have a numeric standard in the Massachusetts surface water regulations, but is directly related to pH. Alkalinity is a measure of the compounds that shift pH toward more basic, higher values and is mostly determined by the concentrations of bicarbonate, carbonates, and hydroxides.[38] Alkalinity is also a measure of the capacity of waters to buffer acidic inputs. Because pH and alkalinity are influenced by shared constituents, they are linked values.

III.B.4. Chlorophyll and Phaeophytin

Chlorophyll is not directly mentioned in Massachusetts surface water regulations, so it is generally addressed in the descriptive standards (see Section II). Chlorophyll is a family of primary photosynthetic pigments in most plants, including both phytoplankton (or algae) and macrophytes (*i.e.*, any aquatic plants larger than microscopic algae, including rooted aquatic plants). Because of its prevalence, measurement of chlorophyll can be used to estimate the biomass of phytoplankton within pond waters. Chlorophyll-*a* is a specific pigment in the

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[36] 105 CMR 435

[37] Eichner, E.M. and others. 2003.

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

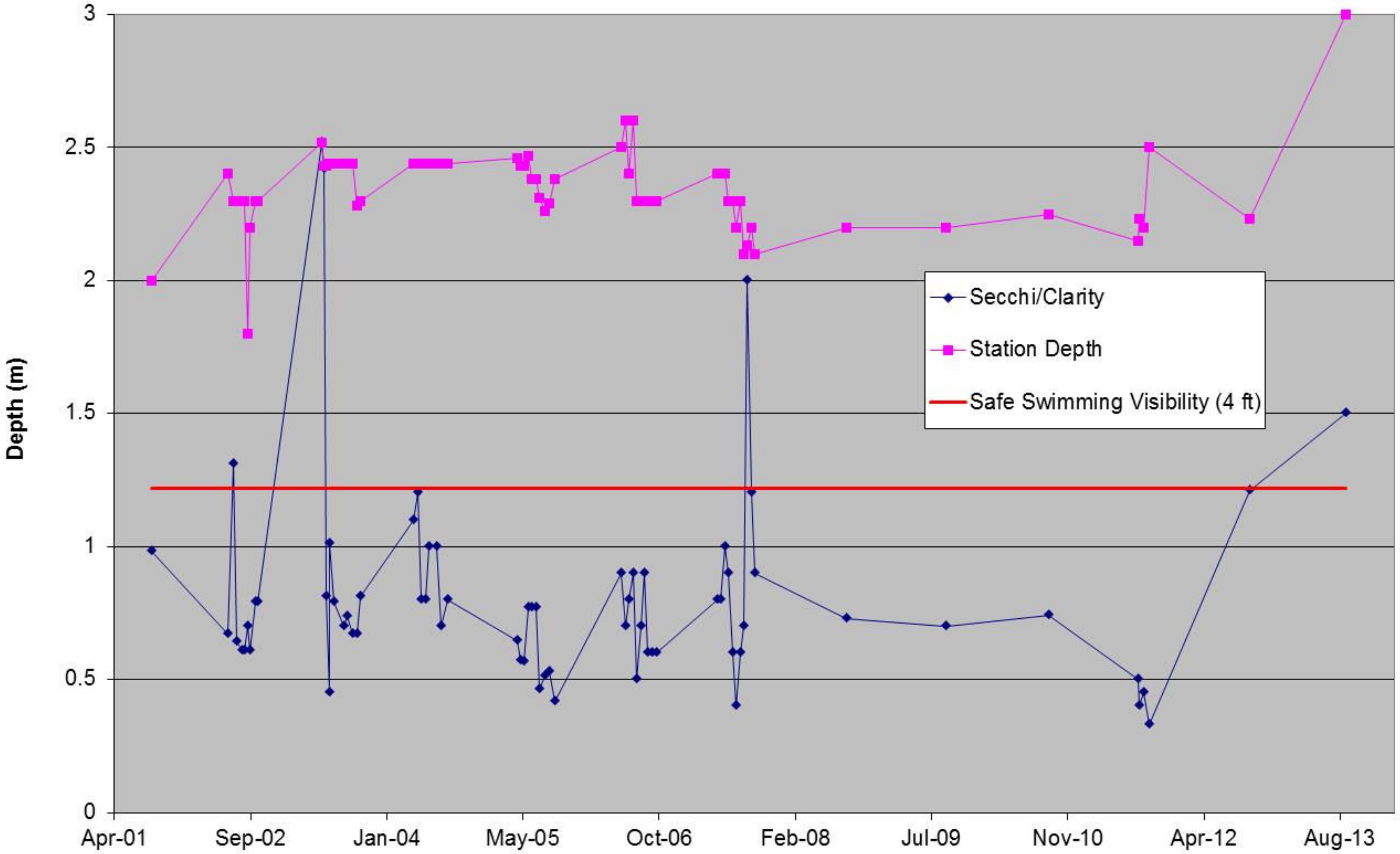

Figure III-7. Clarity in Walkers Pond 2001 - 2013.

Clarity (Secchi) readings in Walkers Pond average 31% of the water column. Lowest readings generally occur in July. State regulations have a clarity limit of 4 feet for safe swimming conditions; all but two of the Secchi readings between June and September in the entire Walkers Pond dataset are less than the 4 ft limit.

Table III-1. Average Concentration of Water Quality Parameters in Mill Ponds

Pond	measure	units	depth	Avg	stdev	Range		n	threshold	
						min	max		min	max
Walkers	pH		Surface	6.80	0.52	6.10	8.22	14	6.5	8.3
			deep	6.68	0.40	6.09	7.42	14		
	Alkalinity (as $CaCO_3$)	mg/L	Surface	6.6	3.5	0.3	11.5	16	none	
			deep	6.4	3.3	0.3	11.1	16		
	Chlorophyll	µg/L	Surface	22.2	14.8	5.5	49.5	15	1.0	1.7
			deep	31.5	19.3	6.8	69.2	15		
	Phaeophytin	µg/L	Surface	4.1	3.0	DL	9.1	15	none	
			deep	6.4	8.9	DL	30.7	15		
	Total Phosphorus	µg/L	Surface	49.4	18.1	15.4	79.3	19	7.5	10
			deep	86.9	95.2	26.5	421.6	18		
	Total Nitrogen	mg/L	Surface	0.89	0.32	0.36	1.61	18	0.16	0.31
			deep	0.98	0.39	0.02	1.76	18		
Upper Mill	pH		Surface	6.58	0.18	6.35	6.93	14	6.5	8.3
			deep	6.36	0.25	5.63	6.70	16		
	Alkalinity (as $CaCO_3$)	mg/L	Surface	4.8	2.3	0.2	8.5	16	none	
			deep	13.6	12.8	0.9	36.7	16		
	Chlorophyll	µg/L	Surface	9.2	4.8	DL	17.9	16	1.0	1.7
			deep	9.6	4.7	1.9	17.1	15		
	Phaeophytin	µg/L	Surface	4.5	6.0	DL	24.7	15	none	
			deep	6.0	4.7	DL	15.9	15		
	Total Phosphorus	µg/L	Surface	22.4	7.6	13.3	37.2	20	7.5	10
			deep	71.8	78.6	11.5	312.7	19		
	Total Nitrogen	mg/L	Surface	0.46	0.13	0.27	0.71	20	0.16	0.31
			deep	0.75	0.39	0.29	1.99	19		
Lower Mill	pH		Surface	6.8	0.4	6.3	7.9	15	6.5	8.3
			deep	6.6	0.2	6.3	7.0	15		
	Alkalinity (as $CaCO_3$)	mg/L	Surface	5.6	1.6	2.5	8.5	14	none	
			deep	6.0	1.4	3.6	8.7	14		
	Chlorophyll	µg/L	Surface	18.4	11.6	0.6	47.4	18	1.0	1.7
			deep	19.9	7.9	2.4	33.7	18		
	Phaeophytin	µg/L	Surface	2.4	3.0	DL	8.5	15	none	
			deep	6.2	7.2	DL	24.1	15		
	Total Phosphorus	µg/L	Surface	31.6	11.3	7.1	55.4	23	7.5	10
			deep	44.9	17.4	20.0	87.6	22		
	Total Nitrogen	mg/L	Surface	0.53	0.18	0.23	0.89	23	0.16	0.31
			deep	0.56	0.18	0.24	0.93	22		

chlorophyll family and plays a primary role in photosynthesis.[39] Pheophytin-*a* is an initial breakdown product of the chlorophyll molecule, which is usually indicative of phytoplankton degradation (e.g. grazing or a senescing bloom).

Anecdotal evidence from Cape Cod ponds with undeveloped land around them suggests that "natural" Cape ponds tend to be phytoplankton-dominated and, therefore, should have a strong relationship between chlorophyll-*a* and total phosphorus concentrations. However, this relationship can be skewed when rooted plants out-compete phytoplankton for phosphorus. For example, Long Pond in Centerville has an extensive rooted macrophyte population[40] that has consumed most of the available phosphorus and kept chlorophyll concentrations relatively low.[41] These types of ponds are largely unrepresentative of the ecology in most Cape Cod ponds.

Because unimpaired Cape Cod ponds tend to have low nutrient concentrations, they also tend to have low chlorophyll-*a* concentrations. The average concentration of surface samples from 191 Cape ponds during 2001 was 8.44 µg/L with a range from 0.01 to 102.9 µg/L.[42] Development of a Cape Cod-specific pond chlorophyll threshold concentration based on the 2001 PALS sampling results determined that unimpacted Cape Cod ponds have a chlorophyll-*a* concentration of 1.0 µg/L and "healthy" Cape Cod ponds would have a concentration of 1.7 µg/L.[43] As a point of comparison, the USEPA ecoregion-specific chlorophyll-*a* reference for the Cape Cod area is 2.9 µg/L.[44]

In the Walkers Pond dataset, chlorophyll-*a* samples have only been collected in August and September (n=16) and have an outlier-corrected average of 22.2 µg/L in surface waters and 31.5 µg/L in deeper waters (average z_{max} = 1.42 m) (see Table III-4). Corresponding pheophytin-*a* concentrations are 4.1 µg/L and 6.4 µg/L . Chlorophyll-*a* averages 84% of the total pigments, indicating an active bloom.

The average Walkers Pond chlorophyll-*a* concentrations significantly exceed available thresholds and are consistent with impaired conditions. Review of the continuous readings between July 2 to September 6, 2012 generally agreed with the individual snapshot samples, all of the readings exceeded 1.7 ppb. The lowest chlorophyll-*a* concentration during the 2012 continuous recording was 5 µg/L and the highest was 72 µg/L; the average July concentration was 29.5 µg/L, while the average August concentration was 18.9 µg/L, greatly exceeding healthy levels.

III.B.5. Nutrients: Nitrogen and Phosphorus

Phosphorus is usually the key nutrient in ponds and lakes because it is usually more limited in freshwater systems than nitrogen, which is also crucial for growth. Typical plant organic matter contains phosphorous, nitrogen, and carbon in a ratio of 1 P: 7 N: 40 C per 500

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[39] USEPA, 2000.

[40] IEP, Inc. and K-V Associates. 1989. Diagnostic/Feasibility Study of Wequaquet Lake, Bearses, and Long Pond. Prepared for Town of Barnstable, Conservation Commission. Sandwich and Falmouth, MA.

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

[42] Eichner and others. 2003.

[43] *Ibid*.

[44] US Environmental Protection Agency. 2001.

wet weight.[45] Therefore, if the other constituents are present in excess, phosphorus, as the limiting nutrient, can theoretically produce 500 times its weight in phytoplankton.

Most Cape Cod lakes have relatively low phosphorus concentrations due to the lack of phosphorus in the surrounding glacially-derived sands, while nitrogen is added to groundwater system via land use sources, such as septic system discharge, fertilizers, and stormwater runoff. These same sources add phosphorus to the groundwater, but nitrogen generally flows with groundwater (~1 ft/d), while phosphorus is significantly slowed (0.01-0.02 ft/d),[46] mostly due to its binding to the iron minerals naturally contained in the aquifer sands. Once nitrogen is in the aquifer system, it is generally fully oxidized to nitrate-nitrogen and largely unattenuated unless it reaches a pond or stream along its flow path. Most of the phosphorus in Cape Cod ponds is generally due to a) additions from the watershed and b) regeneration of past watershed additions from the pond sediments. Since phosphorus movement in the aquifer is so slow, management of P inputs to ponds generally focuses on properties within 250 to 300 ft of the pond[47] shoreline unless there are direct water inputs from streams or stormwater runoff. Shoreline properties generally have impacts on the pond within land use and wastewater planning horizons.

One way to assess the key management nutrient for pond water quality is to review the balance between phosphorus and nitrogen. As a rule of thumb, if the ratio between nitrogen and phosphorus is greater than 16 (also known as the Redfield ratio), phosphorus is the limiting nutrient.[48] It should be noted that this approach to determining nutrient limitation also needs to take into account phototrophs that have the ability to utilize organic phosphorus, not just inorganic phosphorus. For this reason, phosphorus-limited systems generally have N to P ratios that are 2-5 times the Redfield ratio of 16. Review of Walkers Pond N to P ratios show that average ratios are clearly phosphorus limited (surface average = 44; deep average = 35), but there were also individual occasions where the ratios are close to the Redfield ratio especially in deeper waters where phosphorus regeneration from the sediments lowers the ratios toward the Redfield ratio (Figure III-8). This generally occurs when bottom waters go anoxic and chemical release increases the sediment phosphorus release.

Review of the phosphorus and nitrogen concentrations also confirm the impaired conditions observed during the review of the water clarity readings and chlorophyll-*a* concentrations. The median surface concentration of TP in 175 Cape Cod ponds sampled during the 2001 was 16 µg/l, while the median TN concentration was 0.44 mg/L.[49] The Cape Cod pond-specific nutrient threshold ranges developed from the 2001 PALS sampling are 7.5 and 10 µg/l for TP and 0.16 to 0.31 mg/L for TN.[50] In the Walkers Pond dataset, TP and TN samples have generally only been collected in August and September (n=19). Surface water TP concentrations average 49.4 µg/l and deep samples (average z_{max} = 1.43 m) average 86.9 µg/l (see Table III-4). Surface water TN concentrations average 0.89 mg/l and deep samples average 0.98 mg/l. These concentrations significantly exceed their respective Cape Cod-specific threshold ranges and are indicative of impaired water quality conditions.

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[45] Wetzel, R. G. 1983. *Limnology*. Second Edition. CBS College Publishing, New York.

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

[47] *e.g.*, Eichner and others, 2006; Eichner, 2007; Eichner, 2008

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

[49] Eichner and others. 2003.

[50] *Ibid*.

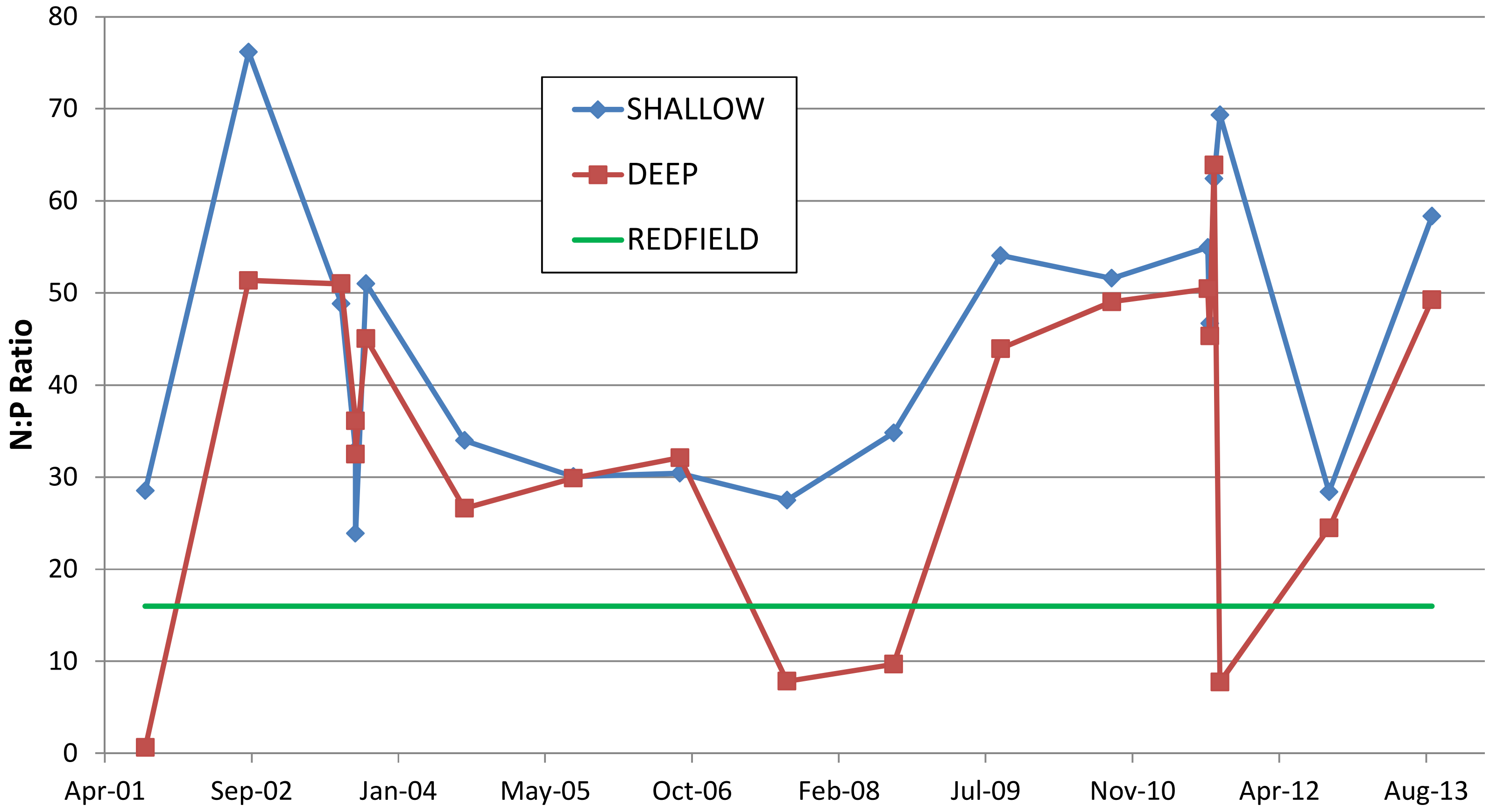

Figure III-8. Changes in Nitrogen to Phosphorus Ratio in Walkers Pond 2001 - 2013.
Ratio between nitrogen and phosphorus generally determines the nutrient controlling growth in surface waters. Waters with a ratio significantly above 16 (Redfield ratio) generally are phosphorus limited and management should target sources of phosphorus, while waters below the Redfield ratio should be managed for nitrogen. Most freshwater ponds have ratios significantly above the Redfield line, but occasionally large additions of phosphorus can alter conditions. On average, Walkers Pond is phosphorus limited with average surface N:P ratio = 44 and a deep average = 35.

III.C. Upper Mill Pond Water Quality Review

Since 2001, water quality data has been collected 44 times from Upper Mill Pond. The majority of these sampling runs have been for collection of environmental data (*e.g.*, temperature and dissolved oxygen profiles); 21 runs have included collection of water samples for nutrients. Most of the water samples for laboratory analysis have been collected in either August or September, while field data sampling runs have mostly been between May and October. This data collection was supplemented with the 2012 targeted data collection.

III.C.1. Dissolved Oxygen and Temperature

Summer temperature profiles show that Upper Mill Pond is generally well-mixed with temperature generally the same down to 7 m (Figure III-9). Individual summer snapshot readings show that mixing through 7 m can occur within days, but that 8 m is usually substantially colder. Analysis of average thermal resistance shows an increase at 7 m and deeper. Average dissolved oxygen (DO) concentrations generally show sustained low oxygen at 7 m and deeper; water column readings at 7 m and 8 m each average below the DEP surface water standard of 5 mg/L (Figure III-10).

Continuous readings between July 2 to September 6, 2012 generally confirm the low DO concentrations at depth, but show these conditions consistently rise into the well-mixed upper layer; 91% of continuous readings, which were collected at ~6.3 m, are below 5 mg/L (see Figure III-1). The continuous readings also detected a significant portion of anoxic readings; 23% or the collected readings were less than 1 mg/L DO. Anoxic events occurred 129 times during the continuous monitoring period with the length of the periods ranging between 15 minutes and 4 days. The average start of these anoxic periods was 3:23 AM. Cooler night temperatures are likely the most quiescent wind periods during the summer and lack of wind during these periods would restrict water column circulation and replenishment of sediment oxygen demand.[51]

While deeper water dissolved oxygen levels regularly declined to anoxia and were frequently below MassDEP regulatory limits, surface waters also regularly rose above 100% saturation. Readings over 100% dissolved oxygen saturation generally are associated with excessive nutrients because photosynthesis by phytoplankton growing on the nutrients push dissolved oxygen concentrations above the levels that would be expected based on simple mixing of the pond surface with atmospheric oxygen. These elevated readings can help to temporarily offset sediment oxygen demand, but low DO can result from the decline and decay of the phytoplankton. Individual sampling readings at 0.5 m, 1 m, and 2 m depths exceeded 100% saturation in at least 40% of the readings with more than half of the 1 m readings above 100% (Figure III-11). These readings are consistent with high nutrient deep waters mixing into the upper, well-mixed waters.

None of the individual snapshot samplings or the continuously recorded readings exceeded the DEP regulatory temperature limit (28.3ºC). The larger volume of Upper Mill Pond compared to Walkers Pond means that it requires more solar energy to raise its temperature, even though its water column is also well mixed. Due to vertical wind driven mixing, temperature readings generally are the same in the top three meters with little thermal mixing resistance down to 6 m. Between 6 and 7 m, thermal resistance increases more than 2X.

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[51] Average maximum wind gusts at the longest term weather station on Cape Cod (i.e., Hyannis Airport) between 1998 and 2014 occurred at 1:06 PM with 25th and 75th percentiles at 9:53 AM and 4:28 PM, respectively.

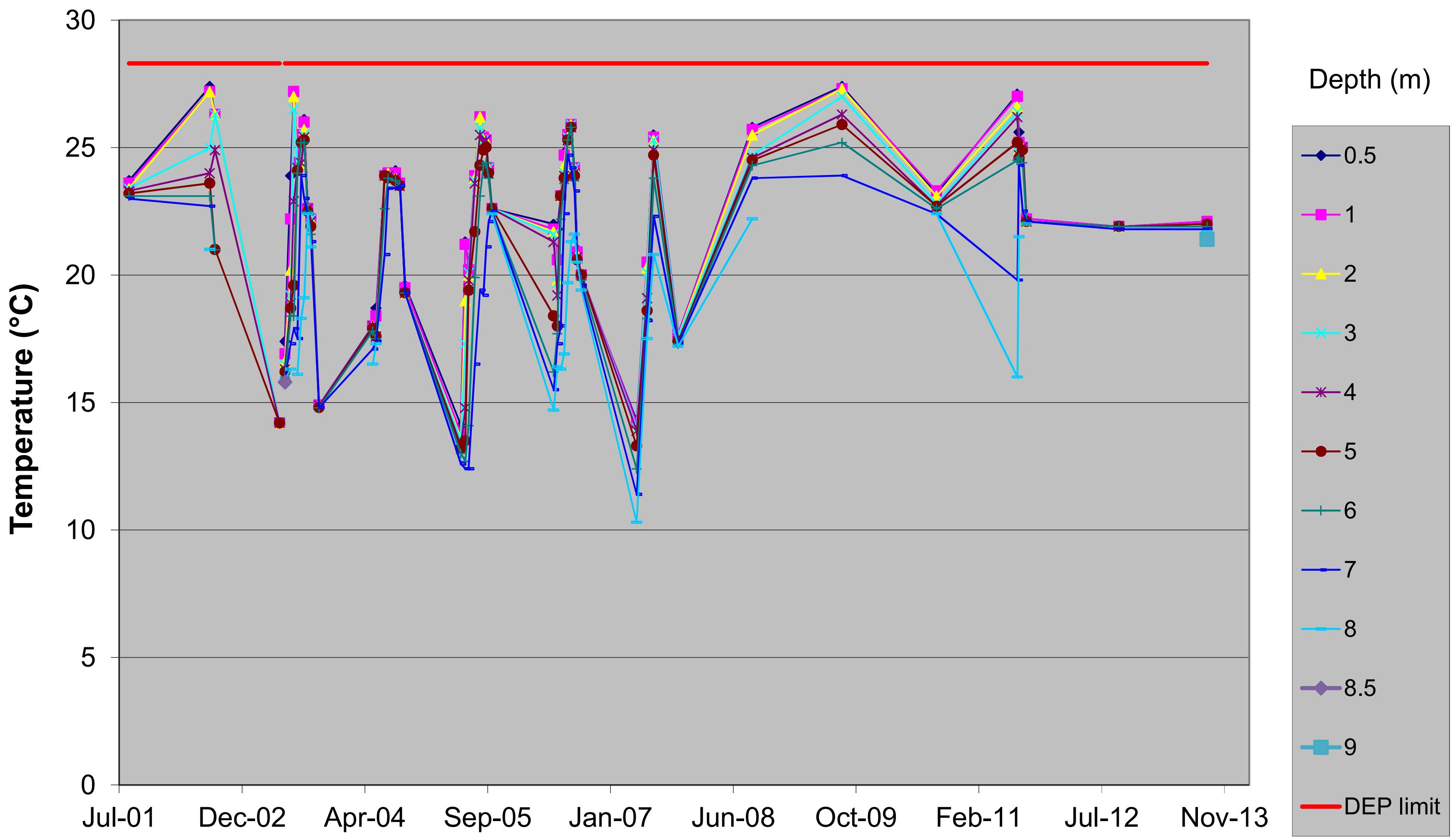

Figure III-9. Temperature Readings in Upper Mill Pond 2001 - 2013.

Temperature readings collected during individual sampling runs (n=44). Review of temperatures show that average summer temperatures generally have little resistance to mixing down to 6 m depth. Waters below this depth require more energy to mix into the upper water column. Review of individual snapshots show 7 m waters often are similar temperature to shallower waters, but 8 m waters usually remain cold enough to resist summer mixing. Colder temperatures matching the seasonal atmospheric temperatures reduce resistance to mixing. All temperature readings are less than the 28.3°C MassDEP regulatory limit.

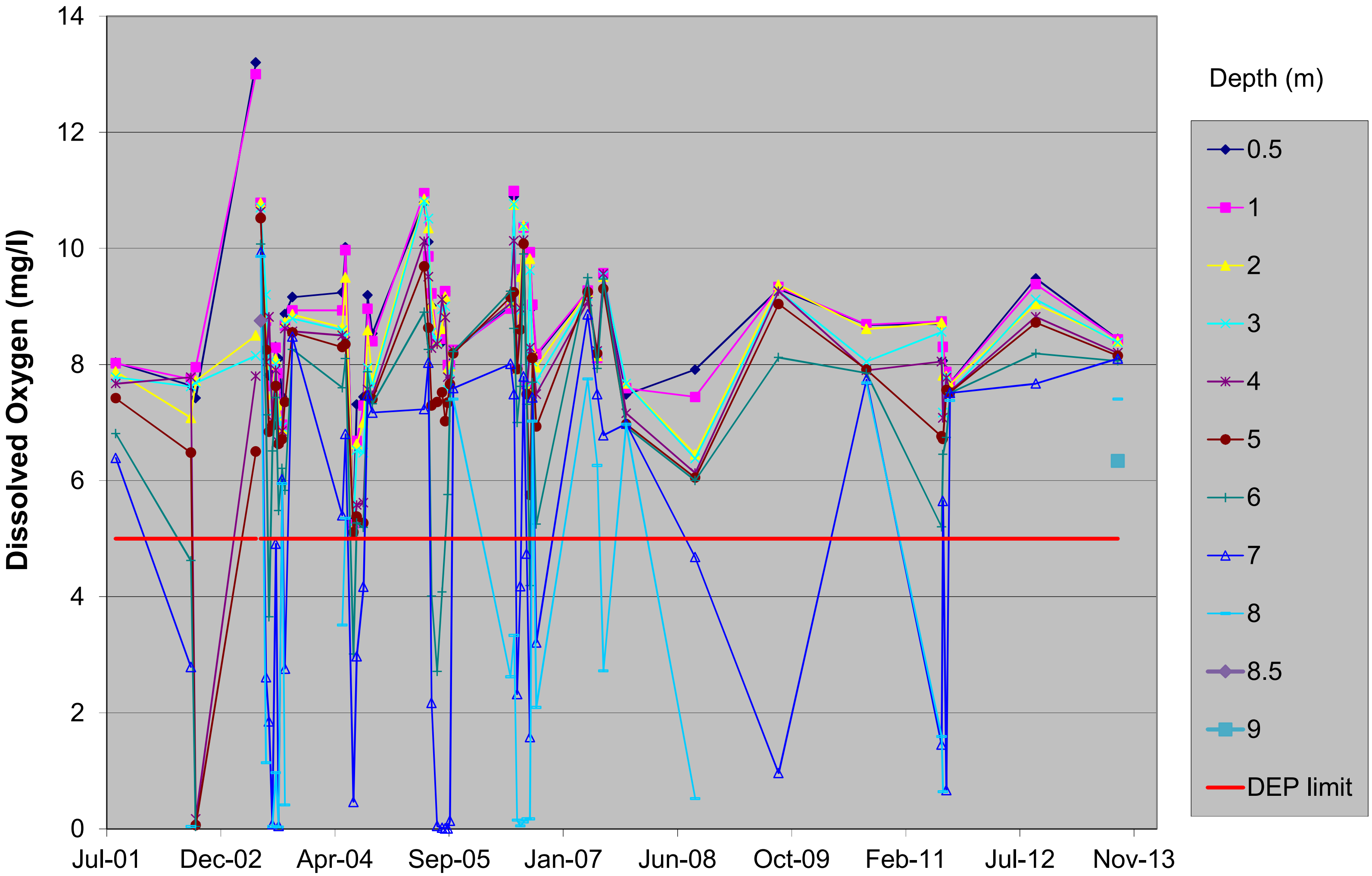

Figure III-10. Dissolved Oxygen Concentrations in Upper Mill Pond 2001 - 2013.
Dissolved Oxygen (DO) concentrations collected during individual sampling runs (n=44). Average readings at surface depths down to 6 m are all above the MassDEP 5 mg/L limit regulatory limit (red line), while average readings at 7 and 8 m depths are less than 5 mg/L. After correcting for data outliers, minimum readings at 6 m and deeper are below the 5 mg/L limit.

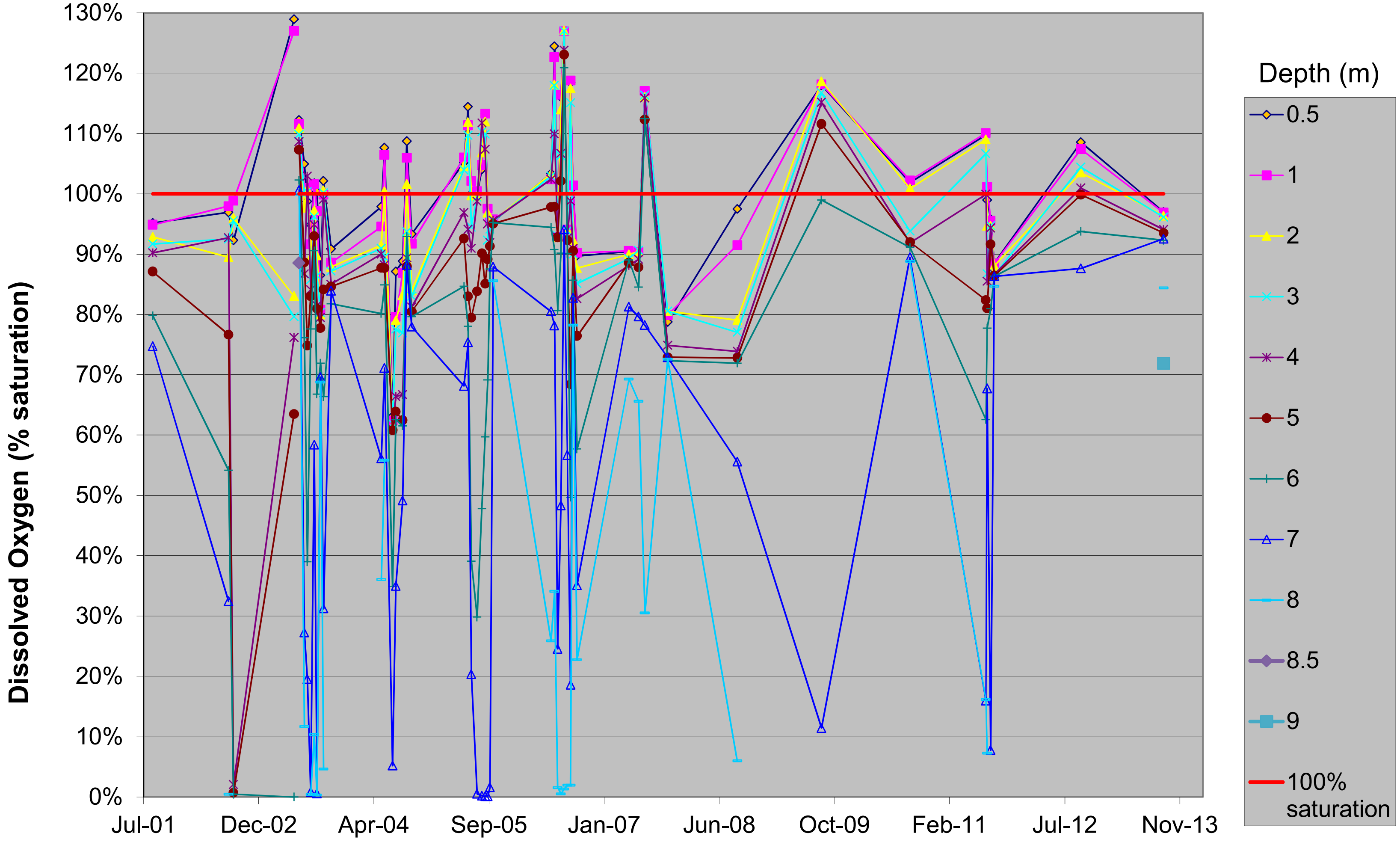

Figure III-11. DO % Saturation in Upper Mill Pond 2001 - 2013.

