Prepared for:
Town of Chatham
Chatham, MA

Lovers Lake and Stillwater Pond Eutrophication Mitigation Plan Report

Final Report

ENSR Corporation
August 2008
12249-001-500

ENSR | AECOM

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Executive Summary

PROJECT BACKGROUND

Lovers Lake and Stillwater Pond are two deep kettlehole ponds located in the Town of Chatham (the "Town") on Cape Cod in Massachusetts (Figure 1-1). These state-designated "Great Ponds" are recreational and ecological resources for the Town of Chatham; featuring one of the two remaining alewife runs in the Pleasant Bay watershed (MA, DEP, 2007).

Currently, the two ponds suffer from poor water quality due to eutrophication (i.e., overabundant nutrient levels) and do not fully support the desired water uses including contact recreation and aquatic life support. Symptoms include low water transparency, frequent and dense algal blooms, loss of oxygen in bottom waters, and degraded ecological habitat. These ponds have been characterized as "highly impacted" and "eutrophic," based on recent assessment studies (CCC, 2003; EcoLogic and S&W, 2003).

In 2006, the Town commissioned an *Eutrophication Mitigation Plan* study of Lovers Lake and Stillwater Pond to identify, design and permit appropriate pond restoration treatments to:

- Eliminate, reduce or mitigate the release of phosphorus from the sediments of Lovers Lake and Stillwater Pond, thus reducing the amount of nutrients available for phytoplankton growth in the two ponds;
- Improve the ecological health of Lovers Lake and Stillwater Pond, including water clarity and dissolved oxygen levels in deeper waters of the pond; and
- Enhance the recreational and aesthetic qualities of the ponds.

ENSR Corporation ("ENSR") of Westford, MA was selected to evaluate four potentially applicable pond restoration methods (dredging, aeration, circulation, and nutrient inactivation) to reduce or eliminate the phosphorus recycling from the sediments. The recommended pond treatment is to be further refined for preparation of bid specifications and the appropriate environmental permit (MA Wetland Protection Act Notice of Intent (NOI)) application prepared.

DIAGNOSTIC PHASE

As the first task of the Eutrophication Mitigation Plan Study, ENSR reviewed the existing data and information on Lovers Lake and Stillwater Pond. Sources of existing information for Lovers Lake and Stillwater Pond and their watersheds were gathered from the Town files and staff (data, GIS files. maps), regional agencies (Cape Cod Commission), state agencies (EOEA, MA DEP, MA DFW), federal agencies (USGS, NOAA), scientific literature, watershed stakeholders, and other sources (e.g., newspapers, internet). Bathymetry in the ponds was measured in 2001 as part of a six pond survey conducted by the Town and the Chatham Department of Health and Environment (CDH&E) provided GIS files of these maps for Lovers Lake and Stillwater Pond.

Lovers Lake (37.7 acres) and Stillwater Pond (18.7 acres) are two hydrologically connected kettlehole ponds located in Chatham, MA that outlet to coastal Ryder's Cove (Section 2.2.1). Lovers Lake (maximum depth = 11 m (36 ft); average depth = 4.6 m (15 ft)) has two deep basins located at ends of an approximate "L"-shaped configuration, while Stillwater Pond (maximum depth = 15.5 m (51 ft); average depth = 7.4 m (22 ft)) has a simple central deep basin. Water volume for Lovers Lake is about 695,000 m^3 and that for Stillwater pond is just slightly below 500,000 m^3.

Both ponds are characterized by small watersheds (Lovers Lake = 86 acres; Stillwater Pond = 128.3 acres). Land use in both watersheds is largely forested, low density residential, and open or protected land, with some

cranberry production (Lovers Lake) and public drinking water wells (Stillwater Pond). There are approximately 21 upgradient residences and septic systems within 300 ft of Lovers Lake and 11 residences for Stillwater Pond (Section 2.2.2).

Both ponds are part of the Pleasant Bay Area of Critical Environmental Concern (ACEC), are classified as Outstanding Resource Waters (ORWs), and have species of special concern identified along shoreline areas and within the watersheds (H&W, 2003). Public use of both ponds includes swimming, fishing, and non-motorized boating. There is informal public access to Lovers Lake and undeveloped access to Stillwater Pond but there are no public swimming beaches or boat launches.

Both ponds support a warmwater fishery community and seasonal runs of anadromous alewife. The herring run is actively managed by water elevation manipulations through outlet structures and pipe conveyances maintained by the Chatham Herring Warden. Herring populations may be declining in these ponds, as elsewhere on the Cape (Section 2.4.1).

The ponds have diverse riparian shoreline vegetation which includes several protected or sensitive species. Emergent reeds, water lilies, and pickerelweed are reported. Submergent aquatic vegetation was not surveyed, but may be limited due to the sandy substrate, rapid depth dropoff, and low summer transparency of the lakes (Section 2.4.3).

Lovers Lake flows into Stillwater Pond which then flows into Ryder's Cover (marine environment); otherwise there are no surface tributaries to either pond (Section 4.2). Precipitation and groundwater in-seepage are the dominant sources of water for both ponds, with a negligible amount of runoff from the very sandy watershed. Most water leaves Lovers Lake as surface overflow into Stillwater Pond. Water exits Stillwater Pond by a combination of outflow and groundwater out-seepage. Total hydrologic through-flow was estimated for both ponds, suggesting an average annual detention time of 1.4 to 1.6 years for Lovers Lake and 1.3 years for Stillwater Pond; both ponds will flush more slowly in the summer (Section 4.3).

As part of characterization of the current conditions of Lovers Lake and Stillwater Pond, periodic observations of water column profiles of temperature and dissolved oxygen (DO) were made, along with discrete water quality sampling at two depths at two locations within the pond. Field surveys were conducted at Lovers Lake and Stillwater Pond during spring through fall 2007 and included sixteen visits, with water quality samples collected on five of those visits. In addition, ENSR conducted a sediment survey to collect sediment samples for testing of physical and chemical properties.

Recent water quality data were available to provide the evaluation of recent trophic conditions and the ability of the Ponds to meet designated uses. Inspection of the Pond and Lakes Stewards (PALS) monitoring database (2000-2006) (Section 2.3), pond assessments (CCC, 2003; EcoLogic, 2003) (Section 2.5), and additional investigation by ENSR and CDH&E in 2007 (Section 3.1) have documented consistent patterns of elevated nutrient conditions and poor transparency in summer and deep water anoxia with regeneration of phosphorus from bottom sediments in >20 ft of water depth.

Bottom sediments were collected and analyzed from both ponds. Most sediment samples were highly organic and contained large amounts of total phosphorus (Section 3.2). It appears that phosphorus has accumulated in the deep organic sediments of both ponds over an extended time period, although the exact nature of the sources contributing to this nutrient reserve was not determined. Analysis of the phosphorus fractions indicated that large amounts were contained in the iron-bound phosphorus fraction that would be susceptible to release under low redox conditions that occur each summer.

Examination of the conditions that promote phosphorus release included assessment of oxygen demand (Section 5.1). Average areal oxygen demand in Lovers Lake is estimated at a predicted range of approximately 386 to 486 mg O_2/m^2/day. This demand causes strong anoxia as soon as stratification sets in

and bottom waters are denied further atmospheric oxygen inputs. Stillwater Pond loses hypolimnetic DO quickly over the season with a maximal oxygen demand between 1482 and 2370 mg/m^2/day.

Estimates of the levels of internal recycling were made on the basis of observations of the accumulation of hypolimnetic phosphorus and by modeling (Section 5.2). The hypolimnion of Stillwater Pond accumulated phosphorus with an overall increase of 75.8 kg over the period between May 3 and August 29; with a large proportion present as dissolved inorganic phosphorus (Table 3-3). These values translate into benthic release rates ranging from 5.8 to 30 mg P/m^2/day; with an average of 18.1 mg P/m^2/day. Redox reactions promoting the release of this phosphorus with only 10-20% reaching the epilimnion could still raise the phosphorus concentration sufficient to support the observed algal blooms in the pond.

Estimation of sediment phosphorus release from Lovers Lake sediments was not calculated from water quality data since little accumulation occurred in the hypolimnion. However, release from the sediments is assumed to have resulted in a transfer of phosphorus to upper waters via diffusion and vertical mixing. The contribution for internal loading was estimated through modeling (Section 5.2.2).

Phosphorus budgets were prepared for both lakes showing an estimated load of 42 kg/yr for Lovers Lake (Table 5-7) and 48 kg/yr for Stillwater Pond (Table 5-8) (Section 5.2.3). There are many assumptions in these budgets and further adjustments are possible (e.g., the runoff contribution may be lower and the ground water contribution might be higher), but it is apparent that the annual input from the watershed is not the dominant influence at this time. The potential influence of the herring run on the ponds' nutrient dynamics was noted but little or no data exist to evaluate this influence (Section 5.2.5). Clearly the internal load is the controlling factor in both ponds' phosphorus dynamics. This trend is unlikely to reverse itself without human intervention.

Overall, the diagnostic summaries show that both ponds are eutrophic with poor water quality due to enrichment by nutrients. Phosphorus levels are at excessive concentrations and nutrient ratios favor the development of undesirable blue-green algae These basins are slowly flushed due to the small watershed and dependency on groundwater discharge; with summer circulation being particularly poor due to increased evapotranspiration, the installation of flashboards at the outlets of both Ponds to store water, and the increased pumping of groundwater in the Stillwater Pond watershed. Due to very strong oxygen demand, the Ponds' bottom waters quickly become anoxic. Internal phosphorus recycling from the sediments forms an important but treatable portion of the phosphorus budget.

FEASIBILITY EVALUATION

In terms of the restoration of desirable water quality, the primary goal is to eliminate nuisance algae blooms, or at least to reduce their frequency and severity. Linked objectives include reducing the internal loading of phosphorus and improving the oxygen level in the hypolimnion of both Lovers Lake and Stillwater Pond. As a secondary goal, the watershed should be managed to minimize future pollutant inputs.

While the *Eutrophication Mitigation Plan* study evaluated four potentially applicable pond restoration methods (dredging, aeration, circulation, and nutrient inactivation), there are other potential pond management options available to control in-lake populations of nuisance algal blooms. These alternative in-lake options that were <u>not</u> selected were identified and the reasons why these are not appropriate for restoration of Lovers Lake and Stillwater Pond (Section 7.2)

<u>Dredging Evaluation</u>

The applicability of dredging for restoration of Lovers Lake and Stillwater Pond was evaluated (Section 7.3), specifically the potential for dredging to reduce internal recycling. The factors used for this evaluation were technical feasibility, expected water quality improvement, longevity, cost-effectiveness, and permitting issues.

The technical feasibility review indicates that removal of sediments provides a very direct way of removing a significant amount of phosphorus mass from the pond. However, if removal of the top sediment simply exposes a new layer of phosphorus-enriched sediments then there will be little reduction in the phosphorus regeneration. This technique is not well suited for either pond due to the depth involved, the lack of readily accessible dewatering and disposal areas, and residential setting.

Dredging could reduce the phosphorus loading but only modest improvements in water quality would be expected. Longevity is expected to be lower than average in these ponds due to lack of knowledge of underlying sediment structure and potential refilling of dredged areas If both ponds were dredged, costs would approach $1.5M or more. These high costs reflect the technical difficulties described earlier. As noted earlier, environmental permitting will be extensive and there may be a large set of conditions and extensive monitoring costs. Taking these factors together, ENSR does not recommend dredging for restoration of Lovers Lake and Stillwater Pond.

Artificial Circulation Evaluation

The second of the four in-lake methods for reduction of nutrients and algal blooms selected for evaluation in the *Eutrophication Mitigation Study* is artificial circulation (Section 7.4). Whole lake circulation, like hypolimnetic aeration discussed next, involves the introduction of more oxygen into the bottom waters of ponds to limit the amount of phosphorus recycling, thereby controlling phytoplankton blooms.

The technical feasibility review indicates that artificial circulation or destratification would be a potential option for restoring deep water oxygen levels in Lovers Lake and Stillwater Pond and reducing internal phosphorus recycling. However, based on the morphometry, depth, and thermal structure of the two ponds, it was judged that the conditions of Lovers Lake make it much more conducive to mixing by aeration than Stillwater Pond.

Review of the literature indicates some uncertainty as to how well the water chemistry and ecosystem would respond to this unnatural limnological state and whether it would be beneficial. However, this treatment provides the additional benefit of greatly increasing the amount of habitat for fish and other aquatic organisms and likely shifting the ponds away from dominance by blue-green algae. There is no substantial longevity associated with this technique since the positive benefits start to decline as soon as the diffuser is taken off-line.

Costs are relatively low compared to other restoration techniques, ranging between $180,000 for Lovers Lake and about $78,000 for Stillwater Pond for operation over a 15 year period. Environmental permitting is expected to be relatively simple and straight-forward. ENSR recommended further consideration of artificial circulation for restoration of Lovers Lake and this is discussed further in Section 8.0 but does not recommend application of this technique in Stillwater Pond.

Hypolimnetic Aeration Evaluation

The third of the four in-lake methods for reduction of nutrients and algal blooms selected for evaluation in the *Eutrophication Mitigation Study* is hypolimnetic aeration (Section 7.5). In general, aeration puts air into the aquatic system, increasing oxygen concentration by transfer from gas to liquid and generating a controlled mixing force. Aeration is commonly used to mix shallow lakes, and is sometimes used as a mixing force for artificial circulation and desertification.

The technical feasibility review indicates that hypolimnetic aeration would be a good potential option to reduce internal phosphorus recycling in Stillwater Pond. The characteristics of this basin and thermal structure are conducive to reduction of the amount of phosphorus generated there. The depth of the hypolimnion and the stability of the thermocline would also provide a better transfer of oxygen and little risk of destratification. On the other hand, it was judged that Lovers Lake would not be a good candidate as it is shallower and lacks significant hypolimnetic volume during summer.

An estimate of 70% reduction of the internal phosphorus load in Stillwater Pond was made by comparison to the range of reduction noted in the literature and best professional judgment (BPJ). This was based on the simple morphometry, adequate depth for oxygen transfer, and very stable thermal structure. It appears to be a good setting for this type of device. In addition, this treatment provides the additional benefit of providing an additional amount of habitat for fish and other aquatic organisms. There is no real longevity associated with this technique since the positive benefits start to decline as soon as the aerating device is taken off-line.

The cost for operation of a hypolimnetic aerator for Stillwater Pond over a 15 year period was estimated at $165,000, but this assumes that a site near the basins for installing the compressors and ancillary power requirements be secured. Environmental permitting is expected to be relatively simple and straight-forward. Taken these factors together, ENSR recommends further consideration of hypolimnetic aeration for restoration of Stillwater Pond but not for application in Lovers Lake.

Nutrient Inactivation Evaluation

The last of the four in-lake methods for reduction of nutrients and algal blooms selected for evaluation in the *Eutrophication Mitigation Study* is nutrient inactivation (Section 7.6). Phosphorus inactivation typically involves some amount of short-term phosphorus precipitation (flocculation) during or just after application, but mainly aims to achieve long-term control of phosphorus release from lake sediments. This technique is most effective after other nutrient loadings from the watershed are sufficiently reduced, as it acts only on existing phosphorus reserves, not new ones added post-treatment.

The technical feasibility review indicates that nutrient inactivation by alum treatment would be a very effective option to reduce internal phosphorus recycling in both Lovers Lake and Stillwater Pond. Application of alum should provide a rapid short-term clearing of the water column and a long-term reduction in sediment recycling. An estimate of 75% reduction of the internal phosphorus load was made by comparison to the range of reduction (60-90%) noted in the literature and BPJ. Increases in the secchi disk transparency (SDT) depth and the amount of DO with depth have been noted at both Hamblin and Ashumet Pond following alum treatment. Longevity associated with this technique was conservatively estimated at 15 years but could be longer.

The cost for nutrient inactivation at Lovers Lake was approximately $122,500-$141,000, with a rounded median of $132, 000. Estimated costs for hypolimnetic alum treatment of Stillwater Pond were approximately $76,000-$87,500, with a rounded median of $82,000. Environmental permitting is critical but not complex (WPA NOI and chemical application permits). Of particular concern for the NOI Order of Conditions will be a detailed list of monitoring requirements, both for activities during and after applications. In summary, ENSR recommends further consideration of nutrient inactivation for restoration of Lovers Lake and Stillwater Pond. The treatment is highly appropriate and should be very effective for both lakes.

Selection of Recommended Pond Restoration Option

ENSR developed a series of potential pond restoration options for Lovers Lake and Stillwater Pond (see Section 8.2; Tables 8-1 to 8-3). These options encompass a variety of approaches, management strategies and costs:

- Option #1, the No Action Alternative, describes the current management of the ponds;
- Option #2, termed the “Maintenance Approach,” calls for installation of an artificial circulation system in Lovers Lake. This option provides modest levels of water quality improvement but does not call for active pond restoration in Stillwater Pond;
- Options #3a and #3b, termed “Phased Approach” describes two alternatives in which there is early management effort in Lovers Lake (alum treatment in about half of the bottom area) followed by an assessment period of 2-3 years and then, as needed, implementation of pond restoration to Stillwater

Pond. If the desired level of water quality is not attained, then two alternatives are suggested. In Option #3a, the second phase will be to conduct an alum treatment of Stillwater Pond. For Option #3b, the second phase would be to install a hypolimnetic aerator in the bottom of that pond; and

- Option (#4) ("Aggressive Approach") includes alum treatment for both ponds as well as the installation of a circulation system in Lovers Lake. This incorporates options for reduction of historic phosphorus stored in the sediment and management of any residual phosphorus entering Lovers Lake.

It should be noted that relevant watershed source control (Section 7.8) best management practices (BMPs) are included as part of all restoration options.

ENSR evaluated the four candidate pond restoration scenarios as to which is most likely to be both technically and fiscally feasible, given the environmental setting and financial circumstances of the watershed and Town (Section 8.4). Based on this evaluation, ENSR recommended that the Town select Option #3a as the appropriate restoration course of action. Option #3a has these advantages:

- It provides sufficient phosphorus reduction to significantly improve water quality and reduce the frequency and magnitude of nuisance algal blooms in both ponds. The additional investment represented by Options #3b or #4 do not provide a commensurate amount of improvement (e.g., mean SDT depth would increase by a few inches);
- Option #3a will improve the ecological health of the ponds, increase the amount of dissolved oxygen in lower depths, and be protective of the herring fishery;
- Nutrient inactivation, if conducted correctly, provides a simple and dependable treatment which can be finished in one season and has good longevity of 15-20 years or more;
- Aeration options, while technically viable, represent a long-term commitment of personnel and labor for the foreseeable future. This has been successfully pursued in situations where institutional staff e.g., water supply staff) are available to operate, maintain, and repair equipment, but would likely be less successful in the case of Lovers Lake or Stillwater Pond due to limits of Town or watershed stakeholders resources;
- Installation of anchored aeration devices could lead to potential impairments of fishing or boating due to snagging or fouling of anchors or fishing gear. Power supply (both accessibility and rising costs) are also a concern. Nutrient inactivation would lead to a short-term disruption to recreational activities but would not leave a tangible obstacle;
- Option #3a represents a single expenditure for a Town budget or applicable grant rather than a continuing operations and maintenance expenditure to be considered annually. Failure to pass such an item would set the ponds back to the current, unimproved conditions. Alternative financial arrangements can be made but may also be complicated; and
- Nutrient inactivation appears to be an acceptable option with regard to some potential funding grants (see below).

There are possible concerns regarding Option #3a namely, access for treatment vessels, the accelerating cost of alum and aluminate, and the potential for lay public fears regarding introduction of "chemicals" to the waterbodies. However, none of these appears insurmountable and the advantages greatly outweigh these concerns.

While recommending Option #3a, ENSR also firmly believes that watershed protection measures should also be implemented, as this will be the best means to prevent future eutrophication of the ponds. ENSR recommends incorporating the selected pond restoration and watershed management into a comprehensive watershed eutrophication mitigation plan to address nutrients in the two ponds and downstream resources

(e.g., Ryder's Cove) as well as related outcomes of cultural eutrophication (e.g., increased pathogens) in Ryder's Cove and Frost Fish Creek.

Pond restoration is imperative to improve the water quality and recreational usage of Lovers Lake and Stillwater Pond, but such activities are expensive and may be beyond the resources of the Town and local stakeholders. Therefore, potential funding sources for pond restoration were identified (Section 8.5), including: Town Budget; Legislative Budget funding; MA DCR Water Quality Grants; Clean Water Act Section 319 Watershed Grants; Coastal Zone Management Grants; and Other grants or funding sources. Each of these funding sources is described and potential applicability to the Lovers Lake and Stillwater Pond restoration evaluated.

1.0 Introduction

1.1 Project background

Lovers Lake and Stillwater Ponds are two deep kettlehole ponds located in the Town of Chatham (the "Town") on Cape Cod in Massachusetts (Figure 1-1). [Note for convenience, both waterbodies will be collectively referred to as ponds]. These state-designated "Great Ponds" are recreational (boating, fishing) and ecological resources for the Town of Chatham; featuring one of the two remaining alewife runs in the Pleasant Bay watershed (MA, DEP, 2007). In addition, these ponds are located within the limits of the Pleasant Bay Area of Critical Environmental Concern (ACEC) and have species of special concern identified along shoreline areas and within the watersheds (H&W, 2003).

Currently, the two ponds suffer from poor water quality due to eutrophication (i.e., overabundant nutrient levels) and do not fully support the desired water uses including contact recreation and aquatic life support. Symptoms include low water transparency, frequent and dense algal blooms, loss of oxygen in bottom waters, and degraded ecological habitat. These ponds have been characterized as "highly impacted" and "eutrophic," based on recent assessment studies (CCC, 2003; EcoLogic and S&W, 2003).

The lack of dissolved oxygen in the bottom water layer during summer thermal stratification leads to a consequent buildup in these ponds of undesirable redox reaction products, including phosphorus and hydrogen sulfide. This internal recycling of sediment phosphorus is thought to be a major component of the nutrient loads of these waterbodies that is driving the undesirable conditions.

In response to apparent declining pond water quality, as well as watershed stakeholder concerns (e.g., Great Hill Association) regarding the status of aesthetic and recreational functions of the Ponds, the Town elected to integrate the assessment of its freshwater bodies as part of its overall Comprehensive Wastewater Management Plant (CWMP). The Town initiated a freshwater pond monitoring program in 2000, participated in the Cape Cod Commission's "*Ponds in Peril Program*" from 2000 to present, and selected Ecologic and Stearns and Wheeler to provide an "*Action Plan for the Town of Chatham Ponds."* This latter report indicated that Lovers Lake and Stillwater Pond had the most problematic water quality of the Town ponds and provided strong and clear recommendations for addressing concerns in both (EcoLogic and S&W, 2003).