Surface dissolved oxygen (DO) % saturation summer averages ~100%, but at least 40% of the surface samples are >100%. These occurrences are likely related to rapid introduction of excessive nutrients into the pond (probably from the sediments).

III.C.2. Water Clarity

Water clarity/Secchi disk readings averaged 1.68 m for individual summer readings collected in Upper Mill Pond between June and September (Figure III-12). Review of monthly readings show that average July readings (n=8) were the highest (1.97 m) with September having the lowest average reading (1.40 m). The overall summer average relative clarity reading included only 19% of the water column.

Although there is no state regulatory standard for water clarity (e.g. Secchi depth), state regulations do have a clarity limit of 4 feet for safe swimming conditions. Among the 43 readings collected between June and September 2001 to 2013, five readings in Upper Mill Pond (12%) are less than the 4 ft limit.

III.C.3. pH and alkalinity

As mentioned in Section II, Massachusetts surface water regulations has numeric standards for pH, which specify that pH should be between 6.5 and 8.3 unless natural conditions cause readings to fall outside of this range. In the Upper Mill Pond dataset, surface pH readings have only been collected in August and September (n=16) and have an outlier-corrected average of 6.6 with a range of 6.35 to 6.93 (see Table III-4). Within the whole dataset, six of the surface pH readings are less than 6.5 and none are greater than 8.3. Average surface and deep pH readings showed little difference. Alkalinity, on the other hand, averaged 4.8 mg CaCO3/L in surface samples and 13.6 mg CaCO3/L in deep samples. The increase in deep alkalinity readings is likely due to regular increases in CO_2 from regular anaerobic digestion in the sediments. This would be consistent with the regular anoxia that is discussed in Section III.3.a.

Surface pH and alkalinity levels in Cape Cod ponds tend to be low unless altered by plant growth associated with excessive nutrients. The average surface pH of 193 ponds sampled in the 2001 PALS Snapshot was 6.16 with a range of 4.38 to 8.92, while the average alkalinity was 7.21 mg/L as CaCO3 with a range of 0 to 92.1 mg/L. The lower 25th percentile among pH readings from the 2001 Snapshot, or the least impacted ponds, is 5.62. This lower quartile is consistent with the pH of natural rainwater, which is 5.65. Photosynthesis is one of the primary ways pH increases in surface waters; when aquatic plants photosynthesize they take carbon dioxide and hydrogen ions out of the water causing pH to increase. Thus ponds with higher nutrient levels, which are needed to support higher phytoplankton concentrations, have higher pH. Alkalinity does not have a numeric standard in the Massachusetts surface water regulations, but is directly related to pH. Alkalinity is a measure of the compounds that shift pH toward more basic, higher values and is mostly determined by the concentrations of bicarbonate, carbonates, and hydroxides. Alkalinity is also a measure of the capacity of waters to buffer acidic inputs. Because pH and alkalinity are influenced by shared constituents, they are linked values.

III.C.4. Chlorophyll and Pheophytin

Chlorophyll is not directly mentioned in Massachusetts surface water regulations, so it is generally addressed in the descriptive standards (see Section II). Chlorophyll is a family of primary photosynthetic pigments in most plants, including both phytoplankton (or algae) and macrophytes (i.e., any aquatic plants larger than microscopic algae, including rooted aquatic plants). Because of its prevalence, measurement of chlorophyll can be used to estimate the biomass of phytoplankton within pond waters. Chlorophyll-a is a specific pigment in the chlorophyll family and plays a primary role in

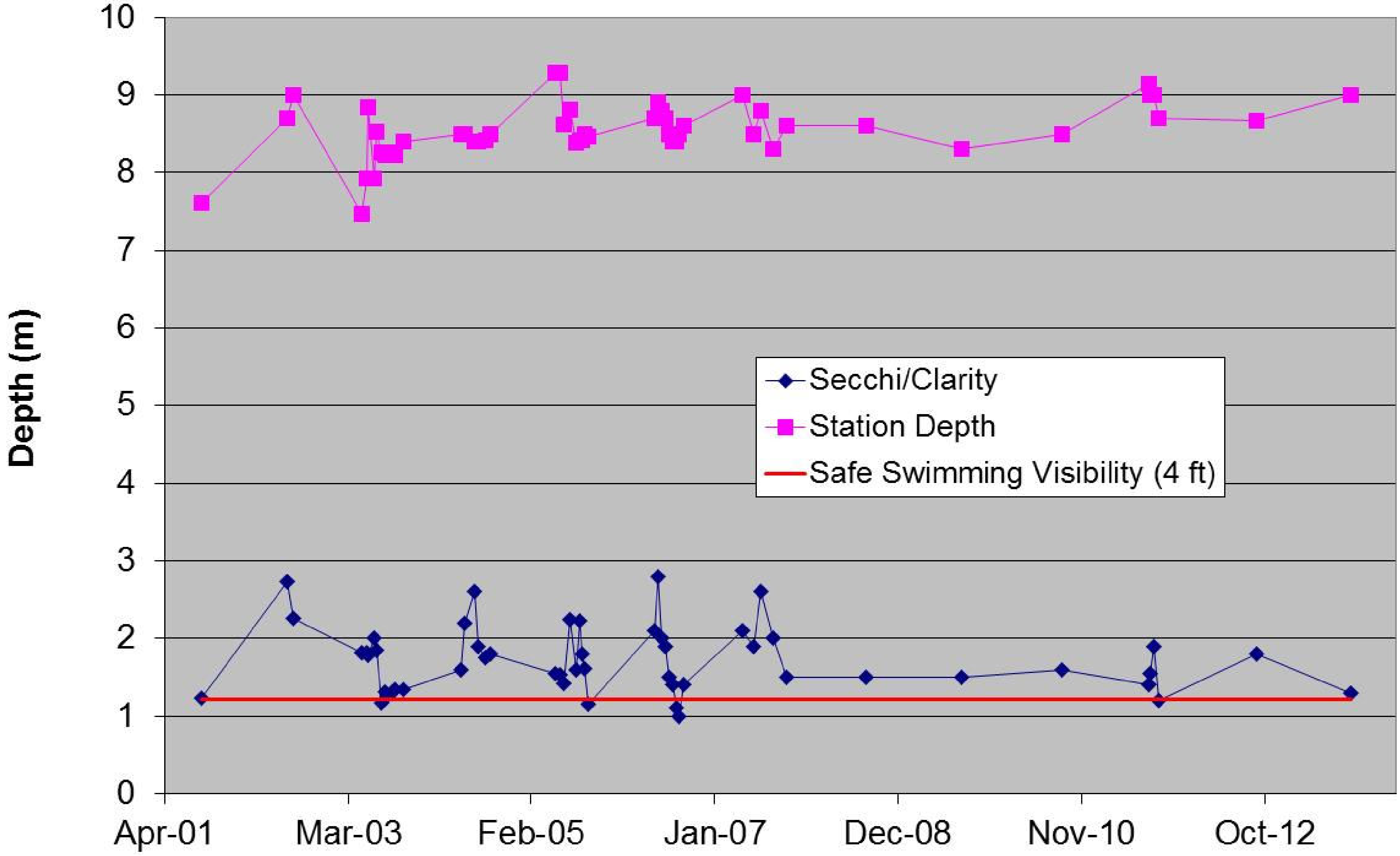

Figure III-12. Clarity in Upper Mill Pond 2001 - 2013.

Clarity (Secchi) readings in Upper Mill Pond average 19% of the water column. Lowest readings generally occur in September. State regulations have a clarity limit of 4 feet for safe swimming conditions; 12% of the Secchi readings between June and September in the entire Upper Mill Pond dataset are less than the 4 ft limit.

photosynthesis.[52] Pheophytin-*a* is an initial breakdown product of the chlorophyll molecule, which is usually indicative of phytoplankton degradation (e.g. grazing or a senescing bloom).

Anecdotal evidence from Cape Cod ponds with undeveloped land around them suggests that "natural" Cape ponds tend to be phytoplankton-dominated and, therefore, should have a strong relationship between chlorophyll-*a* and total phosphorus concentrations. However, this relationship can be skewed when rooted plants out-compete phytoplankton for phosphorus. For example, Long Pond in Centerville has an extensive rooted macrophyte population[53] that has consumed most of the available phosphorus and kept chlorophyll concentrations relatively low.[54] These types of ponds are largely unrepresentative of the ecology in most Cape Cod ponds.

Because Cape Cod ponds tend to have low nutrient concentrations, they also tend to have low chlorophyll-*a* concentrations. The average concentration of surface samples from 191 Cape ponds during 2001 was 8.44 µg/L with a range from 0.01 to 102.9 µg/L.[55] Development of a Cape Cod-specific pond chlorophyll threshold concentration based on the 2001 PALS sampling results determined that unimpacted Cape Cod ponds have a chlorophyll-*a* concentration of 1.0 µg/L and "healthy" Cape Cod ponds would have a concentration of 1.7 µg/L.[56] As a point of comparison, the USEPA ecoregion-specific chlorophyll-*a* reference for the Cape Cod area is 2.9 µg/L.[57]

In the Upper Mill Pond dataset, chlorophyll-*a* samples have only been collected in August and September (n=16) and have an outlier-corrected average of 9.2 µg/L in surface waters and 9.6 µg/L in deeper waters (average z_{max} = 7.5 m) (see Table III-4). Corresponding pheophytin-*a* concentrations are 4.5 µg/L and 6 µg/L. Chlorophyll-*a* averages 72% of the total measured pigments indicating that the majority of the phytoplankton were active at the time of sampling.

The average Upper Mill Pond chlorophyll-*a* concentrations significantly exceed available thresholds and are consistent with impaired conditions. Review of the continuous readings between July 2 to September 6, 2012 generally agreed with the individual snapshot samples: all of the readings at 30 cm off the bottom exceeded 1.7 µg/L. The lowest chlorophyll-*a* concentration during the 2012 continuous recording was 2.8 µg/L and the highest was 36.6 µg/L; the average July concentration was 12.0 µg/L, while the average August concentration was 9.9 µg/L.

III.C.5. Nutrients: Nitrogen and Phosphorus

Phosphorus is usually the key nutrient in ponds and lakes because it is usually more limited in freshwater systems than nitrogen, which is also crucial for growth. Typical plant

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[52] USEPA, 2000.

[53] IEP, Inc. and K-V Associates. 1989. Diagnostic/Feasibility Study of Wequaquet Lake, Bearses, and Long Pond. Prepared for Town of Barnstable, Conservation Commission. Sandwich and Falmouth, MA.

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

[55] Eichner and others. 2003.

[56] *Ibid*.

[57] US Environmental Protection Agency. 2001.

organic matter contains phosphorous, nitrogen, and carbon in a ratio of 1 P: 7 N: 40 C per 500 wet weight.[58] Therefore, if the other constituents are present in excess, phosphorus, as the limiting nutrient, can theoretically produce 500 times its weight in phytoplankton.

Most Cape Cod lakes have relatively low phosphorus concentrations due to the lack of phosphorus in the surrounding glacially-derived sands, while nitrogen is added to groundwater system via land use sources, such as septic system discharge, fertilizers, and stormwater runoff. These same sources add phosphorus to the groundwater, but nitrogen generally flows with groundwater (~1 ft/d), while phosphorus is significantly slowed (0.01-0.02 ft/d),[59] mostly due to its binding to the iron minerals naturally contained in the aquifer sands. Once nitrogen is in the aquifer system, it is generally fully oxidized to nitrate-nitrogen and largely unattenuated unless it reaches a pond or stream along its flow path. Most of the phosphorus in Cape Cod ponds is generally due to a) additions from the watershed and b) regeneration of past watershed additions from the pond sediments. Since phosphorus movement in the aquifer is so slow, management of P inputs to ponds generally focusses on properties within 250 to 300 ft of the pond[60] shoreline unless there are direct water inputs from streams or stormwater runoff. Shoreline properties generally have impacts on the pond within land use and wastewater planning horizons.

One way to assess the key management nutrient for pond water quality is to review the balance between phosphorus and nitrogen. As a rule of thumb, if the ratio between nitrogen and phosphorus is greater than 16 (also known as the Redfield ratio), phosphorus is the limiting nutrient.[61] It should be noted that this approach to determining nutrient limitation also needs to take into account phototrophs that have the ability to utilize organic phosphorus, not just inorganic phosphorus. For this reason, phosphorus-limited systems generally have N to P ratios that are 2-5 times the Redfield ratio of 16. Review of Upper Mill Pond N to P ratios show that average ratios are clearly phosphorus limited (surface average = 45; deep average = 31), but there are also individual occasions where the ratios are below the Redfield ratio especially in deeper waters where more phosphorus than nitrogen is regenerated (Figure III-13).

Review of the phosphorus and nitrogen concentrations also confirm the impaired conditions observed during the review of the clarity readings and the chlorophyll concentrations. The median surface concentration of TP in 175 Cape Cod ponds sampled during the 2001 was 16 µg/l, while the median TN concentration was 0.44 mg/L. The Cape Cod pond-specific nutrient threshold ranges developed from the 2001 PALS sampling are 7.5 and 10 µg/l for TP and 0.16 to 0.31 mg/L for TN. In the Upper Mill Pond dataset, TP and TN samples have generally been collected in August and September (n=20). Surface water TP concentrations average 22.4 µg/l and deep samples (average z_{max} = 7.45 m) average 71.8 µg/l (see Table III-4). Surface water TN concentrations average 0.46 mg/l and deep samples average 0.75 mg/l. These concentrations significantly exceed their respective threshold ranges and are indicative of impaired water quality conditions.

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[58] Wetzel, R. G. 1983. *Limnology*. Second Edition. CBS College Publishing, New York.

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

[60] *e.g.*, Eichner and others, 2006; Eichner, 2007; Eichner, 2008

[61] Redfield, A.C., B.H. Ketchum, and F.A. Richards. 1963.

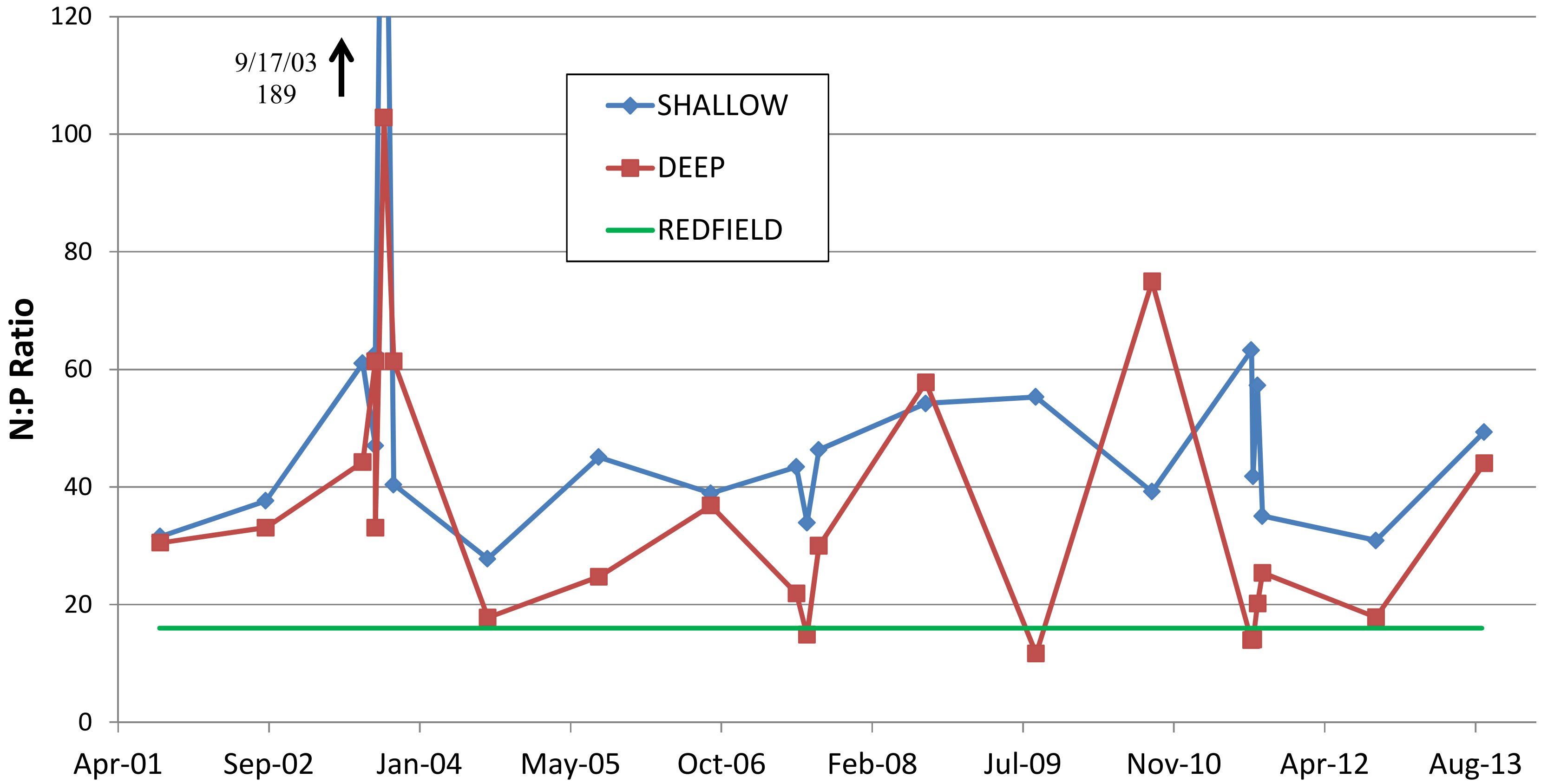

Figure III-13. Changes in Nitrogen to Phosphorus Ratio in Upper Mill Pond 2001 - 2013.

Ratio between nitrogen and phosphorus generally determines the nutrient controlling growth in surface waters. Waters with a ratio above 16 (Redfield ratio) generally are phosphorus limited and management should target sources of phosphorus, while waters below the Redfield ratio should be managed for nitrogen. Most freshwater ponds have ratios significantly above the Redfield line, but occasionally large additions of phosphorus can alter conditions. On average, Upper Mill Pond is phosphorus limited with average surface N:P ratio = 45 and a deep average = 31. Bottom water N/P ratios are reduced due to P release from sediments in this non-photosynthetic zone of the pond.

III.D. Lower Mill Pond Water Quality Review

Since 2001, water quality data has been collected 43 times from Lower Mill Pond. The majority of these sampling runs have been for collection of environmental data (*e.g.*, temperature and dissolved oxygen profiles); 24 runs have included collection of water samples for laboratory analysis. Most of the water samples for laboratory analysis have been collected in either August or September, while field data sampling runs have been between May and September. This data collection was supplemented with the 2012 targeted data collection.

III.D.1. Dissolved Oxygen and Temperature

Collected snapshot temperature profiles show that Lower Mill Pond is generally well-mixed with temperature generally the same throughout the water column (Figure III-14). On average, there is a jump in thermal resistance to mixing between 2.5 m and 3 m, but it is not to levels generally associated with strong resistance. Dissolved oxygen concentrations are similar in that there is a decline with depth with the greatest jump between 3 m and 3.5 m (Figure III-15). The deep (3.5 m) readings occasionally have anoxic conditions (<1 mg/L DO) with the overall average concentration below the DEP surface water standard of 5 mg/L. Continuous readings between July 2 to September 6, 2012 generally show that these low DO concentrations are more prevalent and consistent than in the individual snapshots; 85% of continuous readings, which were collected at ~2.6 m depth, are below 5 mg/L (see Figure III-1). Only two of the continuous readings (0.03%) showed anoxia (<1 mg/L DO).

While dissolved oxygen in deep water regularly dropped below MassDEP regulatory limits, surface waters also regularly rose above 100% saturation. Readings over 100% dissolved oxygen saturation generally are associated with excessive nutrients because photosynthesis by phytoplankton growing on the nutrients push dissolved oxygen concentrations above the levels that would be expected based on simple mixing of the pond surface with atmospheric oxygen. These elevated readings can help to temporarily offset sediment oxygen demand, but low DO can result from the decline and decay of phytoplankton. Individual sampling readings at 0.5 m, 1 m, and 1.5 m exceeded 100% saturation in at least 42% of the individual run profile readings with half of the 0.5 and 1.5 m readings above 100% (Figure III-16).

None of the individual snapshot sampling temperature readings or the continuously recorded readings exceeded the DEP regulatory limit (28.3ºC). Average temperature in Lower Mill during the continuous sampling period (25.7ºC) is approximately the same as in Walkers Pond (26.0°C).

III.D.2. Water Clarity

Water clarity/Secchi disk readings averaged 1.25 m for individual summer readings collected between June and September (Figure III-17). Review of monthly readings show that average July readings (n=5) were the highest (1.48 m) with September being quite low, 1.11 m. The overall summer average relative clarity reading was 34% of the water column.

Although there is no state regulatory standard for Secchi depth, state regulations do have a clarity limit of 4 feet for safe swimming conditions. Among the 37 readings collected between June and September 2001 to 2013, 17 readings in Lower Mill Pond (46%) are less than the 4 ft limit.

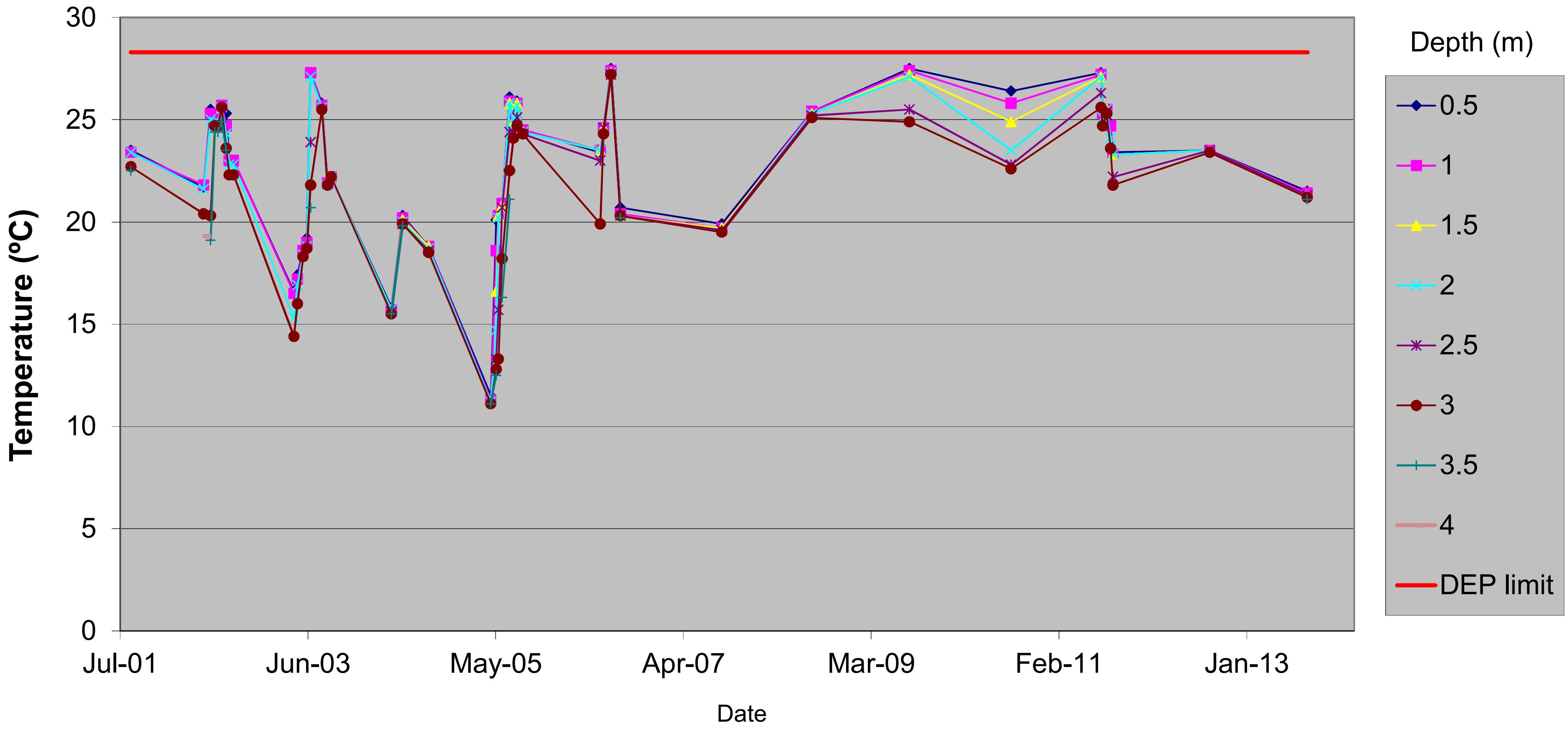

Figure III-14. Temperature Readings in Lower Mill Pond 2001 - 2013.
Temperatures are generally the same at all depths within Lower Mill Pond, indicating a well-mixed water column. There is no statistical difference ($\rho<0.05$) between surface and deep temperatures. Temperature fluctuations generally mirror seasonal air temperature changes. All temperature readings are less than the 28.3°C MassDEP regulatory limit

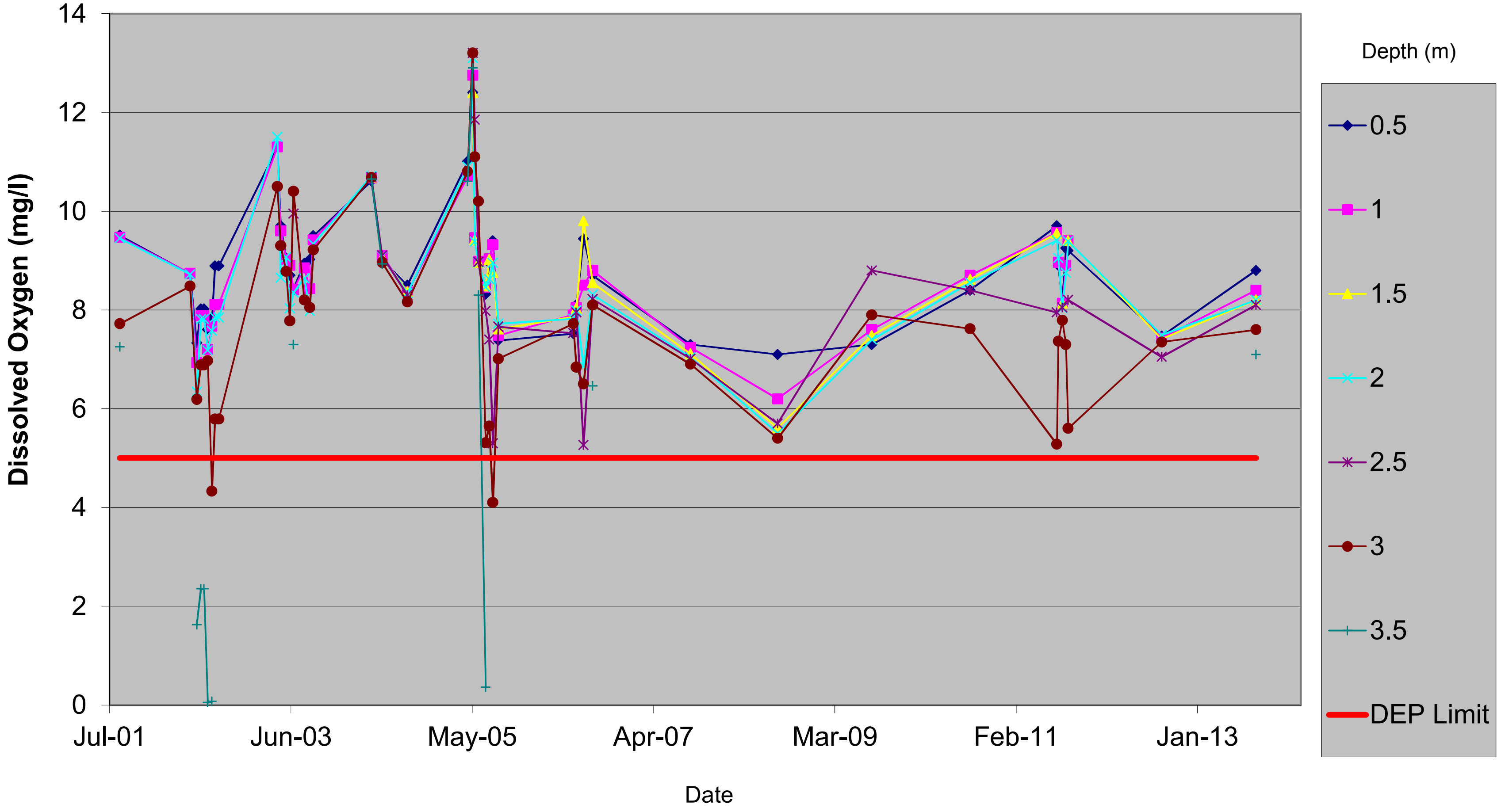

Figure III-15. Dissolved Oxygen Concentrations in Lower Mill Pond 2001 - 2013.

Dissolved Oxygen (DO) concentrations collected during individual sampling runs (n=38). Average readings at surface depths down to 2.5 m are all above the MassDEP 5 mg/L limit regulatory limit (red line), while deeper readings occasionally drop below 5 mg/L. 50% of readings at 3.5 m depths are less than 5 mg/L.

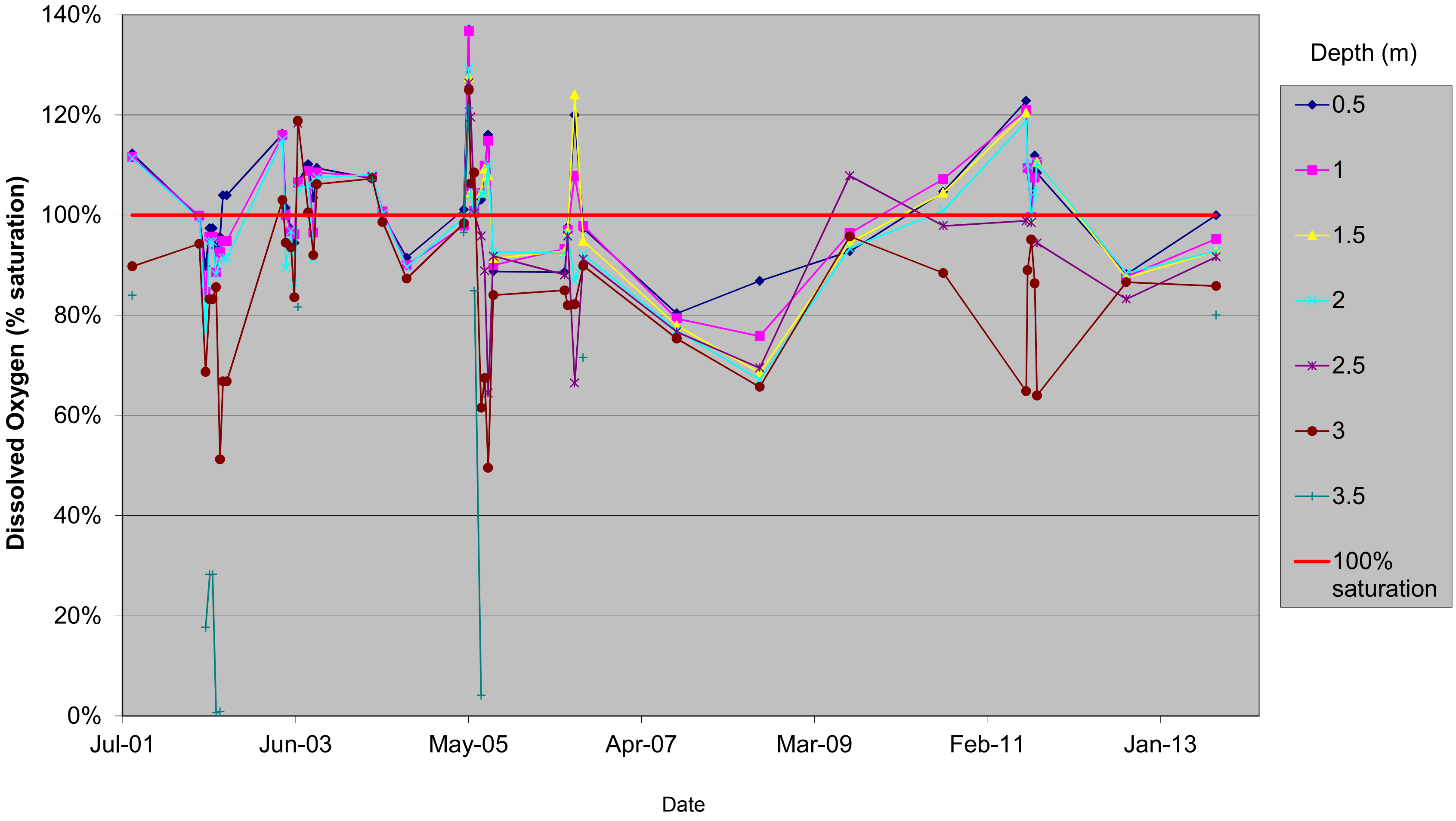

Figure III-16. DO % Saturation in Lower Mill Pond 2001 - 2013.
Dissolved Oxygen (DO) % saturation summer averages ~100%, but at least 50% of the surface samples are >100%. These occurrences are generally mixed throughout the water column and are most prevalent in May. These are occurrences likely occur when excessive nutrients are introduced into the pond.