In 2006, the Town commissioned an *Eutrophication Mitigation Plan* study of Lovers Lake and Stillwater Pond to evaluate four potentially applicable pond restoration methods (dredging, aeration, circulation, and nutrient inactivation) to reduce or eliminate the phosphorus recycling from the sediments. Based on the results of this evaluation, the recommended pond treatment is to be further refined for preparation of bid specifications and the appropriate environmental permit (MA Wetland Protection Act Notice of Intent (NOI)) application prepared. ENSR Corporation ("ENSR") of Westford, MA was selected as the environmental consultant for this project.

ENSR used existing data, supplemented by 2007 water quality and sediment data to provide the basis for the evaluation and recommendation (see Section 1.2 for identification of various tasks). This report summarizes the results of the evaluation and outlines the plan of action to restore Lovers Lake and Stillwater Pond to improve water quality and increase ecological, recreational, and aesthetic functions of these waterbodies.

1.2 Project objectives

The project objectives were discussed during the kickoff meeting for the project held on February 15, 2007 at the Town Hall in Chatham. ENSR is conducting the project under the direction of the Chatham Department of Health and Environment (CDH&E) and the project is managed for the Town by Dr. Robert Duncanson. The

overall goal of the Eutrophication Mitigation Plan is to identify, design and permit appropriate pond restoration treatments to:

- Eliminate, reduce or mitigate the release of phosphorus from the sediments of Lovers Lake and Stillwater Pond, thus reducing the amount of nutrients available for phytoplankton growth in the two ponds;
- Improve the ecological health of Lovers Lake and Stillwater Pond, including water clarity and dissolved oxygen levels in deeper waters of the pond; and
- Enhance the recreational and aesthetic qualities of the ponds.

To meet these project objectives, ENSR proposed the following scope of work including:

- review of current physical, biological and chemical data available for Lovers Lake and Stillwater Pond;
- an initial kickoff meeting to discuss the ponds' watersheds, nutrient inactivation goals, overall lake management objectives, and project coordination;
- supplemental sampling for water quality and sediment chemistry in summer 2007 to address data gaps regarding rates of oxygen depletion and phosphorus release in the two ponds;
- data analysis to support evaluation of four potential pond treatment options (dredging, circulation, aeration, and nutrient inactivation) and recommendation of the best method(s) to reduce internal recycling;
- presentation of recommended choice in pond management workshop with Chatham officials and watershed stakeholders to develop consensus for recommended treatment;
- develop a detailed conceptual design for recommended treatment to support lake management decisions, environmental permitting (NOI) and for preparation of a request-for-proposals (RFP) for subsequent phases of the project;
- preparation of a draft Notice of Intent (NOI) application for the Town and preparation of input for application under the Massachusetts Endangered Species Act (MESA), as needed; and
- a final report summarizing the conceptual design will be provided as well as a draft technical scope of work and schedule to be included in an RFP package for Phase 2 (implementation) of the project.

This report summarizes the results of all 2007 field sampling and supporting data analyses and provides the rationale and decision-making for selection and design of the recommended pond treatment.

1.3 Organization of the report

In addition to this introductory material in **Section 1.0**, the remainder of this document is organized as follows:

- **Section 2** provides an overview of the physical, chemical and biological characteristics of the two ponds and their watersheds, based on the historical data and available information that has been collected on Lovers Lake and Stillwater Pond;
- **Section 3** discusses the field sampling and data collected during 2007 to address data gaps. It briefly describes the methods used to collect surface water and sediments and provides observations made during the sampling trips. Results of the field sampling, water quality analyses and sediment sampling are provided;
- **Section 4** contains a discussion of the hydrologic budgets of the two ponds, focusing on the major sources of water entering and leaving the lake;

- **Section 5** is a focused evaluation on two critical aspects of eutrophication that are to be addressed by the pond restoration efforts. The first is the estimation of the rate of loss of oxygen in the lower (hypolimnetic) waters of the ponds (used in the evaluation of aeration needs) and the second is the rate of release of phosphorus from the bottom sediments, based on the increase in hypolimnetic phosphorus concentrations (used in the evaluation of nutrient inactivation);
- **Section 6.0** summarizes the pond data, analytical results, and diagnostic investigations to provide an updated assessment of the current conditions in Lovers Lake and Stillwater Pond. This will provide the basis for determining the restoration options and target water quality improvement goals;
- **Section 7.0** starts with a brief overview of the range and potential pond management options and then focuses on review, comparison, and evaluation of four potentially applicable methods (dredging, aeration, circulation, and nutrient inactivation); using the criteria of technical feasibility, potential water quality improvement, longevity, cost-effectiveness, permitting issues. At the end of this section, a recommended approach is selected;
- **Section 8.0** provides a detailed discussion of the recommended pond restoration approach, sufficient to help support preliminary design and permitting processes. This section will fully describe the size, location and depth of treated areas within the pond, mobilization points, monitoring program, seasonal timeframe, costs, permit requirements, and funding possibilities. Watershed management options will also be discussed; and
- **Section 9.0** contains the list of references used in developing this document.

As part of this Eutrophication Mitigation Report, additional information, data, and calculations are presented in a series of Appendices, including:

- **Appendix A** is a compilation of historic data, maps, figures and other useful ancillary information for Lovers Lake and Stillwater Pond;
- **Appendix B** provides information on the fisheries of the two ponds, with focus on the herring run;
- **Appendix C** provides information on the plant inventory produced by the shoreline and littoral zone conducted by H&W (2003);
- **Appendix D** contains the field notes and water quality data reports for the 2007 water quality sampling;
- **Appendix E** contains the results of the 2007 sediment sampling and related laboratory analyses;
- **Appendix F** contains additional data analyses and spreadsheets used to support evaluation of diagnostic evaluations and restoration options; and
- **Appendix G** contains information from public meetings held on the two ponds and records of public comments received.

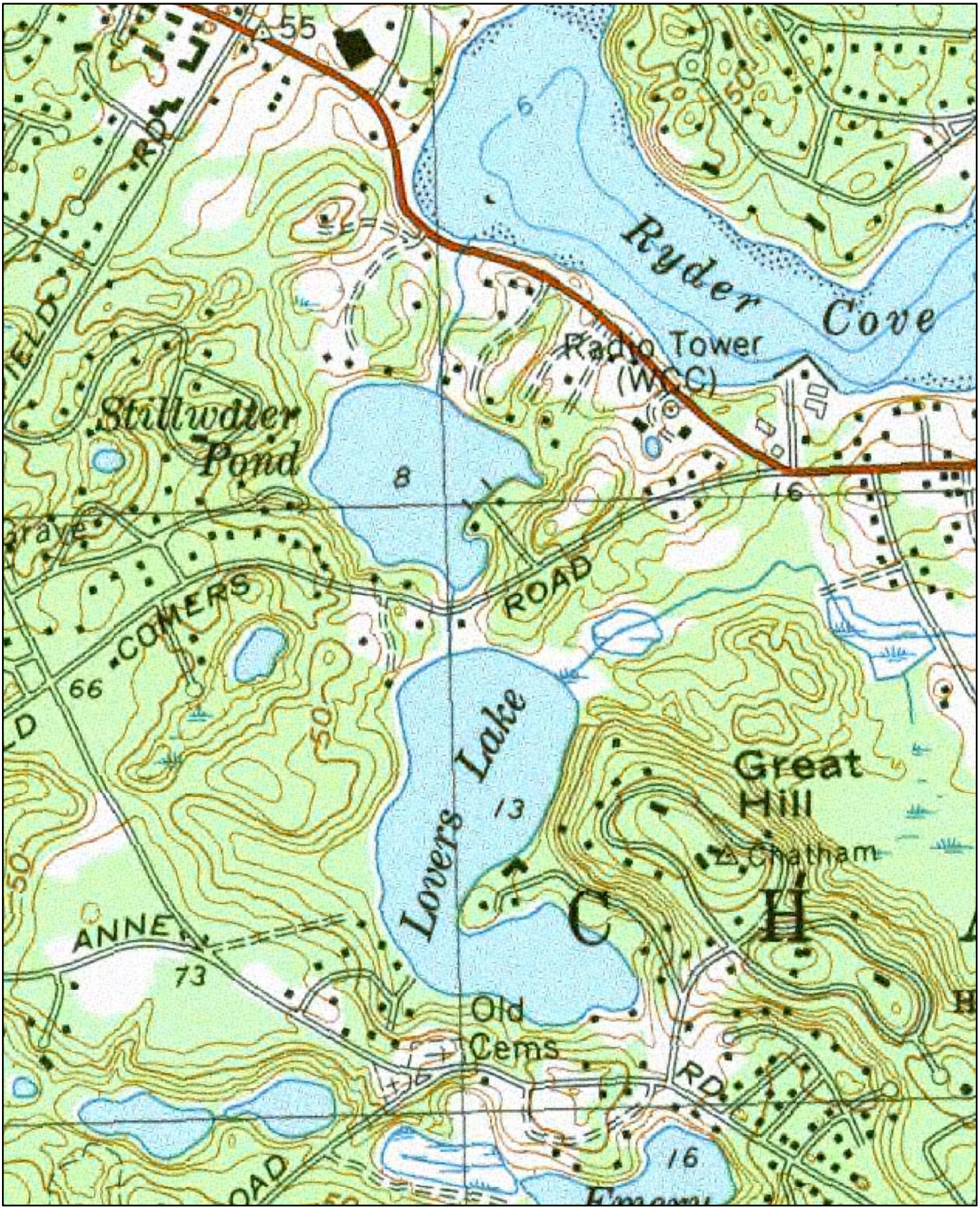

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Figure 1-1 Lovers Lake and Stillwater Pond

(from Chatham USGS Topographic Quadrangle Map 1974)

N W E S

0 370 740 1,480

Feet

ENSR | AECOM

August 2008

2.0 Review of existing data and information

2.1 Introduction

An important part of any pond assessment and restoration effort is the review and integration of the information and data that has been previously collected on the waterbodies of interest. As the first task of the Eutrophication Mitigation Plan Study, ENSR reviewed the existing data and information on Lovers Lake and Stillwater Pond. This information is reviewed and briefly discussed below.

2.1.1 Sources of data and information

Sources of existing information for Lovers Lake and Stillwater Pond were gathered from the Town files and staff (data, GIS files. maps), regional agencies (Cape Cod Commission), state agencies (EOEA, MA DEP, MA DFW), federal agencies (USGS, NOAA), scientific literature, watershed stakeholders, and other sources (e.g., newspapers, internet). These sources include, but were not restricted to, the following:

- Cape Cod Commission. 2003. *Cape Cod Pond and Lake Atlas. Final Report*. CCC Water Resources Office, Massachusetts Executive Office of Environmental Affairs, University of Massachusetts School of Marine Sciences and Technology (SMAST). May 2003;
- CDH&E. 2007. Geographic Information System (GIS) map files, water quality data, paper maps, well locations and data, and other assorted technical information;
- EcoLogic, LLC and Stearns and Wheler. 2003. *Action Plan for Town of Chatham Ponds. Final Report*. November 2003. Hyannis, MA;
- Eichner, E. 2007. Personal communication – updated PALS water quality database for Lovers Lake and Stillwater Pond (2001-2006). CCC Water Resources Office. September 2006;
- Executive Office for Environmental Affairs (EOEA). 2003a. *Cape Cod Watershed Assessment and Action Plan – Pleasant Bay Watershed*. Boston, MA. February 2003;
- Executive Office for Environmental Affairs (EOEA). 2003b. *Pleasant Bay Area of Critical Environmental Concern (ACEC) Factsheet.* Boston, MA. Summer 2003;
- EOEA and MADEP. 2004. *Stage Harbor, Sulphur Springs, Taylors Pond, Bassing Harbor, and Muddy Creek. Total Maximum Daily Loads for Total Nitrogen*. Report #MA96-TMDL-3. November 2004;
- Horsley and Witten (H&W). 2003. *A Qualitative Survey of Pond Shoreline Vegetation and Anthropogenic Threats at Eleven Freshwater Ponds in the Pleasant Bay Area of Critical Environmental Concern*. February 2003;
- Hurley, S. 2007. Personal communication – assorted information from MDFW project files for Lovers Lake and Stillwater Pond. Massachusetts Division of Fisheries and Wildlife;
- Massachusetts Department of Environmental Protection (MA DEP). 2003. Source Water and Protection (SWAP) Report for Chatham Water Department;
- Massachusetts Division of Marine Fisheries. 2004. *A survey of Anadromous Fish Passage in Coastal Massachusetts. Part 2. Cape Cod and the Islands*. MA Department of Fish and Game and EOEA, May 2004;
- Massachusetts Estuaries Program. 2003. *Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Stage Harbor, Sulphur Springs, Taylors Pond, Bassing Harbor, and Muddy Creek. Final Report.* Massachusetts Department of Environmental Protection (MA DEP) and

University of Massachusetts at Dartmouth. School of Marine Science and Technology (SMAST). December 2003;

- Massachusetts Natural Heritage and Endangered Species Program. 2006. Massachusetts Natural Heritage Atlas. 12th edition;
- Pleasant Bay Resource Management Alliance. 2003. *Pleasant Bay Resource Management plan Update.* April 2003;
- St. Pierre, D. 2007. Personal communication regarding status of Stillwater Pond herring run and operation of weirs;
- Tompkins, W.A. 1958. Fisheries report for some southeastern Massachusetts lakes, ponds, and reservoirs, 1951-1952. Bureau of Wildlife Research and Management, MA DFW, Boston, MA. 87 pp.;
- Walter, D. A., Masterson, J.P and K.M. Hess. 2004. *Ground-Water Recharge Areas and Traveltimes of Pumped Wells, Ponds, Streams, and Coastal Water Bodies, Cape* Cod, Massachusetts. Scientific Investigations Report 2004-2857; and
- Walter, D. A. and A.T. Whelan. 2005. Simulated Water Sources and Effects of Pumping on Surface and Ground Water, Sagamore and Monomoy Flow Lenses, Cape Cod, Massachusetts. Scientific Investigations Report 2004-5181.

In addition to these sources, additional information has been obtained from discussion with Town of Chatham staff, newspaper articles, and stakeholders' comments during sampling events or at meetings.

2.1.2 Designated water uses

Lovers Lake and Stillwater Pond are both classified as Class B waters under the Massachusetts surface water quality standards (314 CMR 4.00). The MA water quality standards identify a series of water uses that must be supported for Class B waters. These include: protection of aquatic life (including for their reproduction, growth, migration, and other critical functions), contact (e.g., swimming) and non-contact (e.g., boating) recreation, fish consumption, irrigation, navigation, agricultural and maintain consistently good aesthetic value. Both of these ponds are classified as warm water fisheries. These two ponds are also designated as "Great Ponds" (MA DEP, 2007).

The Pleasant Bay Area of Critical Environmental Concern (ACEC) was designated in 1987 due to the area's important and ecologically-sensitive resources (EOEA, 2003a; 2003b). The ACEC generally follows a 100-ft buffer to the 10-foot contour line and includes coastal wetlands, tidal flats and freshwater features that flow into Pleasant Bay. Both Lovers Lake and Stillwater Pond are included within the ACEC boundaries.

Due to their location within the boundaries of the Pleasant Bay ACEC, both Lovers Lake and Stillwater Pond are designated Outstanding Resource Waters (ORW). This designation, which is most commonly assigned to public drinking water sources, is extended to these two ponds due to "*their outstanding socio-economic, recreational, ecological and/or aesthetic valu*es" so that "*the quality of these waters shall be protected and maintained*" (314 CMR 4.03). Even without the ACEC status, it is probably that the presence of the active herring fishery would further satisfy these criteria for their inclusion as ORW. No functional change in their designated water uses results from their status as ORW but discharges to these ponds are prohibited and/or strictly regulated.

Based on the information available, it was assumed that non-contact recreational uses (both motorized and non-motorized) are supported by both ponds. Irrigation/agricultural use such as transfer of water to adjacent cranberry bogs was historically practiced (see Section 4.0) but is no long applicable; while navigational uses are not relevant to these ponds. No information was available regarding fish consumption, but the existence of

a State-mandated fish consumption advisory (e.g., for mercury) is not based on pond-specific conditions. Aesthetic conditions are impaired by the presence of low transparency and algal blooms.

Accordingly, the focus was on evaluating the ability of the ponds to support aquatic life and contact recreational water uses. Water quality information used to evaluate the criterion for protection of aquatic life will be the levels of dissolved oxygen. Water transparency (estimated by secchi disk transparency (SDT) depth) will be used to evaluate the ponds' ability to support swimming; based on the Massachusetts visibility criterion of 4 ft (1.3 m) for bathing beaches. Additional evidence for aquatic life support can be inferred from other trophic indicators (e.g., nutrients, chlorophyll, presence of blue-green algae, etc).

In addition to the water uses in the Ponds, there is an additional regulatory consideration due to the present listing of the ultimate receiving water (Ryder's Cove) on the Massachusetts 303(d) list of impaired waters. Ryder's Cove (also spelled on various maps as Ryder or Ryders), a coastal embayment of Pleasant Bay, is listed for nutrients and pathogens and has an approved TMDL for total nitrogen (EOEA and MADEP, 2004) as well as TMDLs for bacteria in two contributing sub-watersheds (Frost Fish Creek and Muddy Creek). While the focus of the Eutrophication Mitigation Plan is on the reduction of internally-recycled phosphorus, whatever restoration technique is recommended should also not lead to an increased export of nitrogen downstream to these nitrogen-sensitive waters.

2.2 Pond and watershed characteristics

The Town of Chatham is well provided with pond environments with 44 identified ponds totaling nearly 300 acres identified in the Cape Cod Lake and Pond Atlas (CCC, 2003). Two of the larger of these ponds are Lovers Lake and Stillwater Pond. Some general characteristics of the ponds are presented in Table 2-1.

Key morphological and land use characteristics of Lovers Lake and Stillwater Pond and their watersheds were obtained from several sources (CCC, 2003; EcoLogic and S&W, 2003; CDH&E, 2007; MA GIS, 2007). Bathymetry in the ponds was measured in 2001 as part of a six pond survey conducted by the Town and the CDH&E provided GIS files of these maps for Lovers Lake and Stillwater Pond.

The watershed maps were also available and correspond to areas delineated by USGS using a regional model. The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4, which uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies (MEP, 2003; EOEA & MADEP, 2004). Land use and water resource zoning were available from the Town website (CHD&E) and other sources (MEP, 2003). Finally, an approximate 300 ft buffer zone was established by CCC (2003) for locating residences thought to be relevant to local groundwater quality.

2.2.1 Bathymetry

The bathymetric (bottom) contours of Lovers Lake were established by CDH&E in 2001 and are shown in Figure 2-1a, while those for Stillwater Pond are shown in Figure 2-1b. Lovers Lake forms a rough letter "L" with two deep basins (Figure 2-1a). The larger, deeper basin (maximum depth = 31 ft; 7.9 m) is located at the northern end and is separated from the southern basin (maximum depth = 26 ft; 9.4 m) by a shallower zone (or sill) of 10-15 ft (3 -4.6 m) depth in the central connection. Since the sill is shallower that the typical depth of thermal stratification, it likely provides a functional barrier for mixing of the hypolimnetic waters in these basins during stratified periods

The bathymetric map of Stillwater Pond portrays a simpler basin system (Figure 2-1b). This pond has a classic kettlehole morphometry with just one central basin of considerable depth (maximum depth = 51 ft; 15.5 m), which is steep sloped on most sides except towards the eastern and southeast embayments.

The surface area of Lovers Lake has been variously reported by different organizations as 36 acres (MA DFW map, H&W, 2003), 37.7 acres (CCC, 2003) and 38 acres (MA DFW undated). These slight differences are probably attributable to differences in the water level at the time of observation or due to the method and/or precision of areal estimation. The pond level fluctuates seasonally due to groundwater levels and precipitation patterns. Since there is general good agreement between these three estimates, for purposes of this assessment, we used the CCC (2003) value of 37.7 acres as the base surface area (also used by EcoLogic and S&W, 2003). Similarly, Stillwater Pond's surface area has been reported as 16-18 acres (H&W, 2003), 18 acres (MA DFW, undated), and 18.7 acres (CCC, 2003) and ENSR used the 18.7 acre value as the base surface area.

Using these surface water area estimates, ENSR developed hypsographic depth-area and depth-volume relationships for each of the ponds. These are shown for Lovers Lake in Figure 2-2a and for Stillwater Pond in Figure 2-2b. The volume of water available for a given depth is an important component of later calculations (e.g., Section 5.0) and is shown for both ponds in Table 2-2.

2.2.2 Watershed characteristics

Lovers Lake is located midway between Old Comers Road and Queen Anne Road, just south of Ryder's Cove in north central Chatham. The watershed extends to the southwest to just below Mary's Pond and to the south to just above Emery Pond. The pond is drained by a surface water outlet to Stillwater Pond that goes through a culvert beneath Old Comers Road and which is the site of an outlet structure that is used to maintain the herring run into the pond (see Section 2.4).

Land use in the watersheds of both Lovers Lake and Stillwater Pond is of critical importance due to the predominance of groundwater as the major hydrologic input to these ponds. The watershed land uses, as is true for most freshwater ponds in Chatham, are primarily residential and forested areas (MEP, 2003). The watershed land use, as available from the Town GIS files, is summarized in Table 2-3. The watershed boundaries and land use is shown in Figure 2-3.

The southern, eastern and northwestern shorelines of Lovers Lake are developed with single family residences. It was determined that approximately 38 residences are located within 300 ft of the shoreline (EcoLogic and S&W, 2003). The total number of residences in the watershed or adjacent buffer zone is 62 (Table 2.3).There is non-developed, protected (Chatham Conservation Foundation (CCF)) land abutting to the west, which may provide an informal public access. A privately-owned boat ramp is located off Lake Shore Drive on the northern shoreline of the lower lobe of the lake. Several small beach areas are located in the pond, along with several docks and floating rafts (H&W, 2003).

A former cranberry bog and historic hydraulic connection to Frost Fish Creek is located on the northern shoreline. Land adjacent to the former bog has been reportedly purchased by a local land bank. The historic hydraulic connection has been effectively blocked such that surface water flow is predominantly routed to Stillwater Pond via the northern outlet (Duncanson, 2000). An active cranberry bog is located in the southern end of the watershed, but has a more direct hydrologic connection with Emery Pond (Figure 2-3).

Stillwater Pond is located midway north of Old Corners Road and east of Training Field Road, just south of Ryder's Cove. The watershed extends to the southwest to Schoolhouse Pond and Mary's Pond and is aligned roughly parallel to the Lovers Lake watershed with flow going to the northeast (MEP, 2003). The pond is hydraulically connected to Lovers Lake through the herring run outlet and groundwater influx. Stillwater Pond outlets via a 300 ft stream that enters Ryder's Cove just north of Route 28 (see Figure 2-3).

The watershed land use is split between residential land use in the closer areas, with a good deal of non-developed Town and CCF-protected land at greater distance (Figure 2-3). The shoreline is not heavily developed with residences scattered on its northern and southeastern shorelines. It was determined that 23

residences are located within 300 ft of the shoreline (see Figure 2-3), although only 6 residences are located on the actual shoreline (EcoLogic and S&W, 2003). The total number of residences in the watershed or adjacent buffer zone is 58 (Table 2.3). Five docks were noted by the H&W (2003) shoreline survey. Public access may be possible through Town Conservation lands.

One important feature of the Stillwater Pond watershed is the presence of public drinking water supply wells. Two active Town wells (designated #5 and #8) are located off Training Field Road, to the west of Lovers Lake but still within the Stillwater Pond drainage. Due to the importance of protecting groundwater resources for drinking water, Chatham has adopted a large Water Resources Protection within the Town (MA DEP, 2003). The impact of the pumping of these wells on the hydrologic budget of Stillwater Pond will be considered in Section 4.0.

2.3 Water quality

Recent water quality data were available to provide the evaluation of recent trophic conditions and the ability of the Ponds to meet designated uses. Water quality (nutrients) and trophic indicators (e.g., chlorophyll concentrations, dissolved oxygen (DO), and Secchi disk transparency (SDT) depth) have been regularly monitored from 2000-present in both ponds as part of the Pond and Lake Stewards (PALS) volunteer monitoring program. Some of this information was described and summarized in the Cape Cod Lake and Pond Atlas (CCC, 2003). This information has been supplemented by data from more recent monitoring (2004-2006) of the two lakes (Eichner, 2007). In addition, bacteriological testing records obtained were from CDH&E.

2.3.1 Lovers Lake

Observations of physical and chemical attributes of the water column and water quality sampling were conducted in Lovers Lake by the PALS volunteer monitors during the period 2000-2006 (CCC, 2003; Eichner, 2007). Monitoring and sampling was conducted at the deep hole in the northern lobe (position marked by a permanent buoy) at one of the same locations used for water quality sampling in 2007 (see Section 3.1). Most water quality sampling was conducted during late summer to early fall periods; typically July through September periods during the stratified periods. A more intensive monitoring of SDT (weekly to bimonthly) was conducted during the period July 2001 – August 2002. Bacteriological sampling was conducted periodically from 1998 through 2003, typically during the summer and in response to pond shoreline residents' concerns.

2.3.1.1 Temperature and dissolved oxygen

Water temperature and DO were measured throughout the water column during 2001- 2006. Depth profiles of temperature are presented in Figure 2-4. This figure shows that Lovers Lake is a thermally stratified system and that during the summer the lake can be divided between upper waters (termed the epilimnion) and the bottom waters (termed the hypolimnion). The depth at which there is a rapid decrease in temperature with depth is called the thermocline (also known as the metalimnion). This thermal and density divide occurs at approximately 5 m (i.e., 17 ft) most years, although no distinct thermocline was present during the 2002 observation. This data point may represent a year when the lake mixed earlier than usual during the fall.

During the summer thermal stratification there is very little exchange between the hypolimnion and the epilimnion and surface. This leads to a seasonal decrease in DO as organic material in the isolated hypolimnion is subject to bacterial decay which consumes oxygen. This is indicated by the marked decrease with depth in dissolved oxygen (Figure 2-5) that occurs from between 4 and 6 m (13.2 - 19.7 ft). In most years, there is virtually no DO left in the hypolimnion below 6 m. This lack of oxygen or anoxia has significant implications for the nutrient recycling in the pond (see Section 5.2).

Additional depth profiles of temperature and dissolved oxygen were generated by sampling during 2007. These data are discussed and described in Section 3.1.2.

2.3.1.2 Secchi disk transparency

As part of the monitoring effort, the SDT depth, an approximate measure of water clarity, was measured during the period 2000-2006. As can be seen in Figure 2-6, the SDT depth varied between less than 0.5 m to 3.5 m. In the lower portion of the range, the water clarity would fail to meet the Massachusetts transparency criterion of 4 feet (1.22 m) for swimming beaches.

The most complete seasonal SDT records were from July 2001 to August 2002. During this period, the greatest SDT depth was observed during spring to early summer 2002. SDT depth typically declines over the summer season so that minimum SDT depth usually occurred during late summer to early fall. This is consistent with the build-up of late summer phytoplankton, particularly cyanobacteria (i.e., blue-green algae (BGA)), during this period. High levels of BGA have been reported or photo-documented by shoreline residents on several occasions in the past five years.

2.3.1.3 Water chemistry

Water chemistry data was available for Lovers Lake from the summertime PALS volunteer monitoring program (Eichner, 2007) and includes data from both shallow (0.5 m) and deep (9-9.5 m) stations. These data represent an annual "snapshot" of the Ponds' condition, typically taken during late summer – early fall, when the effects of stratification and season are most pronounced. Summary statistics for Lovers Lake are provided in Table 2-4.

The PALS summary statistics for temperature and DO are consistent with thermally stratified conditions described in Section 2.3.1.1 and shown in Figures 2-6 and 2-7. The shallow epilimnetic station is considerably warmer than the hypolimnion but the big contrast is in the average DO levels found near the surface (8.8 mg/L) as opposed to the bottom waters (1.1 mg/L).

The average TP concentration near the surface was 32.2 ug/L with a range of 23.9 to 46.5 ug/L; while average TN was 0.78 mg/L with a range of 0.44 to 1.55 mg/L. In contrast, both TP (mean of 116.6 ug/L; range of 50.6 to 173.6 ug/L) and TN (mean of 2.63 mg/L; range of 1.9 to 4 mg/L) were elevated in bottom waters, presumably due to anoxic conditions leading to a release of phosphorus and breakdown of organic nitrogen into ammonia. Anoxic conditions are generally considered to be represented by DO values below 2.0 mg/L

Other trophic parameters of note include summer chlorophyll a and SDT depth. Chlorophyll a was highest in upper waters with an average of 25.3 ug/L and range of 5.4 – 68.3 ug/L, while phaeophytin, which is the major breakdown product of chlorophyll *a*, was higher (9.6 to 2.8 ug/L) in the hypolimnion, consistent with the concept that phytoplankton eventually sink out of the epilimnion and are decomposed in the hypolimnion. The SDT depth was generally very shallow with an average of 1.1 m and range of 0.4 to 1.7 m. These shallow readings were taken during a period when water clarity is typically near its seasonal low.

The two general water quality parameters reported were pH and alkalinity. For pH, the upper waters averaged 8.1 standard pH units (S.U.) with a range of 7.0 to 9.3 S.U and the alkalinity was 25.9 mg/L (as $CaCO_3$), with a range of 1.9 - 42.2 mg/L. The hypolimnion was more acidic with an average of 6.7 S.U. with a range of 6.4 - 7.0 S.U and more alkaline (mean of 81.3 mg/L; range of 5.3 – 150.9 mg/L). These late summer values suggest that in upper waters, phytoplankton uptake of CO_2 for photosynthesis is leading to a pH increase and reduction of alkalinity. However the alkalinity minima shown at the two stations (1.9 to 5.3 mg/L) indicate that this system can still be very poorly buffered at times.

2.3.1.4 Pathogens

Testing for bacterial pathogens (fecal coliform, *Escherichia coli* (*E. coli*), and *Enterococci*) was conducted from 1998 through 2003, typically during the summer (June through August) and the results reported to pond shoreline residents. Locations typically tested included beach areas or access points located near the terminus

of the following streets: Old Town Lane, Lake Shore Drive Ramp, and Lovers Lake Circle. During the period 1998 – 2003, none of the results violated the Massachusetts Standards for Bathing Beaches (105 CMR 445.000). During the visits when it was noted, there were no active bathers at the time of the sampling. It should be noted that the downgradient Frost Fish Creek has a TMDLs for pathogens, although Ryder's Cove may be listed on the Section 303(d) list as "impaired" for pathogens.

2.3.2 Stillwater Pond

2.3.2.1 Temperature and dissolved oxygen

Water temperature and DO were measured in Stillwater Pond throughout the water column during 2001- 2006. Depth profiles of temperature are presented in Figure 2-7. This figure shows that Stillwater Pond is a very strongly thermally stratified system during the summer. The thermocline was typically located at approximately 5 m (i.e., 17 ft) most years, although (as noted earlier) the 2002 data may indicate near turnover conditions.

The DO profile is consistent with that of a strongly stratified system but there is complexity in the pattern (Figure 2-8). In general, DO levels declined to less than 2.0 mg/L below 4 – 5 m (13.2 – 16.5 ft) of water depth. However, one exception is the pattern seen in 2001, which is indicative of a phenomenon known as a metalimnetic oxygen maxima. This pattern can occur when a narrow layer of phytoplankton is suspended just at the thermocline where a combination of available light and nutrients provides for a strong, but temporary, growth environment such that the photosynthesizing algae produce a localized DO increase.

Additional depth profiles of temperature and DO were generated by sampling during 2007. These data are discussed and described in Section 3.1.3.

2.3.2.2 Secchi disk transparency

As part of the monitoring effort, the SDT depth, an approximate measure of water clarity, was measured in Stillwater Pond during the period 2000-2006. As can be seen in Figure 2-9, the SDT depth varied between less than about 0.5 m to approaching 5 m. In the lower portion of the range, the water clarity would fail to meet the Massachusetts transparency criterion of 4 ft (1.22 m) for swimming beaches.

The most complete seasonal SDT records were from July 2001 to August 2002. During this period, the greatest SDT depth was observed during early spring to early summer 2002. SDT depth typically declined over the summer season so that minimum SDT depth usually occurs during late summer.

2.3.2.3 Water chemistry

Water chemistry data was available for Stillwater Pond from the summertime PALS volunteer monitoring program (Eichner, 2007) and includes data from both shallow (0.5 m) and deep (9-9.5 m) stations. These data represent an annual "snapshot" of the Ponds' condition, typically taken during late summer – early fall, when the effects of stratification and season are most pronounced. Summary statistics for Stillwater Pond are provided in Table 2-5. In general, the patterns seen in Stillwater Pond are very similar to those observed in Lovers Lake over the same time period.

The PALS summary statistics for temperature and DO are consistent with thermally stratified conditions described in Section 2.3.1.1 and shown in Figures 2-9 and 2-10. The shallow epilimnetic station is considerably warmer than the hypolimnion but the big contrast is in the average DO levels found near the surface 9.1 mg/L as opposed to the bottom waters which are extremely oxygen deficient (average of 0.2 mg/L).

The average TP concentration near the surface was 27.5 ug/L with a range from 14 to 44.6 ug/L; while average TN was 0.77 mg/L with a range of 0.37 to 1.24 mg/L. Similar to Lovers Lake, the bottom waters of Stillwater Pond are nutrient enriched. For the hypolimnetic station, the mean TP was 290 ug/L, with a range of 177 to 427 ug/L); while for TN a mean of 2.97 mg/L and a range of 2.3 to 3.7 mg/L were recorded.

Chlorophyll a in the upper waters had an average of 23 ug/L and ranged from 4.8 to 56.1 ug/L, Phaeophytin averaged higher in the hypolimnion compared to the upper water (12.5 to 3.9 ug/L). The SDT depth had an average of 1.6 m and range of 0.6 to 3.0 m.

For pH, the upper waters of Stillwater Pond averaged 7.8 standard pH units (S.U.) with a range of 6.9 to 8.9 S.U and the alkalinity was 24.7 mg/L (as $CaCO_3$), with a range of 1.8 – 39.4 mg/L. The hypolimnion was more acidic with an average of 6.5 S.U. with a range of 5.9 – 6.7 S.U and more alkaline (mean of 62.9 mg/L; range of 4.9 – 102.3 mg/L).

2.4 Biotic communities

The biotic communities of Lovers Lake and Stillwater Pond have not been well-characterized in recent years. Some information is available regarding the fisheries in the Ponds, with particular emphasis on the herring (alewife) run (MA DFW, 2004; Hurley 2007; St. Pierre, 2007). There has been a recent assessment of the observable shoreline and littoral zone vegetation (H&W, 2003), but little information is available regarding wildlife use except limited observations and anecdotal evidence.

2.4.1 Fisheries

Most information on the two ponds was obtained from Steve Hurley (MA DFW), Southeast District Fisheries Manager, and consisted of excerpts from published reports (e.g., Tompkins, 1958), maps, and unpublished data (Hurley, 2007). A description of the herring run and dimensions of the outlet structures were obtained from - *A survey of Anadromous Fish Passage in Coastal Massachusetts. Part 2. Cape Cod and the Islands* (MA DFW, 2004). The Town herring warden, Don St. Pierre, was also interviewed and provided useful information and insights regarding the herring fishery and operation of the herring run structure (St. Pierre, 2007).

2.4.1.1 Lovers Lake fishery

There are historical data regarding the fishery of Lovers Lake (Tompkins, 1958) and a fishery sample taken in the late summer of 1952 is presented in Table 2-6. The description of the pond indicated that the shoreline was wooded and an accompanying map shows a relatively narrow band of emergent and submergent vegetation extending into the pond. The pond bottom is “comprised of half muck, half gravel and sand” (Tompkins, 1958).

The warmwater fishery was considered well-balanced and no management was considered essential at that time. Based on the MA DFW data and a local fisherman’s letter, the target game species was chain pickerel, although other game fish, including American eel, smallmouth bass, yellow perch, white perch, and brown bullhead, were present (Tompkins, 1958; Hurley, 2007). Forage fish included bridle shiner, golden shiner, killifish and stickleback. No alewife (herring) were captured by the sampling, but the methods (seining) and the time of year (August) suggested that adult herring had returned to Ryder’s Cove and the young-of-the-year (YOY) alewife were too small to capture in this way. MA DFW notes indicated that the pond had been stocked three times from 1915 to 1941, primarily with smallmouth bass, but also with brook trout (Tompkins, 1958). Frost Fish Creek, which was formerly directly connected to Lovers Lake, is considered to have an active herring run (MA DFW, 2004).

2.4.1.2 Stillwater Pond fishery

The MA DFW project files provided fish sample data from an unpublished summary sheet (Hurley, 2007). This information is based on a qualitative sampling (apparently rotenone application) conducted in May 1967 and is summarized in Table 2-6. Game fish caught included chain pickerel, largemouth bass, yellow perch and white perch. American eel is also assumed to be present (Hurley, 2007). Forage fish included alewife (adults), bridle shiner, golden shiner, and stickleback. It was reported that brown trout were stocked in the pond in 1997 (Hurley, 2007).

The herring (i.e., alewife) fishery in Stillwater Pond is considered a significant resource, since it is one of two remaining active herring runs in Chatham (Frost Fish Creek is the other). The Town assumed control of the alewife fishery in 1968 under Massachusetts Chapter 94 (MA DFW, unpublished). During colonial days, alewife constituted a useful protein supplement for local residents, and was an important community resource. However, these days, human consumption is only a minor use and the fish are primarily sought as bait for commercial or sport fishing (MA DFW, 2004).

The common term herring (or river herring) functionally applies to two closely related members of the family Clupedidae - the alewife (*Alosa pseudoharengus*) and the blueback herring (*Alosa aestivalis*). Although the alewife is slightly larger than the blueback (up to about 12 inches), taxonomic identification of the two species is difficult and often entails inspection of the body cavity lining. Alewife tend to spawn 3 to 4 weeks earlier than bluebacks. While both species are capable of spawning in both river and lake environments, there is a decided preference for alewife for lakes; although both species are usually present (MA DFW, 2004).

For Stillwater Pond (and for upstream Lovers Lake), the alewife run begins in mid- to late March and continues to late April to early May. Adults begin to move out after spawning and are generally gone by mid-June. Eggs hatch in early summer and the YOY alewife remain and develop in the Ponds until mid-September, when they migrate to the marine environment (Ryder's Cove).

The Chatham Herring Warden, Don St. Pierre, is responsible for the operation and maintenance of the herring run and has performed this duty for the last 35 years. The herring run consists of four separate structures (MA DFW, 2004), here listed in order from downstream at Ryder's Cove to Lovers Lake:

- eight foot wooden vertical slot structure at the tidal head of Ryder's Cove passing into a 147 ft long 18-inch corrugated plastic pipe with wooden baffles;
- Stillwater Pond outlet structure comprised of wooden flashboards and a concrete structure;
- sixty foot length of 18-inch corrugated plastic pipe acting as a fishway with wooden baffles for going under Lovers Lake culvert; and
- Lovers Lake outlet structure comprised of wood and aluminum.

Further information on the dimension and location of the herring run structures as well as pictures of the structures are provided in Appendix B (MA DFW, 2004).

The Herring Warden increases the pond surface elevations by installation of flashboards in the late winter to store water and opens them in the spring to allow the adults to enter, spawn and return (St. Pierre, 2007). The flashboards are reinstalled around the Fourth of July to maintain pond levels during the summer and then removed again around Labor Day to allow the sea migration of the YOY alewife. He estimates the typical level of surface fluctuation during summer as about 10" for Lovers Lake and 6" for Stillwater Pond. Mr. St. Pierre does not quantitatively sample the herring runs but indicated that while the run has had many good years ("gangbuster") in the previous 10 years, the last few have been decidedly less. Mr. St. Pierre believes that off-shore fishery of the alewife may be reducing the runs during the last few years.

2.4.2 Wildlife

There is little information directly available about wildlife (birds and mammals) living in or around the pond. However, local bird watchers have reported 248 different species of bird within the Pleasant Bay ACEC (EOEA, 2003b). Observations of waterfowl during the watershed reconnaissance and the surface water/sediment collection indicated duck (mallard (*Anas platyrhynchos*); black (*Anas rubripes*)), Canada geese (*Branta canadensis*), and a resident pair of mute swans (*Cygnet olor*). Some of the geese are resident and are contributing to the nutrient load and bacterial inputs, as indicated by accumulations of droppings in shoreline areas. Based on the large amount of undeveloped riparian habitat on Stillwater Pond and, to a certain extent, Lovers Lake, common mammal species (muskrat, weasel, mink, and raccoon) are likely to be present.

2.4.3 Aquatic vegetation and riparian habitats

As part of the evaluation of the Pleasant Bay ACEC (see Section 2.4.4), an evaluation of the aquatic vegetation and riparian habitat areas of Lovers Lake and Stillwater Pond were conducted as part of *A Qualitative Survey of Pond Shoreline Vegetation and Anthropogenic Threats at Eleven Freshwater Ponds in the Pleasant Bay Area of Critical Environmental Concern* (H&W, 2003). These shoreline surveys identified nearshore emersed, floating-leaved, and emergent aquatic vegetation: riparian wetland species: non-native (exotic) or invasive species: and species of special concern. A summary of data gathered by the survey is provided in Appendix C.

2.4.3.1 Lovers Lake plant communities

The H&W 2003 shoreline survey identified aquatic vegetation species within and along the Lovers Lake shoreline including: spatterdock (*Nuphar variegata*), pickerel weed (*Pontederia cordata*), ribbon-leaf pondweed (*Potamogeton epihydrus*), water willow (*Decodon verticillatus*), narrow-leaf cattail (*Typha angustifolia*), wide-leaf cattail (*Typha latifolia*), bayonet rush (*Juncus militaris*), soft rush (*Juncus effusus*), and Olney three-square (*Scirpus americanus*). Overall, 51 plant species, representing 32 Families, were observed (H&W, 2003). An inventory of the plant species observed during the 2002 growing season is provided in Appendix C. Two non-native species, curly dock (*Rumex crispus*) and peppermint (*Mentha piperita*) were documented (H&W, 2003).

2.4.3.2 Stillwater Pond plant communities

The H&W 2003 shoreline survey identified aquatic vegetation species within and along the Stillwater Pond shoreline including: water willow (predominant shoreline species), spatterdock, white water lily (*Nymphaea odorata*) – both the normal and a pink variant, pickerel weed, common watermilfoil (*Myriophyllum sibiricum*), wide-leaf cattail, soft rush, and Olney three-square. An inventory of the plant species observed during the 2002 growing season is provided in Appendix C. Two invasive species, purple loosestrife (*Lythrum salicara*) and common reed (*Phragmites australis*) have become well-established within some stands of water willow and wide-leaf cattail (H&W, 2003).

2.4.4 Sensitive species

In 2002, the MA NHESP identified approximately 7,425 acres (or 80%) of the Pleasant Bay ACEC as core habitat through their BioMap Project (EOEA, 2003). Seven sensitive species were identified in 2002 within the Pleasant Bay ACEC including endangered (E), threatened (T), or special concern (SC). These seven sensitive species include: the short-eared owl, *Asio flamneus* (E – bird), diamondback terrapin, *Malaclemys terrapin* (T – reptile), piping plover, *Charadrius melodus* (T – bird), New England bluet, *Enallagma laterale* (SC – insect), stigose knotweed, *Polygonum spp*. (SC – plant), four-toed salamander, *Hemidactylium scutatum* (SC – amphibian), and the plymouth gentian, *Sabatia kennedyana* (SC – plant) (EOEA, 2000b). The 2006 MA NHESP priority habitat maps indicate the presence of priority habitat both in the watershed and within the basins of the two ponds (MA NHESP, 2006). Central portions of the two ponds are not included (Figure 2-10).

The habitat mapping follows the contours of the lake shoreline and is mostly likely identified as potential habitat for plymouth gentian or possibly endangered odonate species. As part of the preparation of a NOI for the selected pond management, NHESP will be contacted regarding the presence of sensitive species within the lake basin.

The H&W (2003) shoreline survey indicated that the presence of large stands of water willow (also known as swamp loosestrife) may provide habitat for the Water Willow Stem Borer (*Papaipema sulphurata*), a threatened species in Massachusetts and globally restricted to southeastern Massachusetts. The water willow is the required larval food source for the Stem Borer.