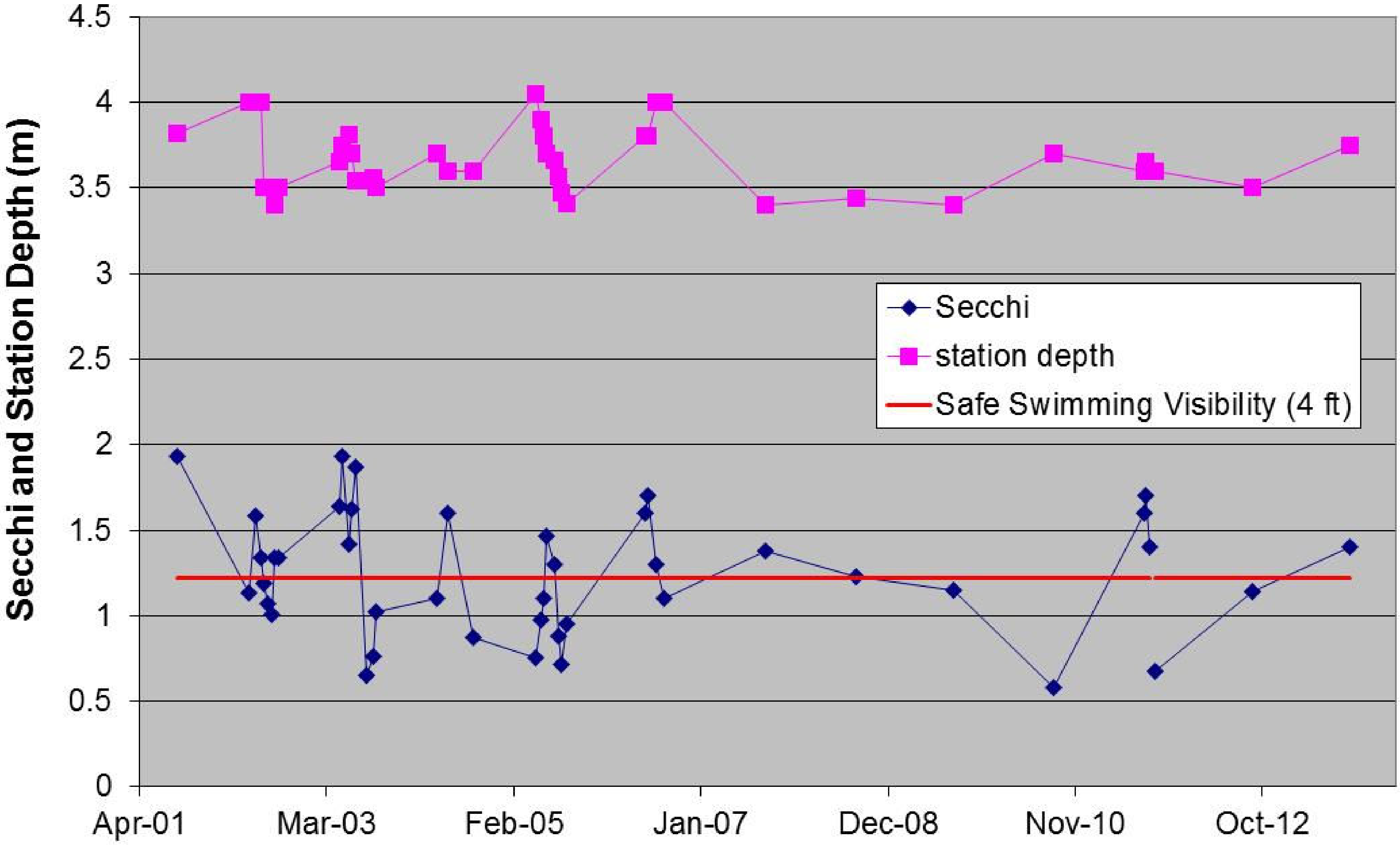

Figure III-17. Water Clarity in Lower Mill Pond 2001 - 2013.

Water clarity (Secchi disk) readings in Lower Mill Pond average 34% of the water column. Lowest readings generally occur in September. State regulations have a clarity limit of 4 feet for safe swimming conditions; 46% of the Secchi readings between June and September in the entire Lower Mill Pond dataset are less than the 4 ft limit.

III.D.3. pH and alkalinity

As mentioned in Section II, Massachusetts surface water regulations has numeric standards for pH, which specify that pH should be between 6.5 and 8.3 unless natural conditions cause readings to fall outside of this range. In the Lower Mill Pond dataset, surface pH readings have only been collected in August and September (n=16) and have an outlier-corrected average of 6.8 with a range of 6.30 to 7.9 (see Table III-4). Within this dataset, four of the surface pH readings are less than 6.5 and one is greater than 8.3. Average surface and deep pH readings showed little difference. Similarly, alkalinity averaged 5.6 mg $CaCO_3$/L in surface samples and 6.0 mg $CaCO_3$/L in deep samples.

Surface pH and alkalinity levels in Cape Cod ponds tend to be low unless altered by growth associated with excessive nutrients. The average surface pH of 193 ponds sampled in the 2001 PALS Snapshot was 6.16 with a range of 4.38 to 8.92, while the average alkalinity was 7.21 mg/L as CaCO3 with a range of 0 to 92.1 mg/L. The lower 25th percentile among pH readings from the 2001 Snapshot, or the least impacted ponds, is 5.62. This lower quartile is consistent with the pH of natural rainwater, which is 5.65. Photosynthesis is one of the primary ways pH increases in surface waters; when aquatic plants photosynthesize they take carbon dioxide and hydrogen ions out of the water causing pH to increase. Thus ponds with higher nutrient levels, which are needed to support higher phytoplankton concentrations, have higher pH. Alkalinity does not have a numeric standard in the Massachusetts surface water regulations, but is directly related to pH. Alkalinity is a measure of the compounds that shift pH toward more basic, higher values and is mostly determined by the concentrations of bicarbonate, carbonates, and hydroxides. Alkalinity is also a measure of the capacity of waters to buffer acidic inputs. Because pH and alkalinity are influenced by shared constituents, they are linked values.

III.D.4. Chlorophyll and Pheophytin

Chlorophyll is not directly mentioned in Massachusetts surface water regulations, so it is generally addressed in the descriptive standards (see Section II). Chlorophyll is a family of primary photosynthetic pigments in most plants, including both phytoplankton (or algae) and macrophytes (i.e., any aquatic plants larger than microscopic algae, including rooted aquatic plants). Because of its prevalence, measurement of chlorophyll can be used to estimate the biomass of phytoplankton within pond waters. Chlorophyll-a is a specific pigment in the chlorophyll family and plays a primary role in photosynthesis.[62] Pheophytin-*a* is an initial breakdown product of the chlorophyll molecule, which is usually indicative of phytoplankton degradation (*e.g.* grazing or a senescing bloom).

Anecdotal evidence from Cape Cod ponds with undeveloped land around them suggests that "natural" Cape ponds tend to be phytoplankton-dominated and, therefore, should have a strong relationship between chlorophyll-*a* and total phosphorus concentrations. However, this relationship can be skewed when rooted plants out-compete phytoplankton for phosphorus. For example, Long Pond in Centerville has an extensive rooted macrophyte population[63] that has

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[62] USEPA, 2000.

[63] IEP, Inc. and K-V Associates. 1989. Diagnostic/Feasibility Study of Wequaquet Lake, Bearses, and Long Pond. Prepared for Town of Barnstable, Conservation Commission. Sandwich and Falmouth, MA.

consumed most of the available phosphorus and kept chlorophyll concentrations relatively low.[64] These types of ponds are largely unrepresentative of the ecology in most Cape Cod ponds.

Because Cape Cod ponds tend to have low nutrient concentrations, they also tend to have low chlorophyll-*a* concentrations. The average concentration of surface samples from 191 Cape ponds during 2001 was 8.44 µg/L with a range from 0.01 to 102.9 µg/L.[65] Development of a Cape Cod-specific pond chlorophyll threshold concentration based on the 2001 PALS sampling results determined that unimpacted Cape Cod ponds have a chlorophyll-*a* concentration of 1.0 µg/L and "healthy" Cape Cod ponds would have a concentration of 1.7 µg/L.[66] As a point of comparison, the USEPA ecoregion-specific chlorophyll-*a* reference for the Cape Cod area is 2.9 µg/L.[67]

In the Lower Mill Pond dataset, chlorophyll-*a* samples have mostly only been collected in August and September (n=18) and have an outlier-corrected average of 18.4 µg/L in surface waters and 19.9 µg/L in deeper waters (average z_{max} = 2.8 m) (see Table III-4). Corresponding phaeophytin concentrations (n=15) are 2.4 µg/L and 6.2 µg/L. Chlorophyll-*a* averages 85% of the total measured pigments in Lower Mill Pond surface waters.

The average Lower Mill Pond chlorophyll-*a* concentrations significantly exceed available thresholds and are consistent with impaired conditions. Review of the continuous readings between July 2 to September 6, 2012 generally agreed with the individual samplings: all of the bottom water readings exceeded 1.7 µg/L. The lowest chlorophyll-*a* concentration during the 2012 continuous recording was 4.1 µg/L and the highest was 101.7 µg/L; the average July concentration was 23.4 µg/L, while the average August concentration was 32.6 µg/L.

III.D.5. Nutrients: Nitrogen and Phosphorus

Phosphorus is usually the key nutrient in ponds and lakes because it is usually more limited in freshwater systems than nitrogen, which is also crucial for growth. Typical plant organic matter contains phosphorous, nitrogen, and carbon in a ratio of 1 P: 7 N: 40 C per 500 wet weight. Therefore, if the other constituents are present in excess, phosphorus, as the limiting nutrient, can theoretically produce 500 times its weight in phytoplankton.

Most Cape Cod lakes have relatively low phosphorus concentrations due to the lack of phosphorus in the surrounding glacially-derived sands, while nitrogen is added to groundwater system via land use sources, such as septic system discharge, fertilizers, and stormwater runoff. These same sources add phosphorus to the groundwater, but nitrogen generally flows with groundwater (~1 ft/d), while phosphorus is significantly slowed (0.01-0.02 ft/d), mostly due to its binding to the iron minerals naturally contained in the aquifer sands. Once nitrogen is in the aquifer system, it is generally fully oxidized to nitrate-nitrogen and largely unattenuated unless it reaches a pond or stream along its flow path. Most of the phosphorus in Cape Cod ponds is

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

[65] Eichner and others. 2003.

[66] *Ibid*.

[67] US Environmental Protection Agency. 2001.

generally due to a) additions from the watershed and b) regeneration of past watershed additions from the pond sediments. Since phosphorus movement in the aquifer is so slow, management of P inputs to ponds generally focusses on properties within 250 to 300 ft of the pond shoreline unless there are direct water inputs from streams or stormwater runoff. Shoreline properties generally have impacts on the pond within land use and wastewater planning horizons.

One way to assess the key management nutrient for pond water quality is to review the balance between phosphorus and nitrogen. As a rule of thumb, if the ratio between nitrogen and phosphorus is greater than 16 (also known as the Redfield ratio), phosphorus is the limiting nutrient. It should be noted that this approach to determining nutrient limitation also needs to take into account phototrophs that have the ability to utilize organic phosphorus, not just inorganic phosphorus. For this reason, phosphorus-limited systems generally have N to P ratios that are 2-5 times the Redfield ratio of 16. Review of Lower Mill Pond N to P ratios show that average ratios are significantly higher than 16 although the differences were smaller than for either of the other two ponds in the Mill Ponds complex. The ratios are phosphorus limited (surface average = 37; deep average = 27), but in general are more evenly balanced (Figure III-18).

Review of the phosphorus and nitrogen concentrations also confirm the impaired conditions observed during the review of the clarity readings and the chlorophyll concentrations. The median surface concentration of TP in 175 Cape Cod ponds sampled during the 2001 was 16 µg/l, while the median TN concentration was 0.44 mg/L. The Cape Cod pond-specific nutrient threshold ranges developed from the 2001 PALS sampling are 7.5 and 10 µg/l for TP and 0.16 to 0.31 mg/L for TN. In the Lower Mill Pond dataset, TP and TN samples have generally been collected in August and September (n=23). Surface water TP concentrations average 31.6 µg/l and deep samples (average z_{max} = 2.83 m) average 44.9 µg/l (see Table III-1). Surface water TN concentrations average 0.53 mg/l and deep samples average 0.56 mg/l. These concentrations significantly exceed their respective threshold ranges and are indicative of impaired water quality conditions.

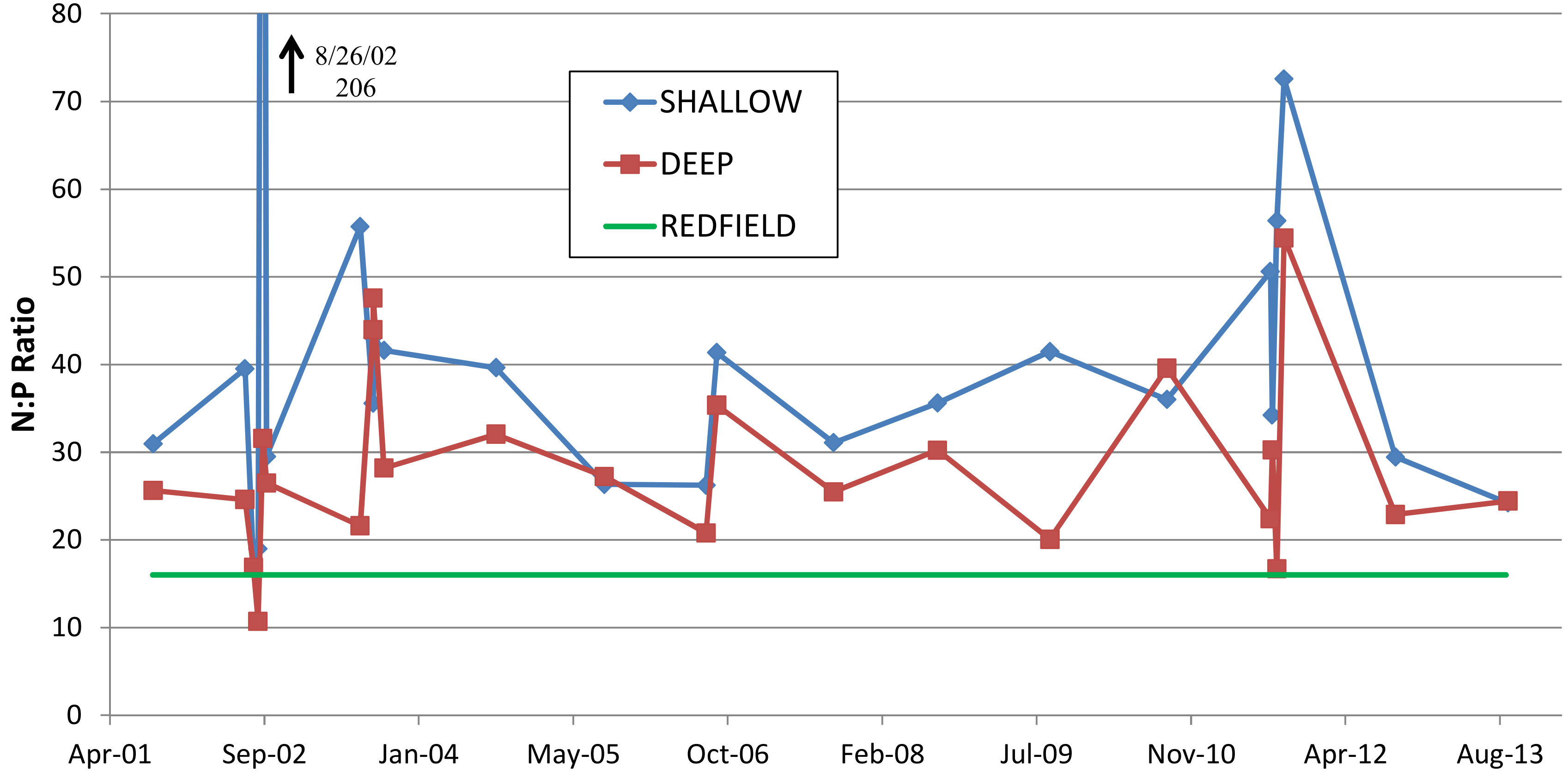

Figure III-18. Changes in Nitrogen to Phosphorus Ratio in Lower Mill Pond 2001 - 2013.
Ratio between nitrogen and phosphorus generally determines the nutrient controlling growth in surface waters. Waters with a ratio above 16 (Redfield ratio) generally are phosphorus limited and management should target sources of phosphorus, while waters below the Redfield ratio should be managed for nitrogen. Most freshwater ponds have ratios significantly above the Redfield line, but occasionally large additions of phosphorus can alter conditions. On average, Lower Mill Pond is phosphorus limited with an average surface N:P ratio = 37 and a deep average = 27.

IV. Other Physical and Ecosystem Characteristics of Walkers Pond, Upper Mill Pond, and Lower Mill Pond

IV.A. Bathymetry and Water Budget

Developing a management plan for a pond or lake requires an understanding of how nutrients enter the pond, how they are utilized, and how they are removed from the pond. Transport of the nutrients is generally via water flows, so understanding the quantities of water entering, leaving, and remaining in the pond are key for understanding how the nutrients are balanced as well. This accounting of all the flows in and out of a pond, plus its volume, is called a water budget. Once all these volumes and their rates of movement are characterized, the flux of water can be used to calculate a pond's residence time or the time that an average volume of water remains in the pond. The water budget is the basis for determining how long nutrients or pollutants remain in the lake and how they are transferred into and out of the lake. These insights are then combined with water quality data to determine management strategies.

During discussions with the Brewster CWPC, CSP/SMAST recommended that new bathymetric information be collected as part of the targeted data collection for the development of the management plan. In order to increase the accuracy of the water balance and residence times for Upper Mill Pond, Lower Mill Pond, and Walkers Pond. CSP/SMAST staff completed bathymetric surveys of all three ponds.[68] The collected depth readings were sufficient to produce bathymetric contours of 0.5 m intervals for Walkers Pond (Figure IV-1) and Lower Mill Pond (Figure IV-2) and 1 m intervals for Upper Mill Pond (Figure IV-3). This contour density is an improvement over the 5-ft contour intervals for Walkers and Upper Mill and the 3-ft contour intervals for Lower Mill Pond that were previously available on the historic MADFW bathymetric maps. The CSP/SMAST surveys were completed using a differential GPS mounted on a boat for positioning coupled to a survey-grade fathometer.

The new bathymetric maps yielded a more accurate measure of the total volume of each of the ponds. The new volumes for Upper Mill Pond, Lower Mill Pond, and Walkers Pond are 5,708,219 m^3, 550,406 m^3, and 730,603 m^3, respectively. These volumes are significantly different from the change from the estimated volumes in the Brewster Ponds Report[69]. Forensic review suggests that the Ponds Report volumes may have suffered a units switch; the new SMAST volumes are ~10% larger than the volumes based on the MADFW maps. The method used by CSP/SMAST for the new pond bathymetries produces significantly more datapoints than previous methods and a more reliable measurement of bathymetry and volume.

In order to provide context for these pond volumes, it is important to understand the hydrogeologic setting of the Mill Ponds and their watersheds. Walkers and Upper Mill are situated within portions of the Harwich Outwash Plain Deposits, while Lower Mill is situated in an area with Lake Cape Cod Deposits and Dennis Ice-Contact Deposits.[70] The ice-contact deposits, which accumulated at the face of the continental ice sheet during the

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[68] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013.

[69] Eichner, E. 2009. Brewster Freshwater Ponds

[70] Oldale, R.N. 1992. *Cape Cod and the Islands: The Geologic Story.* Parnassus Imprints, East Orleans, MA.

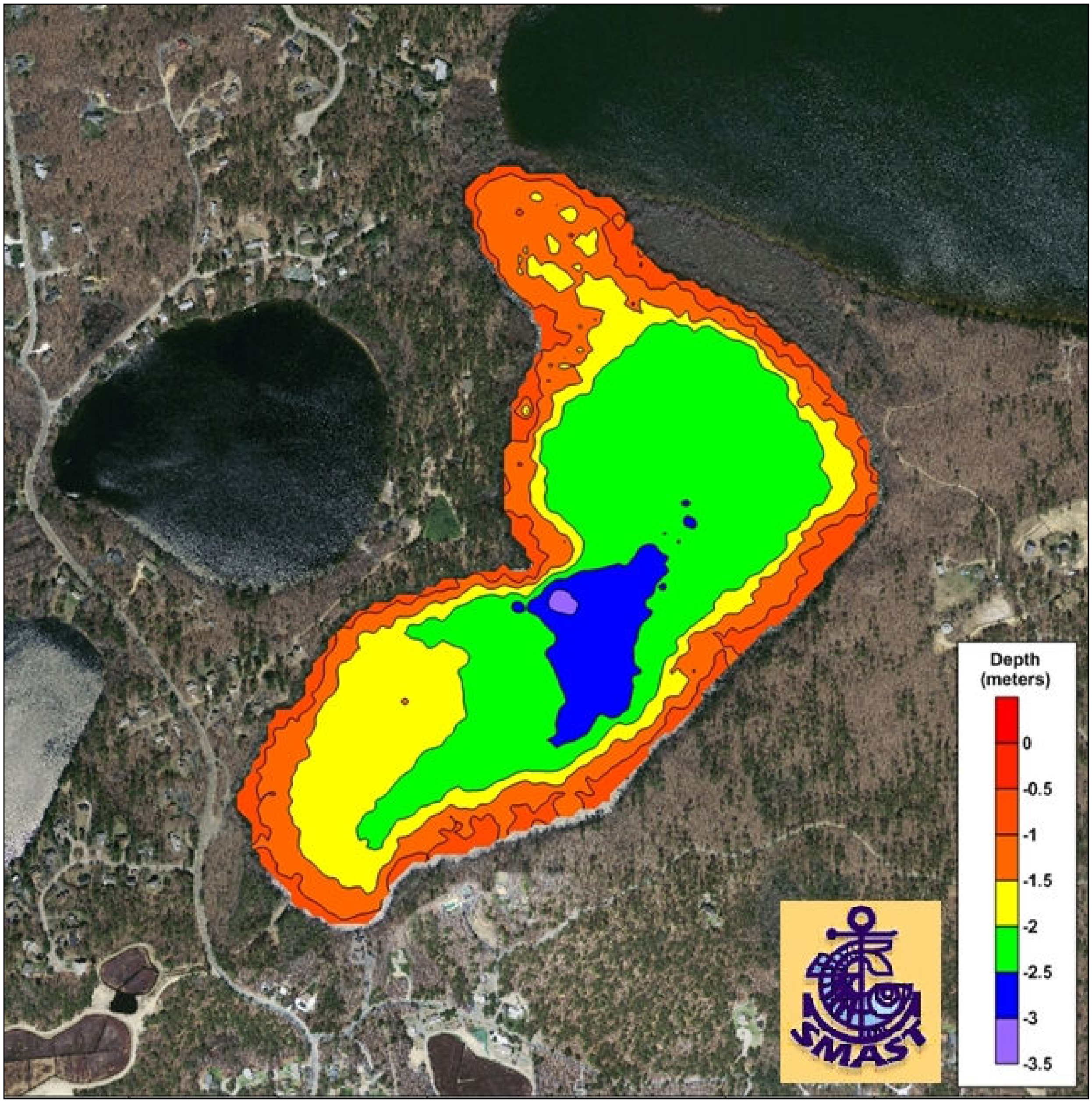

Figure IV-1. Walker Pond Bathymetry
Bathymetry developed by CSP/SMAST personnel using a differential GPS for positioning mounted on a boat with a survey-grade fathometer. Based on this bathymetry, total volume is 730,603 m^3. Depths are relative to NAVD88 datum.

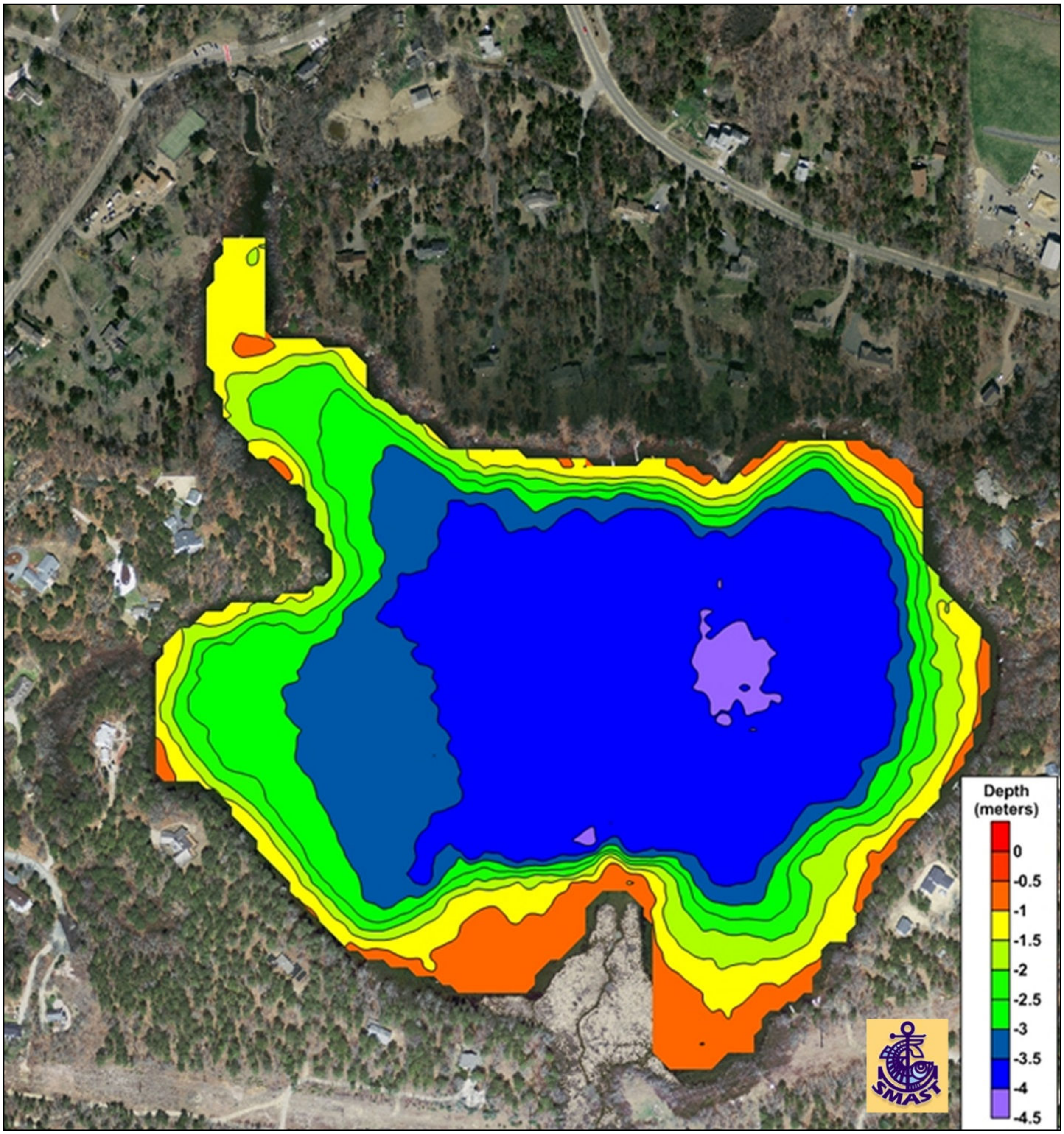

Figure IV-2. Lower Mill Pond Bathymetry
Bathymetry developed by CSP/SMAST personnel using a differential GPS for positioning mounted on a boat with a survey-grade fathometer. Based on this bathymetry, total volume is 550,406 m3. Depths are relative to NAVD88 datum.

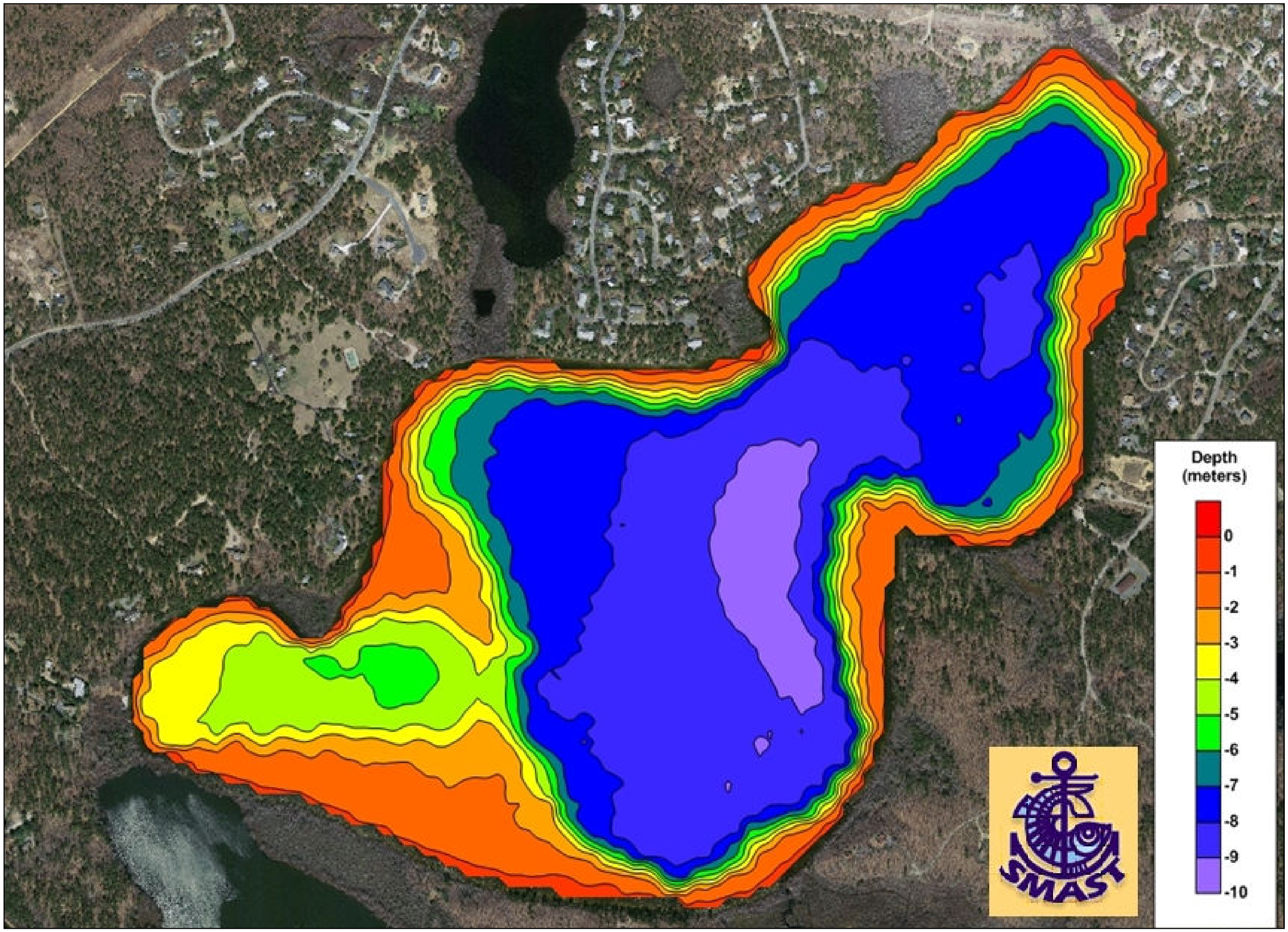

Figure IV-3. Upper Mill Pond Bathymetry
Bathymetry developed by CSP/SMAST personnel using a differential GPS for positioning mounted on a boat with a survey-grade fathometer. Based on this bathymetry, total volume is 5,708,219 m3. Depths are relative to NAVD88 datum.

Laurentide glacial stage, tend to be associated with the area to the west of Lower Mill and Canoe Ponds.[71] These materials tend to be coarse sand and gravel with mixes of silt, clay, and till. The Lake Cape Cod Deposits are younger than the ice-contact deposits and accumulated when the continental ice sheet was located in a relative stable location in Cape Cod Bay and a lake formed south of the ice sheet. The lake trapped sediments flowing off the face of the ice sheet. These materials were deposited along the current Cape Cod shoreline and tend to be fine sediments and clays. These sediments were confirmed during well installation drilling associated with tracking groundwater contamination from the Brewster landfill.[72] The outwash plain deposits tend to be sands and gravels that tend to be sorted by size with coarser materials associated with greater volume of meltwater and closer proximity to the ice sheet during their deposition. Groundwater tends to flow in reasonably predictable patterns in coarser, sandier materials, but finer clays and silts exert more control over groundwater path directions as flows try to move toward coarser materials.