Historic fishery records for Lovers Lake and Stillwater from the 1950's and 1960's indicated the presence of bridal shiner, a Massachusetts-listed species of Special Concern (Section 2.4.1). This species has been in decline throughout Massachusetts and it is not certain what the current status of this species is in the two ponds.

2.5 Prior pond assessments

The conditions of Lovers Lake and Stillwater Pond were evaluated in 2003 (CCC, 2003, EcoLogic and S&W, 2003). The assessments looked at the trophic indicators for the ponds. A brief description of trophic indicators is provided below, along with the results of the Cape Cod Commission and EcoLogic assessments.

2.5.1 Trophic indicators

One way of assessing whether ponds are currently supporting their designated water uses is by comparison of ambient values of trophic indicator data (i.e., phosphorus and nitrogen fractions, chlorophyll a, and SDT) to State water quality criteria or thresholds. The focus for water chemistry in freshwater is principally phosphorus, since previous work has shown that most Cape Cod ponds are phosphorus limited (Ahrens and Siver, 2000), although in some cases, nitrogen may be seasonally limiting (i.e., late summer).

Since the MA DEP is still in the process of developing a state water quality numeric total phosphorus criterion for Massachusetts lakes and ponds, alternative benchmarks may be considered such as the USEPA ecoregional water quality recommendations (U.S. EPA, 2001), the 25th percentile marks from the CCC database of more than 185 Cape Cod ponds (CCC, 2003), accepted trophic state boundaries from the limnological literature (e.g., Wetzel, 2001; Kalff 2002), or other benchmarks.

Ultimately, it was considered most appropriate to use the numerical criterion recommended by CCC (2003) for classifying the trophic status of Cape Cod ponds. This was due to the severe under-representation of Cape Cod ponds in the USEPA database for this ecoregion (Atlantic Coastal Pine Barrens; sub-ecoregion 84) and the acknowledgment that the CCC PALS database provides a more extensive collection of lakes, parameters measured and frequency of measurement. For this same reason, the site-specific database and interpretation is preferred over relying on the geographically-diverse collection of northern temperature lakes discussed in standard limnological texts (Wetzel, 2001; Kalff 2002).

The CCC system identifies both reference (i.e., "*unimpacted*") and target ("*healthy*") values for nutrient and trophic indicators (CCC, 2003). The CCC pond benchmark system derives nutrient and indicator (chl a) thresholds in a similar fashion to U.S.EPA water quality recommendation methodology through a statistical approach, (i.e., the adoption of the upper or lower 25th percentile of an appropriate database). For Cape Cod ponds the CCC established "*unimpacted*" total phosphorus levels as the upper 75% of values from reference ponds judged not to have been significantly altered from historic (1948) trophic levels (=1.7ug/L) and "*healthy*" levels as the upper 25% of values from all ponds in the database (=10 ug/L).

While the term "*unimpacted*" seems appropriate with regard to near-pristine or reference natural water quality conditions, the term "*healthy*" is much more ambiguous in the limnological sense, and may likely be misinterpreted in popular usage since if follows that ponds not meeting these target criteria may be considered not "*healthy*." However many mesotrophic ponds that provide water quality and habitats for a diverse biological assemblage and support all designated water uses may be considered not "*healthy"* under a strict application of these criteria (i.e., minor exceedances of criterion). However, the CCC criteria provide a useful screening tool for sorting ponds into classes with various trophic characteristics.

2.5.2 Cape Cod Commission pond assessment

The *Cape Cod Commission Lake and Pond Atlas* provides an overview of the Cape Cod ponds, PALS monitoring methodology, and a summary of the PALS water quality data from 2000-2002 (CCC, 2003). The *Atlas* provides an evaluation of Lovers Lake and Stillwater Pond

The depth profiles in Lovers Lake indicated that anoxic conditions were observed from greater than 40% of the water column. The surface water chlorophyll a level (= 46.6 ug/L) was in the top 5% of all surface water readings during 2001 monitoring. Surface phosphorus was elevated at 35 ug/L. A high phosphorus concentration in the bottom waters (= 131 ug/L) was considered indicative of phosphorus release from the sediments. SDT depth was shallow at 2.8 ft. Alkalinity was 17 -18 mg/L as $CaCO_3$ in the epilimnion and was 64.8 mg/L at the bottom. Overall, Lovers Lake was considered to be a highly impacted pond with significant water quality problems (i.e., not meeting healthy criteria).

Water quality data was available from 2000-2002 for Stillwater Pond (CCC, 2003). As with Lovers Lake, anoxic conditions were observed from greater than 40% of the water column. The surface water chlorophyll a level was at 8.3 ug/L. Surface phosphorus was at 15 ug/L. High phosphorus concentration (= 325 ug/L) in the bottom waters was considered indicative of phosphorus release from the sediments. SDT was reasonably deep at 9.9 ft. Alkalinity was 16.5 mg/L as $CaCO_3$ in the epilimnion and was 48.2 mg/L at the bottom. Overall, Stillwater Pond was classified to be a highly impacted pond with significant water quality problems.

2.5.3 EcoLogic assessment

As part of the *Action Plan for Town of Chatham Ponds,* EcoLogic considered the water quality data from the PALS 2001 Snapshot, morphometric parameters, and a visual inspection to provide an evaluation of the freshwater ponds in Chatham (EcoLogic and S&W, 2003). Based on the depth, surface area, and fetch, Lovers Lake was considered to have a moderate tendency for entrainment (mixing) of bottom waters, while the probability for Stillwater Pond was considered low. Based on their assessment of current conditions, EcoLogic classified both Ponds as eutrophic and not meeting desired water uses (EcoLogic and S&W, 2003).

2.5.4 Report recommendations

Both of the prior assessment recommended further action on the Ponds. The CCC (2003) report recommended that further annual monitoring continue for both Lovers Lake and Stillwater Pond with a better characterization of nutrient loads to and within the lake. The EcoLogic (2003) *Action Plan* identified both Lovers Lake and Stillwater Pond as good candidates for alum application for reducing internal recycling from sediments. EcoLogic also recommended additional monitoring on a biweekly basis of the water column profile, water quality sampling, and sediment sampling to help support the design of the alum application. As will be shown in Section 3.0, these recommendations were incorporated into the design of the water quality and sediment sampling program conducted in 2007.

Table 2-1. Characteristics of Lovers Lake and Stillwater Pond, Chatham, MA

	Lovers Lake	Stillwater Pond
Lake Surface Area (SA)(ac)	37.7	18.7
Mean depth (ft)	15.1	21.8
Maximum depth (ft)	36	51
Lake Classification	Temperate dimictic	Temperate dimictic
Watershed area (WA) without lake (ac)	86.3	128.3
WA:SA Ratio	2.3	6.9
Hydrologic Connections	Stillwater Pond and formerly Frost Fish Creek	Lovers Lake and Ryders Cove
Recreational Uses	Swimming, boating, fishing	Swimming, boating, fishing

Table 2-2a. Lovers Lake Hypsographic Relationships - Area and Volume.

Interval (m)	Strata mid-point depth	Surface Area (m2)	% of SA* (%)	Depth Interval (m)	Volume in strata (m3)	% Volume in strata (%)
	0	152566	100.0			
0-1	0.5	143412	94.0	1	143412	20.6
	1	134259	88.0			
1-2	1.5	125867	82.5	1	125867	18.1
	2	117476	77.0			
2-3	2.5	110611	72.5	1	110611	15.9
	3	103745	68.0			
3-4	3.5	95354	62.5	1	95354	13.7
	4	86963	57.0			
4-5	4.5	77046	50.5	1	77046	11.1
	5	67129	44.0			
5-6	5.5	58738	38.5	1	58738	8.4
	6	50347	33.0			
6-7	6.5	41193	27.0	1	41193	5.9
	7	32039	21.0			
7-8	7.5	25173	16.5	1	25173	3.6
	8	18308	12.0			
8-9	8.5	13731	9.0	1	13731	2.0
	9	9154	6.0			
9-10	9.5	4577	3.0	1	4577	0.7
	10	0	0.0			

Total Volume = 695703 m^3

Mean depth = 4.56 m^3

Table 2-2b. Stillwater Pond Hypsographic Relationships - Area and Volume.

Interval (m)	Strata mid-point depth	Surface Area (m2)	% of SA* (%)	Depth Interval (m)	Volume in strata (m3)	% Volume in strata (%)
	0	75676	100.0			
0-1	0.5	73784	97.5	1	73784	14.8
	1	71892	95.0			
1-2	1.5	68487	90.5	1	68487	13.7
	2	65082	86.0			
2-3	2.5	60919	80.5	1	60919	12.2
	3	56757	75.0			
3-4	3.5	54108	71.5	1	54108	10.8
	4	51460	68.0			
4-5	4.5	48811	64.5	1	48811	9.8
	5	46162	61.0			
5-6	5.5	43892	58.0	1	43892	8.8
	6	41622	55.0			
6-7	6.5	37838	50.0	1	37838	7.6
	7	34054	45.0			
7-8	7.5	30649	40.5	1	30649	6.1
	8	27243	36.0			
8-9	8.5	24216	32.0	1	24216	4.8
	9	21189	28.0			
9-10	9.5	18541	24.5	1	18541	3.7
	10	15892	21.0			
10-11	10.5	13622	18.0	1	13622	2.7
	11	11351	15.0			
11-12	11.5	9649	12.8	1	9649	1.9
	12	7946	10.5			
12-13	12.5	6622	8.8	1	6622	1.3
	13	5297	7.0			
13-14	13.5	4541	6.0	1	4541	0.9
	14	3784	5.0			
14-15	14.5	3027	4.0	1	3027	0.6
	15	2270	3.0			
15-16	15.5	1135	1.5	1	1135	0.2
	16	0	0.0			

Total Volume = 499841 m^3

Mean depth = 6.6 m^3

Table 2-3. Land Use Characteristics in Lovers Lake and Stillwater Pond Watershed

Lovers Lake	Current Conditions		Build-out Conditions	
LAND USE CATEGORY	**Area in Watershed (ha)**	**Area in 300 ft Buffer (ha)**	**Area in Watershed (ha)**	**Area in 300 ft Buffer (ha)**
Residential	13.81	8.68	15.92	8.98
Roads	2.69	0.96	2.69	0.96
Open Land	2.20	0.00	2.14	0
Cranberry Bog	1.65	0.00	1.65	0
Forest	12.08	4.66	10.04	4.36
Water/Wetlands	3.20	0.00	3.20	0
# of Residences	62	40	66	41
Total	**35.64**	**14.29**	**35.64**	**14.29**

Stillwater Pond	Current Conditions		Build-out Conditions	
LAND USE CATEGORY	**Area in Watershed (ha)**	**Area in 300 ft Buffer (ha)**	**Area in Watershed (ha)**	**Area in 300 ft Buffer (ha)**
Residential	17.77	3.16	18.66	3.16
Roads	3.71	0.94	3.71	0.94
Forest	28.77	1.41	27.22	0.74
Water/Wetlands	1.85	0	1.85	0.00
Municipal Developed	0.00	0	0.66	0.67
# of Residences	58	23	61	23
Total	**52.10**	**5.50**	**52.10**	**5.50**

Table 2-4. Historic water quality data for Lovers Lake from PALS monitoring (2001-2006)

		Shallow (0.5 m)			Max Depth (9-9.5m)		
Parameter	Units	Average	Minimum	Maximum	Average	Minimum	Maximum
Temperature	(^{o}C)	23.10	22.03	24.66	12.85	10.20	20.90
Diss. Oxygen	(mg/L)	8.79	7.33	10.24	1.06	0.13	5.37
pH	(S.U.)	8.12	6.95	9.27	6.71	6.47	7.01
Alkalinity	(mg/L as $CaCO_3$)	25.92	1.86	42.18	81.34	5.40	150.95
TP ug/L	(ug/L)	32.20	23.87	46.50	116.62	50.60	173.60
TN ug/L	(ug/L)	781.70	435.66	1546.65	2634.98	1934.80	3974.10
Chlorophyll a	(ug/l)	25.34	5.42	68.25	4.68	1.93	9.35
Phaeophytin	(ug/l)	2.84	0.00	5.97	9.55	0.41	18.96

Parameter	Units	Average	Minimum	Maximum
Total Depth	(m)	9.97	9.60	10.47
Secchi Depth	(m)	1.14	0.44	1.69

Table 2-5. Historic water quality data for Stillwater Pond from PALS monitoring (2001-2006)

		Shallow (0.5 m)			Max Depth (9-9.5m)		
Parameter	Units	Average	Minimum	Maximum	Average	Minimum	Maximum
Temperature	(^{o}C)	23.08	21.48	24.76	8.25	6.44	15.35
Diss. Oxygen	(mg/L)	9.13	7.74	10.10	0.23	0.16	0.29
pH	(S.U.)	7.79	6.92	8.92	6.50	5.94	6.68
Alkalinity	(mg/L as $CaCO_3$)	24.66	1.84	39.35	62.86	4.87	102.31
TP ug/L	(ug/L)	27.53	13.95	44.64	289.45	176.70	426.87
TN ug/L	(ug/L)	765.51	371.24	1241.80	2973.52	2270.80	3720.88
Chlorophyll a	(ug/l)	22.96	4.84	56.10	3.94	0.05	7.49
Phaeophytin	(ug/l)	3.87	0.05	14.57	12.51	1.37	22.16

Parameter	Units	Average	Minimum	Maximum
Total Depth	(m)	14.19	13.80	15.06
Secchi Depth	(m)	1.58	0.56	3.03

Table 2-6. Historical Fish Community of Lovers Lake and Stillwater Pond.

Fish		Lovers Lake (8/25/52)[a]		Stillwater Pond (5/4/67)[b]	
Common Name	**Scientific Name**	**#**	**%**	**#**	**%**
American eel	*Anguilla rostrata*	3	0.4	-	-
Chain pickerel	*Esox niger*	20	2.7	1	2.0
Smallmouth bass	*Micropterus dolomieui*	2	0.3	-	-
Largemouth bass	*Micropterus salmoides*	-	-	2	4.1
Yellow perch	*Perca flavescens*	50	6.7	12	24.5
White perch	*Morone americana*	81	10.9	2	4.1
Brown bullhead	*Ameiurus nebulosus*	16	2.1	-	-
Alewife	*Alosa spp.*	-	-	7	14.3
Bridle shiner	*Notropis bifrenatus*	172	23.1	20	40.8
Golden shiner	*Notemigonus crysoleucas*	207	27.7	4	8.2
Killifish	*Fundulus diaphanus*	193	25.9	-	-
Sticklebacks	*Gasterosteus spp.*	2	0.3	1	2.0
	Totals:	**746**	**100.0**	**49**	**100.0**

Sources: a = Tompkins, 1958.
b = unpublished fish survey data (Hurley 2007)

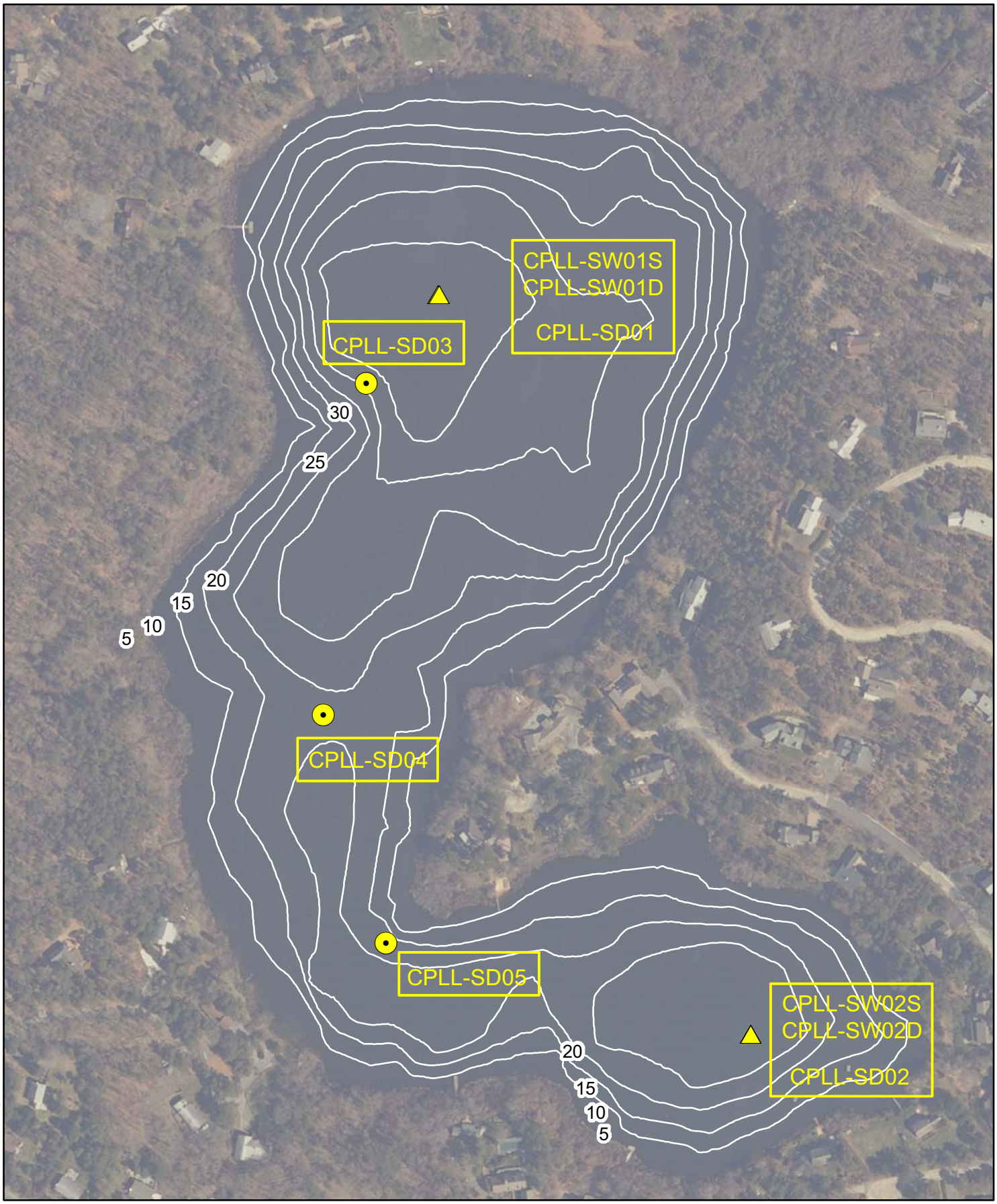

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Figure 2-1a Lovers Lake
Surface Water & Sediment Sampling Locations
2007

ENSR | AECOM

Surface Water and Sediment Sample Location

Sediment Sample Location

Note: "SW" refers to surface water sample;
"SD" refers to sediment sample.
Bathymetric Contours are in feet

0 130 260 520
Feet

N W E S

August 2008

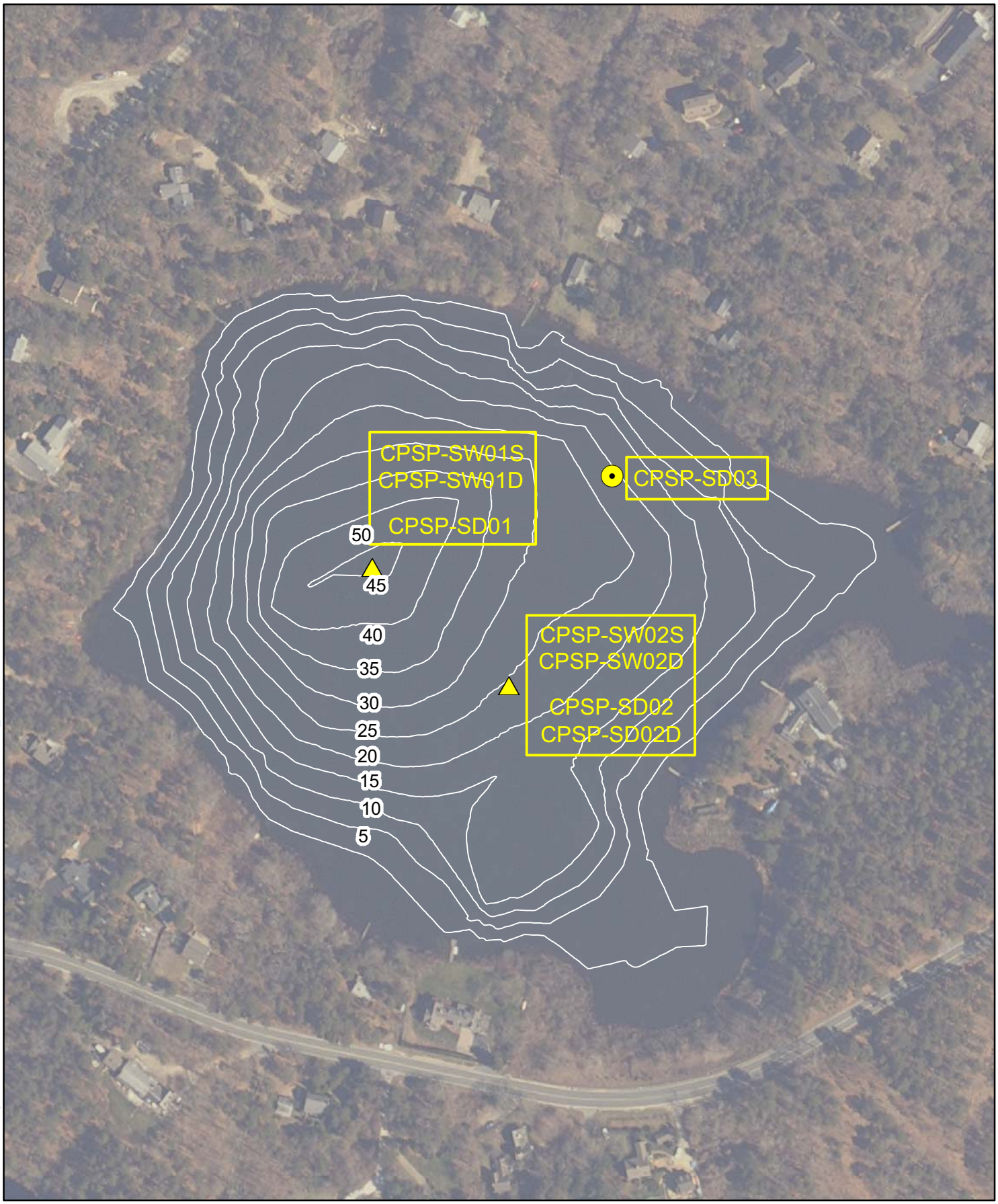

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Figure 2-1b Stillwater Pond
Surface Water & Sediment Sampling Locations
2007

ENSR | AECOM

Surface Water and Sediment Sample Location

Sediment Sample Location

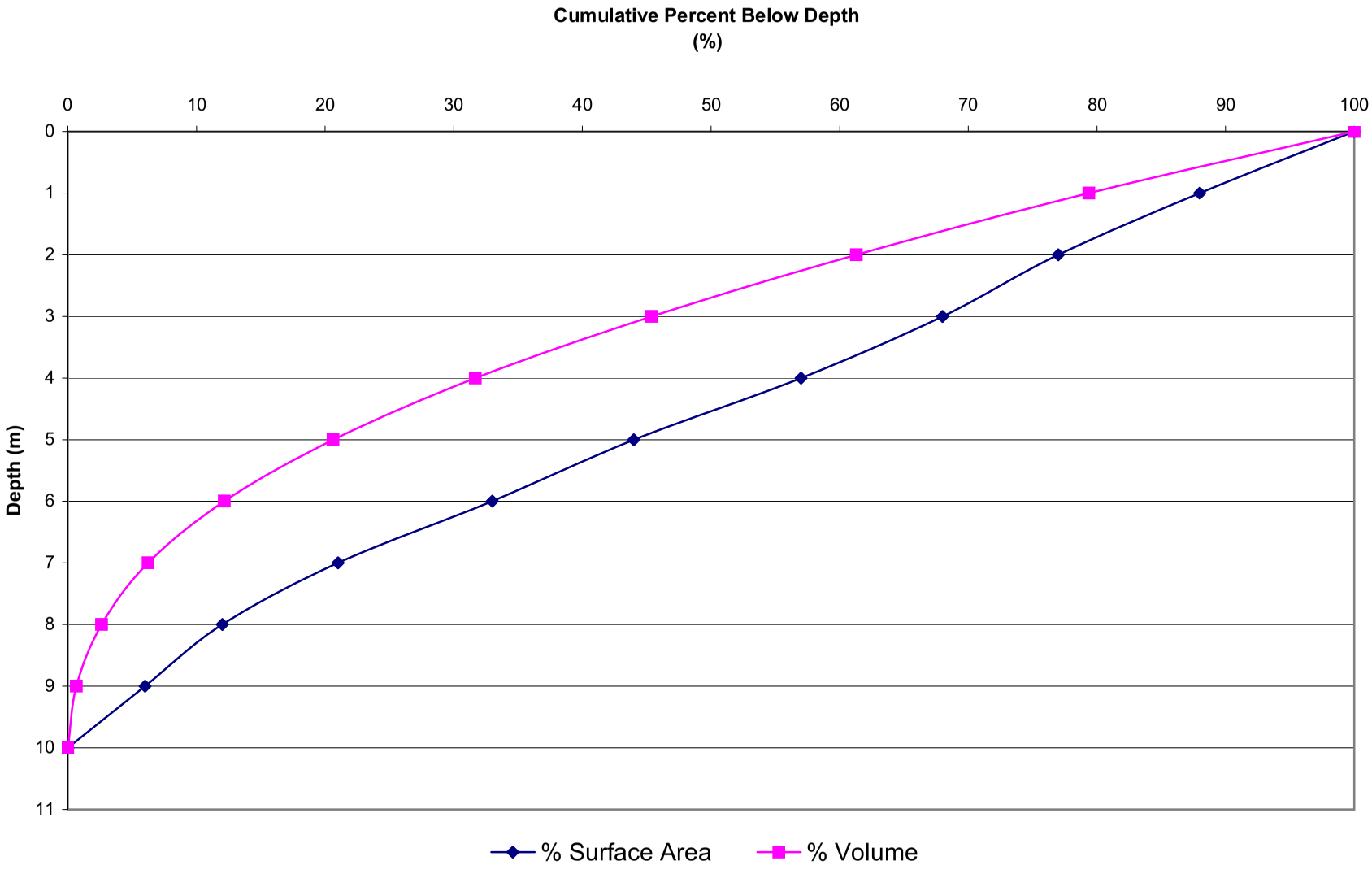
Note: "SW" refers to surface water sample;
"SD" refers to sediment sample.
Bathymetric contours are in feet.

0 125 250 500
Feet

N W E S

August 2008

Figure 2-2a. Lovers Lake Hypsograph



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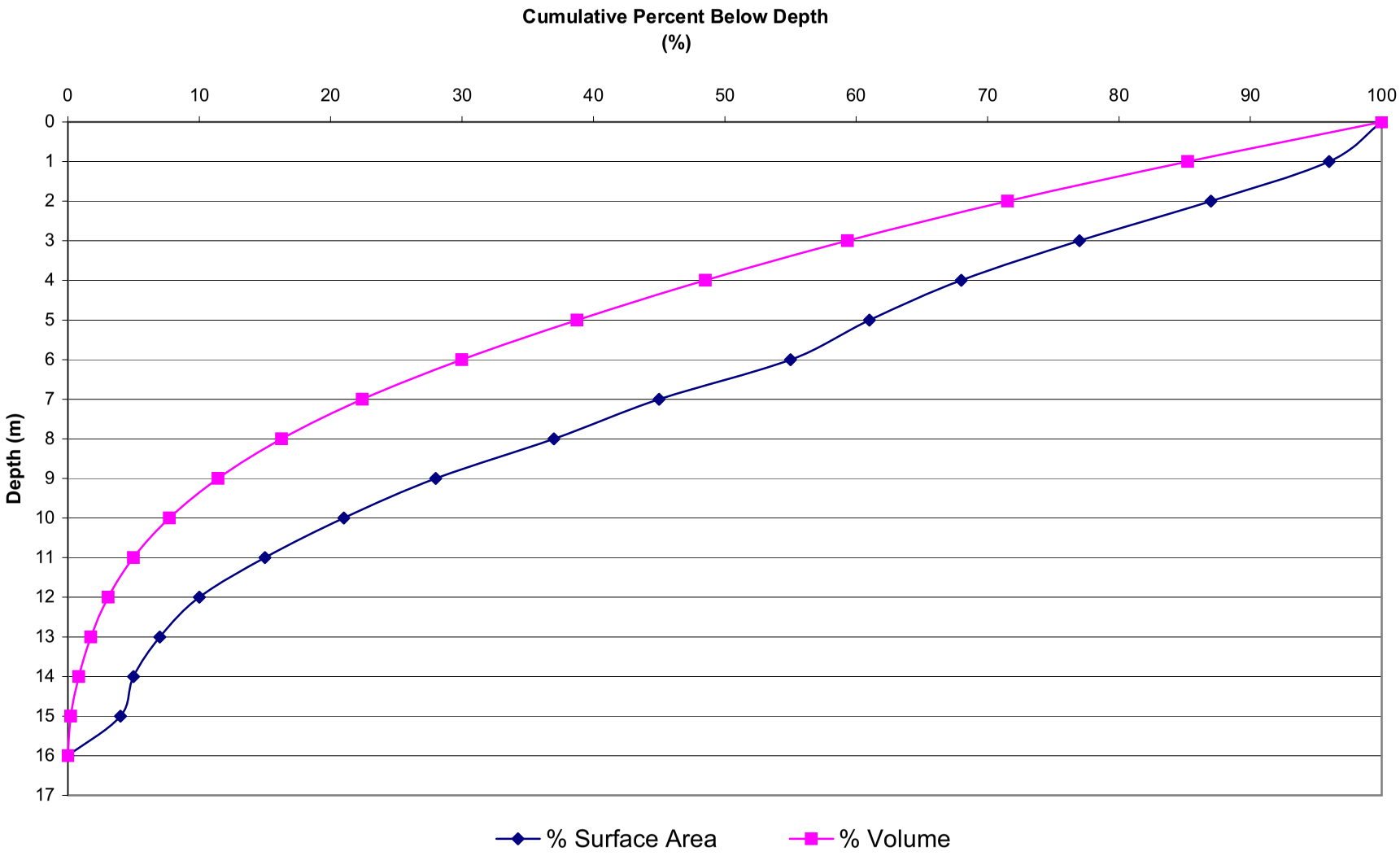
August 2008

Figure 2-2b. Stillwater Pond Hypsograph



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August 2008

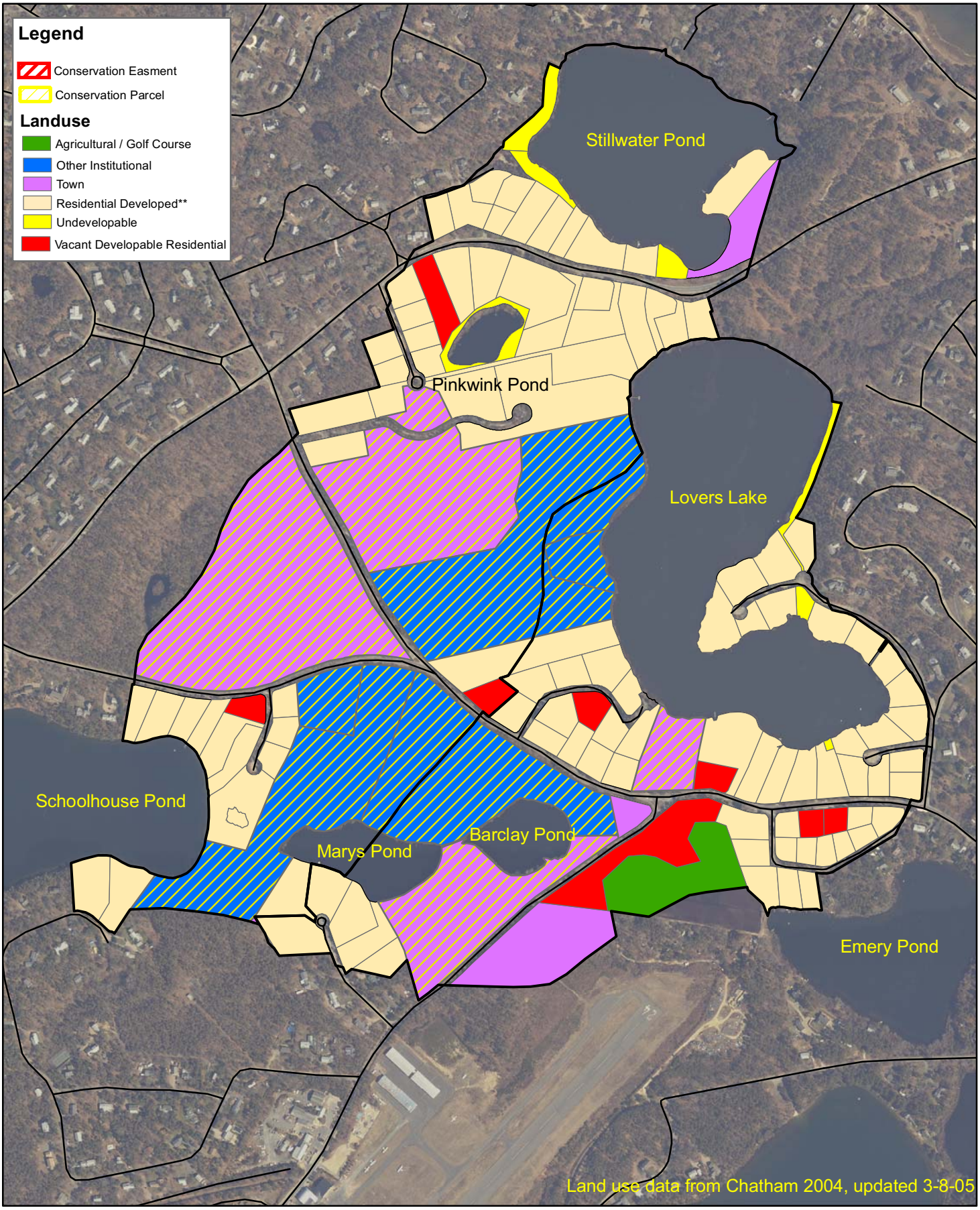

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Figure 2-3 Lovers Lake and Stillwater Pond Watershed Land Use

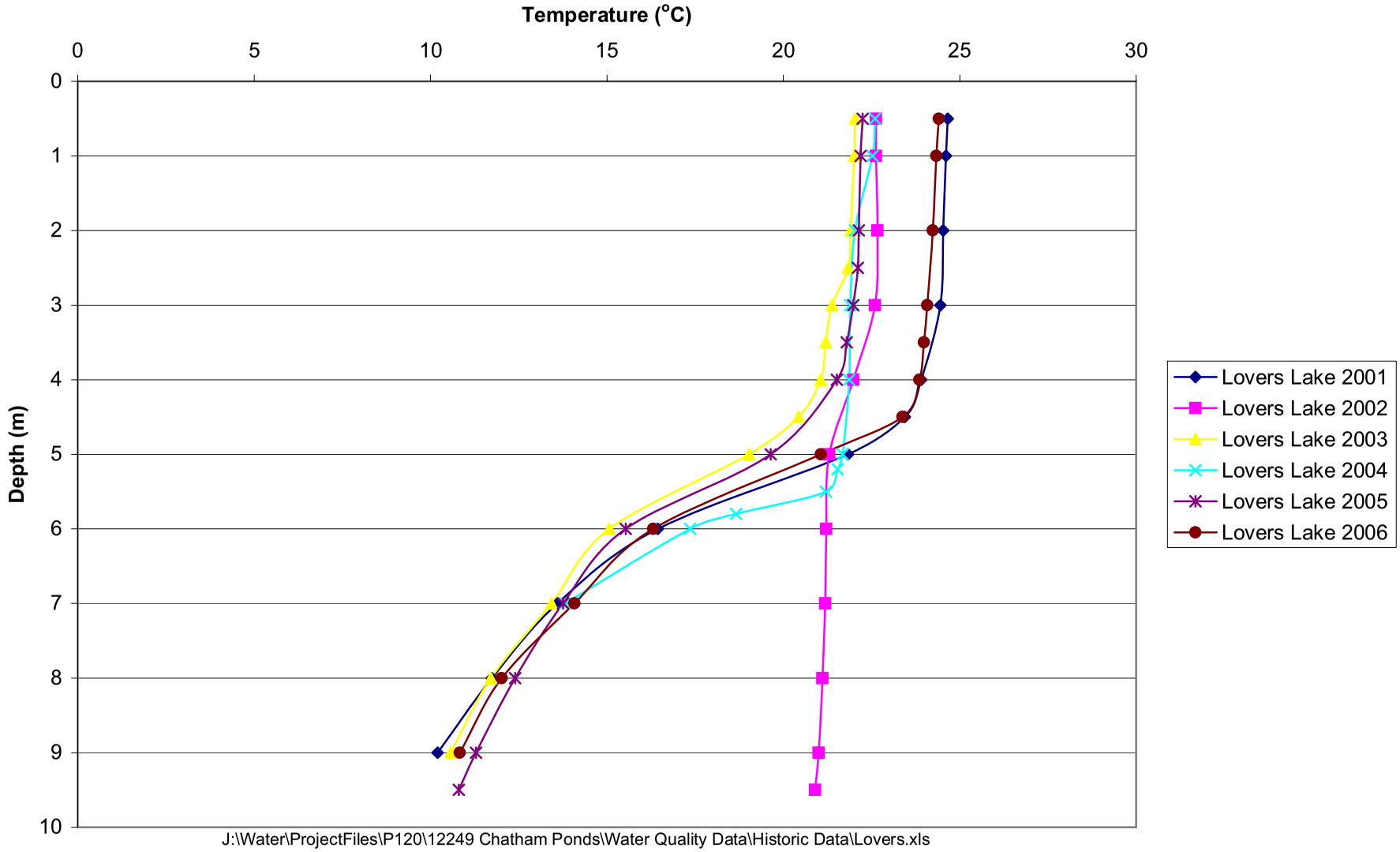
N
W E
S

0 300 600 1,200
Feet

ENSR | AECOM

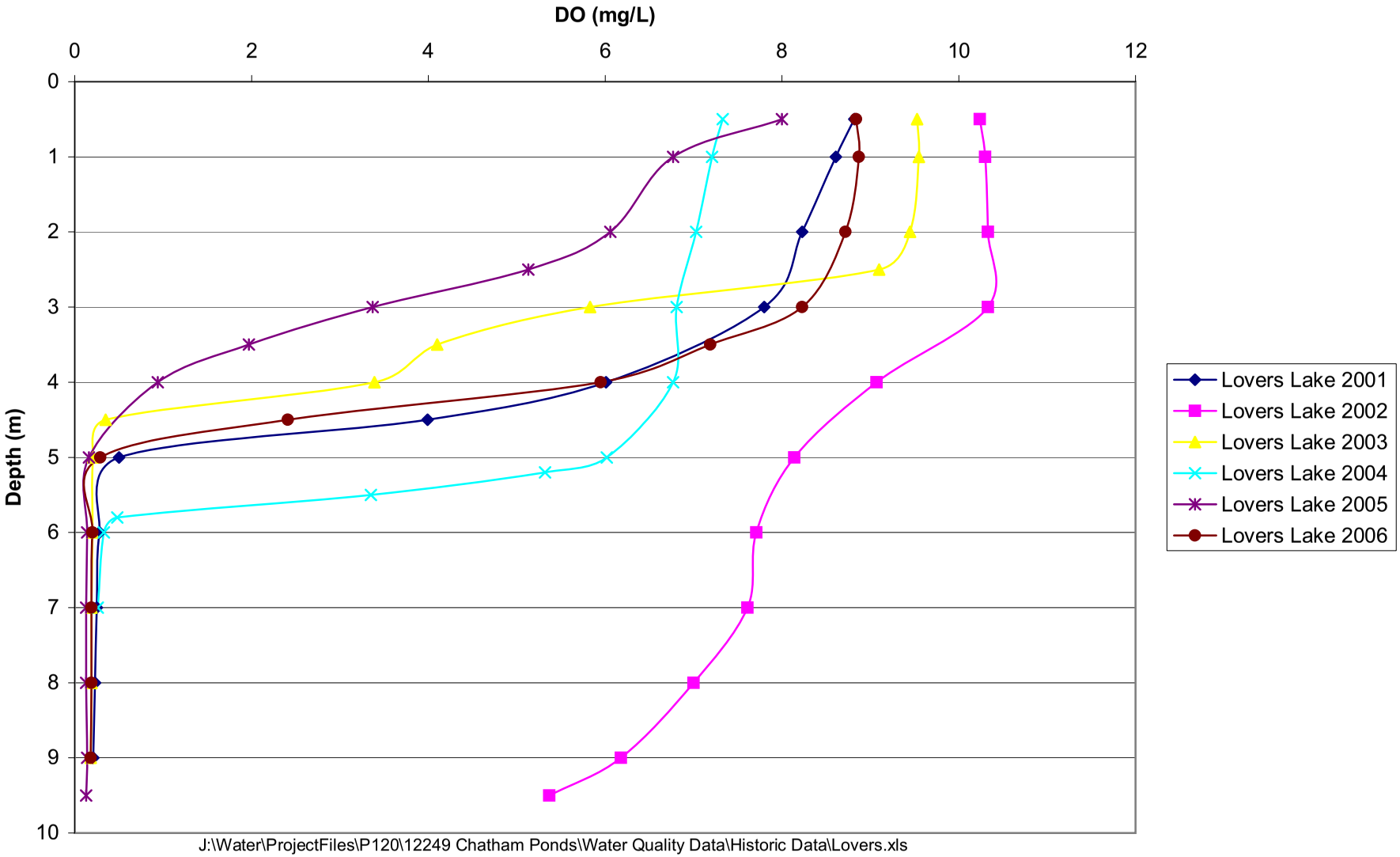
August 2008

Figure 2-4. Lovers Lake Summer Temperature Depth Profiles (2001-2006)



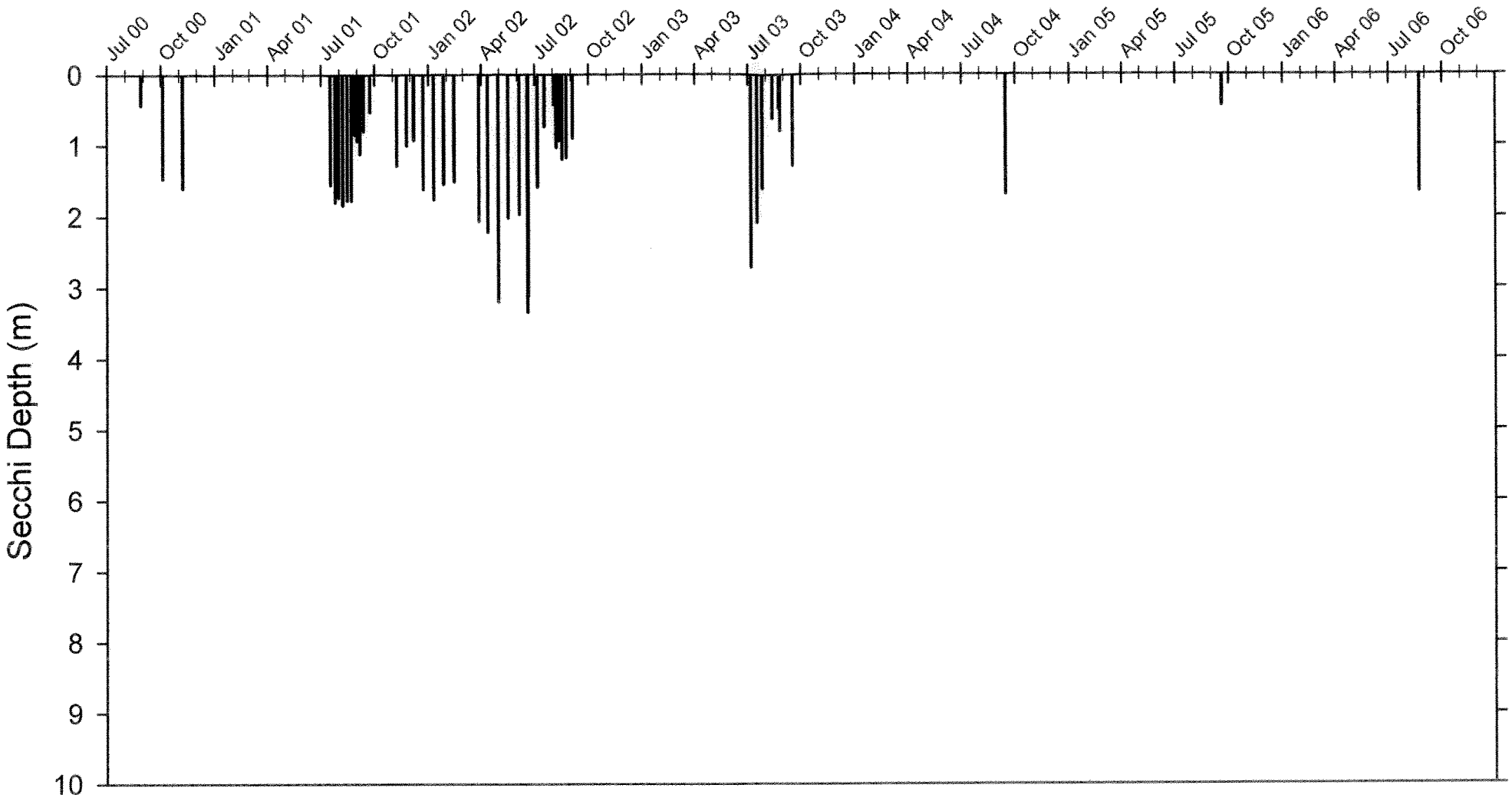
August 2008

Figure 2-5. Lovers Lake Summer Dissolved Oxygen Depth Profiles (2001-2006)