The United States Geological Survey (USGS) has created a regional groundwater model that includes the area of the Mill Ponds.[73] Since groundwater generally determines watersheds in hydrogeologic settings like those found on Cape Cod,[74] the USGS groundwater model was used to delineate recharge areas (or groundwater watersheds) to the ponds in the Mill Ponds complex (Figure IV-4). These watersheds were delineated as part of the USGS work to delineate watersheds to coastal estuaries under the Massachusetts Estuaries Project (MEP), so they are part of a comprehensive watershed mosaic for all of Cape Cod. Generally, the USGS modeled watersheds are refined during the course of the individual MEP estuary assessments to ensure that the modeled watersheds match the configuration of pond and estuary shorelines and agree with measured streamflow data collected during the MEP.

The USGS regional groundwater model can be used to determine watershed flows. The USGS model uses the three-dimensional, finite-difference groundwater model MODFLOW-2000[75] to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4[76] uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer and was then used to delineate the recharge areas/watersheds to ponds, estuaries, and rivers/streams. Based on this modeling, the average respective watershed flows to Walkers Pond, Upper Mill Pond, and Lower Mill Pond are: 4,427 m^3/d, 8,471 m^3/d, and 1,435 m^3/d (Table IV-1).

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[71] 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.

[72] Cambareri, T.C. and E.M. Eichner. 1993. Hydrogeologic and Hydrochemical Assessment of the Brewster Landfill, Brewster, Massachusetts. Cape Cod Commission, Water Resources Office. Barnstable, MA.

[73] Walter, D.A. and A.T. Whealan. 2005.

[74] Cambareri, T.C. and E.M. Eichner. 1998. Watershed Delineation and Ground Water Discharge to a Coastal Embayment. *Ground Water*. 36(4): 626-634.

[75] Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, The U.S. Geological Survey modular ground-water model—User guide to modularization concepts and the ground-water flow process: U.S. Geological Survey Open-File Report 00-92, 121 p.

[76] Pollock, D.W., 1994, User's guide for MODPATH/ MODPATH-PLOT, version 3—A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 94-464, 234 p.

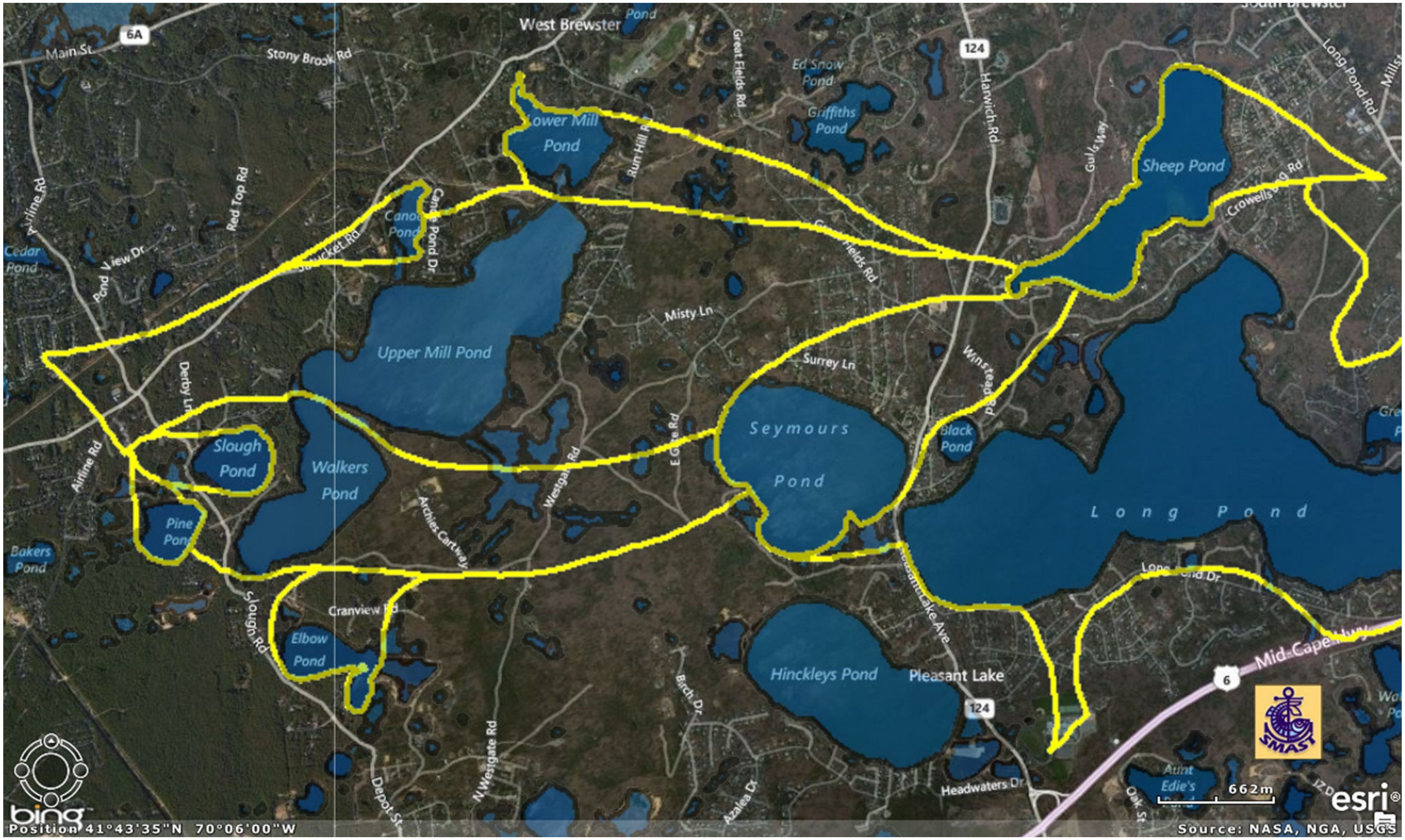

Figure IV-4. Pond Watersheds: Mill Ponds Area

Watersheds for Walkers Pond, Upper Mill Pond, and Lower Mill Pond are shown, along with watersheds to nearby or contributing ponds. Watersheds are based on USGS regional groundwater model recharge areas (Walter and Whealan, 2005). Watersheds to the south of this area discharge into the Herring River in Harwich, while watersheds to the west discharge into Bass River. Base map is a Bing aerial and ponds and wetland outlines are based on MassGIS 1:12,000 wetlands coverage.

Within the watersheds to the Mill Ponds are a number of other ponds. Some of these ponds are situated on the watershed boundaries of the Mill Ponds. In these cases, the discharge from these ponds is divided between downgradient watersheds based on the length of the discharging shoreline within each downgradient watershed. For example, Seymour Pond is in the watershed to both Walkers Pond and Upper Mill Pond. The total length of the Seymour Pond downgradient/discharging shoreline is 1,950 m with 444 m (23%) along the top of the Walkers Pond watershed and 243 m (12%) along the top of the Upper Mill Pond watershed. The remainder discharges to the Herring River MEP watershed.[77] The water discharge from Seymour Pond is divided among the downgradient watersheds based on these shoreline percentages. Both Walkers Pond and Upper Mill Pond receive watershed flow from other ponds.

Table IV-1. Measured and Modeled water flows between Walkers Pond, Upper Mill Pond, and Lower Mill Pond

Pond	Modeled Watershed Recharge Flows[a]	Cumulative Modeled Watershed Flow[e]	Measured 2012 Average Water Flow[f]	Measured 2012 Summer Average Flow[g]
	m^3/d	m^3/d	m^3/d	m3/d
Bog to Walkers	-[b]	-	331	69
Walkers Pond/ Walkers to Upper Mill	4,426[c]	4,426	3,636	2,310
Upper Mill Pond/ Upper Mill to Lower Mill	8,471[d]	12,957	11,477	7,640
Lower Mill Pond/ Lower Mill to Stony Brook	1,435	14,333	5,949	2,902

Notes:

a. Watershed flows based on USGS regional groundwater model outputs (Walter and Whealan, 2005)
b. USGS model places the cranberry bog south of Cranview Road on opposite side of regional groundwater divide, so no modeled flow exists
c. Modeled watershed flow to Walkers Pond includes watershed flow from Slough Pond and partial watershed flow from Seymour Pond, Sheep Pond, and Pine Pond
d. Modeled watershed flow to Upper Mill Pond includes partial watershed flow from Seymour Pond, Sheep Pond, and Canoe Pond
e. Cumulative modeled watershed flow as water moves through system for discharge into Stony Brook
f. Measured flow from 2012 water year (September 2011 to August 2012), documented in 2013 CSP/SMAST Technical Memorandum
g. Measured average flow from June 2012 to September 2012 (n=4 or 5).

The comparison of modeled watersheds and measured streamflow data is also part of the development of the management plan for Upper Mill Pond, Lower Mill Pond, and Walkers Pond. As noted above, watershed water entering Cape Cod kettle ponds enters the pond along the upgradient shoreline and generally discharges back to the groundwater system along the

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[77] Howes, B., H.E. Ruthven, J.S. Ramsey, R. Samimy, D. Schlezinger, and E. Eichner. 2012. Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for the Herring River Embayment System, Harwich, Massachusetts. Massachusetts Estuaries Project, Massachusetts. Department of Environmental Protection. Boston, MA.

downgradient shoreline.[78] If there is a stream entering or leaving the pond, it can act as a path of least resistance and will focus groundwater into the pond or pond water discharging out of the pond into the stream. The hydroconnections between the three ponds in Mill Ponds study area function in this way. Walkers Pond has a hydrologic connection to Upper Mill Pond, which in turn, has a connection to Lower Mill Pond. The connection between Walker Pond and Upper Mill is a small natural connection across a very narrow (2-5 m) strip of land separating the two ponds, while the connection between Upper Mill and Lower Mill has been enhanced and armored with rip-rap (Figure IV-5). Lower Mill Pond discharges into Stony Brook through an area that contains a grist mill and a water level drop of approximately 10 feet. There is also an intermittent connection between the cranberry bog south of Cranview Road and Walkers Pond.

Flow between the ponds was part of the information gathering documented in the 2013 CSP/SMAST technical memorandum.[79] These flows are generally lower than the modeled watershed flows from the USGS regional groundwater model, but within a reasonable range. Flow was measured monthly between August 2, 2011 and September 20, 2012 (Figure IV-6). Average flows based on a September to August water year were: Cranview Bog to Walkers Pond, 331 m3/d; Walkers Pond to Upper Mill Pond, 3,636 m3/d; Upper Mill Pond to Lower Mill Pond, 11,477 m3/d, and Lower Mill to Stony Brook, 5,949 m3/d (see Table IV-1). The differences between measured and modeled flows are likely due to a number of factors including:

a) groundwater discharge (*e.g.*, some groundwater is still discharging downgradient bypassing the hydroconnections even though these offer an easier downstream path)
b) local factors that are not in the regional model (*e.g.*, the large former cranberry bog system that is connected to the southeast shoreline of Upper Mill Pond extends into the USGS Walkers Pond watershed. This system might be capturing groundwater and delivering it to Upper Mill Pond rather than allowing it to discharge to Walkers Pond.)
c) annual fluctuations (*e.g.* fluctuations in precipitation, groundwater levels, and evaporation can alter measured flows from the average conditions represented by the USGS modeling.)

Review of seasonal impacts shows that measured flows between the ponds decreased during the 2012 summer (June to September). Average flow from Walkers Pond to Upper Mill Pond decreased to 2,310 m3/d, while average flow from Upper Mill Pond to Lower Mill Pond decreased to 7,640 m3/d. These decreases are roughly the same: 36% and 34%, respectively. The flow from Lower Mill Pond to Stony Brook also decreased from 5,949 m3/d to 2,902 m3/d or a 50% decrease.

It should be noted that comparison of the measured and modeled flows at the system's discharge to Stony Brook was not within reasonable agreement. Average measured flow into

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[78] Walter, D.A., J.P. Masterson, and D.R. LeBlanc. 2002. Simulated Pond-Aquifer Interactions under Natural and Stressed Conditions near Snake Pond, Cape Cod, Massachusetts. U.S. Geological Survey Water-Resources Investigations Report 99-4174. Northborough, MA.

[79] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013.

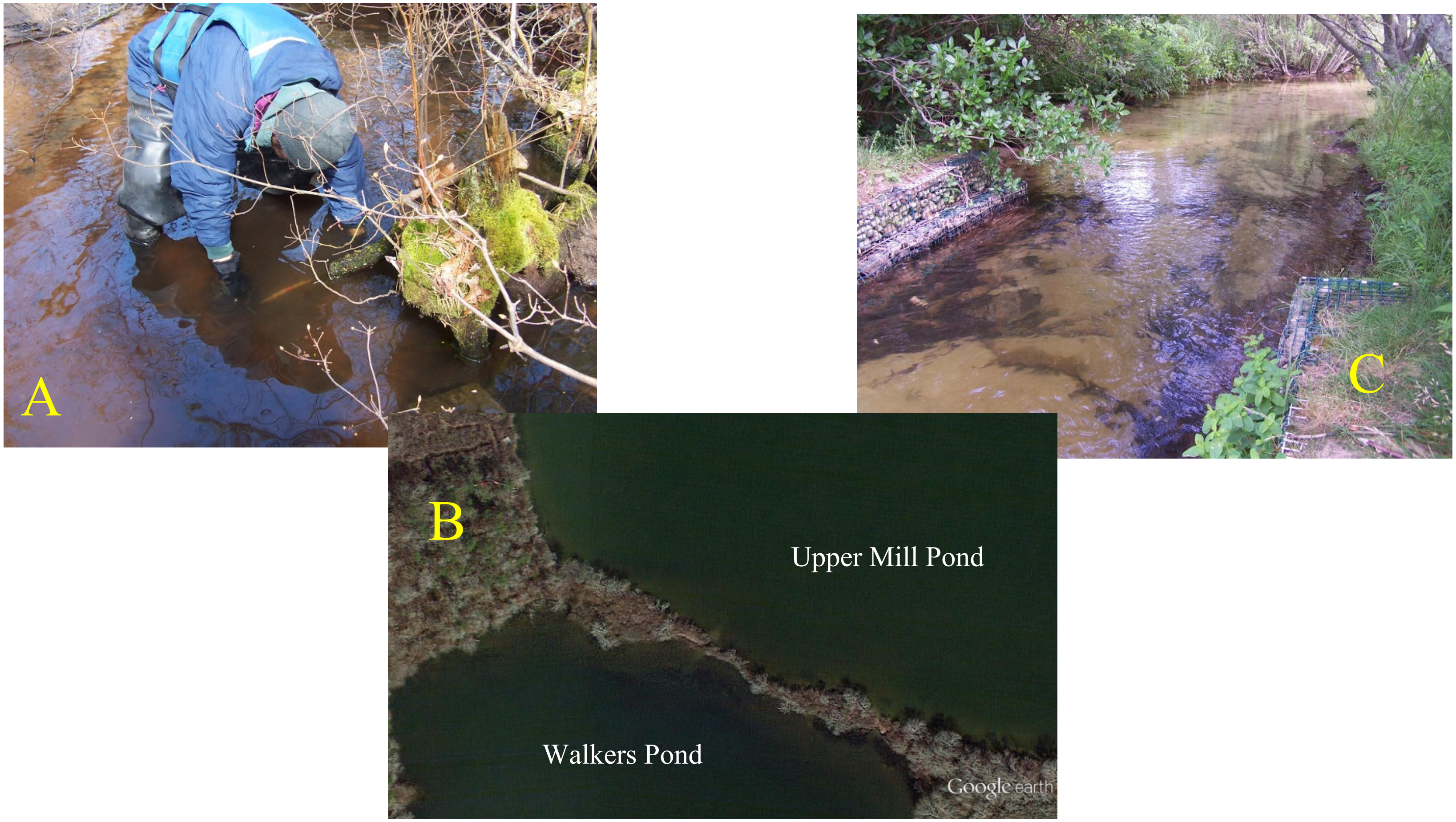

Figure IV-5. Hydroconnections between ponds in the Mill Ponds Complex.
"A" shows a CSP/SMAST staffer measuring the end of conduit that sometimes discharges into southern shoreline of Walkers Pond from cranberry bog south of Cranview Road. "B" shows area of connection between Walkers Pond and Upper Mill Pond (~2-5 m across at the discharge point). "C" shows armored connection between Upper Mill Pond and Lower Mill Pond (looking north toward Lower Mill Pond). Lower Mill Pond discharges into Stony Brook. Modified from Figure 8 in 2013 CSP/SMAST Technical Memorandum.

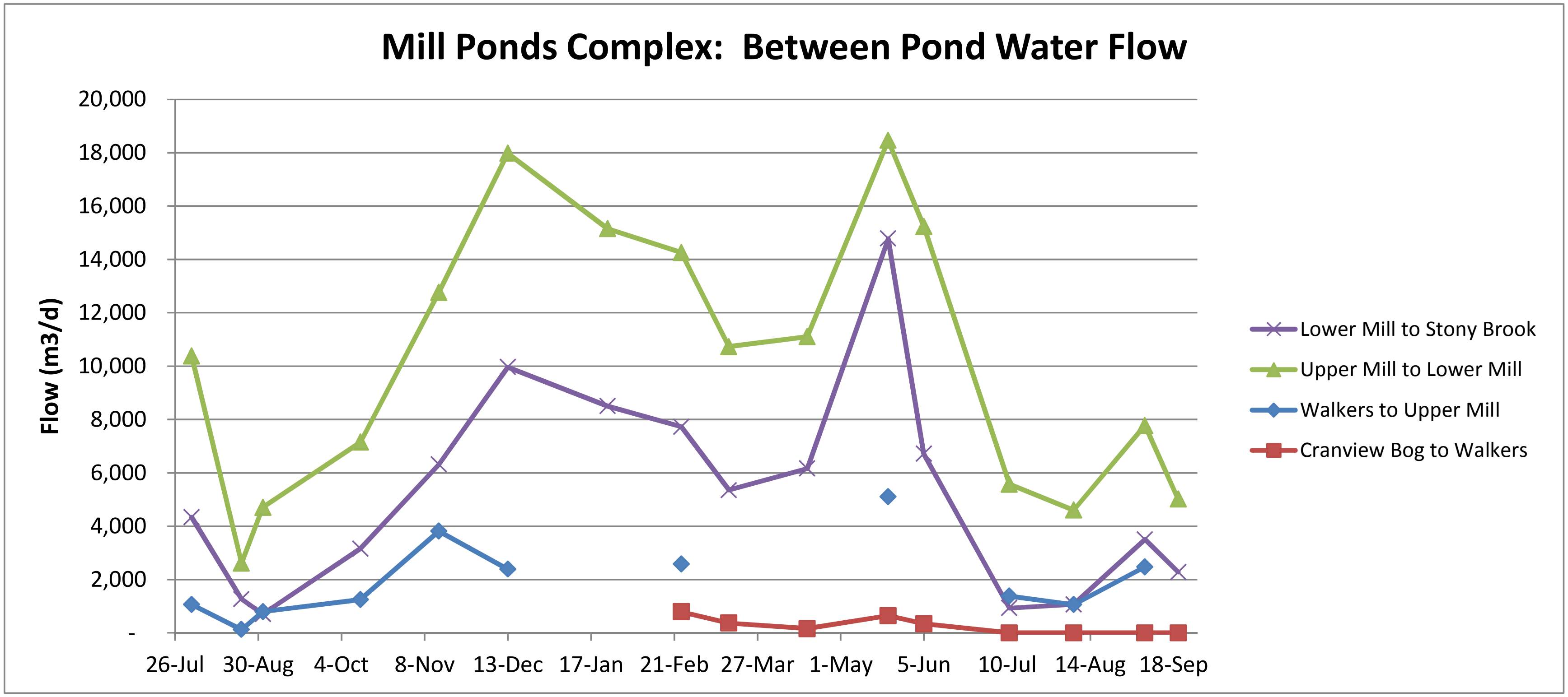

Figure IV-6. Water Flow through hydroconnections between ponds in the Mill Ponds Complex. Water flows were measured on a monthly basis from August 2, 2011 through September 20, 2012 at four connections between: a) the cranberry bog south of Cranview Road and Walkers Pond, b) Walkers Pond and Upper Mill Pond, c) Upper Mill Pond and Lower Mill Pond, and d) Lower Mill Pond and Stony Brook. The connection between the Cranview Bog and Walkers Pond had no measured flow beginning in July 2012. Measurements at the connection between Walkers Pond and Upper Mill Pond were complicated by winds piling water up at the gauge location; these measurements are removed from the record. Average daily water year (September to August) flows are: Cranview Bog to Walkers Pond, 331 m^3/d; Walkers Pond to Upper Mill Pond, 3,636 m^3/d; Upper Mill Pond to Lower Mill Pond, 11,477 m^3/d, and Lower Mill to Stony Brook, 5,949 m^3/d. The drop in flow discharge to Stony Brook suggests that the Grist Mill dam is artificially raising water levels in Lower Mill Pond and promoting groundwater discharge from the pond to the surrounding aquifer bypassing the stream. Modified from Figure 9 in 2013 CSP/SMAST Technical Memorandum.

Lower Mill Pond from Upper Mill Pond is 11,477 m3/d, but the average measured flow out of Lower Mill Pond is only 5,949 m3/d or 52% of this flow (see Table IV-1). These flow measurements appear to be the most extensive and complete continuous dataset that has been collected at this measurement point. A search of historic USGS readings shows one instantaneous reading collected in October 1978[80], while Woods Hole Group collected 13 instantaneous readings in December 2007.[81] These readings generally agree with the USGS modeling, but are sparse and limited to a time of the year when water discharge would tend to be elevated due to seasonally high groundwater levels and precipitation.

Review of other information in the project area helps to explain why the measured readings at Lower Mill Pond outflow are lower than the modeled readings and appear to be somewhat separate from the relationships between the other ponds. Review of elevations in the area of the Grist Mill north of the retaining wall/dam along the northern boundary of Lower Mill Pond show a large drop in water levels. An elevation survey completed for the town on November 2, 2011 shows that the small pond below the waterwheel at the Grist Mill was approximately 10 ft lower than the elevation of Lower Mill Pond.[82] Given the short distance between these two locations, this finding suggests that the elevation of Lower Mill Pond is artificially elevated and this elevated water level is sufficient enough to force some of the water in Lower Mill back into the surrounding groundwater system rather than flowing into Stony Brook. Water table readings in the area collected for a water quality assessment of the Brewster Landfill generally support this hypothesis. Subregional groundwater flowpaths based on these readings show paths from Lower Mill Pond back to groundwater then discharging into Stony Brook north of the Grist Mill.[83] Review of the shape of Lower Mill Pond would also seem to support this hypothesis. Most kettle ponds on Cape Cod tend to be relatively symmetrical and rounded, reflective of their origins as collapse features from melting glacial iceblocks. Lower Mill Pond bathymetry tends to match this shape, but also includes what may be an artificially deepened arm leading to the Grist Mill discharge. In addition, there is a somewhat novel wetland area that is elevated above the pond surface surrounding the hydroconnection from Upper Mill Pond. The wetland area would be consistent with it being a depositional area for fine materials settling into a filled basin. In addition, the Lower Mill Pond outlet area is very shallow (<3 ft deep) with a submerged channel approximately 400 ft south of the retaining wall connecting the main basin of Lower Mill Pond to the basin that abuts the retaining wall. Collectively, these features seem to suggest that a longer stream once drained into Stony Brook from a smaller Lower Mill Pond. In this scenario, building a Grist Mill at this location and raising the level of the pond with the dam increased the size of Lower Mill Pond and increased the head drop and power at the Mill. However, the increased hydraulic head also changed the local hydraulic gradients and increased the likelihood that flow into the pond would discharge back into the groundwater system rather than flowing exclusively past the mill. In consideration of all these features, the area water table and water level information provide a reasonable hypothesis for the difference between the modeled and measured flow out of Lower Mill Pond. Further

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[80] http://waterdata.usgs.gov/nwis/measurements/?site_no=011058789

[81] Woods Hole Group, Inc. October, 2008. Hydraulic Study to Assess Feasibility of Tidal Restoration Stony Brook, Brewster, MA. East Falmouth, MA.

[82] November 9, 2011 elevation survey map completed by WSP-Sells for Tighe and Bond, Inc. Map provided by Chris Miller.

[83] Cambareri, T.C. and E.M. Eichner. 1993.

clarification of this issue could be addressed through more refined measurement of groundwater levels and discharges in the downgradient/downstream areas of Lower Mill Pond.

Finally, it is also worth noting the small connection between the cranberry bog south of Cranview Road and Walkers Pond. The USGS model results place a regional groundwater divide between Walkers Pond and Elbow Pond (see Figure IV-4), in the area of this bog. Field investigations in the area found a buried conduit of undetermined construction connecting the cranberry bog to Walkers Pond. The cranberry bog has a headwall on the north end of one its main ditches that is connected to the conduit. The northern end of the conduit was found by CSP/SMAST staff as a partially buried pipe in an indentation in the southern shoreline of Walkers Pond (see Figure III-5). This conduit/pipe had limited flow during the winter and early spring of 2012, no flow on dates after June 5, and was completely dry on September 20. It is clear that this pipe connects all the way to the cranberry bog because cranberries were noted near the Walkers Pond end of the pipe during the February and April flow measurements, but the lack of flow during the summer suggests that flow may also be related to groundwater elevations with flow only during the higher elevations that typically occur during winter and/or due to winter flood conditions at the bog. It is also unclear whether the conduit is fully intact; if it is not intact, some of the measured flow may represent upgradient groundwater drainage rather than only flow from the bog. Further site-specific evaluation might help to clarify these relationships, but the flow is very minor compared to the connections between the primary ponds or to the overall watershed input to Walkers Pond.

Collectively, the watershed and flow information provide a basis for the overall water budgets for Walkers Pond, Upper Mill Pond, and Lower Mill Pond (Table IV-2). Pond water budgets are typically represented as:

$$\text{groundwater}_{\text{in}} + \text{streamflow}_{\text{in}} + \text{precipitation} = \text{groundwater}_{\text{out}} + \text{streamflow}_{\text{out}} + \text{evapotranspiration}$$

In Table IV-2, the water budgets are condensed based on the source of the information. Inflowing groundwater ($\text{groundwater}_{\text{in}}$) is based on the modeled USGS watersheds. Pond surface precipitation is also based on USGS modeling, which includes evaporation. $\text{Streamflow}_{\text{in}}$ and $\text{Streamflow}_{\text{out}}$ are the average measured flows at the monitoring locations and $\text{groundwater}_{\text{out}}$ is determined by difference between the total input and the stream outflow. This water budget is an update and refinement of the budget included in Eichner (2009). The 2009 budget included water inputs from projected runoff from roads within a 300 feet buffer along the downgradient side of the lake, but did not have the benefits of all the collected targeted data included in this more refined water budget.

Based on the measured flows, modeled inputs, and pond volumes determined for this management plan, CSP/SMAST staff determined pond water residence times for Walkers, Upper Mill, and Lower Mill of 154 days, 441 days, and 38 days, respectively. Residence times are the average amount of time a standard volume of water remains within a pond basin before being lost via downgradient groundwater recharge or to surface water outflows. These times will vary as water levels in the pond rise and fall with the surrounding groundwater, something seen in the measured stream outflows. The differences between these average residence times means that water quality in Walkers Pond is largely determined within 5 month windows, while in Upper

Table IV-2. Annual Water Budgets for Walkers Pond, Upper Mill Pond and Lower Mill Pond

Pond	Pond sheds	% to pond	IN				OUT		
			Groundwater	Pond Surface	Stream	TOTAL	Groundwater	Stream	TOTAL
			m^3/yr	m^3/yr	m3/yr	m^3/yr	m^3/yr	m^3/yr	m^3/yr
Walkers (PALS# BR-313)	Walkers	100%	1,082,527	169,727		1,252,254			
	Pine	41%	29,531			29,531			
	Slough	100%	121,534			121,534			
	Seymour	23%	212,115			212,115			
	Hydro: Cranview Bog				120,746	120,746			
	Hydro: to Upper Mill							1,326,998	
	Pond Total/ Cumulative Total		1,445,706	169,727	120,746	1,736,179	409,181	1,326,998	1,736,179
Upper Mill (PALS# BR-272)	Upper Mill	100%	2,498,663	423,330					
	Canoe	54%	53,911						
	Seymour	12%	116,081						
	Sheep	5%	21,918						
	Hydro: from Walkers				1,326,998				
	Hydro: to Lower Mill							4,189,275	
	Pond Total		2,690,574	423,330	1,326,998	3,113,904			
	Cumulative Total		4,136,280	593,057	1,447,744	4,729,337	540,062	4,189,275	4,729,337
Lower Mill (PALS# BR-245)	Lower Mill	100%	441,012	82,890		523,901			
	Hydro: from Upper Mill				4,189,275	4,189,275			
	Hydro: to Stony Brook							2,171,372	
	Pond Total		441,012	82,890	4,189,275	523,901			
	Cumulative Total		4,577,292	675,947		5,253,239	3,081,867	2,171,372	5,253,239

Notes:

a. Incoming groundwater and pond surface inputs are based on USGS groundwater modeling results
b. Outgoing stream flow is based on average measured flow during 2011-2012 water year.
c. Outgoing groundwater is based on the difference between the total input and the measured stream output
d. Pond water residence times are: Walkers, 154 days; Upper Mill, 441 days; Lower Mill, 38 days.

Mill Pond the water quality over more than a year needs to be considered. In Lower Mill Pond, water quality conditions are largely determined month to month. The role these residence times and streamflows play in determining water quality in each pond is discussed in subsequent sections.

IV.B. Freshwater Mussels and Aquatic Rooted Plants

Extensive populations of freshwater mussels and macrophytes (aquatic rooted plants) have the potential to alter nutrient cycling and can complicate development of management strategies. In order to begin to address these issues, CSP/SMAST staff recommended to the Brewster Comprehensive Water Planning Committee that a visual survey of both mussels and plants be completed. During October 2013, CSP/SMAST staff completed a visual survey to determine the distribution of freshwater mussels and macrophytes (or rooted plants) in Walkers Pond, Upper Mill Pond and Lower Mill Pond.

The visual survey was conducted by collecting underwater video recordings of the pond bottoms. Cameras were synced with GPS and recording at five frames per second. Each frame represents approximately 0.25 m^2 and the collected video was reviewed frame-by-frame for mussel valves and plant densities within each frame.

Many of the freshwater mussel species on Cape Cod are listed by the Massachusetts Natural Heritage Program as endangered species or species of special concern, including the Tidewater Mucket (*Leptodea ochracea*) and Eastern Pondmussel (*Ligumia nasuta*).[84] In the Town of Barnstable, an alum treatment was delayed for over a year in order to address mussel issues associated with Massachusetts Endangered Species Act.[85] 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.[86] Reviews of available freshwater mussel studies suggest mussels must have a complex response to nutrient availability with both positive and negative impacts due to high or low loads.[87] They are generally restricted to areas that do not experience hypoxia. The visual survey was recommended as a relatively low cost approach to assess whether mussels would have to be a consideration in development of management strategies for Walkers Pond, Upper Mill Pond and Lower Mill Pond.

During the review of the video recordings, CSP/SMAST staff also completed a plant (macrophyte) density survey. Macrophytes are typically sparse in Cape Cod ponds, but some more eutrophic ponds can have extensive plant populations.[88] Macrophyte abundance is a complex interaction of a number of factors, including sediment characteristics, nutrient

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

[85] Water Resources Services, Inc. March, 2011. Internal Phosphorus Load Inactivation in Mystic Lake, Barnstable, Massachusetts.

[86] CSP/SMAST Technical Memorandum: Eagle Pond and Cedar Pond Technical Support Project: Bathymetry, Submerged Aquatic Vegetation and Mussel Surveys, Water Bird Survey. December 18, 2012.

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

[88] 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.

availability, pond depth, and light limitations.[89] Extensive macrophyte populations can alter nutrient cycling by favoring settling of suspending particles within beds, but also can increase uptake of buried phosphorus by roots and transport to above ground plant parts, which during senescence and decay is released to pond waters.[90] The plant survey was completed to provide preliminary insights into the influence of macrophytes on the overall phosphorus balance and effects on water quality management strategies in Walkers Pond, Upper Mill Pond and Lower Mill Pond.

The densities of macrophytes and mussels differ significantly among the three ponds. Walkers Pond had extensive macrophyte coverage from the shoreline to approximately 1.5 m; macrophyte coverage within this area was 80% or greater (Figure IV-7). In deeper waters, macrophyte density was generally less than 10%. Plant coverage and growth is strongly influenced by water clarity and light penetration. The maximum recorded, summer, Secchi depth reading in Walkers Pond is also 1.5 m, which suggests that rooted plant community is restricted to areas of the pond where the clarity is acceptable. Mussels are relatively sparse in Walkers Pond with the greatest densities along the eastern shoreline.

Upper Mill Pond, in contrast, had a very limited macrophyte population (Figure IV-8). Only 0.5% of the pond area has macrophyte density greater than 20%. These areas were concentrated in two shoreline areas along the western side of the pond. Light limitation does not appear to be an issue since the average Secchi depth reading is 1.7 m. Mussel populations were quite extensive in Upper Mill Pond with 1 or more per frame (~0.25 m^2) throughout most of pond bottom from the shoreline to approximately 7 m depth; no mussels were recorded in waters 7 m or deeper (Figure IV-9). The 7 m depth is where significant anoxia occurs; the minimum recorded snapshot DO reading at 6 m is 2.7 mg/L, while 23% of snapshot readings at 7 m are <1 mg/L.

The mix of mussels and macrophytes in Lower Mill Pond is intermediate between those measured in Upper Mill Pond and Walkers Pond. Mussels were sparser than Upper Mill Pond, generally confined to areas from the shoreline to approximately 2 m (Figure IV-10). The greatest density of macrophytes tended to be co-located with the mussels, although there are deeper areas where mussels were found and macrophytes were not present. Anoxic conditions were not recorded within the upper 3 m among the snapshot monitoring; only three summer readings at 3.5 m were <1 mg/L. Average Secchi depth in Lower Mill Pond is 1.25 m with a maximum of 1.93 m. Notable macrophytes densities tend to follow the 1.25 m contour with macrophyte densities greater than 40% at depths between the shoreline and 1 m.

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[89] 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.

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

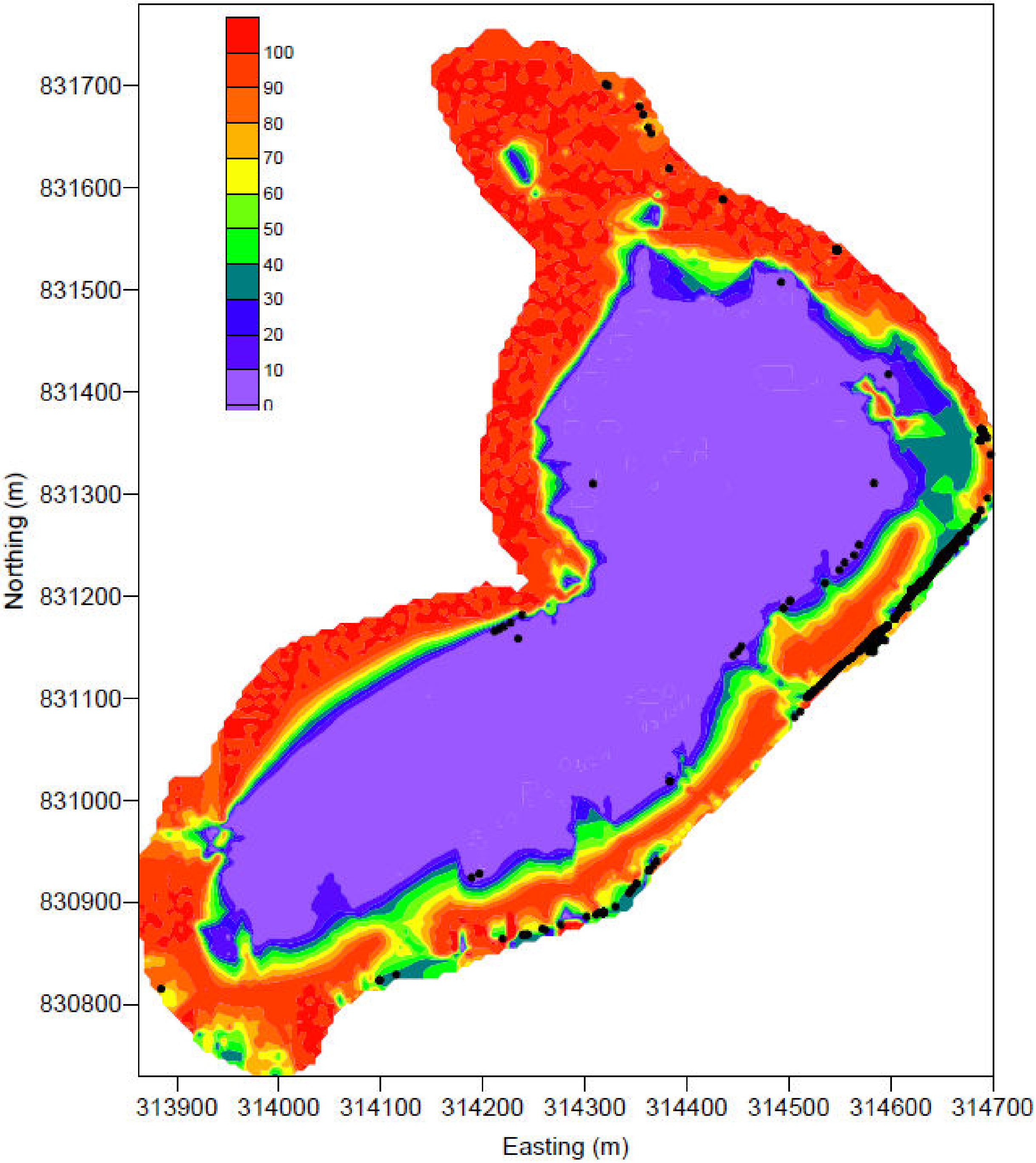

Figure IV-7. Macrophyte Density and Mussel Distribution in Walkers Pond.
Macrophyte density is shown as % coverage based on the imbedded color scale, while mussel distribution is shown by the black dots indicating individual mussels. These readings are based on frame-by-frame review of collected underwater video. Walkers Pond had extensive macrophyte coverage from the shoreline to approximately 1.5 m; Macrophyte density between the shoreline and ~1.5 m was generally 80% or greater all around the pond. Macrophyte density deeper than 1.5 m was generally less than 10%.

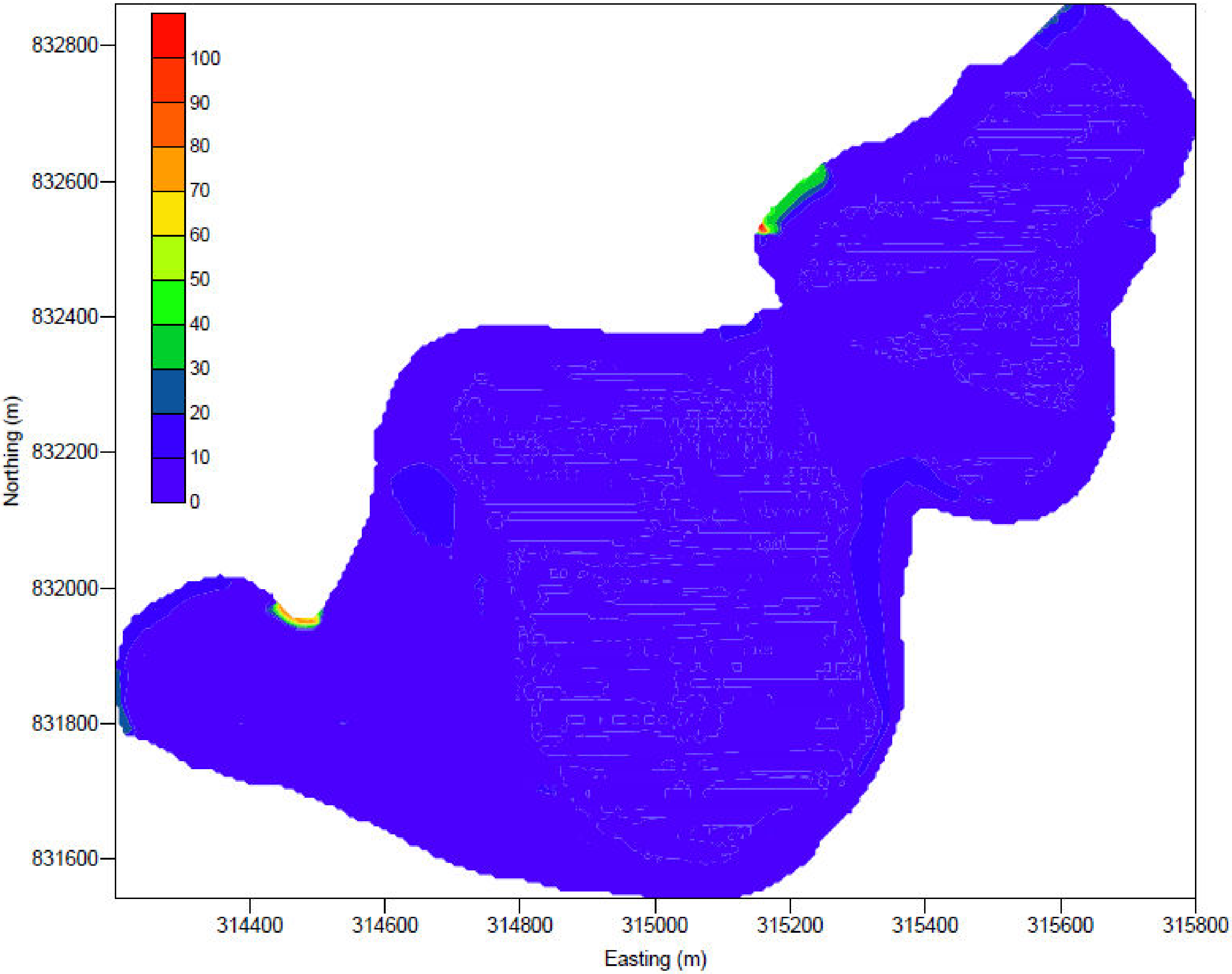

Figure IV-8. Macrophyte Density in Upper Mill Pond.

Macrophyte density is shown as % coverage based on the imbedded color scale. These readings are based on frame-by-frame review of collected underwater video. Upper Mill Pond had very limited macrophyte coverage, largely confined to two small shoreline areas along the west side of the pond. Only 0.5% of the pond area has macrophyte density greater than 20%.

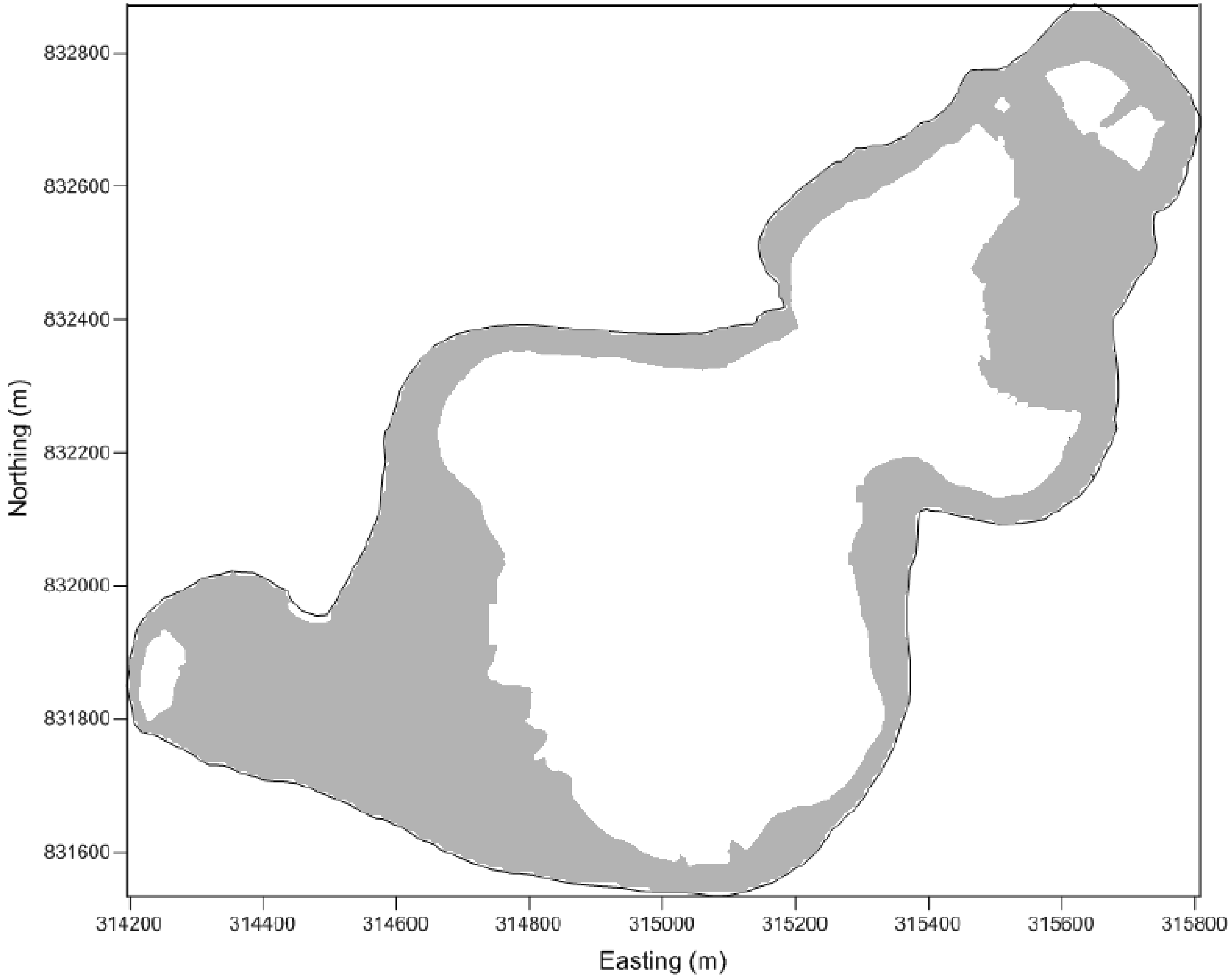

Figure IV-9. Mussel Presence in Upper Mill Pond.

Mussel presence in Upper Mill Pond was based on frame-by-frame review of collected underwater video. Frames (~0.25 sq m) within the gray areas had at least one mussel, but in many areas mussels filled the frames to the point that counting was difficult. Because of these difficulties, the gray areas on the above map show where mussels were present, while the white areas show the absence of mussels. Mussels generally were confined to depths of 7 m or less.

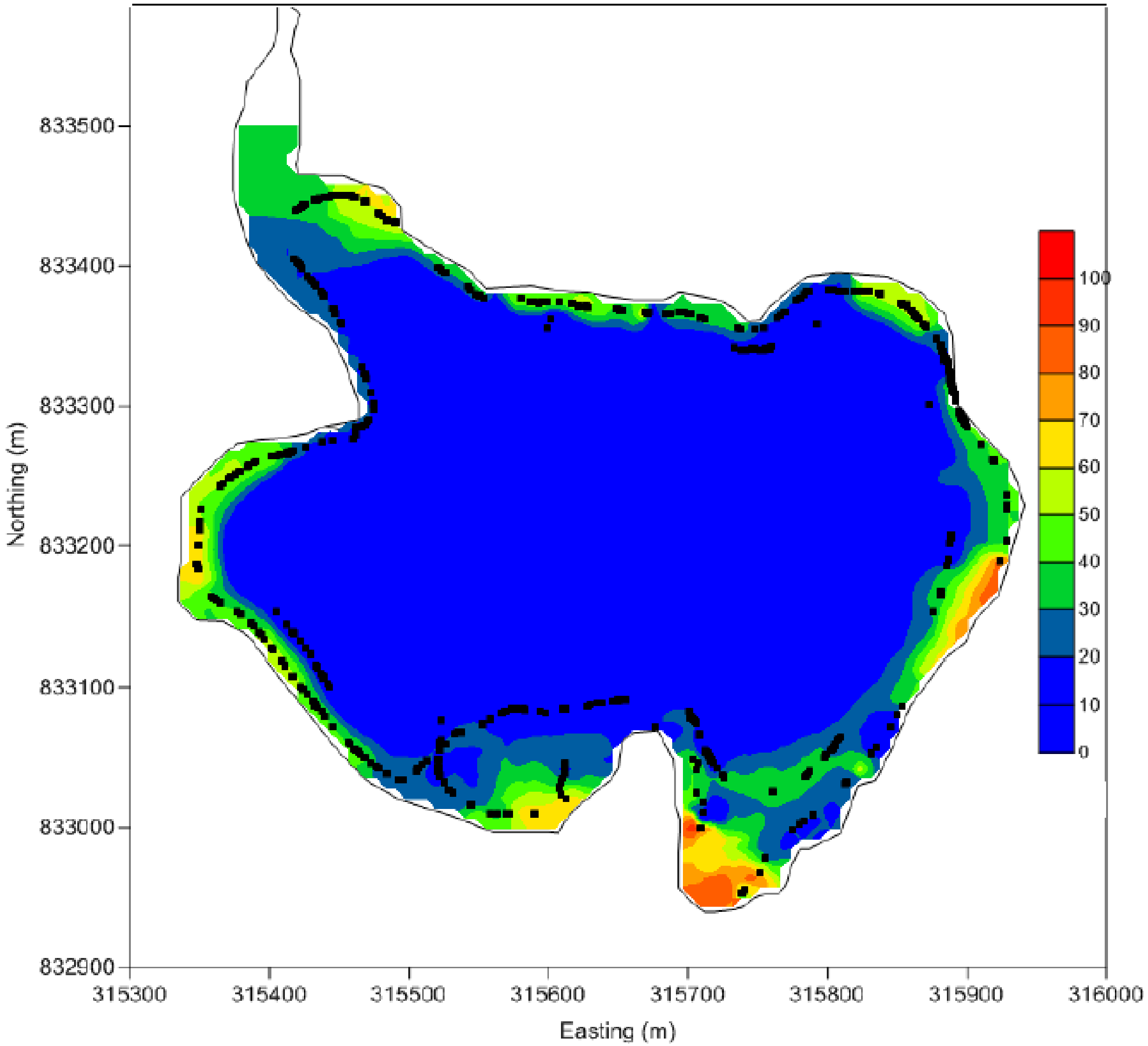

Figure IV-10. Macrophyte Density and Mussel Distribution in Lower Mill Pond. Macrophyte density is shown as % coverage based on the imbedded color scale, while mussel distribution is shown by the black dots indicating individual mussels. These readings are based on frame-by-frame review of collected underwater video. Mussels were generally confined to areas from the shoreline to approximately 2 m. The greatest density of macrophytes tended to be co-located with the mussels, although there are deeper areas where mussels were found and macrophytes were not present. Average Secchi depth in Lower Mill Pond is 1.25 m with a maximum of 1.93 m. Notable macrophytes densities tend to follow the 1.25 m contour with macrophyte densities greater than 40% at depths between the shoreline and 1 m.

V. Phosphorus Budget and Loading Sources

Review of the water quality data showed that water quality conditions in Walkers Pond, Upper Mill Pond, and Lower Mill Pond are impaired by high nutrients and resulting plant and phytoplankton growth. This data also confirmed that phosphorus is the key nutrient to be managed to address these impaired conditions. Once the amount and sources of water entering and leaving a pond have been adequately characterized (see Section IV), the next step is to determine the amount of phosphorus in each of the ponds and determine its sources. This step is done to provide a basis to guide potential phosphorus management strategies.

Part of developing a pond management plan is measuring or estimating all of the sources of phosphorus entering the pond. For the three ponds in the Mill Ponds complex, sources of phosphorus to the ponds come from: 1) their watersheds and the respective land uses within those watersheds, 2) loading from internal sources, such as sediment regeneration, and 3) transport into the ponds from the hydroconnections between the ponds. The phosphorus budget organizes and compares the relative contribution the loads from all these sources.

V.A. Phosphorus Mass in the Ponds

Because of the structure of the connections between the ponds in the Mill Ponds complex, discussion of a phosphorus budget begins with Walkers Pond, which is located at the most upgradient/upstream position. Walkers Pond averages 50 kg of TP in its water column during the summer with no statistical difference ($\rho<0.05$) between shallow and deep TP concentrations, although the average deep concentration is higher ($\rho=0.12$; see Table III-1) indicating some internal loading. Most of the data for the mass estimates is based on August and September water quality data, so these estimates likely include TP regenerated from the sediments. Review of mass calculations shows that the median mass is 43 kg, while the 25th percentile among this data of 33 kg.

As one moves downstream in the Mill Ponds complex, the next pond is Upper Mill Pond. Based on available water quality data, Upper Mill Pond averages 158 kg of TP in its water column with a significant ($\rho<0.05$) difference between shallow and deep TP concentrations likely due to regular summer anoxia causing TP release from the sediments (see Table III-1). Most of the data for the mass estimates is based on August and September water quality data, so the water column mass likely includes TP regenerated from the sediments. Review of mass calculations shows that the median mass is 137 kg, while the 25th percentile among this data of 112 kg.

The last, most downstream, pond is Lower Mill Pond. Lower Mill Pond averages 23 kg of TP in its water column with a significant ($\rho<0.05$) difference between shallow and deep TP concentrations indicating internal P loading, likely due sediment regeneration (see Table III-1). Most of the data for the mass estimates is based on August and September water quality data, so these estimates likely include TP regenerated from the sediments. Review of mass calculations shows that the median mass is 21 kg, while the 25th percentile among this data of 15 kg.

The mass of TP in the water column of each of these ponds is a reflection of external/watershed loads and internal/sediment loads, the volume of each pond, and its residence time. As part of the 2012 targeted data collection, measurements were collected for certain loads, while others have to be based on reasonable estimates. The following section discusses each of the components of the phosphorus budget.

V.B. Watershed Land Use Phosphorus Loading

Watershed land use phosphorus loading is composed of estimates or measurements of sources based on specific types of land use. For Walkers Pond, Upper Mill Pond, and Lower Mill Pond, estimates were developed for wastewater discharge, fertilizer, birds, and precipitation on the pond surfaces, while the 2012 targeted data collection provided measurements of stormwater runoff and the loads added to each pond via the hydroconnections.

Table V-1 lists the factors used in the development of the watershed phosphorus loading for Walkers Pond, Upper Mill Pond, and Lower Mill Pond. These factors are similar to those used in the 2009 Brewster Pond Report with some modifications to account for subsequent refinements developed during the course of other pond management plans[91] and assessments.[92]

The individual pond land use information was combined with other phosphorus loading factors to produce pond-specific watershed phosphorus loads (Table IV-2). The phosphorus loading factors used to develop these loads were based on direct measurement, regional information or phosphorus loading in conditions similar to those encountered on Cape Cod. Brief discussions of the derivation of the loading factors are included below.

V.B.1 Wastewater Phosphorus Loading Estimates

The watershed phosphorus loads from wastewater disposal are based on data developed from a review of town Board of Health records. In the 2009 Brewster Pond Report,[93] town volunteers reviewed town records to determine the age and distance from the pond shorelines for septic system leachfields, pits and cesspools on properties within 300 ft of the pond shorelines for six Brewster ponds including the three ponds in this management plan. This data was re-reviewed for development of the current management plan.

Previous Cape Cod pond phosphorus budgets[94] have typically used a septic system loading rate of 1.0 lb P/yr developed by the Maine Department of Environmental Protection (MEDEP) for use in sandy soils.[95] The MEDEP phosphorus loading methodology accounts for the differential transport of phosphorus through a variety of soil types. Available studies with measurements of phosphorus transport from septic systems in sandy soils generally support this value as a reasonable planning number.

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[91] *e.g.*, Eichner, E., B. Howes, and D. Schlezinger. 2012. Scargo Lake Water Quality Management Report. Coastal Systems Program, School for Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA. 65 pp.

[92] *e.g.*, Eichner, E., B. Howes, and C. DeMoranville. 2012.

[93] Eichner, E. 2009. Brewster Freshwater Ponds

[94] Eichner, E.M., S. Michaud, and T.C. Cambareri. 2006. First Order Assessment of Indian Ponds (Mystic Lake, Middle Pond, and Hamblin Pond). Cape Cod Commission. Barnstable, MA.

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

Table V-1. Phosphorus Loading Factors for Pond Watershed Loading Estimates
Listed below are factors used in the development of the watershed phosphorus loading estimates for the Brewster ponds. Modified from Table V-3 in Eichner (2009).

Factor	Value	Units	Source
Wastewater P load	1	lb P/septic system	MEDEP, 1989 load
P retardation factor	25 - 37	Groundwater velocity/solute velocity	Robertson, 2008
Road surface P load	measured	CSP/SMAST Technical Memorandum: Mill Ponds Complex Project. January 16, 2013.	
Roof surface P load	3.5	lb P/ac	MEDEP, 1989
Natural Areas P conc.	0.05 – 0.35	kg/ha	Cadmus, 2007; Hendry and Brezonik, 1980
Watershed Recharge Rate	27.25	in/yr	Walter and Whealan, 2005
Precipitation Rate	44.8	in/yr	Walter and Whealan, 2005
Building Area	2,000	ft2	Eichner and Cambareri, 1992
Road Area	Actual value	ft2	Mass. Highway Information
Lawn Factors			
Area per residence	5,000	ft2	Eichner and Cambareri, 1992
Fertilizer lawn load	0.02 to 0.3	lb P/ac	Literature review
Waterfowl Factors			
P load	0.156	g/m2/yr	Scherer, *et al.*, 1995
New P load	13	%	Scherer, *et al.*, 1995
Alt external P load	0.5 – 1.3	kg/yr	Non-areal load based on Cape Cod bird counts

Available studies have shown that annual *per capita* phosphorus loads range from 1.1 to 1.8 pounds[96], while sandy soil retention factors range between 0.5 to 0.9.[97] 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 average annual occupancy in the Town of Brewster during the 2010 Census (2.24 people per house), the *per capita* range results in an average individual septic system load range of 0.2 to 2.0 lbs. In the 2009 Brewster Ponds Report, CSP/SMAST staff utilized an annual phosphorus load of 1.0 lb per residence and modified this rate based on a likely groundwater travel time for phosphorus (*i.e.,* whether the septic wastewater phosphorus had reached the pond shoreline). For this Management Plan, project staff reviewed development since the 2009 Report and found that the 2009 wastewater estimates are still reasonable for the Mill Ponds.

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[96] 1.1 lb/yr example publications: Reckhow and others, 1980; Panuska and Kreider, 2002; 1.8 lb/yr example publication: Garn and others, 1996

[97] Robertson, W.D. 2008.

Table V-2. External Watershed Phosphorus Loading Estimates: Mill Ponds

All loads in kg/yr. Loads based on mix of measured loads and estimates developed based on pond-specific application of factors in Table V-1. Wastewater, fertilizer, bird, and runoff loads are within local control to adjust. Precipitation loads would be beyond local control.

Pond	wastewater			fertilizer		birds		runoff	precipitation		TOTAL	
	low	high	steady state[a]	low	high	low	high	measured[b]	low	high	low	High
Walkers	2.7	4.5	6.4	0.03	0.48	0.5	1.3	1.18	2.0	3.3	6.5	10.9
Upper Mill	8.2	13.6	17.2	0.08	1.31	0.5	1.3	3.40	5.1	8.3	17.2	28.0
Lower Mill	3.6	3.6	5.4	0.03	0.41	0.5	1.3	1.81	1.0	1.6	7.0	8.8

notes:

a. Steady state wastewater load assumes all loads from septic system leachfields within 300 ft have reached the pond
b. Runoff load is based on measured discharges collected for 2011 targeted data collection (CSP/SMAST, 2012)

V.B.2 Lawn Fertilizer Phosphorus Loading Estimates

The only extensive review of fertilizer application rates and practices on Cape Cod generally found that homeowners do not fertilize lawns as frequently or as extensively as recommended by lawn care guidelines unless commercial companies tend the lawns.[98] Fertilizer phosphorus reaching groundwater depends on a number of factors, including irrigation rates, precipitation rates, soil characteristics and chemistry, and turf types. Available research shows a wide range of phosphorus loads assigned to residential lawns. For example, Erickson and others (2005) tested phosphorus application rates on mixed turf and monoculture lawns over sandy soils for nearly four years. These studies found that leaching rates stabilized around 35% with average loading rates 33.7 and 20.3 lbs/ac, respectively.[99] Conversely, Sharma and others (1996) evaluated phosphorus concentrations in recharge under urban lawn areas and found concentrations equivalent to loading rates between 0.02 and 0.2 lbs/ac. Rhode Island Department of Environmental Management (RIDEM) has developed a phosphorus loading model based on various land uses that uses a range of 0 to 4.5 lbs/ac depending on the land use and the soil types and assigns a range of 0.6 to 0.7 lb/ac to the cumulative phosphorus load of low density residential development.[100] Given that Brewster residential fertilization practices appear to favor low annual application rates, CSP/SMAST staff completed the 2009 Brewster Ponds Report phosphorus budgets using a range of rates: 0.02 to 0.3 lbs/ac. These rates were used with assumed 5,000 sq ft lawn areas, which are based on a CSP/SMAST survey of over 3,000 Cape Cod lawns[101] and which is also the standard area assumption also used in MEP analyses. This approach was also used in the lawn fertilizer phosphorus loads in this management plan (see Table V-1). Since state-wide Massachusetts phosphorus fertilizer restrictions have not been implemented, these are not included under current conditions.

V.B.3. Bird Phosphorus Loading Estimates

Phosphorus loading from birds has been a difficult factor to resolve for Cape Cod ponds. Previous analyses completed by CSP/SMAST staff have relied on the factors shown in Table V-1. These factors are derived from a highly detailed study of birds and pond water quality from Seattle, Washington.[102] This study evaluated bird counts for a large pond (259 acres), determined the phosphorus load per various species, and the percentage of the phosphorus load that was new additions to the pond by the birds versus how much was reworking of existing phosphorus sources already in the pond. This evaluation found that the annual average phosphorus load from birds is 0.156 grams of P per square meter of lake surface with 13% of the load as new P additions to the lake. Because this load is determined by the area of the pond, applying this factor to Cape Cod ponds would result in larger ponds having greater bird loading.

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[98] White, L.M. 2003. The Contribution of Lawn Fertilizer to the Nitrogen Loading of Cape Cod Embayments. A Thesis submitted in the partial fulfillment of the requirements for the degree of Master of Arts in Marine Affairs, University of Rhode Island.

[99] Erickson, J.E., J.L. Cisar, G.H. Snyder, and J.C. Volin. 2005. Phosphorus and Potassium Leaching under Contrasting Residential Landscape Models Established on a Sandy Soil. *Crop Science.* 45: 546–552.

[100] Kellogg, D., M.E. Evans Esten, L. Joubert, and A. Gold. 2006. Database Development, Hydrologic Budget and Nutrient Loading Assumptions for the "Method of Assessment, Nutrient-loading, and Geographic Evaluation of Nonpoint Pollution" (MANAGE) including GIS-based Pollution Risk Assessment Method. 2006 update of 1996 original. Rhode Island Department of Environmental Management. University of Rhode Island Cooperative Extension. Kingston, RI.

[101] White, L.M. 2003.

[102] Scherer, N.M., H.L. Gibbons, K.B. Stoops, and M. Muller. 1995. Phosphorus loading of an urban lake by bird droppings. *Lake and Reservoir Management.* 11(4): 317 - 327.

The 2009 Brewster Ponds Report watershed phosphorus loading estimates used these same bird TP loading estimates, but also reviewed bird counts from the annual Cape Cod Bird Club surveys.[103] These surveys are usually conducted during the first week of December, have been done since 1984, and generally include counts from over 300 ponds. The average for all surveys since 1984 is 33 birds per pond. If pertinent factors from Scherer and others (1995) are used with the Cape Cod bird counts and it is further assumed that December counts are representative of year-round populations, the resulting average annual load of new phosphorus from bird populations is 0.9 kg per pond with a range of 0.5 to 1.3 kg/pond.

Given the lack of Cape Cod-specific studies and year-round counts, CSP/SMAST recommended a year-long bird survey during the development of a water quality management plan for Scargo Lake in the Town of Dennis.[104] This survey found that bird populations on the lake fluctuated between 0 and 167 birds with a year-long daily average of 34 birds. Using the species-specific phosphorus loads from Scherer and others (1995), the count data was used to develop an annual phosphorus loading rate of 0.57 kg. Bird counts using similar methods were also used for Cedar Pond and Eagle Pond in Dennis, which resulted in average counts of 4.6 and 1.3 birds, respectively.[105] Using the same methods, the respective pond-specific annual phosphorus loading estimates were 0.096 kg and 0.027 kg. The availability of the bird counts show loading estimates that are above and below the estimates based on regional averages, but the estimated loads based on actual bird counts are generally an order of magnitude lower than the pond area rate determined in Scherer and others (1995).

The original scope for the targeted data collection for the Mill Ponds included a bird count task, but volunteers could not be recruited to complete the counting.[106] The 2009 Brewster Ponds report used both the regional average bird counts and pond surface area loads to determine a range of bird phosphorus loading. Based on the year-long bird counts for the three ponds in Dennis, CSP/SMAST staff decided to rely on a range of phosphorus loads based on average bird counts rather than the load per pond area estimate. These loads better approximate the information developed for the Dennis ponds and are included in the phosphorus loading estimates for the Mill Ponds Management Plan (see Table V-1).

V.B.4. Pond Surface Phosphorus Loading Estimates

Phosphorus deposition in precipitation and dry deposition is site-specific and poorly constrained due to the variability in the factors that impact deposition (*e.g.*, particle size, precipitation rates).[107] Previous pond phosphorus budgets on Cape Cod have used a 0.14

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[103] www.capecodbirds.org/waterfowl.htm

[104] Eichner, E., B. Howes, and D. Schlezinger. 2012.

[105] CSP/SMAST Technical Memorandum: Eagle Pond and Cedar Pond Technical Support Project: Bathymetry, Submerged Aquatic Vegetation and Mussel Surveys, Water Bird Survey. December 18, 2012. From Ed Eichner, Brian Howes, and Dave Schlezinger, CSP/SMAST. To Suzanne Brock, Dennis WQAC Chair and Karen Johnson, Dennis Director of Natural Resources.

[106] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013.