August 2008

Figure 2-6. Lovers Lake Secchi Disk Transparency Dept Measurement (2000-2006)



August 2008

Figure 2-7. Stillwater Pond Summer Temperature Depth Profile (2001-2006)

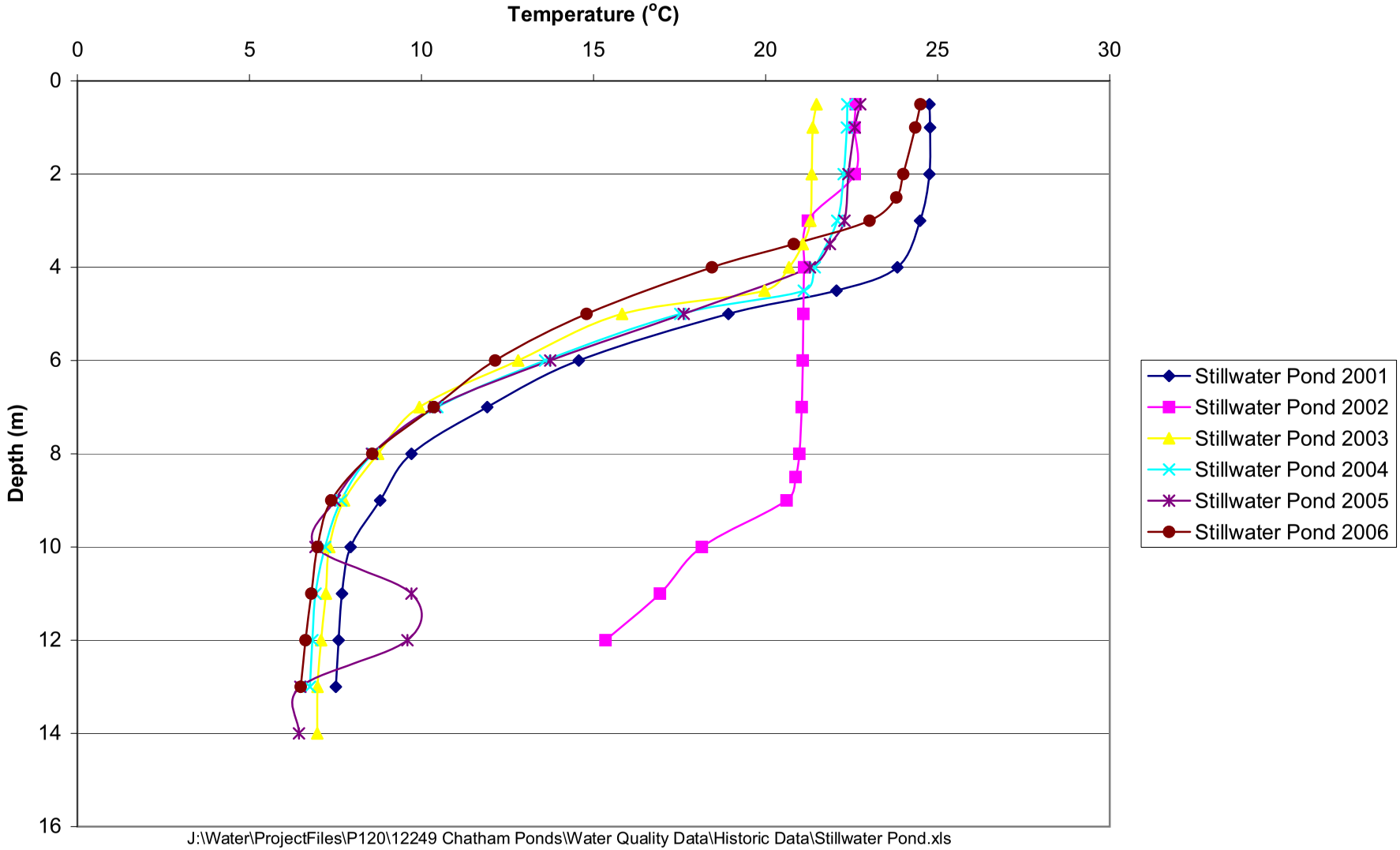
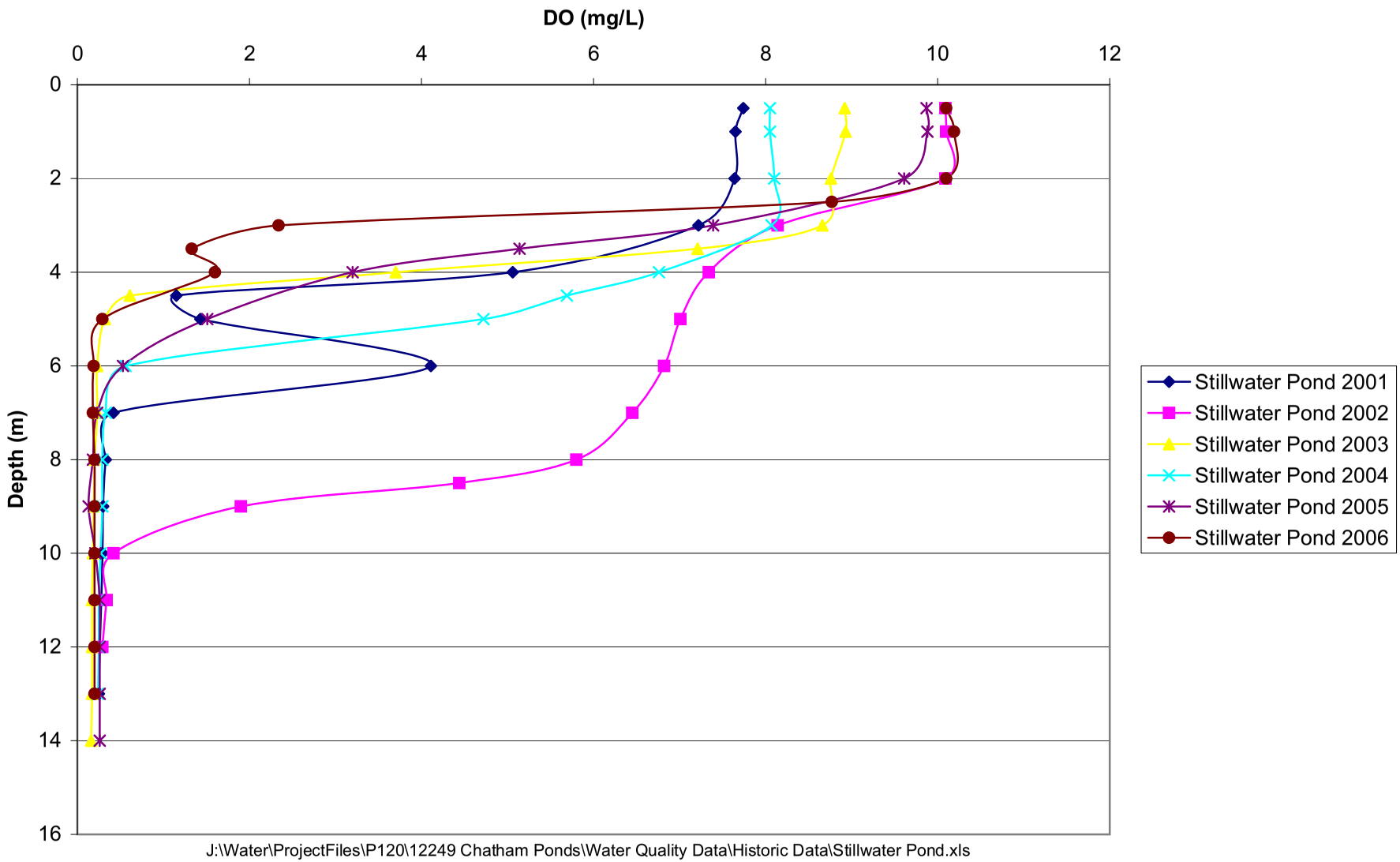
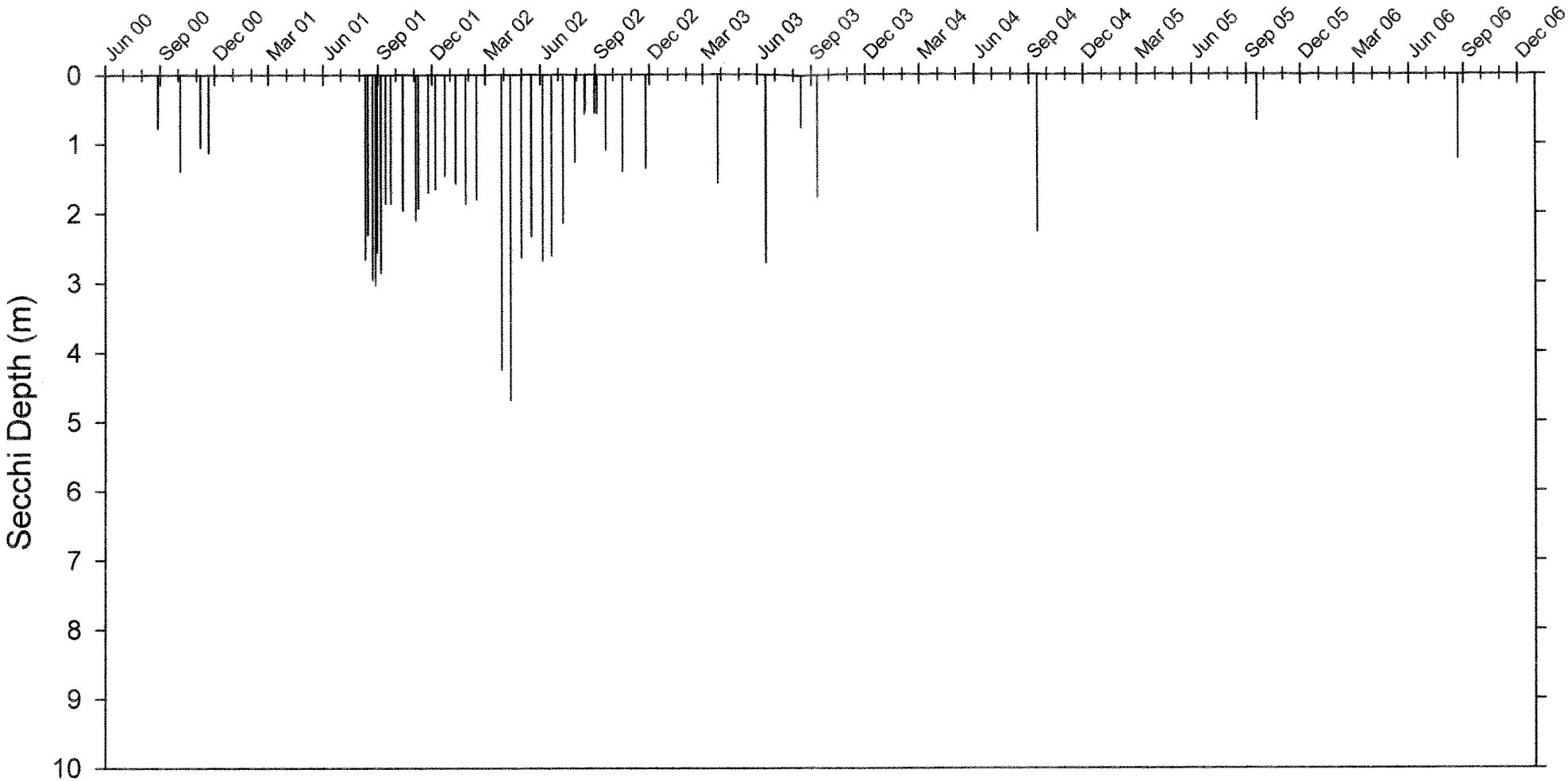


Figure 2-8. Stillwater Pond Summer Dissolved Oxygen Depth Profiles (2001-2006)



August 2008

Figure 2-9. Stillwater Pond Secchi Disk Transparency Depth Measurement (2000-2006)



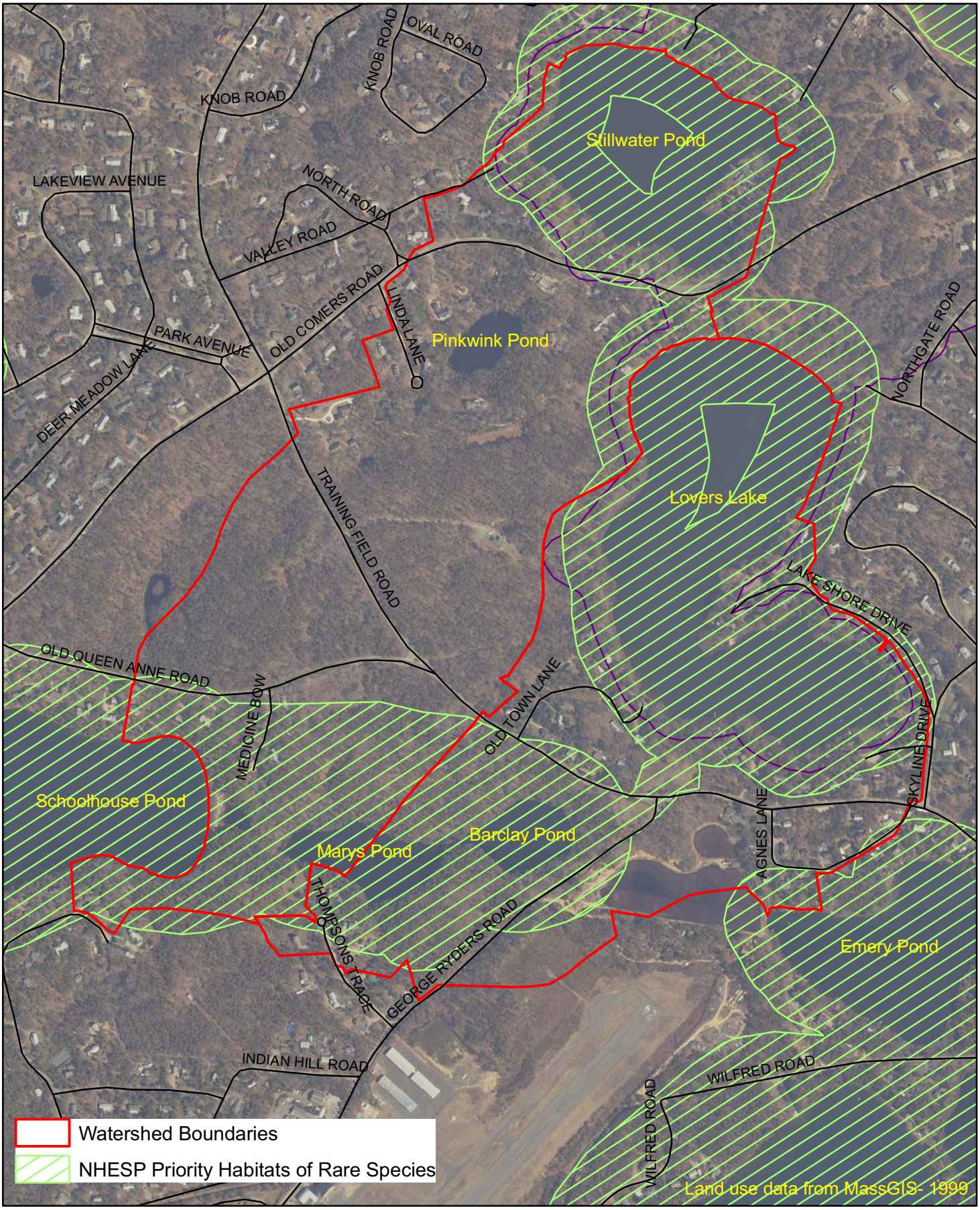


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Figure 2-10. Lovers Lake and Stillwater Pond Priority Habitats of Rare and Endangered Species

ENSR | AECOM

N W E S

0 287.5 575 1,150
Feet

August 2008

3.0 Field investigations and laboratory analyses

As part of characterization of the current conditions of Lovers Lake and Stillwater Pond, periodic observations of water column profiles of temperature and DO were made, along with discrete water quality sampling at two depths at two locations within the pond. This monitoring provides a good tracking of seasonal shifts in the DO content and water chemistry of the pond. In addition, we conducted a sediment survey to collect sediment samples for testing of physical and chemical properties. These surveys and the results are discussed below.

3.1 Water quality sampling

3.1.1 Methods

Field surveys were conducted at Lovers Lake and Stillwater Pond during spring through fall 2007 and included sixteen visits, with water quality samples collected on five of those visits. ENSR staff (Dunlap, Mitchell) were present during the May 3, 2007 visit to go over methods with CDH&E staff (Cook) and confirm the selection of the sampling locations. Two stations were routinely visited at Lovers Lake (CPLL-SW01 and CPLL-SW02, see Figure 2-1a), and Stillwater Pond (CPSP-SW01 and CPSP-SW02, see Figure 2-1b). The two stations at each pond were chosen because ponds can exhibit spatial differences due to a variety of reasons, including: proximity to hydrologic sources (inlets, seepage), substrate, fetch (wave action), local land uses, etc. These locations are similar to those used for previous water quality sampling (e.g., PALS program) and the GIS coordinates are given in the Table 3-1.

Temperature and dissolved oxygen profiles were performed on sixteen occasions, from May to December, 2007. Measurements were taken at each site on both ponds at approximate 1 m interval depths, except in the depth region associated with the thermocline (if present). [Note: the thermocline refers to the depth at which there is a significant decline (which can be sharp or more gradual) of temperature with depth]. At both Lovers Lake and Stillwater Pond, pH was measured at 1 m intervals during the May and early June events, but the data were discarded due to instrumentation failure. From mid-June to the end of August, water from near the surface and at the bottom depth at each of the sites was taken back to the Chatham Water Quality Laboratory for pH measurement. At both lakes, specific conductivity was measured at 1 m intervals during the May through end of August sampling events. From September through December, sampling was primarily to verify the timing of autumnal mixing in the lake, so neither pH nor specific conductivity were measured in the field. In both lakes, both water color and SDT depth were noted at each site during each sampling event. Field data and notes are contained in Appendix D.

At each site, water quality samples were collected at the surface (0-0.5 ft depth) and near the bottom (approximately 1-2 ft off the bottom) using a Van Dorn sampler for the May 3, 2007 or a Niskin sampler for all other sampling events. This approach provided an assessment of water quality in the upper waters (i.e., epilimnion) and the bottom waters (i.e., hypolimnion). For both ponds, monitoring of bottom waters was critical for determining the rate of loss of oxygen over time and to measure the expected increase of phosphorus due to internal recycling from the nutrient-rich sediments under anoxic conditions. The surface and bottom depth water samples were sent to an independent analytical laboratory (Berkshire Enviro-Laboratory, Lee, MA) for determination of total phosphorus, dissolved phosphorus, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, alkalinity, hardness, total suspended solids, chlorine, sulfate, iron, and pH. The pH readings were taken as an approximate measure of pond pH since they were held for one day before processing, but were used due to concerns regarding available field equipment calibration. For quality control purposes, a duplicate sample was taken during each sampling event from a randomly-selected depth and location.

3.1.2 Water quality results from Lovers Lake sampling, 2007

3.1.2.1 Temperature and dissolved oxygen

Temperature and DO depth profiles were taken at both stations in Lovers Lake during each field survey. However, the depth patterns exhibited by both stations were generally very similar so the information taken only from the deeper northern station (CPLL-SW-01) is displayed here. To better display the seasonal patterns, the depth profiles were grouped into sets of profiles for two periods: (1) from May until early August (Figure 3-1a) and (2) from late August to November (Figure 3-1b).

Temperature profiles for Lovers Lake shown in Figure 3-1a display the water column from an early stratified condition (5/3/07) to a well-developed summer condition (8/1/07). This shows the pond shortly after the spring or vernal mixing when the pond is the same temperature (isothermal) from top to bottom. As the season progresses, the water in the upper layer is heated faster than the ability of the pond to mix uniformly, leading to the beginning of a layering of the lake, usually called thermal stratification.

Comparison of the profiles from the various dates indicates the seasonal increase in the upper portion of the lake, also termed the epilimnion. The epilimnion is the zone where the temperature, light availability, and nutrient levels are considered most conducive to phytoplankton growth. This water layer also supports the primary recreational and ecological functions of the pond and is where potential impairment is most apparent to lake users and the general lay public.

For each of the profiles, temperature is fairly uniform with depth until below 4 to 4.5 meters (11.2 – 14.8 ft), where a transition area (termed the thermocline) indicates a more rapid temperature decrease with depth. The area below the thermocline is termed the hypolimnion. The hypolimnion contains denser cooler water and is the zone where low dissolved oxygen conditions can have a profound effect on the water chemistry and pond metabolism. For Lovers Lake, the thermocline is fairly distinct in early summer, but exhibits a much more gradual transition in July and August. The reasons for the more gradual thermocline are not known but could be related to the influx of cooler groundwater at intermediate depths or wind influence (i.e., internal waves or seiches).

Temperature profiles for Lovers Lake shown in Figure 3-1b are from late August to late November. It displays the water column during a period in which the pond is cooling off until it is isothermal and mixing from top to bottom (so-called autumnal mixing). Note that the breakdown of the thermal stratification is initiated by the cooling and expansion downward of the epilimnion. In limnological terms, this progressive deepening is often term as the “erosion” of the thermocline. As indicated by the straight vertical line for temperature, Lovers Lake is fully mixing at about 12°C by the time of the 11/7/07 survey.

The patterns of DO in Lovers Lake are shown in Figures 3-2a and 3-2b using the same division of sampling dates used for the temperature profiles. The concentration of oxygen that can be dissolved in water is very sensitive to the temperature of the water and is inversely related to it. For example, as water heats up, less oxygen can be dissolved in it; therefore the DO content of pond water at the surface in August will be less than that found in April, even though both are in equilibrium with the atmosphere. To allow a better comparison of oxygen availability in water columns at different temperatures, DO is reported as percent saturation, a measure of how much oxygen is present relative to the temperature-corrected concentration in water which is fully saturated with oxygen (i.e., 100% saturation).

As can be seen in Figure 3-2a, in most cases the epilimnetic waters are fairly close to 100% saturation for DO, with a few exceptions. The 5/23/07 survey found the water to be less than saturated (84%) for unknown reasons. A different oxygen pattern is shown is shown by the 6/5/07 survey results where there is a narrow band of oversaturation of oxygen located at the top of the thermocline. As noted in the historic data, this is a metalimnetic oxygen maxima and occurs due to a combination of high nutrients and good light availability for

phytoplankton at that depth. It is not unusual for very clear water conditions to occur after the spring bloom since this is often a time of high rates of grazing by zooplankton.

The 8/1/07 survey provides a profile which also has an oversaturated (140%) epilimnion, but this one is very close to the surface. This can occur due to high levels of phytoplankton photosynthesis producing during bloom conditions, which temporarily leads to an overabundance of DO in surface water. Note also that the depth at which low DO is encountered is also quite shallow. This can occur under conditions of low light and high respiratory demand in a dense bloom. These observations coincide with a very shallow SDT depth noted on this day (see Figure 3-3). These patterns are consistent with the presence of an algal bloom and light availability restricted to the upper few meters. This combination of high temperature and low light often leads to a competitive advantage for the development of blue-green algae (BGA), the common term for cyanobacteria.

At or below the thermocline, DO levels start to sharply decline with depth (Figure 3-2a). This decrease in DO to very low levels (termed anoxia) is due to the combined oxygen demand from degradation of organic material in the water column as well as the sediment. The amount of hypolimnetic DO shows a progressive decline with season as well. Looking at the 7/16/07 survey, it can be seen that there is little oxygen below 6 m and by the 8/1/07, there is no oxygen below 5 m. This means that about 44% of the lake area (found below 5 m) and 20% of the pond volume has little or no function as aquatic habitat for fish or benthic organisms.

The DO profiles for the later period are shown in Figure 3-2b. As with temperature, there is a progressive increase in DO at great depth as the thermocline sinks. The combination of natural breakdown of organic material in the epilimnion in the fall with the mixing of the oxygen-poor hypolimnetic waters depresses the epilimnetic DO below 100% saturation. The nearly vertical DO condition on 11/7/07 is proof of vernal mixing. It would be expected that after several days to a few weeks of additional mixing that the entire water column would be back to equilibrium with the atmosphere at 100% saturation.

The results from the 2007surveys were compared to those seen during the PALS monitoring (2001-2006) displayed in Figures 2-6 and 2-7. The “snapshot” vertical profiles taken during mid-summer show the thermocline region usually was observed at between 4 and 6 m (Figure 2-4) which is similar to that observed in 2007, with the exception of the 2002 data. The pattern of DO (measured as mg/L) in Figure 2-5 consistently shows anoxia below 6 m (except for 2002 data), while the 2007 data measured a less pronounced pattern of oxygen deficit with depth.

3.1.2.2 Secchi disk transparency

Secchi disk transparency (SDT) is a measure of the clarity of the water as determined by lowering a marked disk down until it is no longer visible and pulling it up until it is just visible; the mean of these two values is the SDT depth. It provides an easy and inexpensive means to evaluate the availability of light in the water column.

The pattern of SDT depth in Lovers Lake over the period of the field investigation is shown in Figure 3-3. These values represent those taken at the deeper of the two sampling stations (CPLL-SW-01) within the lake since these measurements are usually quite similar. The Massachusetts criterion for visibility of 4 ft (1.2m) to support contact recreation (i.e., swimming) has been added (dashed line) for comparison purposes.

The seasonal pattern shows that SDT depth is between 4 and 6 m during late spring and early summer with a seasonal maximum of nearly 7 m on 5/23/07. During July and August, the SDT declines markedly with a minimum value of 0.5 m in early August. This is the same period when the DO pattern suggests the influence of high levels of phytoplankton. The SDT depth still stays relatively shallow during the fall which suggests that concentration of suspended material (algae or senescing organic material) in the water is still high.

The SDT results from the 2007 surveys were compared to those seen during the PALS monitoring (2001-2006) displayed in Figure 2-6. The maximum values in 2007 were deeper than those previously observed, but there is still a progressive decreased in SDT value with season and the lowest values (<0.5 m) are similar. It is

interesting to note that the SDT at the northern basin of Lovers Lake averages 5.0 m before mid-July (when flashboards are reinstalled) and 1.6 m from mid-July to November turnover.

3.1.2.3 Water chemistry

Water quality samples were taken in Lovers Lake on five occasions in 2007 ranging from May to late August at approximate 4 week intervals (5/9/07; 6/5/07; 7/3/07; 8/2/07; 8/30/07). Samples were taken from both top (0.5 m) and bottom (1m off bottom) at two locations - CPLL-SW-01 and CPLL-SW-02 (Figure 2-1a).These water quality samples were analyzed for total phosphorus, dissolved phosphorus, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, alkalinity, hardness, total suspended solids, chloride, sulfate, iron, and pH.

The results for the 2007 samples are organized by station in Table 3-2 for Lovers Lake. The mean and range (minimum and maximum values) are displayed for each parameter. Note that concentrations reported below the detection limit were numerically treated as ½ the detection limit and the duplicate samples for a station were averaged together. Total nitrogen was calculated by combining inorganic NO_3-N and NO_2-N and total Kjeldahl nitrogen (TKN). A nitrogen to phosphorus ratio was calculated by comparison of the molar ratio (concentration corrected by molecular weight) of the TN and TP fractions. This is discussed in Section 5.2.4.

Water chemistry results from Lovers Lake were examined for variation with regard to station (CPLL-SW-01 vs. CPLL-SW-02, depth (surface vs. bottom) and season (Table 3-2). Examination of some of the nitrogen fractions indicates that nitrate-nitrogen (NO_3-N) generally ranged about at or slightly below 10 ug/L in the surface water and bottom across Lovers Lake. Nitrite-nitrogen (NO_2-N) was not detected in any of the samples. .

Ammonia-nitrogen (NH_3-N) in the surface water stations of Lovers Lake averaged approximately 50 ug/L but was seasonally variable. It was available in surface waters in the spring and late summer but below detection in mid-summer. This would be expected in the presence of phytoplankton since ammonia is the preferred nitrogen fraction for uptake and use to support growth. As would be expected under the reducing conditions found in the anaerobic hypolimnion, ammonia was much greater in bottom waters. The average value for the bottom waters at CPLL-SW-01 was 694 ug/L and that for the shallower CPLL-SW-02 was 185 ug/L. These increased values reflect the breakdown of organic material and limited bacterial conversion to NO_3-N and NO_2-N with low oxygen.

The most important nitrogen fraction at all stations and depths was the TKN fraction, which when corrected for the ammonia fraction, generally represents the organic-nitrogen fraction. Some portion of the TKN represents nitrogen bound in organic material (e.g., amino acids) that is resistant to degradation and is less bioavailable (i.e., available for uptake to support algal growth). TKN averaged 676-684 ug/L at the surface and from 758-1252 ug/L at the bottom. Hence, a considerable portion of the total nitrogen in Lovers Lake may not be available for algal growth, which may lead to increased success of “nitrogen-fixing” BGA species that can use atmospheric nitrogen. Total nitrogen levels were from 160 to 1,215 ug/L; with means of 690-700 ug/L in the surface water and were from 510-2,115 ug/L with means of 771-1269 in the bottom waters.

The two phosphorus fractions measured in Lovers Lake in 2007 included dissolved (DP) and total phosphorus (TP) (Table 3-3). Total phosphorus includes both the particulate and dissolved fractions. The DP fraction of phosphorus is readily bioavailable and often rapidly taken up by algae.

Looking at the surface water stations, TP ranged from below detection at 10 ug/L to 63 ug/L with the means at 32-38 ug/L. A considerable amount of this TP is due to the presence of DP, which ranged from below detection to 60 ug/L, with the means at the surface water stations at 25-29 ug/L. The presence of elevated levels of DP in the water column in mid-summer is unusual since this form of phosphorus is so readily taken up by algae. Further, the DP tended to increase in concentration from spring to summer, which is the opposite trend usually seen in tributary-fed ponds where the spring loading brings the greatest inputs of phosphorus. It suggests that there is a ready supply of DP relative to the biological demand from an internal source.

One potential source of this mid-summer phosphorus appears in the pattern shown by the bottom stations. These stations have a greater mean of both TP (63-64 ug/L; with range of 21 to 107 ug/L) and DP (average of 35-38 ug/L; with a range of 19-54 ug/L). As noted earlier, these are waters where low oxygen conditions persist during the summer. As will be discussed in detail in Section 5.2, the internal cycling of phosphorus in the sediments of Lovers Lake is the major portion of the phosphorus budget.

Other parameters which were measured during the field surveys include those which relate to the buffering capacity of the waters, including pH, alkalinity, and hardness. As noted earlier, there was some uncertainty regarding the calibration performance of the field instrument used by CDH&E, so pH was measured in the water quality samples by BEL. These pH measurements should be considered approximate only since the measurements were made the following day.

In general, the upper waters of Lovers Lake were alkaline with means of 8.0 - 8.2 standard pH Units (or S.U.) and the bottom waters were acidic with means of 6.5 - 6.6 S.U. (Table 3-2). The difference is likely due to the effect of the withdrawal of CO_2 from the upper waters by photosynthesizing organisms, which leads to an elevated pH value; while to a lesser degree, the reverse occurs in the hypolimnion. Alkalinity values, measured as mg/L $CaCO_3$, averaged 16 - 18 mg/L in the upper waters and 25 - 32 mg/L in the bottom waters. Hardness had a similar pattern, being 30 - 33 mg/L at the surface and 38 - 48 mg/L at the bottom.

Measurement for chloride did not indicate much in the way of spatial or depth patterns; averages of all stations in Lovers Lake ranged from 33.5 – 33.9 mg/L. This is not unexpected for this biologically conservative element. Sulfate concentrations were somewhat decreased in the hypolimnion, most likely due to the reducing conditions found there.

The implications of the low oxygen, low redox conditions are particularly noticeable for total iron. The surface concentrations of iron were uniformly low at 0.1 mg/L, while those of the bottom stations were 3.0 mg/L at CPLL-SW-01 (ranged of 0.1 to 8.6 mg/L) and 0.8 mg/L (range of 0.2 - 2.5 mg/L) at the shallower CPLL-SW-02. Iron concentrations in the hypolimnion increase as the season progresses and are related to the same low reduction-oxidation (redox) conditions that lead to release of phosphorus (see Section 5.2).

Total suspended solids in surface waters averaged 2.6 – 2.9, but shows increase with season, which may be due to accumulation of algae. As expected, the hypolimnion has greater TSS values (5.6 -8.5 mg/L) since it is the depth zone where organic particulate matter sinks and decays.

3.1.2.4 Comparison with historic water quality data

The results from the 2007 water quality surveys in Lovers Lake were compared with previous results to see if conditions were comparable with previous observations. [Note: for this comparison, we only considered 2007 data from the bottom waters from CPLL-SW-01 for comparison with the PALS deep sample.] These comparisons indicate that conditions in 2007 were similar to those in the PALS monitoring dataset (Table 2-4).

For example, the PALS TP surface water average was 32 ug/L compared with 32-38 ug/L in 2007; while the TP at maximum depth averaged 116 ug/L for the PALs as opposed to 64 ug/L in 2007. The PALS TN surface water average was 780 ug/L as compared to 690-700 ug/L in 2007; with 2,630 vs. 1,269 ug/L for the deep sample at CPLL-SW-01. Similar patterns were observed for pH in surface waters (PALS = 8.1 vs 8.0 - 8.2 for 2007) and at the bottom (PALS = 6.7 vs. 6.6 for 2007). Alkalinity was also significant elevated in the hypolimnion in both surveys. Overall, the results indicate reasonably good agreement between the PALS dataset and those obtained in 2007, indicating that this sampling year is representative of what has been observed in the last six years.

3.1.3 Water quality results from Stillwater Pond sampling, 2007

3.1.3.1 Temperature and dissolved oxygen

Temperature and DO depth profiles were taken at both stations in Stillwater Pond during each field survey. However, the depth patterns exhibited by both stations were generally very similar so the information taken only from the deeper northern station (CPSP-SW-01) is displayed here. To better display the seasonal patterns, the depth profiles were grouped into sets of profiles for two periods: (1) from May until early August 1 (Figure 3-4a) and (2) from late August to early December (Figure 3-4b).

Temperature profiles for Stillwater Pond shown in Figure 3-4a display the water column from an early stratified condition (5/3/07) to a well-developed summer condition (8/1/07). What is immediately evident from this figure is the very distinct and stable thermocline that exists between 4 and 6 m and the nearly constant temperature of the hypolimnion at approximately 8°C. The pattern of stratification does not show the seasonal progression downward as does the Lovers Lake thermal profiles. It appears likely that the influence of the input of warm surface water from Lovers Lake helps maintain this profile. This same sharp and stable thermal contrast is maintained even during the cooling of the upper waters in the fall (Figure 3-4b). Only during November does downward erosion of the thermocline start to significantly occur with full vernal mixing confined to the early December observations, when the entire water column is mixing at 4°C (the temperature of the maximum density of water). Comparison between the November and December surveys indicate the rapid cooling of the pond during this period.

The seasonal DO profiles for Stillwater Pond are shown in Figures 3-5a and 3-5b. As with Lovers Lake, the epilimnion shows values generally around the 100% saturation value, with a particularly strong oversaturation on the 8/1//07 survey [Note: the small decrease near the surface may be due to the photoinhibition of phytoplankton due to sunlight]. There is also evidence of an early June metalimnetic oxygen maxima similar to Lovers Lake.

Figure 3-5a shows evidence of a particularly strong sediment oxygen demand at even the earliest observation (53/07). Shortly after (5/9/07) there is already less than 40% DO saturation below 10 m (32.9 ft). Over the next two weeks there is a further rapid decrease in oxygen with anoxia being observed below 12 m (39.5 ft). The depth of anoxia rises over the following weeks so that by early July, oxygen-deficient water is as shallow as 6 m (19.7 ft). This pattern means that by early summer approximately 30% of the pond volume and 45% of the benthic habitat is devoid of oxygen and would not be expected to support aquatic life.

Following the seasonal DO patterns in Figure 3-5b indicates that the anoxic layer gets as close as 4 m (14.2 ft) below the surface and affects approximately 51% of the pond volume and 68% of the benthic habitat. The cooling process proceeds more slowly in Stillwater Pond relative to Lovers Lake and the mixing down of the epilimnion and entrainment of the oxygen-poor hypolimnion combines to reduce the overall oxygen content of the former. It is not until December that DO is measurable in the waters at the pond bottom.

The temperature and DO results from the 2007surveys were compared to those seen during the PALS monitoring (2001-2006) as displayed in Figures 2-9 and 2-10. The “snapshot” vertical profiles taken during mid-summer show the thermocline region usually was observed at between 4 and 6 m (Figure 2-7) which is similar to that observed in 2007 (again the 2002 data appear anomalous). The pattern of DO (measured as mg/L) in Figure 2-8 shows a more complex pattern with metalimnetic oxygen maxima. During 2002 and 2003, the anoxia layer was encountered about 5 m (16.5 ft) down in the water column.

3.1.3.2 Secchi disk transparency

The pattern of SDT depth in Stillwater Pond over the period of the field investigation is shown in Figure 3-6 with measurements taken at the deeper of the two sampling stations (CPSP-SW-01). The Massachusetts criterion for visibility to support contact recreation has been added for comparison purposes.

The seasonal pattern shows that SDT depth is generally much shallower than for Lovers Lake and that it did not exceed 3 m at any time during the sampling period. The average value through early July was 2.5 m. From that period on until late turnover in December it averaged 1.3 m and generally did not meet the MA visibility criterion.

The SDT results from the 2007surveys were compared to those seen during the PALS monitoring (2001-2006) as displayed in Figure 2-09. Overall, the SDT values during the 2007 surveys were shallower that those seen during the PALS monitoring. This may indicate that water quality in Stillwater Pond is deteriorating, but a direct comparison between the two sets of data are difficult because of the lack of multi-seasonal data other than in 2001-2002.

3.1.3.3 Water chemistry

Water quality samples were taken in Stillwater Pond on five occasions in 2007 ranging from May to late August at approximate 4 week intervals (5/9/07; 6/5/07; 7/3/07; 8/2/07; 8/30/07). Samples were taken from both top (0.5 m) and bottom (1m off bottom) at two locations - CPSP-SW-01 and CPSP-SW-02 (Figure 2-1b). On one occasion (8/29/07) an additional deep sample was taken 2 m off the bottom. These water quality samples were analyzed for total phosphorus, dissolved phosphorus, ammonia, nitrate, nitrite, total Kjeldahl nitrogen, alkalinity, hardness, total suspended solids, chloride, sulfate, iron, and pH.

The results for the 2007 samples for Stillwater Pond are organized by station in Table 3- 3. Water chemistry results from Stillwater Pond were examined for variation with regard to station (CPSP-SW-01 vs. CPSP-SW-02, depth (surface vs. bottom) and season (Table 3-3). In general, the surface water stations had comparable results, while the deep sample at CPSP-SW-01 (sampled at 14 m) had the most extreme chemistry with the bottom station at CPSP-SW-02 (sampled at about 8 m) having results intermediate between the other stations.

Examination of some of the nitrogen fractions indicates that NO_3-N was measured as high as 80 ug/L at the surface early in the season, but otherwise was found at or below the detection limit of 10 ug/L. Higher values found in the bottom water (130 – 150 ug/L) may indicate the influence of NO_3-N in groundwater. NO_2-N was not detected in any of the samples.

Ammonia-nitrogen (NH_3-N) in the surface water stations of Stillwater Pond averaged approximately 66 - 75ug/L, but was seasonally variable. It had high concentration in the spring and late summer but declined by mid-summer. The ammonia concentrations in the deepest samples were highly elevated. The average value for the bottom waters at CPSP-SW-01 was 1,698 ug/L, with two samples exceeding 2,400 ug/L. These levels of ammonia may approach toxic levels under some combinations of pH and temperature. The average ammonia concentration for the deep sample at CPSP-SW-02 was less elevated at 110 ug/L.

TKN was again the most significant nitrogen fraction. TKN concentrations in the upper waters of Stillwater Pond averaged 828-1,194 ug/L; with a range of 330-2,500 ug/L. TKN averaged a very impressive 3,580 ug/L at the bottom station in the deep hole with a range from 1,100 to 8,700 ug/L. The bottom sample from CPSP-SW-02 averaged 958 ug/L. Total nitrogen levels were from 345 – 2,500 ug/L with means of 858 -1,222 ug/L in the surface water and were from 375 to 8,713 ug/L with means of 1,000 - 3,618 in the bottom waters.

Phosphorus was measured in Stillwater Pond in 2007 and showed very strong differences between top and bottom waters (Table 3-3). TP in surface ranged from 26 ug/L to 68 ug/L with the means at 40-43 ug/L. DP ranged from below detection to 39 ug/L with the means at the surface water stations at 18 - 23 ug/L. DP tended to increase in concentrations from spring to summer.

TP concentrations at the bottom station at CPSP-SW-01 exhibit a strong seasonal increase consistent with the increased release of phosphorus from the sediments as anoxia occurs. The average at that station for the 6 hypolimnetic samples was 288 ug/L; with a range of 54 to 566 ug/L and about half of the TP was present as

DP. The other bottom sample at CPSP-SW-02 was not as P-enriched; the average was 67 ug/L; with a range of 29 to 93 ug/L. This will be discussed in detail in Section 5.2.

With regard to other general water quality parameters, the upper waters of Stillwater Pond average 7.8 -7.9 S.U., and the bottom waters were acidic with means of 6.5 - 6.8 S.U. (Table 3-3). Alkalinity values, measured as mg/L $CaCO_3$, averaged 18 - 20 mg/L in the upper waters and 17 - 35 in the bottom waters. Hardness had a similar pattern, being 32 - 34 mg/L at the surface and 32 - 40 mg/L at the bottom.

Average chloride at all stations in Stillwater Pond ranged from 31 – 35 mg/L (Table 3-3). The surface concentrations of iron were uniformly low at 0.1 mg/L, while those of the bottom stations were 6.0 mg/L at CPSP-SW-01 (ranged of 0.6 to 13.3 mg/L) and 0.2 mg/L (range of 0.1- 0.3 mg/L) at the shallower SW-02. TSS in surface waters averaged 3.0 – 3.9; while the hypolimnion TSS values average 4.6 and 14.1 mg/L

3.1.3.4 Comparison with historic water quality data

The results from the 2007 water quality surveys in Stillwater Pond were compared with previous results to see if conditions were comparable with previous observations. These comparisons indicate that conditions in 2007 were generally similar to those in the PALS monitoring dataset (Table 2-5). For example, the PALS TP surface water average was 27 ug/L, compared with 40 - 43 ug/L in 2007; while the TP at maximum depth averaged 289 ug/L for the PALS dataset, as opposed to 288 ug/L in 2007. The PALS TN surface water average was 770 ug/L as compared to 858 -1222 ug/L in 2007; with 2,970 vs. 3,618 ug/L for the deep sample at CPSP-SW-01. Similar patterns were observed for pH in surface waters (PALS = 7.8 vs 7.8 - 7.9 for 2007) and at the bottom (PALS = 6.5 vs. 6.5 - 6.8 for 2007). Alkalinity was also significantly elevated in the hypolimnion in both surveys. Overall, the results are in general agreement between the PALS dataset, but there is a trend of increasing nutrients in surface water for 2007, which may be related to the relative dry year conditions or may be indicative of accelerating eutrophication of Stillwater Pond.