[107] Vet, R., *et al. in press (2013).* A global assessment of precipitation chemistry and deposition of sulfur, nitrogen, sea salt, base cations, organic acids, acidity and pH, and phosphorus. *Atmospheric Environment*. http://dx.doi.org/10.1016/j.atmosenv.2013.10.060

kilogram per hectare (kg/ha) phosphorus load on the pond surfaces.[108] Subsequent literature reviews of phosphorus in precipitation have resulted in loads ranging from 0.05 kg/ha[109] to 0.35 kg/ha.[110] For somewhat isolated Cape Cod ponds where surface precipitation would be expected to be the predominant external source of phosphorus (*i.e.*, ponds with little or no development around them), review of their TP concentrations suggest that the lower end of available surface loading rates is more appropriate for Cape Cod ponds. Based on this review, the 2009 phosphorus budgets for Brewster's ponds used a phosphorus load of between 0.05 and 0.14 kg/ha for annual phosphorus loading on pond surfaces. Subsequent further literature review reinforces use of lower rates, so the upper limit has been reduced to 0.08 kg/ha[111] in the development of the pond surface P loads for the Mill Ponds Management Plan (see Table V-1).

V.B.5. Road Runoff Phosphorus Loading Measurements/Stormwater Survey

As part of the targeted data collection documented in the 2013 Mill Ponds Technical Memorandum,[112] CSP/SMAST staff completed stormwater measurements at direct discharge points into each of the three ponds. This effort was undertaken based on a recommendation in the 2009 Brewster Ponds Report that stormwater nutrient inputs should be measured, rather than estimated, in order to develop effective management for these sources.

The stormwater survey for the three ponds was begun by first conducting a field survey around the ponds during a significant storm event. This survey identified six (6) discharge sites by either direct observation of discharge or signs of direct stormwater runoff to a pond (Figure V-1). Four of the six sites discharge to Upper Mill Pond, while Lower Mill Pond and Walkers Pond each have one storm discharge site. CSP/SMAST staff also consulted with the town's Phase 2 stormwater consultants to ensure that all sites with potential direct stormwater discharge to the ponds were included.[113] No additional sites were identified. This total of six sites was a reduction from the number of sites originally identified during volunteer surveys for the 2009 Brewster Pond Report.

CSP/SMAST staff collected stormwater samples at all six sites on four dates during 2012: May 1, May 9, June 13, and September 5. The measured rainfall amounts for these storms were: 0.58 in, 1.11 in, 0.37 in, and 1.57 in. Even with these high rainfall amounts, runoff was not generated at some of the sites during selected storms. Due to the lack of specific discharge pipes, sample collection and volume measurements were made by channeling the runoff using sand bags to create a central point to collect water samples and allow accurate flow measurements.

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[108] *e.g.*, Eichner, E.M. 2008. Lake Wequaquet Water Quality Assessment. Prepared for the Town of Barnstable and Cape Cod Commission. Coastal Systems Group, School of Marine Science and Technology, University of Massachusetts Dartmouth. New Bedford, MA.

[109] Cadmus Group, Inc. 2007. Total Maximum Daily Load (TMDL) for Phosphorus in Little Sodus Bay, Cayuga County, New York. Prepared for: U.S. Environmental Protection Agency, Region 2 and New York State Department of Environmental Conservation.

[110] Hendry, C.D. and P.L. Brezonik. 1980. Chemistry of precipitation at Gainesville, Florida. *Environmental Science and Technology*. 14:843–849.

[111] Vet, R., *et al. in press (2013)*.

[112] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013.

[113] Personal communications, 2012 with Kirsten Ryan, Project Manager, Kleinfelder/SEA Consultants

Flow readings and water quality samples were collected a number of times during each storm event in order to gauge changes during events and provide a reliable basis for event-mean concentrations (EMC). Efforts were made to capture the initial “first flush” and peak of each stormwater event, as well as a reasonable sampling of the whole event. Water samples for chemical analysis were collected into acid-leached one liter polypropylene bottles using a Geo Pump, with analysis by the Coastal Systems Analytical Facility at the School of Marine Science and Technology (SMAST), University of Massachusetts Dartmouth in New Bedford. Samples were analyzed for the following constituents: total phosphorus (TP), ortho-phosphorus, total nitrogen (TN), nitrogen component species (NH4, NO3+NO2, TDN, and PON), POC, and alkalinity.

Flow and EMC data were used to determine total flow volumes and loads of TP during each storm (Figure V-2). Annual TP stormwater loads conservatively based on a 44 in/yr of precipitation were determined: Upper Mill Pond, 0.63 kg; Lower Mill, 0.93 kg; and Walkers, 0.16 kg. The loads for Upper Mill Pond and Walkers Pond are less than estimated in the 2009 Brewster Ponds Report, while the Lower Mill Pond load is greater than the Ponds Report estimate. These measured loads are used in the watershed phosphorus loading for each pond and the review of management options.

Figure V-1. Direct Stormwater Discharge Sites to Walkers Pond, Upper Mill Pond, and Lower Mill Pond.

Six (6) sites with either direct observation of discharge or signs of direct stormwater runoff to Walkers Pond, Upper Mill Pond, and Lower Mill Pond. Four sites of these sites discharge to Upper Mill Pond, while Lower Mill and Walkers each have one site; no additional sites were identified. Runoff was measured and sampled during four (4) storms in 2012: May 1, May 9, June 13, and September 5. Efforts were made to capture the initial "first flush" and peak of each stormwater event, as well as a reasonable sampling of the whole event. Samples were analyzed for the following constituents: total phosphorus (TP), ortho-phosphorus, total nitrogen (TN), nitrogen component species (NH_4, NO_3+NO_2, TDN, and PON), POC, and alkalinity. Modified from Figure 13 in 2013 CSP/SMAST Mill Ponds Technical Memorandum.

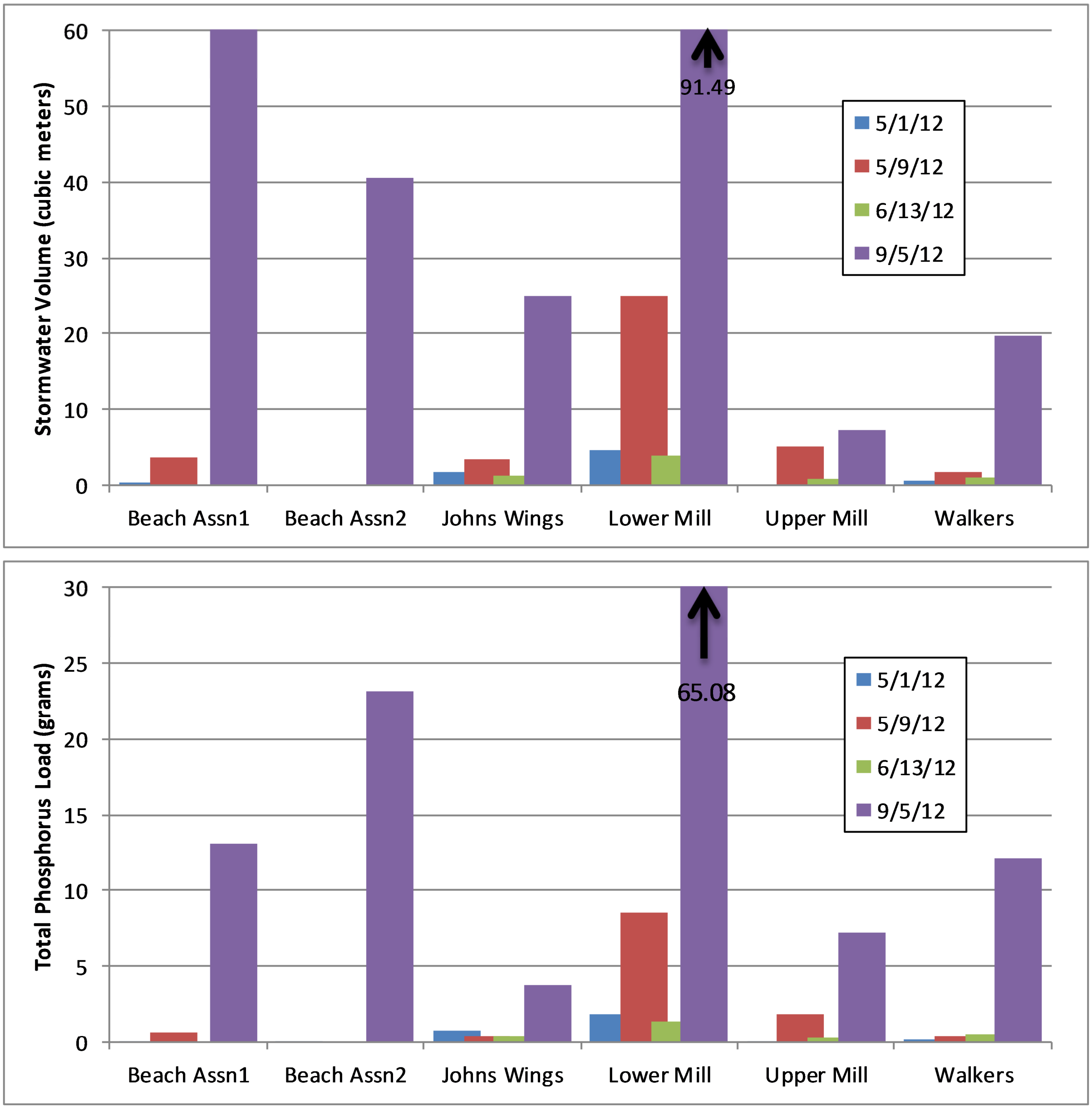

Figure V-2. 2012 Measured Stormwater Runoff Volumes and TP load: Walkers Pond, Upper Mill Pond, and Lower Mill Pond, Brewster, MA.

Runoff volumes are sum totals of each storm event at each direct discharge location. The September 5 storm generated much larger stormwater runoff volumes than the other three storms. According to precipitation recordings at a North Harwich weather station, precipitation on each of the dates was: 0.58 inches, 1.11 inches, 0.37 inches, and 1.57 inches, respectively. Runoff volumes are based on an estimate of storm event totals. Differences in generated volumes can be based on the catchment areas and surface materials (*e.g.*, blacktop vs. stone), as well as timing of measurements and tree cover. Modified from Figure 14 in 2013 CSP/SMAST Mill Ponds Technical Memorandum.

V.B.6. Inter-pond Phosphorus Transfer Measurements: Hydroconnections

Included in the watershed P inputs to each of the ponds are P inputs added through the hydroconnections connecting the ponds. These P transfers were measured as part of the targeted data collection completed by CSP/SMAST in 2011/2012.[114] At the same time as flow data was collected between the ponds (see Section IV), water quality samples were also collected to measure the transfer of nutrients between the ponds (Figure V-3). The measured average annual phosphorus transfers based on the 2012 water year are shown in Table V-3, along with the June to September transfers.

Table V-3. Surface Water Phosphorus Load transfer between Walkers Pond, Upper Mill Pond, and Lower Mill Pond through the hydroconnections

Transfer point	2012 Water Year Average P Load[a]	2012 Water Year P Load[b]	2012 Summer Load[c]	reduction in Summer Loads
	kg/d	kg	kg	%
Bog to Walkers	0.017	2.2	0.5	79%
Walkers to Upper Mill	0.160	55.1	14.2	74%
Upper Mill to Lower Mill	0.317	115.6	21.2	82%
Lower Mill to Stony Brook	0.185	65.6	14.6	78%

Notes:

a. Average of measured daily loads during water year; no removal of statistical outliers
b. Rolling average of measured daily loads accounting for time between sampling dates
c. Summer is defined as June through September

Comparison of the load transfers shows how the hydroconnections play a role in the function of the overall Mill Pond system. Walkers Pond transferred 55.1 kg to Upper Mill Pond during the 2012 Water Year and Upper Mill Pond added additional phosphorus to increase the transfer load to Lower Mill Pond to 115.6 kg. The load to Stony Brook from Lower Mill Pond is then reduced to 65.6 kg, likely because of hydrologic transfer of pond water to the surrounding groundwater prior to discharge through Stony Brook (see Section IV). During the summer, transfers are significantly reduced to 18% to 25% of the year-round loads.

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[114] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013.

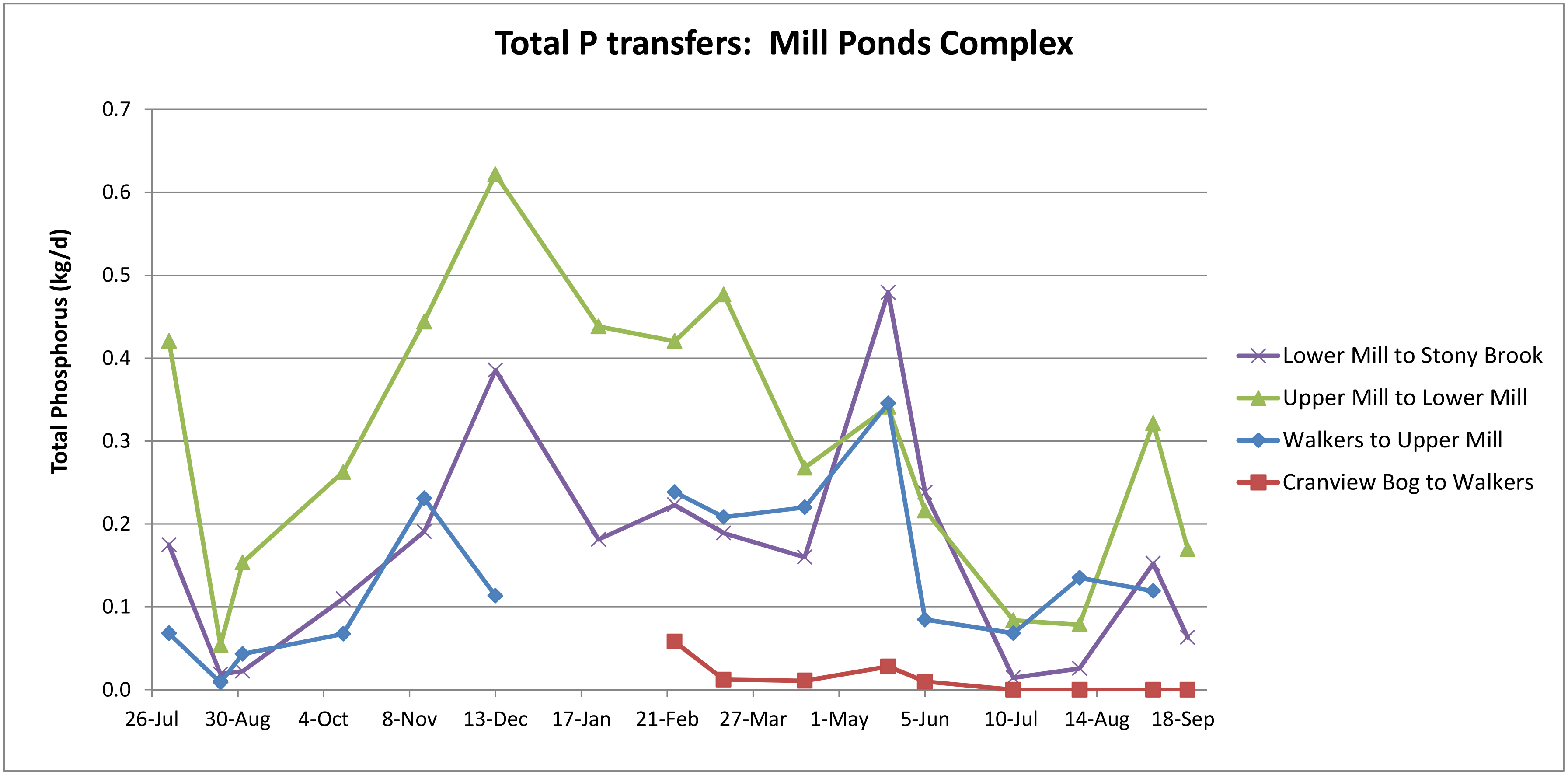

Figure V-3. Total Phosphorus Loads through hydroconnections between ponds in the Mill Ponds Complex.
Total phosphorus loads were determined on a monthly basis from August 2, 2011 through September 20, 2012 at the connections between: a) the cranberry bog south of Cranview Road and Walkers Pond, b) Walkers Pond and Upper Mill Pond, c) Upper Mill Pond and Lower Mill Pond, and d) Lower Mill Pond and Stony Brook. The connection between the Cranview Bog and Walkers Pond had no water flow beginning in July 2012. Average water year loads are: Cranview Bog to Walkers Pond, 0.017 kg/d; Walkers Pond to Upper Mill Pond, 0.160 kg/d; Upper Mill Pond to Lower Mill Pond, 0.317 kg/d, and Lower Mill to Stony Brook, 0.185 kg/d. Summer loads are significantly lower. Modified from Figure 10 in 2013 CSP/SMAST Technical Memorandum.

V.C. In-lake Phosphorus Loading/Sediment Phosphorus Regeneration Measurements

Sediment regeneration of nutrients regularly occurs in ponds, as organic detritus (usually phytoplankton) settle to the bottom and are consumed and recycled by sediment bacteria. The consumption of the detrital material breaks it down into its constituent chemicals, including nutrients. Some of the chemicals are bound together into solid precipitates and are buried in the sediments, while others are recycled into the overlying pond water column. If the sediment bacterial population consumes more oxygen than is available in sediments during this normal biodegradation, redox conditions in the sediments can change from oxic conditions to hypoxic or even anaerobic conditions. During these redox transitions, chemical bonds in compounds that are solid during oxic conditions can break and the constituents can be re-released into the water column. This kind of transition occurs when dissolved oxygen concentrations drop in near-sediment waters. Phosphorus is particularly susceptible to release from solid compounds when oxygen levels drop. In these situations, phosphorus solids, such as strengite ($FePO_4 \cdot 2H_2O$), which has an iron:phosphorus bond, are broken into their component parts and phosphorus is released from the sediments into the overlying water column.

These relationships can be further complicated by aquatic plants/macrophytes and mussels. Extensive macrophyte populations can alter nutrient cycling by favoring settling of suspending particles within beds, but also can increase the transfer of otherwise buried sediment phosphorus to the plants and, during aerobic decay of above-ground parts, to the water column.[115] Some research has found that macrophyte beds are net sources of phosphorus to the water column.[116] Mussel impact on phosphorus cycling is not well studied, but extensive populations have been shown to decrease phosphorus available to phytoplankton.[117] 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 the potential sediment nutrient regeneration within Walkers Pond, Upper Mill Pond, and Lower Mill Pond, CSP/SMAST staff collected and incubated sediment cores in each of the ponds. The incubation process moves the sediments through the various redox cycles and measures the nutrient release. During the CSP/SMAST targeted data collection,[118] staff also collected sediment cores on August 8, 2011 at three locations in Walkers Pond, five locations in Upper Mill Pond, and four locations in Lower Mill Pond (Figure V-4). These undisturbed sediment cores were collected by SCUBA diver and were incubated at *in situ* temperatures to evaluate nutrient regeneration from the sediments under oxic and anoxic conditions. Three rounds of water quality samples were also collected to evaluate water quality conditions before, during, and after the collection of the cores: August 2, August 8, and August 23. Duplicate cores were also collected at one location in each pond for quality assurance/quality control purposes. The sediment regeneration measurements were undertaken based on the recommendation in 2009 Brewster Ponds Report to measure sediment recycling of nutrients in order to have pond-specific data for development of management strategies.[119]

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

[116] 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.

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

[118] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013.

[119] Eichner, E. 2009. Brewster Freshwater Ponds

Latitude	Longitude	Site	Latitude	Longitude	Site
41 43.488	-70 7.504	Walkers1	41 44.422	-70 6.696	Lower Mill1
41 43.325	-70 7.508	Walkers2	41 44.513	-70 6.675	Lower Mill2
41 43.325	-70 7.508	Walkers3 FD	41 44.432	-70 6.545	Lower Mill3
41 43.229	-70 7.712	Walkers4	41 44.432	-70 6.545	Lower Mill4 FD
41 43.700	-70 7.377	Upper Mill1	41 44.477	-70 6.459	Lower Mill5
41 43.752	-70 7.119	Upper Mill2			
41 43.708	-70 7.207	Upper Mill3			
41 43.708	-70 7.207	Upper Mill4 FD			
41 43.947	-70 6.846	Upper Mill5			
41 44.068	-70 6.64	Upper Mill6			

Figure V-4. Sediment core locations in Walkers, Upper Mill, and Lower Mill ponds. Sediment cores were collected on August 8, 2011 from the indicated locations. Cores were incubated under both aerobic and anoxic conditions. Duplicate cores were collected at one location in each pond for QA/QC purposes. Modified from Figure 2 in 2013 CSP/SMAST Mill Ponds Technical Memorandum.

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 are incubated to first sustain aerobic conditions, matching conditions when oxygen conditions are near atmospheric equilibrium throughout the water column. Dissolved oxygen is then removed and sediment conditions move through a redox sequence that begins with chemical release (severing of weak chemical bonds) and ends with anoxia, similar to water column conditions where dissolved oxygen concentrations drop to less than 1 mg/L. The laboratory followed standard methods for analysis and sediment geochemistry as currently used by the Coastal Systems Analytical Facility at SMAST-UMass Dartmouth.

Cores from Walkers Pond showed higher sediment oxygen demand than either of the Mill Ponds and Upper Mill Pond had higher sediment oxygen demand than Lower Mill Pond (WP>UMP>LMP) (Table V-4). The observed rates of sediment oxygen uptake are much higher than measured in deeper ponds in the region[120], likely indicating a higher organic carbon/nutrient load to the sediments in these shallow basins from phytoplankton plus macrophytes and some relationship to the varying residence times. Because of the regular mixing of the whole water column, shallower ponds also have readily available atmospheric oxygen to address sediment demand. Photosynthesis from a vigorous phytoplankton population can also provide additional oxygen to address the demand. These interactions can help to forestall low oxygen events in the water column provided adequate wind-driven mixing is maintained and nutrient loads do not overwhelm this replenishment.

During the aerobic portion of the core incubation, Upper Mill Pond had the greatest aerobic inorganic phosphorus release (driven by aerobic decomposition), while Walkers Pond had the lowest (see Table V-4). During the anaerobic portion of the incubation, these conditions switch with the greatest chemical and anaerobic phosphorus releases in Walkers Pond and the least in Upper Mill Pond. This flip of phosphorus release depending on oxygen availability likely results from the generally aerobic conditions in the bottom water of Walkers Pond compared to the other two ponds (see Figure III-1). The result is that these sediments store greater amounts of inorganically-bound phosphorus than the other ponds, which also shows up in the chemical release rates in Walkers that are approximately 2X the rates in the other two ponds. These rates suggest that the cause of the Walkers Pond blue-green algal bloom in 2011 likely was due to a large pulse of inorganic phosphorus release from the sediments caused by an anoxic event, likely associated with cloudy, quiescent wind weather conditions. The 2012 continuous DO readings show that Walkers Pond was generally aerobic with only periodic hypoxic levels. While these levels do affect the thickness of the sediment oxidized layer trapping inorganic phosphorus, it is typically too elevated to cause a large chemical release. However, this record also indicate that hypoxic events can be sustained long enough to allow a substantial sediment phosphorus release; DO concentrations dropped below a hypoxic 5 mg/L in Walkers Pond for 5.5 hours.[121]

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[120] *e.g.*, Eichner, E., B. Howes, and D. Schlezinger. 2012..

[121] This event occurred from 6:16 AM to 11:46 AM on August 10, 2012.

The chemical release rates in all the ponds are significantly higher ($\rho<0.05$) than the aerobic or anaerobic release rates. The difference between chemical release and anaerobic conditions shows that the initial transition to anaerobic conditions will release phosphorus into the water column at rates 2-8 times higher than the anaerobic conditions that follow. The switch to these conditions, likely occurs in the two shallower ponds during quiescent wind periods. In Upper Mill Pond, which is deeper, the chemical release events are likely to occur more frequently or early in the summer (as indicated by the regular anoxia in the continuous monitoring). More frequent events would tend to deplete the sediment storage pool making later events release a lower mass of P per unit area; a similar effect would be seen with a larger early summer release and subsequent depleted releases throughout the rest of the summer. The larger volume in this pond also tends to make the concentration increases associated with events smaller. Even so, chemical release conditions in the sediments of Walkers Pond for a few hours would release more TP than birds, fertilizers, or runoff add to the pond in a year. The next sufficient wind gust would mix that load throughout the water column. The sediment incubation results also show the secondary nutrient role that nitrogen plays in freshwater ponds: ammonia-nitrogen releases were relatively consistent among the ponds.

Net release of phosphorus from sediments is dependent on the balance between the P released from the sediments and the amount of P settling to the sediments from the water column. Water column nutrient concentrations at the time of the core collection were generally much higher than August/September average water-column conditions seen in the 2001 to 2013 water quality dataset. Clarity and dissolved oxygen generally were within one standard deviation of long term averages (2001 to 2013) in Upper and Lower Mill Ponds, but clarity in Walkers Pond matched the historic minimum recorded clarity (0.4 m). Surface TP and TN concentrations in Walkers and Upper Mill were all higher than average: Walkers Pond surface TP was above the 90th percentile and Upper Mill was above the 75th percentile. Lower Mill Pond levels, on the other hand, were generally consistent with past August/September averages/medians. Deep concentrations generally had similar patterns, although concentrations in Upper Mill Pond were exceptionally high; greater than two standard deviations above the mean, 4X to 6X higher than the historic averages. These concentrations are consistent with the anoxia (<1 ppm dissolved oxygen) recorded near the sediments in Upper Mill Pond. Although these conditions were recorded 23% of the time in the continuous recordings, these were not average conditions. The anoxia, in particular, combined with extremely high total phosphorus (TP) concentrations appears to show that Upper Mill Pond released a portion of its sediment phosphorus prior to the core collection. Close review of the Walkers Pond data does not seem to show similar situation.

Table V-4. Walkers Pond, Upper Mill Pond, and Lower Mill Pond Sediment Nutrient Release August 2011.

Sediment cores were collected at three sites in Walkers Pond, five sites in Upper Mill Pond, and four sites in Lower Mill Pond during August 2011. Cores were incubated at temperatures consistent with water temperatures at the time of core collection. Cores were incubated to measure nutrient release under both aerobic and anaerobic conditions with particular focus on the anaerobic, chemical release phase. Sediment release rates below represent averages of multiple (4-6) samples during each phase. Note that cores were collected at different depths and sites (*i.e.,* are not replicates), which is reflected in the observed rates. Net sediment release rates reflect balance between sediment flux release rates and settling of particulates from the water column. Net releases phosphorus release rates for Walkers Pond and Upper Mill Pond are based on median water column concentrations to account for sediment release at the time of the core collection. Lower Mill Pond net releases are based on water quality data at the time of collection; water quality at the time of collection generally matched average conditions. Modified from Table 1 in 2013 CSP/SMAST Mill Ponds Technical Memorandum.

Pond	Site	Latitude	Longitude	Water Depth	Sediment Oxygen Demand	Aerobic Flux Rate				Total Phosphorus		Net Total Phosphorus Release Rate		
						Ammonium Nitrogen	Total Nitrogen	Inorganic Phosphorus	Total Phosphorus	Anaerobic Release Rate	Chemical Release Rate	Aerobic	Chemical Release	Anaerobic
				m	mMoles/m²/d	µMoles/m²/d	µMoles/m²/d	µMoles/m²/d	µMoles/m²/d	µMoles/m²/d	µMoles/m²/d	kg/d	kg/d	kg/d
Walkers	1	41 43.488	70 7.504	2.15	206	4,754	6,030	26	70	23	573	-0.82	3.05	-0.87
	2	41 43.325	70 7.508	2.30	148	3,351	4,338	73	92	35	299			
	3	41 43.325	70 7.508	2.30	182	3,746	4,482	7	20	98	260			
	4	41 43.229	70 7.712	1.95	107	3,450	2,644	3	8	16	327			
Upper Mill	1	41 43.700	70 7.377	4.45	18	1,810	2,001	8	56	29	186	0.28	4.33	-1.30
	2	41 43.752	70 7.119	7.73	115	5,130	6,636	55	78	45	219			
	3	41 43.708	70 7.207	7.00	127	3,009	2,622	165	140	11	528			
	4	41 43.708	70 7.207	7.00	89	3,759	2,948	130	137	9	343			
	5	41 43.947	70 6.846	8.24	191	3,608	3,898	132	153	12	131			
	6	41 44.068	70 6.64	7.96	69	5,791	4,267	48	40	57	276			
Lower Mill	1	41 44.422	70 6.696	3.00	77	2,357	1,929	79	59	29	238	0.39	1.17	-0.42
	2	41 44.513	70 6.675	3.04	63	3,857	3,720	70	113	25	228			
	3	41 44.432	70 6.545	3.65	147	6,028	6,026	89	322	53	384			
	4	41 44.432	70 6.545	3.65	115	7,341	6,857	138	301	79	440			
	5	41 44.477	70 6.459	3.63	82	4,814	5,270	43	90	17	247			

Overall, the net sediment phosphorus release calculations show that the chemical release phase in all three ponds results in a net addition to the water column (see Table V-4). Walkers Pond has the greatest net chemical release rate, followed by Lower Mill, and then Upper Mill. Sensitivity analysis to account for prior chemical release from Upper Mill sediments increases its rate above Walkers release rate. A check of Upper Mill Pond deep water column total phosphorus concentrations around the core collection date show that the TP mass in the deeper waters increased by ~3.5 kg/d; this rate is approximated if median TP concentrations from the water quality dataset are used with the sediment release data. This finding would seem to support the hypothesis that Upper Mill Pond sediments had already moved into a chemical release phase, at least periodically, around the time that the cores were collected.

Further review of core data show that under aerobic conditions, Walkers Pond sediments are retaining phosphorus, while the other two ponds are releasing phosphorus at a low rate. Under anaerobic conditions, net sediment TP release in all three ponds favors retention (see Table V-4). This finding is the result of very low additional TP release and high settling rates due to high water column concentrations. Overall, the data shows that most of the sediment phosphorus is contained in rapidly released, chemical release forms and that these “fast twitch” release conditions can release loads in a number of days that are higher than annual watershed loads. Therefore management actions need to take this anaerobic release into account.

V.D. Individual Pond Phosphorus Budgets

A phosphorus budget provides a baseline for development of management strategies. Just as a water budget accounts for all the various sources of water and how it is transferred into and out of a pond, a phosphorus budget provides the same balancing, but is much more complex because of all the various sources/inputs, how some sources are also sinks depending on conditions, and how seasonal factors may influence the balancing of the budget.

V.D.1. Walkers Pond

As mentioned in Section V.1., Walkers Pond averages 50 kg of TP in its water column with a median mass of 43 kg and a 25th percentile mass of 33 kg. The variability in the average, which is mostly August and September data, is 70%, which indicates a large amount of variability even during similar months. The average annual residence time of Walkers Pond is 154 days, so in order to maintain a given TP mass within the pond, the equivalent mass needs to be added to the pond every 154 days.

Based on the combination of measured and estimated inputs, 2.7 to 4.6 kg of watershed phosphorus loads are added to Walkers Pond during its 154 day residence time (see Table V-2). According to the measured annual hydroconnection data, the flow from the cranberry bog south of Cranview Road adds an annualized 2.6 kg within the residence time, but this drops to 0.5 kg during the residence time that includes the summer. Walker Pond discharges 24.5 kg P into Upper Mill Pond during Walkers' residence time during both year-round conditions and during the summer.

In order to balance the inputs and outputs and maintain the measured mass in the pond, an internal source (*i.e.*, sediments, mussels and/or macrophytes) within Walkers Pond would have to add the remaining phosphorus mass. These sources would add between 68-70 kg based on average pond TP mass and 50-52 kg based on 25th percentile mass (Figure V-5). These TP loads work out to 0.44-0.45 kg/d and 0.32-0.34 kg/d, respectively. Since the mussel population is relatively sparse, this was ruled out as a potential source. These estimated rates would be approximately 10-15% of the measured sediment phosphorus chemical release rate. However, attaining the chemical release phase would require sustained hypoxic/anoxic conditions and these were not measured except during rare occurrences in either the continuous monitoring or the long-term snapshots. The remaining potential source would be the macrophyte stands, which have >80% density around the whole pond shoreline and at 1.5 m depth or less (see Figure IV-7). In order to provide the required mass in the water column, the stands would need to provide between 3.8×10^{-4} and 5.1×10^{-4} kg/m^2/d during the residence time.

Research on sediment nutrient release under macrophyte stands has produced a mix of results that seem to indicate that release varies depending on water quality conditions, macrophyte composition, and age and density of the macrophyte stands. Extensive macrophyte stands seem to buffer TP mass within ponds, acting as a sink or source of TP depending on inputs from other sources.[122] Macrophytes can provide nutrient and clarity stability in clear water

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

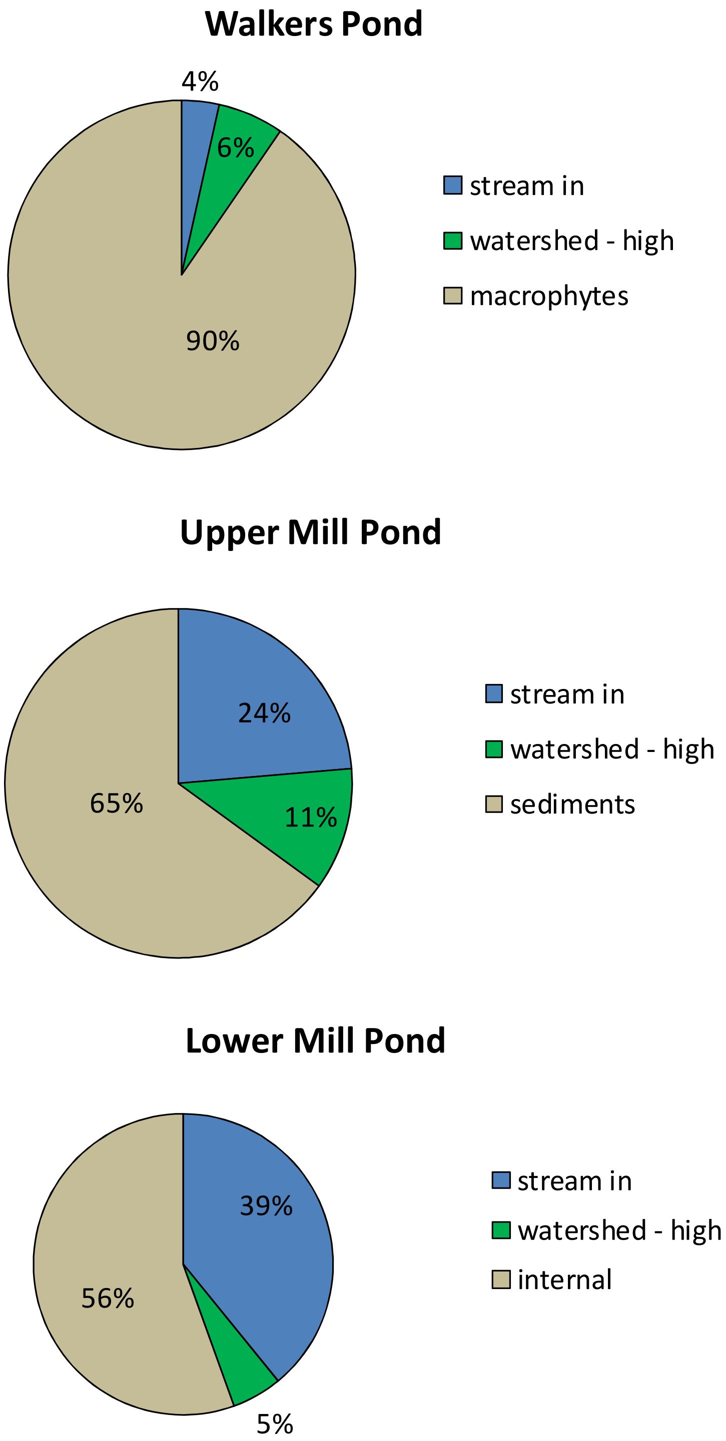

Figure V-5. Overall Phosphorus Budget for Walkers Pond, Upper Mill Pond, and Lower Mill Pond. Watershed loads include measured stream loads, stormwater runoff and mass within each pond. High watershed loading estimates are used and developed from a range of factors. Stream loads are generally based on annual measured loading collected in the 2011-2012 water year except for Lower Mill Pond which is based on summer loads. Internal loads are based on difference between measured pond mass and stream and watershed inputs. All loads are based on water residence times developed from the water budget.

settings,[123] but some studies show that older, dense stands can become significant internal sources of phosphorus.[124] Dense canopies can create high organic loads to the sediments; some research has indicated that aerobic decay of plant material releases significant phosphorus.[125,126]

Given that most of the expected use of Walkers Pond occurs during summer and usual weather conditions would tend to favor better water quality conditions during the winter, development of a phosphorus budget and subsequent management strategies should focus on summer conditions. The available water quality data shows that the pond has impaired water quality across a range of metrics: 1) high TP, TN and chlorophyll concentrations, 2) low clarity, and 3) regular DO concentrations exceeding atmospheric saturation. Review of nutrient data, shows that phosphorus is the controlling nutrient, while review of the potential sources shows that the macrophytes are the likely primary source of phosphorus in Walkers Pond. Macrophytes cycling P represent 90-93% of the loading to the pond waters as P is released during senescence and decay.. Management strategies should focus on controlling macrophyte phosphorus contributions.

V.D.2. Upper Mill Pond

As mentioned in Section V.1., Upper Mill Pond averages 158 kg of TP in its water column with a median mass is 137 kg, while the 25th percentile among this data of 112 kg. Variability in the TP mass is 41% with most of the variability in the deeper waters; there is a significant ($\rho<0.05$) difference between shallow and deep TP concentrations and deep mass has a variability of 109%. This type of variability should be expected even though almost all the readings are from August and September given the measured fluctuations in the anoxic dissolved oxygen concentrations. All of these observations are consistent with periodic anoxia and chemical release events.

Upper Mill Pond receives water and phosphorus inputs from its own watershed, as well as flow and load inputs through the hydroconnection from Walkers Pond. It also discharges pond water and nutrients through the downstream hydroconnection to Lower Mill Pond. Upper Mill Pond is deeper than Walkers Pond and has roughly 8 times its volume. In large part because of this greater volume, Upper Mill Pond has residence time of 441 days (~15 months). As such, the water quality measurements within the pond are influenced by both current conditions and conditions that occurred more than one year ago.

In order to maintain a given TP mass within the pond, the equivalent mass needs to be added to the pond during each residence time period. Based on the combination of measured and estimated inputs, between 21 and 34 kg of watershed phosphorus are added to Upper Mill Pond each 441 days (see Table V-2). According to the measured hydroconnection data, the flow from the Walkers Pond adds 70 kg TP within the Upper Mill Pond residence time and 140 kg TP leaves the pond and discharges into Lower Mill Pond.

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[123] Jeppesen, E. & Søndergaard, M., Søndergaard, M. & Christoffersen, K. (1997) The Structuring Role of Submerged Macrophytes in Lakes. Ecological Studies Series 131. Springer Verlag, New York, NY.

[124] Scheffer, M. and E.H. vanes. 2007. Shallow lakes theory revisited: various alternative regimes driven by climate, nutrients, depth and lake size. *Hydrobiologia*. 584: 455-466.

[125] Carpenter, S.R. and Lodge, D.M., 1986.

[126] Søndergaard, M., J.P. Jensen, and E. Jeppesen. 2003. Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia*. 506-509: 135-145.

Similar to Walkers Pond, Upper Mill Pond also has a seasonal fluctuation in streamflows, both in and out. Review of streamflow data seems to indicate 4-5 months of reduced flows. Water flow readings show that four month, summer discharge from Walkers Pond drops by 36%, while summer discharge from Upper Mill Pond to Lower Mill Pond drops by 33%. It is likely this is accompanied by a drop in water level and volume of the pond, but measurements do not exist to quantify this change. If the volume remained roughly the same, and groundwater levels seem to indicate this, the adjusted residence time would increase to an annually adjusted 626 days. These summer conditions mean that water is held longer, but since the general residence time is longer than one year, the seasonal impact is somewhat muted. Review of measured stream loads indicates that the ratio between entering and leaving loads tilts slightly toward the entering mass, but the impact is nominal.

In order to balance the inputs and outputs and maintain the measured mass in the pond, an internal source (*i.e.*, sediments, mussels and/or macrophytes) within Upper Mill Pond would have to add the remaining phosphorus mass (see Figure V-5). This source would add between 193-206 kg based on average pond TP mass and 148-161 kg based on 25th percentile mass. These masses work out to 0.44-0.47 kg/d and 0.34-0.36 kg/d, respectively. Since the macrophyte population is relatively sparse, this was ruled out as a potential source. Most reviews of mussel P cycling in whole-lake nutrient dynamics seem to show that they reduce nutrient levels subject to overall water quality conditions.[127] In contrast, the estimated rates would be approximately 10-15% of the measured sediment phosphorus chemical release rate. And this primary watercolumn source is consistent with the regular hypoxia and frequent anoxia that was measured by the continuous monitoring in 2012 and the longer-term snapshots (see Section III).

Given that most of the expected use of Upper Mill Pond occurs during summer and usual weather conditions would tend to favor better water quality conditions during the winter, development of a phosphorus budget and subsequent management strategies should focus on summer conditions. The available water quality data shows that the pond has impaired water quality across a range of metrics: 1) high TP, TN and chlorophyll concentrations, 2) low clarity, and 3) regular near bottom anoxia and surface DO concentrations exceeding atmospheric saturation. Review of nutrient data, shows that phosphorus is the nutrient controlling plant productivity, while review of the potential sources shows that the sediments are the primary source of phosphorus in Upper Mill Pond. Sediments are 65% to 69% of the loading to the pond, but the input from Walkers Pond is also a substantial source (24% of TP loadings to the pond)(see Figure V-5). Management strategies should focus on controlling sediment phosphorus regeneration, but surface water inputs from Walkers Pond may also play an important role in phosphorus management. Because of the influence of Walkers Pond water quality on Upper Mill Pond, water quality management improvements in Walkers Pond will also benefit Upper Mill Pond.

V.D.3. Lower Mill Pond

As mentioned in Section V.1., Lower Mill Pond averages 23 kg of TP in its water column with a median mass is 21 kg, while the 25th percentile among this data of 15 kg. Variability in

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

the TP mass is 42% with most of the variability in the deeper waters. There is a significant ($\rho<0.05$) difference between shallow and deep TP concentrations, which indicates sediment TP regeneration. Almost all TP data (95%) is from August or September.

Lower Mill Pond receives water and phosphorus inputs from its own watershed, as well as flow and load inputs through the hydroconnection from Upper Mill Pond. It also discharges pond water through the downstream hydroconnection to Stony Brook. Lower Mill Pond is shallower than Upper Mill Pond, but deeper than Walkers Pond and has volume that is roughly 75% of Walkers Pond. Given its location at the downgradient edge of a large watershed and with a relatively small volume, it has a comparatively short residence time of 38 days. As such, the water quality measurements within the pond can change from month to month and within a season or year.

Review of the measured streamflow data shows that summer inflows (June to September) of water and phosphorus drop 33% and 45%, respectively. Because of this drop, the residence time of Lower Mill Pond would increase from 38 days to 78 days during the summer. Summer increases in residence times also happen in the other two ponds, but it is more impactful in Lower Mill Pond because of its usual short year-round residence time. Additional non-summer pond water quality data would be needed to resolve the annual vs summer conditions.

In order to maintain a summer TP mass within the pond, 23 kg needs to be added to the pond every 78 days during the summer. Based on the combination of measured and estimated inputs, 1.6 to 2.0 kg of watershed phosphorus loads would be added during summer residence time. According to the measured hydroconnection data, the TP loading rate from the Upper Mill Pond and out through Stony Brook/back to groundwater are balanced, both are 14.8 kg TP within the summer residence time.

In order to balance the inputs and outputs and maintain the measured mass in the pond, an internal source (i.e., sediments, mussels and/or macrophytes) within Lower Mill Pond would have to add the remaining phosphorus mass (see Figure V-5). This source would add approximately 21 kg during the summer, which works out to 0.25 kg/d during the summer residence time.

Lower Mill Pond has macrophyte and mussel densities that are between the other two ponds; *i.e.*, more mussels than Walkers, but less than Upper Mill and more macrophytes than Upper Mill, but less than Walkers (see Section IV.B.). Water column DO readings show regular hypoxia close to the sediments, but no significant anoxia (<1 mg/L) (see Section III.D.1). Review of the sediment core incubations show that attaining 0.25 kg/d is at the upper end of the measured chemical release rates from the incubated cores (see Table V-3), so this combined with the general lack of chemical release conditions in the water column over the sediments suggest that the sediments are not the primary source of the internal TP loading. Closer review of reasonable particle settling rates, however, suggests that TP particles in the upper water column would not reach the bottom within an average residence time. This finding suggests that water quality conditions during the non-summer portions of the year are more influenced by the sediments than during the summer. Review of the macrophyte densities show that densities are roughly half of those in Walkers Pond. In order to attain the necessary TP addition, rates from these less dense stands would need to average nearly 3X the estimated input from the Walkers Pond stands. Review of mussel contributions generally show cleansing of nutrients from water columns, but only when ponds have long residence times and mussel biomass is large.[128] However, some studies have indicated that mussels may serve as a nutrient source if the population is declining. This review reinforces the conclusion that water quality conditions in Lower Mill Pond are extremely variable with a host of potential nutrient sources and changeable hydrologic conditions.

Given that most of the expected use of Lower Mill Pond occurs during summer and usual weather conditions would tend to favor better water quality conditions during the winter, development of a phosphorus budget and subsequent management strategies should focus on summer conditions. The available water quality data shows that the pond has impaired water quality across a range of measurements: 1) high TP, TN and chlorophyll concentrations, 2) low clarity, and 3) regular near bottom hypoxia and surface DO concentrations exceeding atmospheric saturation. Review of nutrient data shows that phosphorus is the controlling nutrient for plant growth, hence eutrophication. Review of the potential phosphorus sources shows that an internal source of nutrients is largely determining summer conditions (56%), but inputs from Upper Mill Pond also play a significant role (39%). Based on the uncertainty of the Lower Mill Pond phosphorus balance, it is suggested that management strategies should focus initially on surface water inputs from and impacts of management strategies in Upper Mill Pond with monitoring to assess the benefits in Lower Mill Pond. It is expected that this type of adaptive management approach will help to clarify the future management strategies and options for Lower Mill Pond.

VI. Water Quality Management Goals and Management Options

Walkers Pond, Upper Mill Pond, and Lower Mill Pond have impaired water quality conditions across a number of measures. These tend to be ecological concerns, but occasional lack of sufficient clarity for safe swimming, especially in Upper Mill Pond, which has a town beach, is a concern as well. The primary cause of these impairments is excessive phosphorus. Excessive phosphorus is also concern because it may establish conditions that favor blue-green algal blooms; blue-greens produce toxins that can cause skin and eye irritation, rashes and other allergic reactions and have caused several dog deaths due to consumption.[129] Sediments are the primary source of phosphorus in all three ponds, although inputs from upstream ponds grow in importance as the system flows toward Stony Brook. Since regulatory target thresholds for phosphorus have not been established in Massachusetts, restoration of these ponds is somewhat open to definition by the Town of Brewster.

As mentioned previously, potential Cape Cod-specific TP thresholds were developed by the Cape Cod Commission using the initial PALS Snapshot data and an EPA regional threshold determination method.[130] These thresholds were 7.5 to 10 µg/L. In contrast, MassDEP's only freshwater pond TMDL in the Cape Cod Ecoregion over the past 10 years assigned a 19 µg/L TP regulatory limit. Attaining any of these concentrations will require significant reductions in the

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[128] Vaughn, C.C. and C.C. Hakenkamp. 2001.

[129] Massachusetts Department of Public Health (https://www.neiwpcc.org/neiwpcc_docs/protocol_MA_DPH.pdf) or California Department of Public Health (http://www.cdph.ca.gov/healthinfo/environhealth/water/pages/bluegreenalgae.aspx)

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

mass of phosphorus in the ponds: reduction of 72-86% in Walkers Pond; 31-64% in Upper Mill Pond, and 54-76% in Lower Mill Pond.

For the purposes of evaluating management options, CSP/SMAST staff used 10 µg/L total phosphorus as the planning concentration threshold. This threshold appears to be most appropriate based on Cape Cod-specific data and reviews of water quality and impairments in other Cape Cod ponds. At this concentration, the acceptable mass in each pond would be: Walkers Pond, 7 kg; Upper Mill Pond, 57 kg, and Lower Mill Pond, 6 kg. The average mass reductions to attain these loads would be: 86%, 64%, and 76%, respectively.

In order to attain the necessary phosphorus reductions, the primary sources to be managed are internal sources in all three ponds. Based on phosphorus budget details, the primary internal source in Walkers Pond is the extensive macrophyte stands, while the primary internal source in Upper Mill Pond is the sediments. The internal source in Lower Mill Pond is unresolved. Since loads from the hydroconnections between the ponds are also significant, especially in the discharge into Lower Mill Pond, there is an opportunity to implement and then evaluate the benefits of management activities in upstream ponds on Lower Mill Pond. Watershed inputs tend to be tertiary sources of phosphorus within the current pond configurations, but control of these sources will also provide long-term water quality benefits.

VI.A Sediment Phosphorus Controls

Among the three ponds, Upper Mill Pond is the only one where sediments are clearly the primary phosphorus source in the pond. The other two ponds have significant sources of rapidly released sediment phosphorus, but due to acceptable or high dissolved oxygen conditions, releases from the sediments are not generally a significant source. However, Walkers Pond has the greatest potential for sediment release creating phytoplankton blooms. For these reasons, CSP/SMAST staff reviewed potential management strategies to reduce potential sediment nutrient regeneration in both Upper Mill Pond and Walkers Pond.

Reductions in sediment nutrient regeneration in ponds are generally addressed through one of three approaches: a) sediments and their associated nutrients can be removed from the pond via dredging, b) regeneration of nutrients from the sediments can be inhibited through the application of chemicals, such as aluminum, that will bind the phosphorus or c) through the addition of more oxygen to facilitate chemical binding between phosphorus and the iron particles that are already present. Each of the approaches has varying costs, ease of implementation issues, permitting challenges, and applicability to each pond.

VI.A.1 Dredging in Upper Mill and Walkers Ponds

Removal of the sediments would remove much of the sediment oxygen demand, much of the sediment phosphorus, and restore the lake to conditions that existed before any monitoring occurred. Dredging that removed 90% of the sediment phosphorus regeneration from Upper Mill Pond, would allow the pond to meet a 10 µg/L TP threshold and be restored. One major problem with dredging is that P regeneration rates depend on both the rate of deposition and the sediment storage. Dredging will address the storage, but will not address the on-going deposition as the watershed and pond transfer P loads continue to be added to the pond. After a few years (maybe 5-10 years), sediment P regeneration rates will rise based on newly deposited P and additional dredging would have to be considered.

Equally problematic, sediment removal is technically complicated and difficult to permit. Sediment removal from freshwater ponds has not been used extensively in Massachusetts and does not appear to ever have been used on Cape Cod.[131] Removal of sediments in off-Cape lakes typically is accompanied by a drawdown in the level of the lake, so sediments can be more easily accessed by large equipment. In an unconfined aquifer system like the Cape, 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 of a pond on the Cape would be technically arduous as the surrounding aquifer would replenish withdrawn water and attempt to maintain the general water level of the aquifer. Dredging would also require at the very least securing a dewatering area and a sediment disposal location, testing of the sediments for metals and hydrocarbons, and accommodations to protect/restore the mussel populations. This effort would also require difficult permitting with both state agencies and local boards, largely because of its general lack of use in Massachusetts. Dredging would also require additional evaluation of sediment characteristics in order to evaluate disposal options, size the dewatering areas for the dredged sediments, and evaluate equipment demands. It is conceivable that the town could utilize the Barnstable County dredge to assist in the dredging, but this this has not been done before and would require transportation costs to move the dredge from its current salt water docking to the pond. Based on the dissolved oxygen profiles, bathymetric data and the depth of the cores, CSP/SMAST staff estimated that dredging would occur at depths of >2 m in Walkers Pond and >6 m in Upper Mill Pond. Based on the factors in Table VI-1, the low end cost estimate for sediment dredging in Upper Mill Pond is $21.8 million, while the low end cost for Walkers Pond is $6.9 million. High end cost estimates would be more than double these estimates. Because of these costs, dredging is not recommended.

Table VI-1. Dredging Cost Estimates for Mill Pond of Sediment P Removal

Pond	units	Walkers	Upper Mill
Pond Area	m2	393,469	982,031
Depth to be dredged	> m	2	6
Dredge Area	m2	176,926	555,773
Depth of sediments	m assumed	0.5	0.5
Dredge material	m3	88,463	277,886
Low Dredge Cost	$/cubic yd	$ 30	$ 30
High Dredge Cost	$/cubic yd	$ 60	$ 60
Low Overall Cost	$	$ 3,471,149	$ 10,903,846
High Overall Cost	$	$ 6,942,299	$ 21,807,692

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[131] 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.

VI.A.2. Phosphorus Inactivation: Chemical Addition in Upper Mill and Walkers Ponds

Sediment phosphorus inactivation through chemical addition is typically attained by adding salts of aluminum, iron, or calcium that chemically bind with the phosphorus and form solid precipitates that sink to the bottom of the pond. There are some other, recently developed, chemical treatments that are being evaluated, such as lanthanum[132], but most of these have not seen extensive use in natural systems at this point. In contrast, alum has a long track record. Alum reacts with inorganic phosphorus and precipitates/solids that are not sensitive to redox conditions, so aluminum additions can be used in anoxic settings. Typically, 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 and forming solids which are unstable in anoxic environments; more iron will not resolve these binding issues. 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 pH's above 8 (Stumm and Morgan, 1981). For these reasons, application of aluminum for phosphorus inactivation is typically favored in Cape Cod water conditions.

Alum applications, typically a mix of aluminum sulfate and sodium aluminate, have been used at a number of Cape Cod ponds, including: Ashumet Pond in Mashpee/Falmouth, Hamblin Pond and Mystic Lake in Barnstable, Long Pond in Brewster/Harwich, and Lovers Lake/Stillwater Pond in Chatham. Follow-up monitoring of each of these applications has generally showed reduced phosphorus regeneration and reduced sediment oxygen demand. The Hamblin Pond treatment, which occurred in May 1995, increased dissolved oxygen concentrations above the MassDEP 6 ppm threshold for 4 meters worth of water that was anoxic prior to the treatment and this restoration was sustained through at least 2006.[133] Surface TP concentrations in Hamblin Pond were reduced by 85%. Alum applications generally work for 10 or more years with variability dependent on the features of the pond, the application process and dose, and the control of external watershed loads. Aluminum sulfate and sodium aluminate are generally used in a 2:1 mix to buffer pH reductions that would occur if only aluminum sulfate was used. At low pH's (<6), aluminum tends to become soluble and unbound Al(III) is toxic to fish at high enough concentrations.[134] For this reason, buffering, which is achieved through balancing the mix of aluminum salts, is especially important in Cape Cod lakes, which have naturally low pH and little alkalinity.

Since sediments are such a significant phosphorus source in Walkers Pond and Upper Mill Pond, alum applications offer the opportunity to meet various potential TP thresholds and flexibility in management option for other phosphorus sources. For example, if an alum application in both ponds removed 80% of the sediment regeneration, all ponds could attain a 19 µg/L TP threshold with no other phosphorus management activities. As another example, if a 10 µg/L TP threshold was attained in Walkers Pond[135] and an alum application removed 80% of

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[132] Gibbs, M.M., C.W. Hickey, and D. Özkundakci. 2011. Sustainability assessment and comparison of efficacy of four P-inactivation agents for managing internal phosphorus loads in lakes: sediment incubations. *Hydrobiologia*, 658: 253-275.

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

[134] 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.

[135] Can be attained a number of ways. Example: removal of phosphorus inputs from of stream and watershed and alum application to remove 84% of sediment regeneration.

Upper Mill phosphorus, it is conceivable that Lower Mill sediments would eventually naturally reduce their phosphorus regeneration by 70%.

Costs for alum applications typically include the cost of aluminum, pre-treatment dosage refinements, and equipment mobilization. Alum dosage is typically determined based on the availability of phosphorus that would bind with iron in the sediments. Data from the sediment cores shows that the majority of phosphorus in the sediments is released during the initial loss of oxygen (*i.e.*, the chemical release phase of the incubation) and that this release is largely ortho-phosphate (95-100%), which the phosphorus form most readily available for phytoplankton use and also the form that readily binds with iron.

Achieving the proper 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 avoid an excessive drop in pH and creating toxicity effects. As with any chemical treatment of water or wastewater, treatment effectiveness is dependent on the dose of the chemical 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.

Calculation of aluminum dose typically relies on the available sediment data, but also requires some judgment based on the variability in the water quality data. For phosphorus inactivation of pond sediments, dose determinations have been estimated in three ways in the past:

1) Alkalinity method: Dose is proportional to alkalinity or buffering capacity of the lake, which is progressively lost as the alum dose increases, and is associated with a decrease in pH and an increase in soluble Al_{+3}, the toxic aluminum form. A dose is selected from batch assays that prevent pH from falling below approximately 6.0 to protect aquatic organisms from potentially toxic concentrations of dissolved aluminum.[136] This method tends to maximize the mass of aluminum addition.

2) Internal loading method: Dose is estimated from internal phosphorus loading, which is multiplied by a nominal ratio of 1.0 for aluminum added: aluminum-bound phosphorus formed and the years of expected phosphorus inactivation. This method tends to underestimate the aluminum needed because the 1:1 ratio of Al:P does not account for other chemicals that may bind the applied aluminum.

3) Sediment phosphorus method: Sequential chemical extraction of sediment samples is used to determine various forms of phosphorus (iron-bound phosphorus and loosely sorbed or labile phosphorus) in sediments. Extraction P results are used to determine

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[136] Cooke, G.D. and R.H. Kennedy. 1981. Precipitation and Inactivation of Phosphorus as a Lake Restoration Technique. EPA-600/3-81-012.

the amount of aluminum.[137] This approach has been refined over a number of years to look at binding of Al by other chemicals in the water (*i.e.*, increasing the ratio between Al:P). Therefore, this method requires some judgment about the appropriate Al amount.

The sediment phosphorus method has largely been adopted as the preferred approach for estimating aluminum mass to be used in applications, but there is still variability associated with the previously mentioned pH impacts and better understanding of how other ligands in the pond water may compete for aluminum. Selection of Al:P ratios have ranged between 5:1 and 100:1 depending on a number of factors, including estimates of the depth of active phosphorus release in the sediments, the mobility of phosphorus under test conditions vs. *in situ* releases, and variability in water quality conditions.[138] Generally, these concerns have been addressed by being reasonably conservative in the application rates in order to avoid underdosing and placing an upper limit on aluminum concentrations to avoid pH issues.

The sediment chemical extraction method that is usually used is different from the incubations used in the CSP/SMAST assessment. The sediment extraction method begins by using a spring-loaded sediment dredge to collect a grab sample of surficial sediment. This sample is then subjected to a series of chemical extractions that gradually mobilize phosphorus from chemical bonds with solids in the sediments. This approach is different than the core incubation discussed above, where the amount of phosphorus release is based on measurements under different redox conditions and cores are removed with minimal disturbance in order to maintain their redox structure. By the nature of approach, the core incubation results should be more appropriate, as they more accurately represent the conditions in the pond. But comparisons between methods are not available. The chemical release phase of the core incubation would generally be equivalent on a definitional basis to the "loosely-sorbed" and "iron-bound" phosphorus associated with the extraction methods. The chemical release phase averaged 88 to 91% of the released anoxic/anaerobic total phosphorus in the Mill Ponds. Average total phosphorus released during the chemical release phase of the core incubation was roughly equivalent in all three ponds: Walkers, 124 mg/m^2; Upper Mill, 101 mg/m^2, and Lower Mill, 109 mg/m^2 (Table VI-2). And, although cores were all collected at similar depths in each of the ponds, variability among the release rates is high: variation coefficients are 110%, 120% and 92%, respectively. These overall release amounts are generally less than those found in the deeper lakes that have been assessed on Cape Cod.[139]

Using the core incubation data, CSP/SMAST staff reviewed the amount of aluminum required to address the total phosphorus released from the sediments. Based on the variability in the methods and the sediment incubation results, staff utilized an aluminum to phosphorus ratio of 100:1 and the maximum available P results from the core data to determine a potential alum dose. Using this ratio and the core incubation results provides the following average Al applications for Walkers and Upper Mill: 16.9 g/m^2 and 15.6 g/m^2, respectively. Based on the

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[137] Rydin, E. and E.B. Welch. 1998. Aluminum Dose Required to Inactivate Phosphorus in Lake Sediments. *Water Research*. 32:2969-2976. and Rydin, E. and E.B. Welch. 1999. Dosing Alum to Wisconsin Lake Sediments Based on in Vitro Formation of Aluminum-Bound Phosphate. *Lake and Reservoir Management*. 15:324-331

[138] Cooke, G.D., Welch, E.B., Peterson, S.A, Nichols, S.A. 2005. *Restoration and Management of Lakes and Reservoirs*.

[139] *e.g.*, ENSR. 2008. Lovers Lake and Stillwater Pond Eutrophication Mitigation Plan Report. Prepared for Town of Chatham, MA

dissolved oxygen profiles, bathymetric data and the depth of the cores, staff determined these Al application rates should be applied at depths of >2 m in Walkers Pond and >6 m in Upper Mill Pond. Total areas of prospective applications are shown in Table VI-2 along with the estimated rates doses of aluminum sulfate and sodium aluminate. Table VI-2 also lists the estimated costs of application for the individual ponds: $54,711 for Walkers Pond and $158,274 for Upper Mill Pond. As mentioned previously, since the ponds are linked together, water quality improvement in upstream ponds will benefit downstream ponds and reduce the remedial requirements in the downstream ponds. This issue is addressed in the recommended plan section (see Section VII). Overall, a treatment of the sediments with a mixture of aluminum salts is considered a reasonable option to address sediment P regeneration within Upper Mill Pond. In Walkers Pond, the macrophyte beds are the primary P source, but the sediments contain large quantities of P that will likely be released by desorption if dissolved oxygen concentrations near the sediments become anoxic.

Table VI-2. Aluminum Salt Application Estimates for Mill Ponds for Reducing Sediment P Regeneration

Pond	Walkers	Upper Mill
Treatment Depth	>2m	>6 m
Target Area (ac)	44	137
Target Area (m2)	176,926	555,773
Avg P avail (umoles/m2)	6,270	5,774
Avg P avail (g/m2)	0.194	0.179
assume thickness (cm)	2	2
Available P (ug/cm3)	9.71	8.94
Available P (mg/m3)	9,710	8,942
P release (moles)	1,109	3,209
P release (g)	34,359	99,397
P loading release estimate (g)	67,706	193,307
Al:P ratio	100	100
Al needed (moles): sed data	110,929	320,906
Al needed (g): sed data	2,993,034	8,658,529
Al dose (g/m2): sed data	16.92	15.58
Al needed (kg): P loading data	2,993	8,659
Al needed (lb): P loading data	6,599	19,089
Al needed (moles): P loading data	218,593	624,098
Al needed (g): P loading data	5,897,970	16,839,127
Al dose (g/m2): P loading data	33.34	30.30
Al needed (kg): P loading data	5,898	16,839
Al needed (lb): P loading data	13,003	37,124
Aluminum sulfate (alum) @ 11.1 lb/gal and 4.4% aluminum (lb/gal)	0.4884	0.4884
Sodium aluminate (aluminate) @ 12.1 lb/gal and 10.38% aluminum (lb/gal)	1.256	1.256
Ratio of alum to aluminate during treatment (volumetric)	2.00	2.00
Dose (gal alum) @ specified ratio of Alum to Aluminate	5911	17099
Dose (gal aluminate) @ specified ratio of Alum to Aluminate	2955	8549
Application (gal/ac) for Alum in Alum+Aluminate Trtmt	135	125
Application (gal/ac) for Aluminate in Alum+Aluminate Trtmt	68	62
Applied cost of alum per gallon	$ 2.50	$ 2.50
Applied cost of sodium aluminate per gallon	$ 3.80	$ 3.80
Total cost of applied alum	$ 14,776	$ 42,747
Total cost of applied sodium aluminate	$ 11,230	$ 32,487
TOTAL APPLIED CHEMICAL COST	$ 26,007	$ 75,234
Mobilization -- 20% of total applied costs	$ 5,201	$ 15,047
SUBTOTAL 1	$ 31,208	$ 90,281
Tax -- 6.25% of total applied costs and mobilization	$ 1,950	$ 5,643
SUBTOTAL 2	$ 33,158	$ 95,923
Planning/Design/Permiting (P/D/P) -- 35% of applied costs plus mobilization and taxes	$ 11,605	$ 33,573
Contigency -- 30% of applied costs plus mobilization and taxes	$ 9,947	$ 28,777
TOTAL ESTIMATED COST	$ 54,711	$ 158,274

VI.A.3 Phosphorus Inactivation: Oxygen Addition in Upper Mill Pond

Since phosphorus is released from sediments due to the lack of oxygen facilitating the breaking of iron:phosphorus chemical bonds, another common remediation technique is to add oxygen near the sediment/water interface and stop the chemical release of phosphorus to the water column. This technique is generally known as artificial circulation. Aeration is a type of artificial circulation and generally includes aerators installed on the pond bottom that add air or oxygen from shoreline-based pumps. Other artificial circulation techniques include downdraft or updraft pumping, which use pumps to exchange surface or bottom waters, respectively, in order to bring higher oxygen waters down to the sediments.

Since water columns in shallow Cape Cod ponds tend to be well-mixed, largely by the readily available wind energy, this technique usually has limited application to shallower ponds. In Walkers Pond, for example, the collected temperature and dissolved oxygen profiles, as well as the continuous datasets (see Figures III-1 and III-2), show these measures are generally similar throughout the water column. These kinds of results indicate well-mixed conditions that are maintained by normal winds in the study area. Similar temperature profiles are maintained in both Upper Mill Pond and Lower Mill Pond. Lower Mill Pond dissolved oxygen profiles (see Figure III-15) generally match Walkers Pond, although the continuous data showed sediment oxygen demand is greater than the oxygen regularly mixed into the water column (see Figure III-1). Upper Mill Pond profiles, on the hand, show that sediment oxygen demand is greater than the oxygen provided by atmospheric replenishment near the sediments. In addition, on average, there is some slight temperature layering beginning at 6 m and deeper. Artificial circulation would likely remove this layer, but review of individual temperature profiles show that this is regularly removed during the summer. Sediment oxygen demand and phosphorus release could be addressed through this approach. Based on this review, artificial circulation was reviewed as a potential approach for only Upper Mill Pond.

In order to provide a planning cost estimate for installing an aeration system in Upper Mill Pond, cost factors near the median of values cited in the MassDEP FGEIR[140] were used: $1,800/acre for capital costs and $135 /acre for annual operational costs. Using the area deeper than 6 m (137 acres), the capital cost estimate is $247,202 (Table VI-3). The annual operational cost estimate is $18,540. Assuming a 10 year operation in order to match conservative longevity of an alum application and provide a reasonable comparison of costs, the length of service operational cost would be $185,401. Total 10 year cost would be $432,603. Additional costs would also be incurred for permitting, annual monitoring/reporting, and securing of land for the installation of compressors and other equipment associated with the aeration system. Recent, more detailed review of costs associated with this kind of system found that the FGEIR estimates are reasonable.[141] Operation of the system would be for five months, May through September. Care would have to be taken to ensure the system would be continuously operational; recent experience at Lovells Pond in Barnstable showed that an intermittent operation resulted in more

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[140] 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.

[141] ENSR. 2008. Lovers Lake and Stillwater Pond Eutrophication Mitigation Plan Report.

frequent phytoplankton blooms and greater impairment.[142] Review of performance of aeration installations generally shows phosphorus declines of one to two thirds.[143]

Updraft pumping generally involves floating units, often solar powered, over the deeper portions of the pond with hypoxic or anoxic conditions. These systems bring deep water to the surface to allow atmospheric oxygen to the address the oxygen deficit that has occurred due to sediment demand. Care must be taken in the depth of the placed inlet so that internal phosphorus loading is not enhanced; sediment regenerated phosphorus brought to the surface would favor phytoplankton growth and increase opportunities for blue-green blooms. Original planning on the use of these systems assumed a 35 acre coverage for each unit, which would lead to the use of four systems in the >6 m area of Upper Mill Pond. At a cost of $50,000 per solar unit and $5,000 annual maintenance for 15 years, total estimated cost would be $275,000 (see Table VI-3). Since these are floating, there would be no land costs and no power costs because they are solar-powered. Additional issues to be addressed would be aesthetics since each system is approximately 10 ft in diameter.

More recent analysis of these types of systems has raised concerns about a more limited area of influence (25-50 ft).[144] Wagner (2014) reviewed performance of commercially available units and found that updraft pumps have been unable to overcome the heat input during hot, sunny summer periods, reducing the effective mixing zone to as little as an acre and rarely more than 5 acres. If the above estimates are adjusted to a 5 acre coverage, the number of units would increase to 28 and the cost estimate would increase to $1.4 million (see Table VI-3).

A downdraft circulator would work similar to an updraft circulator except that surface water would be pumped down to the deeper waters. These surface waters should be close to equilibrium with atmospheric oxygen and this oxygen will address the sediment oxygen demand and cause the precipitation of Fe:P compounds to the sediments. These types of circulators have not been extensively used, but concerns are similar to updraft circulators with uncertain circulation patterns and enhanced internal phosphorus loading.

VI.B. Macrophyte Management in Walkers Pond

Based on the phosphorus budget, the primary single source of water column phosphorus in Walkers Pond is release from the dense macrophyte stands: >80% density for all areas around the pond between the shoreline and 1.5 m depth. As mentioned above, management of phosphorus in Walkers Pond should also consider the extensive pool of sediment phosphorus that can be released during low oxygen conditions.

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

[143] Cooke, G.D., Welch, E.B., Peterson, S.A, Nichols, S.A. 2005. *Restoration and Management of Lakes and Reservoirs*.

[144] Schafran, G., Engebrigtsen, P., Yoon, J., Sherman, B. and J.C. Brown. 2007. Influence of surface circulators on reservoirs/lake water composition: observations and theoretical considerations. Presentation at National NALMS Conference. Orlando, FL

Table VI-3. Aeration/Circulation Cost Estimates for Upper Mill Pond for Sediment P Reduction

Pond	units	Upper Mill
Total Pond Area	m2	982,031
Treatment Area	m2	555,773
Treatment Area	acres	137
Days of Treatment	days	90
Years of operation[1]		10
Aeration		
Treatment Capital Cost	$/ac	1800
Annual Operational Cost	$/ac/yr	135
TOTAL: Capital Cost		$ 247,202
TOTAL: Operational Cost		$ 185,401
TOTAL COST: 10 year		$ 432,603
Updraft Pumping		
Unit coverage	acres	35
Number of units per pond	round up	4
Capital Cost	per unit	$ 50,000
Annual Operational Cost		$ 5,000
TOTAL: Capital Cost		$ 200,000
TOTAL: Operational Cost		$ 50,000
TOTAL COST: 10 year		$ 250,000
Unit coverage	acres	5
Number of units per pond	round up	28
Capital Cost	per unit	$ 50,000
Annual Operational Cost		$ 5,000
TOTAL: Capital Cost		$ 1,400,000
TOTAL: Operational Cost[2]		$ 50,000
TOTAL COST: 10 year		$ 1,450,000

Notes:

1. Years of operation chosen to match a conservative estimate of alum efficacy
2. Operational cost would likely rise if 28 units were required.

Macrophyte control generally is approached through direct removal of the plants, some form of extermination, or some combination of both.[145] Direct removal techniques can include mechanical harvesting or trimming or hand pulling. Extermination techniques include biological controls, benthic barriers, and herbicides. Typically, macrophytes are a component of most lake ecosystems, so control techniques focus on attaining a population and density that matches water quality goals. Given the number of variables, especially in shallow pond systems, matching goals to macrophyte populations is often an active management issue that requires regular monitoring and adjustment. Table VI-4 lists the potential macrophyte control options, as well as summary of their applicability to Walkers Pond.

The current assessment indicated that the macrophyte population in Walkers Pond has approached an approximate maximum density with 80% to 100% coverage within the littoral area of the pond as defined by the average depth limit of light penetration (1.5 m). The phosphorus loading analysis suggests that this population is now the primary source of phosphorus measured in the watercolumn. If the macrophyte population can be selectively reduced to shift it from its current non-growth status to a growth-oriented status where it is accumulating P and directing competing for P with the extensive phytoplankton population, the P concentrations in Walkers Pond will be reduced. It may be possible to remove phosphorus with regular harvesting of the macrophytes and then follow this with an herbicide treatment when the phosphorus concentrations or ecosystem conditions have attained desired targets.

Reduction in the macrophyte population should be done in such a way that the phosphorus contained in the plants will not be released back into the water column, so reduction in the population will also have to include removal of the plants. Using average macrophyte phosphorus content, the estimated mass of phosphorus in the maximum density areas in Walkers Pond is ~700 kg.[146] The plants must be removed during harvesting as leaving them in Walkers Pond to decay would also present an opportunity for any phosphorus released to discharge into Upper Mill Pond through the hydroconnection. For this reason, the following alternatives in Table VI-4 were eliminated: benthic barriers, herbicides, dyes and surface covers, and biological controls. Among the listed options that address the reduction in the macrophyte population and removal of the plant material are: dredging and harvesting. For planning purposes, it is assumed that 50% of the >80% area (~16.5 acres) will have plant materials removed.

Dredging was previously reviewed as an option for sediment removal and would present the same issues for an activity focused on the littoral zone: securing a dewatering area, securing a sediment disposal location, testing of the sediments for metals and hydrocarbons, accommodations to protect/restore the mussel populations and difficult permitting with both state agencies and local boards, largely because of its lack of use in Massachusetts. Dredging would also require additional evaluation of sediment characteristics in order to evaluate disposal options, size the dewatering areas for the dredged sediments, and evaluate equipment demands.

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[145] Massachusetts Department of Environmental Protection and Department of Conservation and Recreation. 2004.

[146] Graneli, W. and D. Solander. 1988. Influence of aquatic macrophytes on phosphorus cycling in lakes. *Hydrobiologia*. 170: 245-266.

Table VI-4. Potential Macrophyte Controls for Walkers Pond.
Modified from list in MassDEP/MassDCR (2004).

Option	Mode of Action	Advantages	Disadvantages	Applicability/ Concerns in Walkers Pond
Benthic Barriers	Mat laid on pond bottom to prevent plant growth	• Highly flexible control (limited or permanent installation) • Reduces turbidity from soft bottoms • Can cover undesirable substrate • Can improve fish habitat by creating edge effects	• May cause anoxia at sediment-water interface • May limit benthic invertebrates • Non-selective interference with plants in target area • May inhibit spawning/feeding by some fish species	❖ Re-release of P as plants decay ❖ Accelerated release in areas driven anoxic when removed
Dredging	Sediment and plants are physically removed by wet or dry excavation, with deposition in a containment area for dewatering/disposal	• Temporary if nutrient inputs not managed as well. • Increases water depth • Can reduce pollutant reserves • Can reduce sediment oxygen demand • Can improve spawning habitat for many fish species • Allows complete renovation of aquatic ecosystem	• Temporarily removes benthic invertebrates • May create turbidity • May eliminate fish community (complete dry dredging only) • Possible impacts from containment area discharge • Possible impacts from dredged material disposal • Interference with recreation or other uses during dredging • Usually very expensive	❖ Very expensive ❖ Likely protracted permitting due to sparse use in MA
Herbicides a) Copper b) Endothall c) Diquat d) Glyphosate e) 2,4-D f) Fluridone g) Triclopyr	Applied to target area or to plants directly kill plants or limit growth ♦ Typically requires application every 1-5 yrs	• Wide range of control is possible • May be able to selectively eliminate species • May achieve some algae control as well	• Possible toxicity to non-target species • Possible downstream impacts • Restrictions of water use for varying time after treatment • Increased oxygen demand from decaying vegetation • Possible recycling of nutrients to allow other growths	❖ Re-release of P as plants decay if treated plants are not removed

Table VI-4. Potential Macrophyte Controls for Walkers Pond (continued).

Option	Mode of Action	Advantages	Disadvantages	Applicability/ Concerns in Walkers Pond
Harvesting a) Hand pulling b) Cutting (without collection) c) Cutting (with collection) d) Rototilling e) Hydroraking	Plants reduced by mechanical means, possibly with disturbance of soils ♦ Application once or twice per year usually needed	• Highly flexible control • May remove other debris • Can balance habitat and recreational needs	• Possible impacts on aquatic fauna • Non-selective removal of plants in treated area • Possible spread of undesirable species by fragmentation • Possible generation of turbidity	❖ Cutting with collection addresses concerns ❖ Other approaches either labor intensive (hand pulling) or allowing re-release of P
Dyes and surface covers	Limits light penetration to inhibit plant growth ♦ Dyes remain in solution until washed out of system. ♦ Opaque sheet material applied to water surface	• Light limit on plant growth without high turbidity or great depth • May achieve some control of algae as well • May achieve some selectivity for species tolerant of low light	• May not control peripheral or shallow water rooted plants • May cause thermal stratification in shallow ponds • May facilitate anoxia at sediment interface • Covers inhibit gas exchange with atmosphere	❖ Re-release of P as plants decay ❖ Chemical release in areas where sediments go anoxic
Biological Controls a) Herbivorous fish b) Herbivorous insects c) Pathogens d) Selective plantings	Fish, insects or pathogens feed on or parasitize plants ♦ Most common used organism is the grass carp (which is illegal to bring into MA)	• Provides potentially continuing control with one treatment • Harnesses biological interactions to produce desired conditions • May produce potentially useful fish biomass as an end product	• Typically involves introduction of nonnative species • Effects may not be controllable • Plant selectivity may not match desired target species • May adversely affect indigenous species	❖ Re-release of P as plants decay

In addition, there would likely be additional evaluations necessary to characterize habitat issues, since the littoral zone is more biologically active than the pelagic zone that was previously considered for Upper Mill Pond. If 50% of the area with >80% macrophyte coverage in Walkers Pond were selectively dredged the planning cost estimate range is $1.3 to 2.6 million.

Harvesting of aquatic plants can be approached a number of ways. As listed in Table VI-4, common approaches include hand pulling, cutting without collection, cutting with collection, rototilling, and hydroraking. Hand pulling typically involves a snorkeler or diver selectively pulling out plants. This is a highly selective technique, and a labor intensive one. Suction dredging can be used to somewhat automate hand pulling, as the diver/snorkeler does not have to carry out pulled plants. Given that 16.5 acres is the planning area for plant removal, this does not seem to be a practical option.

Cutting involves severing the submerged or emergent stem of the macrophyte from its roots. Given that the roots are maintained, regrowth within the cut areas is expected and can be quite rapid (one year or less). If cut materials are left in the pond, they will decay while consuming oxygen and releasing bound nutrients. Collected cuttings are typically composted and then used as mulch. Cutting is typically done from specially designed lake harvesters, which range in size depending on the area to be covered. Larger versions of these boats are often retrofitted for alum applications. Cutting rates for commercial harvesters tend to range from about 4 to 8 hours per acre, depending on machine size and operator ability.[147] Cutting the 16.5 acres estimated for Walkers Pond would require 9 to 18 days and the plant population might require frequent cutting (*e.g.*, twice a summer to annually) in order to maintain the growth-oriented status for the overall population.

Rototilling and hydroraking are both very disruptive approaches that tear out macrophyte roots. Rototilling does not appear to have extensive use and usually has its best results in combination with water level drawdown.[148] Hydroraking is similar to rototilling in that it removes roots, but without drawdown. Both techniques would create plant fragments and increased turbidity due to sediment disturbance. Use of either technique in Walkers Pond does not appear to be practical given drawdown limitations for rototilling and goals to remove plant materials/phosphorus for hydroraking. This technique would also have significant issues related to destruction of other littoral zone habitats.

Based on the review of options, the optimal technique for Walkers Pond appears to be mechanical harvesting with collection of cuttings. Harvesters can be purchased for $50,000 to $150,000. Estimates for rental in New York State in 2005 were $150 to $300 per hour with operating costs of $200 to $300 per acre.[149] Based on the time required for the estimated area, the total cost for an annual cutting run rental would be between $15,000 and $52,000 in 2014 dollars with additional costs for plant disposal. Further consideration is whether the harvester would have to be used more frequently or whether it might be used in other ponds either in Brewster or nearby towns. It is recommended that monitoring thresholds be established both in

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[147] New York State, Department of Environmental Conservation. 2005. A Primer on Aquatic Plant Management in New York State. Albany, NY.

[148] Massachusetts Department of Environmental Protection and Department of Conservation and Recreation. 2004..

[149] New York State, Department of Environmental Conservation. 2005.

phosphorus concentrations and plant growth to guide how often the harvester is used. Details on thresholds, harvesting areas, harvesting frequency, and monitoring to attain water quality goals could be organized in a macrophyte monitoring plan. It is recommended that harvesting occur once during late summer initially with accompanying monitoring; given the residence time of Walkers Pond, feedback on impacts and regrowth should be available the following summer if monitoring is sufficient. If, as expected, regular harvesting lowers phosphorus concentrations over a period of time, the town may want to consider use of a herbicide within Walkers Pond to limit future harvesting; if this is pursued steps would need to be taken to avoid drift of herbicides into Upper Mill Pond.

VI.C. Between Lake Phosphorus Controls

While the hydroconnection P loads to Upper Mill Pond and Lower Mill Pond are not the predominant source, the loads are significant (24% and 35%, respectively of phosphorus inputs). Treatment of these loads while they are in the streams may present an additional opportunity to lower the loads within a relatively compact area. Given this possibility, CSP/SMAST staff reviewed the potential options to treat P loads within the hydroconnections.

Review of available literature shows that most phosphorus removal treatment focusses on concentrated sources, such as wastewater treatment facilities, or concentrated sinks, such as pond sediments. Some effort has been made in recent years to focus on more diffuse sources (such as the historic wastewater plume at the Massachusetts Military Reservation) and these efforts have included using various iron-rich filtering materials, membranes, or natural systems (*e.g.*, in-line wetlands) to remove phosphorus from water. Filtering materials have included iron filings, sludge ash, and steel slag. Review of available research shows treatments similar to lake phosphorus removal treatments have been used on large rivers.[150]

It would appear from the literature review that this sort of approach is relatively unconventional, which means it would have a number of issues to address during review and development. Addition of a structure or inline materials between Walkers Pond and Upper Mill Pond seems to be highly improbable given the narrowness of the strip of land between the two ponds (20-30 ft wide). More land is available between Upper Mill Pond and Lower Mill Pond; the town owns the land/wetland parcel that connects the two ponds and appears to have ~1,000 sq ft of upland. However, it appears that access to this land from upland areas would need to be conferred by adjacent land owners. Construction of a wetland or filtering structure would likely require provisions to allow herring to bypass the structure, as well as a potential assessment of biological impacts. Phosphorus removal efficiency of constructed wetlands can often be in the high 90%, while removal from BMP style, stormwater runoff structures with the addition of ash, slag or filings can range from 30% to 90%.

Further evaluation of this option largely depends on the level of phosphorus reduction achieved within Upper Mill Pond. If upstream management activities, such as in-pond sediment treatment, reduce the phosphorus input to Lower Mill Pond by 90%, that removal would be roughly equivalent to the best-case removal expected of most of the in-stream options. And the in-pond removals could be accomplished without the current uncertainties in performance,

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[150] *e.g.*, Swan River Trust. 2001. Spraying of Phoslock™ Trial: Swan-Canning Cleanup Program. East Perth, Australia.

design, and permitting. For this reason, CSP/SMAST staff recommends that this option await performance data on phosphorus reduction activities in Upper Mill Pond.

VI.D. Watershed Phosphorus Controls

The watersheds to Walkers Pond, Upper Mill Pond, and Lower Mill Pond are the ultimate source of all phosphorus that is collected in the pond sediments and is transported between the ponds. However, the current overall phosphorus budgets for the ponds show that the watersheds are currently adding only small percentages of the overall loads: 6%, 11%, and 3% of the loads to Walkers Pond, Upper Mill Pond, and Lower Mill Pond, respectively.

However, since the watersheds are the ultimate source, application of watershed management activities are recommended as prudent complementary activities for the protection of the resources spent for in-lake phosphorus control techniques. As indicated in the watershed phosphorus loading assessment, wastewater is generally the largest watershed phosphorus source, followed by surface precipitation, runoff, birds, and then fertilizers (see Table V-2). Among these sources, wastewater, runoff, and fertilizers are within reasonable local control.

As mentioned in the phosphorus loading evaluation, the 2009 Brewster Ponds Report reviewed development within 300 ft of each pond's shoreline, as well as reviewing the year built for each building in order to estimate whether phosphorus had arrived at the pond shoreline from individual septic systems. A range of P travel times was utilized, that roughly translates into a nine year range (prior to 1981 to 1990) for construction of buildings and their septic systems that have P reaching the pond shorelines. Based on a re-review of the land use completed for this project and the range of P travel times, Walkers Pond has 6 to 10 buildings of a total of 16 that are upgradient, within 300 ft of the watershed shoreline, and that are discharging wastewater P to the pond. Upper Mill Pond has 19 to 32 of the total of 47 buildings within 300 ft of the watershed shoreline discharging wastewater P to the pond. Lower Mill Pond has 8 buildings of the total of 12 buildings within 300 ft of the watershed shoreline discharging wastewater P to the pond.

The delay in phosphorus transport to the pond shoreline is caused by P binding with iron in the aquifer sand. If a leachfield is moved or replaced within a different flowpath, additional binding sites are made available and the P travel-time delay restarts its clock. The Town of Brewster currently has Board of Health regulations that require "All new and replacement leaching facilities of sewage disposal systems in Brewster shall be located or installed more than 300 feet from all Ponds and Lakes."[151] This regulation further requires attaining the 300 ft setback (or maximum allowed by lot configuration) at the time of transfer of ownership for all properties. Given that the phosphorus travel time for 300 ft is 21 to 31 years[152] and this exceeds the likely planning time efficacy for the various in-lake sediment treatments, this regulatory approach seems to be a reasonable balance for an area where wastewater is treated with septic systems and where sewer connects are not currently available or planned. Greater watershed, wastewater P reductions could be attained by removing all wastewater from the watershed or moving leachfields further back from the shorelines.

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[151] Town of Brewster. Leach Facility Set Back regulation. Effective: September 1, 2006

[152] Robertson, W.D. 2008.

The next largest watershed P source is road runoff discharged to the pond, which was measured during the 2011 targeted data collection phase of the Mill Ponds assessment.[153] As detailed in Section V.A.5., six (6) sites with either direct observation of discharge or signs of direct stormwater runoff were identified: 4 to Upper Mill Pond, 1 to Lower Mill and 1 to Walkers. Runoff P from these sites could be addressed through simple infiltration of runoff prior to direct discharge to the pond surfaces. The specifics of each site would determine the best options to address these discharges. Based on CSP/SMAST field observations, discharge from most the sites could be addressed through berms across primary flow paths with designs to encourage infiltration. The boat ramp on Walkers Pond would be more of a challenge due to the paved surfaces leading down to the pond edge and the rather steep surrounding elevations. Evaluation of potential options at all sites will require, at a minimum, elevation surveys of the areas and clarification of land ownership around the discharges.

Reduction in fertilizer P loads, which are generally 1 to 5% of the watershed P load, could be accomplished by providing homeowner education on ways to minimize pondshore P loads, including providing details on readily available turf alternatives. Available Cape Cod data on fertilizer use shows that a majority of homeowners do not use fertilizers and among those that do use fertilizers, most apply less than the annual loads recommended by fertilizer companies.[154] Regional discussions about fertilizer restrictions to address nitrogen loading to estuaries have resulted in some regulatory efforts to limit applications.[155] However, given that the majority of residents do not apply fertilizers, further reductions in fertilizer applications would likely be more successful with educational efforts for near pond residents. Educational efforts could include: a) the potential impacts of fertilizers and b) guidance on minimizing applications and pond-friendly landscaping. Part of this educational effort would be to research and provide options on turf types or alternative groundcover that do not require fertilizer applications, while meeting homeowner expectations regarding groundcover use and appearance. Further research and consultation with turf specialists, such as local golf superintendents and the county Extension Service, may be helpful in development of a list of potential alternatives.

Other types of watershed activities that are conventional best management practices for preserving pond water quality and minimizing P watershed loading are: 1) maintenance of natural buffer strips along the pond shoreline (width dependent on slope), 2) limiting additional shoreline development, and 3) stabilizing any steep slopes to avoid runoff potential. It is recommended that the town consider reviewing the pond shorelines on a regular (1-2 years) basis to see if any runoff channels are observed; observations should be focused on the steepest slopes. Review of the town Assessor's land use codes show there are additional properties to be developed within a 300 ft buffer to each of the ponds: two for Walkers Pond, six for Upper Mill Pond, and five for Lower Mill Pond. The Town may want to consider evaluating these properties for their potential to be developed and contribute additional phosphorus to the ponds. If reasonable septic leachfield setbacks cannot be attained, the Town may want to consider purchase of these properties and/or working with a local Land Trust or conservation group to purchase the development rights.

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[153] CSP/SMAST Technical Memorandum: Mills Ponds Complex Project. January 16, 2013.

[154] White, L.M. 2003. The Contribution of Lawn Fertilizer to the Nitrogen Loading of Cape Cod Embayments.

[155] Nantucket has adopted a lawn fertilizer bylaw and guidance manual.

VII. Recommended Water Quality Management Plan

The above review of water quality in Walkers Pond, Upper Mill Pond, and Lower Mill Pond shows that each of these ponds has impaired water quality. The review also shows that the primary cause of this impairment is excessive phosphorus loads with differing predominant sources in each case: a) macrophyte stands in Walkers Pond, b) sediments in Upper Mill Pond, and c) a combination of macrophyte stands and sediments in Lower Mill Pond. The overall goals of this Management Plan are to identify appropriate pond water quality restoration options to: 1) improve the ecological health of the ponds, 2) reduce or mitigate the sources of phosphorus to the ponds and 3) enhance the recreational and aesthetic qualities of the Walkers Pond, Upper Mill Pond, and Lower Mill Pond.

Achieving these goals will require implementation of a treatment strategy that acknowledges the differences between the ponds, as well as their interconnections and cumulative influences as water and phosphorus moves downstream. The initial management strategy for Walkers Pond is reducing its extensive macrophyte stands to move the overall population back to a growth-oriented status. This harvesting will remove plant material and its associated nutrients from the pond, while attaining a growth-oriented status that should begin to remove phosphorus from the water column and sediments. The harvesting will likely have to occur at least annually, but may need to be more frequent to attain a goal of 50% reduction from current macrophyte density in waters between the shoreline and 1.5 m depth. If this is accomplished over a number of years, the P levels in the pond may drop enough to consider an herbicide treatment to limit future harvesting.

Monitoring will be a key factor in this adaptive management approach and will serve two purposes: 1) tracking P reductions due to harvesting and 2) monitoring potential impacts from the pond sediments. Pond sediments in Walkers Pond contain considerable P loads, but these do not generally release significant amounts because of the high dissolved oxygen concentrations. The high DO concentrations are maintained in part by the high P concentrations, so monitoring is a prudent step to ensure that conditions do not shift to lower DO concentrations and increased release of sediment P. Increased sediment releases would be a concern for both water quality conditions in Walkers Pond, as well as increased transfer of P to Upper Mill Pond. In order to implement the macrophyte harvesting strategy in Walkers Pond, the Town will need to resolve permitting issues at both the state and local levels, select a location for disposal or composting of harvested plants, and decide whether to rent or purchase a harvester.

Upper Mill Pond is much larger than Walkers Pond; its volume is nearly 8x larger and its average depth is more than 3x deeper. Because of its larger size, it also has a residence time greater than one year (441 days). In addition, it has almost no macrophyte stands, but has extensive freshwater mussel populations. Review of the collected data show that the predominant source of P in Upper Mill Pond is its sediments and this sediment release is caused by regular anoxia in its deeper waters. Three potential strategies were reviewed to address sediment P additions: 1) dredging, 2) nutrient inactivation through chemical addition, and 3) aeration through artificial circulation. Dredging is not recommended because of its projected high costs and disturbances. Nutrient inactivation and aeration are recommended as potential treatment options for Upper Mill Pond. Review of potential costs showed that nutrient inactivation had the lowest cost and least disturbance, in addition to being a common approach on Cape Cod and southeastern Massachusetts. The Town will need to resolve permitting issues at both the state and local levels and develop more refined cost estimates, likely through a request for proposals process.

Lower Mill Pond is the most downstream of the three ponds and, as such, is influenced by the water quality conditions and implementation of future management activities in the other ponds. However, it has individual characteristics that must be considered in development of management strategies: a) its average depth is ~1 m deeper than Walkers Pond (2.9 m vs. 1.9 m, respectively), b) it volume is ~75% of Walkers Pond, and c) its annual average residence time is approximately one month, but this increases to approximately three months during the summer. It has a macrophyte population that is greater than the sparse Upper Mill Pond populations, but less than the extremely dense Walkers Pond population (*i.e.*, densities ~40% in littoral zone). Its mussel population is similar to Walkers Pond, but more extensive. Both macrophytes and mussels are mostly in a narrow strip along the shoreline; macrophytes are generally are confined to depth of 1.25 m and less, while mussels are confined to 2 m and less. The deep bowl shape of Lower Mill Pond and limited light penetration with generally oxic conditions seem to be driving these limits. Review of the phosphorus budget for Lower Mill Pond showed that internal sources of P were the predominant source, but the review of sediment incubation, dissolved oxygen concentrations, and research on potential macrophyte and mussel contributions showed that this internal contribution is likely complex with many sources contributing and potentially varying by season and, perhaps, month to month because of the short residence time. Further review of potential management options showed that realistic P reductions in Upper Mill Pond will have a significant impact on the conditions in Lower Mill Pond. For this reason and to avoid significant expenditures to further resolve the internal P sources in Lower Mill Pond, it is recommended that water quality conditions in Lower Mill Pond be monitored following the implementation of P reduction strategies in Upper Mill Pond and that review of management options be revisited in an adaptive approach once that information was available.

Complementary watershed activities are also recommended for all three ponds. These best management tasks are generally already part of the Town of Brewster regulatory structure, but should be paired with educational activities that stress the links between watershed development and water quality and provide reasonable, easy-to-implement, site-plan development options for all lakeside property owners.

Management of water quality in Walkers Pond, Upper Mill Pond, and Lower Mill Pond is complex because of the direct connections between the ponds, but these connections also present an opportunity to implement in-pond management in a sequential, adaptive fashion. Restoration can occur within Walkers Pond, the results can be monitored, and subsequent restoration activities in Upper Mill Pond can be crafted based on that performance. Similarly, the restoration activities in Lower Mill Pond can be adjusted/adapted based on the performance of restoration activities in Upper Mill Pond. This approach can also be beneficial by spreading funding needs over a number of years. In order for this approach to succeed, regular monitoring is required, as well as flexibility in permitting.

After reviewing the restoration costs, CSP/SMAST staff recommends that the Town of Brewster follow an adaptive management strategy of sequential implementation, monitoring, and adjustment. This strategy incorporates the idea that there is some uncertainty in the expected performance of the restoration strategies, as well as variability in the underlying water quality data. It is based on the concept that improvements in the upstream ponds will also result in improvements in the downstream ponds. This approach includes the following recommended sequence:

1. Macrophyte harvesting in Walkers Pond
   A. Plan and implement macrophyte harvesting in Walkers Pond. Complete the initial harvesting in September/October to minimize conflict with recreational use of the pond and spawning of herring. The initial targeting will be 16.5 acres (~50% of the >80% density area). It is recommended that the harvesting target areas along the western shoreline where no mussels were detected during the CSP/SMAST survey. Harvested sections should be monitored for regrowth with additional harvesting if plants regain more than half of their pre-harvest height or density.
   B. Water quality monitoring should occur before and after the harvesting using standard PALS protocols, including collection of water quality samples. Similar monitoring should also occur in April and August/September of the year following the harvesting with Secchi readings and dissolved oxygen/temperature profiles on a monthly basis between the sample collection runs. Flow measurements and water quality samples should also be collected in the hydroconnection between Walkers Pond and Upper Mill Pond on a monthly basis between April and the August/September samplings. Monitoring results should be compared to past measurements and management procedures should be adjusted if indicated.

2. Aluminum salt application in Upper Mill Pond
   A. Plan and implement an aluminum salt application in Upper Mill Pond. Complete the application in September/October to avoid conflict with recreational use of the pond and spawning of herring. The application should target areas of the pond greater than 6 m in depth.
   B. Water quality monitoring should occur before, during, and after the application using standard PALS protocols, including collection of water quality samples. Similar monitoring should also occur in April and August/September of the two years following the application in order to encompass the pond's 15 month pond residence time. In addition, Secchi readings and dissolved oxygen/temperature profiles should be collected on a monthly basis between the sample collection runs. Flow measurements and water quality samples should also be collected in the hydroconnection between Upper Mill Pond and Lower Mill Pond on a monthly basis between April and the August/September samplings. Monitoring results should be compared to past measurements and management procedures should be adjusted if indicated.
   C. Water quality monitoring should also occur in Lower Mill Pond. This monitoring should include April and August/September for at least two years following the Upper Mill Pond aluminum salt application and use standard PALS protocols, including collection of water quality samples. Between these twice-yearly monitoring runs, Secchi readings and dissolved oxygen/temperature profiles should be collected on a monthly basis. Flow measurements and water quality samples should also be collected at the discharge from Lower Mill Pond to Stony Brook on a monthly basis between April and the August/September samplings.

3. Complete water quality performance review for data from all three ponds

   After the completion of the recommended two years of monitoring in Upper Mill Pond, it is recommended that the collected water quality data from all three ponds be reviewed. If water quality conditions in Lower Mill Pond are judged to be adequately resolved or have attained an average TP concentration of 10 µg/L, then no further restoration activity in Lower Mill Pond is recommended. If further P reductions are recommended, further evaluation of alternatives based on the review in this report is suggested.

4. Implement Landowner Education Program

   Phosphorus in the ponds and their sediments was added by land uses within their watersheds. Opportunities to reduce watershed loads will help prolong and preserve the benefits of in-pond sediment regeneration reductions. Since sewer systems are not available, septic systems will continue to be the predominant wastewater treatment technology and the primary source of watershed P loads. The town already has Board of Health regulations to maximize septic system leachfield setbacks and groundwater P travel times, but additional efforts should be considered to assist and educate homeowners with clear understanding of setbacks, buffer designs, alternative groundcover options, and other activities that will minimize stormwater and fertilizer phosphorus loading to the ponds.

5. Implement Stormwater Infiltration Program

   Preventing direct stormwater discharges to the pond surface appears to be a step that can be taken relatively easily. Direct discharge sites have been identified and most appear to have opportunities of encourage subsurface infiltration through directed flowpaths. It is recommended that the initial step to revamp these sites is to complete elevation surveys in the areas and then review design options to encourage infiltration. Part of this program would also be a regular (1-2 year) visual inspection of steeper slopes along the pond shorelines to look for stormwater scour channels and develop strategies to encourage stormwater infiltration rather than worsening of any identified channels.

6. Regularly monitor pond water quality

   After the completion of the collection of monitoring data for the performance review, it is recommended that the town continue regular maintenance monitoring of all three ponds. Regular monitoring will provide data for trend analysis on the on-going performance of restoration activities and provide a basis for future planning. It is recommended that monitoring occur at a minimum in April and August/September using PALS sampling protocols. The April sampling will provide an annual baseline and comparison of the late summer conditions, while the late summer sampling is designed to measure worst-case conditions. Collected data should be publicly presented annually, much like drinking water consumer confidence reports, and reviewed every five years for trends and comparison to past data.

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

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

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