3.2 Sediment sampling and analytical results

3.2.1 Sampling and analytical methods

Sediment samples were collected in May, 2007 at five sites on Lovers Lake (CPLL-SD01, CPLL-SD02, CPLL-SD03, CPLL-SD04, CPLL-SD05, Figure 2-1a) and three sites on Stillwater Pond (CPSP-SD01, CPSP-SD02, CPSP-SD03, Figure 2-1b). The GPS coordinate locations of the samples are provided in Table 3-4. The purpose of collecting sediment samples was to determine the composition of the sediments (i.e. muck, sand) which would show the sediments ability to retain phosphorus, and to also determine the quantity of phosphorus within the sediments in different areas of the lake.

Using an Ekman dredge, a sample containing the top ~10 cm of profundal sediment was collected at each sampling site, representing this portion of the basin. For quality control purposes a duplicate sediment sample was taken at Stillwater Pond at station CPSP-SD-02. For each site, two 8 oz amber bottles were filled with sediment and sent to an independent analytical laboratory for determination of total iron, total phosphorus, iron bound phosphorus, loosely sorbed phosphorus, and percent solids.

At Lovers Lake, a composite of sediment samples at CPLL-SD-01, CPLL-SD-02, and CPLL-SD-04 were placed in two 1-liter amber bottles and sent to the laboratory for analysis of grain size. At Stillwater Pond, a composite of the sediment samples at CPSP-SD-01, CPSP-SD-02, and CPSP-SD-03 was sent to the laboratory for analysis of grain size. Raw chemistry results are provided in Appendix E.

3.2.2 Sediment quality

Table 3-5 summarize the sediment chemistry of Lovers Lake and Stillwater Pond at the locations shown on Figures 2-1a and 2-1b, respectively. Sediment samples were typically very dark brown-black, highly flocculent in nature, with little observable internal structure. Sediments at all sites would be considered highly organic in matter (i.e., muck) although there was a somewhat greater representation of sand (denoted by higher % solids total and visual observations) at locations CPLL-SD-04 (29% solids) and CPSP-SD02 (19-23% solids). As seen in Figure 2-1a, location CPLL-SD-04 is the shallow sill area between the two distinct ends of the "L"-shaped pond. Location CPSP-SD02 is located in the southern, central portion of Stillwater Pond located near where a shallower arm of the pond extends southeast.

Comparison of the grain size of the composite samples indicates that the sediments have a large percentage of fine-grained materials (all samples have 50% < 250 um particles), again consistent with the generally muck-silt composition (limnologically termed "gyjtta" sediments). This type of material represents the final remains of organic material derived largely from within-lake processes, as would be expected in these systems (e.g., no major surface water drainages).

Sediment phosphorus measurement was conducted at Spectrum Analytical of Agawam, MA using a modification of the method of Rydin and Welch (1998, 1999). This analysis was used because total phosphorus has proven to be a poor indicator of available phosphorus, but it was not until about 1998 that a method for reliably determining available phosphorus was developed at a practical level. Therefore, the method used for the Lovers Lake and Stillwater Pond sediments involved sequential extractions that separate the "loosely-sorbed" and "iron-bound" phosphorus fractions from the remaining fractions that make up the total phosphorus content of the sediment.

Loosely-sorbed phosphorus is considered the most available fraction. The iron-bound phosphorus, determined after extraction for loosely-sorbed phosphorus, is that fraction bound to iron and often mobilized from anoxic sediment as a consequence of redox reactions. The sum of the loosely-sorbed and iron-bound phosphorus fractions are summed to estimate an "available phosphorus" fraction that is considered representative of the phosphorus that may be potentially released, depending on redox conditions (Table 3-5).

As indicated by Table 3-5, sediments of both Lovers Lake and Stillwater Pond contain elevated concentrations of total phosphorus and iron, with two significant exceptions. The two sediment samples that contained more sand (CPLL-SD-04; CPSP-SD-02 and duplicate) also contain the least phosphorus. These sampling locations are also areas where oxygen may be more present during most of the year.

For all sediments the loosely-sorbed phosphorus was determined to be a very small fraction of the total sediment phosphorus, with most samples below reporting limits. However, the iron-bound phosphorus was a significant portion of the total phosphorus and resulted in elevated available phosphorus concentrations ranging as high as 1,811 mg P/kg sediment. These results are shown in Figure 3-7 for Lovers Lake and in Figure 3-8 for Stillwater Pond. These results clearly indicate that most sediments in the two ponds are highly enriched with phosphorus in a form which will be readily released under anoxic conditions.

The sediment samples were grouped according to their location in or near the three deeper basins: for the deeper, northern basin in Lovers Lake – CPLL-SD-01 and CPLL-SD-03 were considered together; for the southern basin in Lovers Lake – CPLL-SD-02 and CPLL-SD-05; for the central basin in Stillwater Pond – CPSP-SD-01 and CPSP-SD-03. Available phosphorus fractions for the northern LL basin ranged from 1,380 – 1,811 mg/kg and averaged 1,590 mg/kg; while that for the southern LL basin ranged from 1,490 – 1,755 mg/kg and averaged 1,623 mg/kg. For the SP central basin, the available phosphorus ranged from 1,075 – 1,495 mg/kg and averaged 1,285 mg/kg. These values indicate that the sediment available phosphorus concentrations in the deep areas of both ponds and their potential for phosphorus recycling are very comparable.

These sediment phosphorus concentrations were further refined by considering just the volume and phosphorus contained in the top sediment layers that would be most actively involved in phosphorus release. Rydin and Welch (1998, 1999) suggest that the upper 2 to 4 cm of sediment are involved, indicating that the active volume is therefore 0.02 to 0.04 m^3. Multiplying by the percent solids and the available phosphorus concentration yields the mass of phosphorus available for recycling per m^2 (Table 3-5). The mass of phosphorus contained in the 0-2 cm layer is termed the “minimum available phosphorus” and that contained in the 0 to 4 cm layer is termed the “maximum available phosphorus.”

By this process, it is estimated that sediments like those found at stations CPLL-SD-01 and CPLL-SD-03 will provide approximately 33 - 86 g available P/m^2 while sediments like those at CPLL-SD-02 and CPLL-SD-05 will offer 36 to 85 g available P/m^2. In Stillwater Pond, there was from 26 to 72 g available P/m^2. In contrast, the sandier sediments from both ponds would provide a rather modest 2.5 to 10 g available P/m^2.

Section 5.2 evaluates the actual observed release rates based on observations in the hypolimnion. While this method only recognizes the potential for release, it appears that if only a small fraction reached the epilimnion, it would still be enough to raise the phosphorus level sufficiently to account for the summer DP concentrations and to support algal blooms.

Table 3-1. Field Survey and Water Quality Sampling Locations on Lovers Lake and Stillwater Pond (5/11/07)

Waterbody	Station ID	Description	GPS Coordinates	
			Northing	Westing
Lovers Lake	CPLL-SW01S	Deep hole, surface	41°41.974'	-69°59.079'
	CPLL-SW01D	Deep hole, bottom		
	CPLL-SW02S	SE basin, surface	41°41.390'	-69°58.992'
	CPLL-SW02D	SE basin, bottom		
Stillwater Pond	CPSP-SW01S	Deep hole, surface	41°42.219'	-69°59.212'
	CPSP-SW01D	Deep hole, bottom		
	CPSP-SW02S	SE corner, surface	41°42.167'	-69°59.159'
	CPSP-SW02D	SE corner, bottom		

Table 3-2. Summary of Lovers Lake Water Quality Parameters- 2007 Results

Summary of Lovers Lake Water Quality-CPLL-SW-01.

Date	Sample Name	NH3	NO3	NO2	TKN	TN	DP	TP	TN:TP	DIN:DP	pH	Alk	Hardness	Cl	SO4	Fe	TSS
Surface		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L			SU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
5/9/2007	SW01S	60	<10	<10	500	510	22	38	29.6	7.0	6.9	14	28	34.0	7.7	0.1	<1
6/5/2007	SW01S	120	10	<10	1200	1215	13	13	206.5	22.9	7.1	18	32	32.3	7.6	0.1	<1
7/2/2007*	SW01S	48	10	<10	145	160	52	56	6.9	2.4	7.3	18	38	35.5	7.2	0.2	1
8/1/2007*	SW01S	<10	10	<10	635	650	36	59	24.6	1.3	9.6	18	32	33.8	7.0	0.1	3
8/29/2007	SW01S	30	10	<10	900	915	21	26	77.7	4.7	9.1	15	34	34.0	7.0	0.1	8
	Min	***<10***	***<10***	***<10***	***145***	***160***	***13***	***13***	***7***	***1***	***6.9***	***14***	***28***	***32.3***	***7.0***	***0.1***	***<1***
	Mean	***52.5***	***9***	***<10***	***676***	***690***	***29***	***38***	***69***	***8***	***8.0***	***16***	***33***	***33.9***	***7.3***	***0.1***	***3***
	Max	***120***	***10***	***<10***	***1200***	***1215***	***60***	***63***	***206***	***23***	***9.6***	***19***	***44***	***36.0***	***7.7***	***0.2***	***8***

Date	Sample Name	NH3	NO3	NO2	TKN	TN	DP	TP	TN:TP	DIN:DP	pH	Alk	Hardness	Cl	SO4	Fe	TSS
Bottom		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L			SU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
5/9/2007	SW01D	300	10	<10	500	515	30	49	23.2	23.2	6.4	18	32	33.0	7.6	0.1	<1
6/5/2007	SW01D	710	10	<10	2100	2115	27	29	161.1	59.3	6.5	22	56	32.2	6.9	0.7	3.0
7/2/2007	SW01D	890	10	<10	1100	1115	44	107	23.0	45.4	6.4	36	52	35.0	3.6	4.7	11.0
8/1/2007	SW01D	430	10	<10	660	675	54	54	27.6	18.2	6.7	36	52	35.3	4.5	0.7	8.0
8/29/2007	SW01D	1140	20	<10	1900	1925	37	79	53.8	69.6	6.6	46	48	32.0	2.2	8.6	20.0
	Min	***300***	***10***	***<10***	***500***	***515***	***27***	***29***	***23.0***	***18.2***	***6.4***	***18***	***32***	***32.0***	***2.2***	***0.1***	***<1***
	Mean	***694***	***12***	***<10***	***1252***	***1269***	***38***	***64***	***57.8***	***43.1***	***6.5***	***32***	***48***	***33.5***	***5.0***	***3.0***	***8.5***
	Max	***1140***	***20***	***<10***	***2100***	***2115***	***54***	***107***	***161.1***	***69.6***	***6.7***	***46***	***56***	***35.3***	***7.6***	***8.6***	***20.0***

Note: If concentration below reporting limit, the stats were calculated using half the reporting limit

*Average of Duplicates

Summary of Lovers Lake Water Quality-CPLL-SW-02.

Date	Sample Name	NH3	NO3	NO2	TKN	TN	DP	TP	TN:TP	DIN:DP	pH	Alk	Hardness	Cl	SO4	Fe	TSS
Surface		**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**			**SU**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
5/9/2007	SW-02S	70	<10	<10	500	510	19	49	23.0	9.3	6.9	18	28	34.0	7.8	0.1	<1
6/5/2007	SW-02S	100	10	<10	900	915	<10	<10	404.2	50.8	7.1	16	40	32.2	7.5	0.2	1.0
7/2/2007	SW-02S	<10	10	<10	240	255	44	31	18.2	1.0	7.7	20	40	36.0	7.3	0.2	1.0
8/1/2007	SW-02S	<10	10	<10	580	595	39	44	29.9	1.1	9.6	20	40	33.8	6.9	0.1	1.0
8/29/2007	SW-02S	50	20	<10	1200	1225	18	29	93.3	9.2	9.8	16	2	34.0	6.8	0.2	11.0
	Min	***<10***	***<10***	***<10***	***240***	***255***	***<10***	***<10***	***18.2***	***1.0***	***6.9***	***16***	***2***	***32.2***	***6.8***	***0.1***	***<1***
	Mean	***46***	***11***	***<10***	***684***	***700***	***25***	***32***	***113.7***	***14.3***	***8.2***	***18***	***30***	***34.0***	***7.3***	***0.1***	***2.9***
	Max	***100***	***20***	***<10***	***1200***	***1225***	***44***	***49***	***404.2***	***50.8***	***9.8***	***20***	***40***	***36.0***	***7.8***	***0.2***	***11.0***

Date	Sample Name	NH3	NO3	NO2	TKN	TN	DP	TP	TN:TP	DIN:DP	pH	Alk	Hardness	Cl	SO4	Fe	TSS
Bottom		**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**	**µg/L**			**SU**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**	**mg/L**
5/9/2007	SW-02D	10	<10	<10	500	510	32	46	24.5	1.4	6.7	16	28	33.0	7.8	0.2	1.0
6/5/2007	SW-02D	440	<10	<10	1000	1010	19	21	106.2	52.3	6.6	22	40	32.1	7.1	0.7	2.0
7/2/2007	SW-02D	<10	10	<10	570	585	55	83	15.6	0.8	6.5	26	40	40.0	5.8	0.5	5.0
8/1/2007	SW-02D	190	10	<10	620	635	37	83	16.9	12.2	6.5	34	44	32.7	4.4	0.4	9.0
8/29/2007	SW-02D	280	10	<10	1100	1115	31	81	30.4	21.0	6.4	28	40	32.0	4.6	2.5	11.0
	Min	***5***	***5***	***5***	***500***	***510***	***19***	***21***	***15.6***	***0.8***	***6.4***	***16***	***28***	***32.0***	***4.4***	***0.2***	***1.0***
	Mean	***185***	***8***	***5***	***758***	***771***	***35***	***63***	***38.7***	***17.6***	***6.6***	***25***	***38***	***34.0***	***5.9***	***0.8***	***5.6***
	Max	***440***	***10***	***5***	***1100***	***1115***	***55***	***83***	***106.2***	***52.3***	***6.7***	***34***	***44***	***40.0***	***7.8***	***2.5***	***11.0***

Note: If concentration below reporting limit, the stats were calculated using half the reporting limit

*Average of Duplicates

J:\Water\ProjectFiles\P120\12249 Chatham Ponds\Water Quality Data\2007 Data\Water Quality Data\Chatham Ponds Water Quality Summary.xls

Table 3-3. Summary of Stillwater Pond Water Quality Parameters- 2007 Results

Summary of Stillwater Pond Water Quality-CPSP-SW-01

Date	Sample Name	NH3	NO3	NO2	TKN	TN	DP	TP	TN:TP	DIN:DP	pH	Alk	Hardness	Cl	SO4	Fe	TSS
Surface		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L			SU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
5/9/2007	SW-01S	130	80	<10	700	785	<10	35	49.5	95.0	7.4	14	36	33.0	6.4	0.1	1
6/5/2007*	SW-01S	125	<10	<10	1350	1360	14.5	25.5	122.5	20.9	7.1	16.0	38.0	33.0	6.6	0.2	<1
7/2/2007	SW-01S	10	10	<10	350	365	36	68	11.9	1.5	7.3	20	40	35.0	6.7	0.1	<1
8/1/2007	SW-01S	<10	10	<10	440	455	<10	34	29.6	8.8	8.9	18	36	34.7	6.4	0.1	3
8/29/2007	SW-01S	60	20	<10	1300	1325	29	37	79.1	6.5	8.8	32	22	35.0	6.3	0.2	10
	Min	***<10***	***<10***	***<10***	***350***	***365***	***<10***	***26***	***11.9***	***1.5***	***7.1***	***14***	***22***	***33.0***	***6.3***	***0.1***	***<1***
	Mean	***66***	***25***	***<10***	***828***	***858***	***18***	***40***	***58.5***	***26.5***	***7.9***	***20***	***34***	***34.1***	***6.5***	***0.1***	***3***
	Max	***130***	***80***	***<10***	***1350***	***1360***	***36***	***68***	***122.5***	***95.0***	***8.9***	***32***	***40***	***35.0***	***6.7***	***0.2***	***10***

Date	Sample Name	NH3	NO3	NO2	TKN	TN	DP	TP	TN:TP	DIN:DP	pH	Alk	Hardness	Cl	SO4	Fe	TSS
Bottom		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L			SU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
5/9/2007	SW-01D	1050	130	<10	1100	1235	7	54	50.5	373.9	6.2	18	32	34.0	5.9	1.1	2
6/5/2007	SW-01D	2490	<10	<10	3200	3210	46	123	57.6	120.1	6.5	29	32	33.2	4.5	4.6	4
7/2/2007	SW-01D	1680	10	<10	2500	2515	250	327	17.0	15.0	6.5	34	56	35.0	3.1	10.4	11
8/1/2007	SW-01D	840	10	<10	2400	2415	231	371	14.4	8.2	6.7	50	40	33.9	2.0	0.6	12
8/29/2007*	SW-01D	2430	7.5	<10	8700	8713	233	565.5	35.9	23.0	6.5	46	40	17.6	5.0	13.3	42
	Min	***840***	***<10***	***<10***	***1100***	***1235***	***7***	***54***	***14.4***	***8.2***	***6.2***	***18***	***32***	***17.6***	***2.0***	***0.6***	***2***
	Mean	***1698***	***33***	***<10***	***3580***	***3618***	***153***	***288***	***35.1***	***108.0***	***6.5***	***35***	***40***	***30.7***	***4.1***	***6.0***	***14***
	Max	***2490***	***130***	***<10***	***8700***	***8713***	***250***	***566***	***57.6***	***373.9***	***6.7***	***50***	***56***	***35.0***	***5.9***	***13.3***	***42***

Note: If concentration below reporting limit, the stats were calculated using half the reporting limit

*Average of Duplicates

Summary of Stillwater Pond Water Quality - CPSP-SW-02

Date	Sample Name	NH3	NO3	NO2	TKN	TN	DP	TP	TN:TP	DIN:DP	pH	Alk	Hardness	Cl	SO4	Fe	TSS
Surface		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L			SU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
5/9/2007	SW-02S	140	80	<10	600	685	<10	41	36.9	99.4	7.4	16	32	34.0	6.4	0.1	1
6/5/2007	SW-02S	180	<10	<10	2500	2510	24	27	205.4	17.5	7.1	18	32	32.9	6.6	0.2	1
7/2/2007	SW-02S	<10	10	<10	330	345	39	44	17.3	1.1	7.1	18	36	39.0	6.7	0.2	<1
8/1/2007	SW-02S	<10	10	<10	590	605	16	60	22.3	2.8	8.7	20	32	34.7	6.4	0.1	4
8/29/2007*	SW-02S	45	10	<10	1950	1965	31	41	107.4	4.3	8.5	19	28	0.1	35.5	6.4	13
	Min	***<10***	***<10***	***<10***	***330***	***345***	***<10***	***27***	***17.3***	***1.1***	***7.1***	***16***	***28***	***32.9***	***6.4***	***0.1***	***<1***
	Mean	***75***	***23***	***<10***	***1194***	***1222***	***23***	***43***	***77.9***	***25.0***	***7.8***	***18***	***32***	***35.2***	***6.5***	***0.1***	***4***
	Max	***180***	***80***	***<10***	***2500***	***2510***	***39***	***60***	***205.4***	***99.4***	***8.7***	***20***	***36***	***39.0***	***6.7***	***0.2***	***13***

Date	Sample Name	NH3	NO3	NO2	TKN	TN	DP	TP	TN:TP	DIN:DP	pH	Alk	Hardness	Cl	SO4	Fe	TSS
Bottom		µg/L	µg/L	µg/L	µg/L	µg/L	µg/L	µg/L			SU	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
5/9/2007*	SW-02D	235	150	<10	800	955	13	72	29.5	70.9	6.8	17	30	0.2	31.5	6.0	2
6/5/2007	SW-02D	0.12	<10	<10	1600	1610	11	29	122.6	26.1	7.2	18	32	32.7	6.4	0.3	3
7/2/2007	SW-02D	<10	10	<10	360	375	34	60	13.8	1.3	6.6	18	36	34.0	5.9	0.3	2
8/1/2007	SW-02D	140	10	<10	630	645	23	93	15.3	14.9	6.6	18	32	33.6	5.4	0.2	5
8/29/2007	SW-02D	50	10	<10	1400	1415	42	76	41.1	3.4	6.5	12	32	35.0	5.7	0.1	11
	Min	***<10***	***<10***	***<10***	***360***	***375***	***11***	***29***	***13.8***	***1.3***	***6.5***	***12***	***30***	***31.5***	***5.4***	***0.1***	***2***
	Mean	***110***	***37***	***<10***	***958***	***1000***	***25***	***66***	***44.5***	***23.3***	***6.8***	***17***	***32***	***33.4***	***5.9***	***0.2***	***5***
	Max	***235***	***150***	***<10***	***1600***	***1610***	***42***	***93***	***122.6***	***70.9***	***7.2***	***18***	***36***	***35.0***	***6.4***	***0.3***	***11***

Note: If concentration below reporting limit, the stats were calculated using half the reporting limit

*Average of Duplicates

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Table 3-4. Sediment sampling locations on Lovers Lake and Stillwater Pond and composites (5/07)

			GPS Coordinates	
Waterbody	**Station ID**	**Description**	**Northing**	**Westing**
Lovers Lake	CPLL-SD01	Deep hole; N.basin	41°41.974'	-69°59.079'
	CPLL-SD02	SE basin	41°41.390'	-69°58.992'
	CPLL-SD03	SW area; N.basin	41°41.928'	-69°59.135'
	CPLL-SD04	Between 2 basins	41°41.827'	-69°59.155'
	CPLL-SD05	S. of peninsula	41°41.757'	-69°59.131'
	CPLL-SDP	Composite of SD-01; SD-02, SD-04	NA	NA
Stillwater Pond	CPSP-SD01	Deep hole; central	41°42.219'	-69°59.212'
	CPSP-SD02	Near big house	41°42.167'	-69°59.159'
	CPSP-SD02D	Duplicate; SD-02	41°42.167'	-69°59.159'
	CPSP-SD03	NE area	41°42.218'	-69°59.124'
	CPSP-SDP	Composite of SD-01; SD-02, SD-03	NA	NA

Note: GPS coordinates in Degrees Minutes

Table 3-5. Sediment Chemical and Physical Characteristics - Chatham Ponds, May 2007.

2007 Lovers Lake Sediment Data
Date: May 9, 2007

Station	Iron (mg/kg)	Total Phosphorus (mg/kg)	% Solids	Iron Bound Phosphorus (mg/kg)	Loosely Sorbed Phosphorus (mg/kg)
CPLL-SD01	88,200	3,260	14.7	1810.0	BRL
CPLL-SD02	123,000	6,360	15.5	1490.0	BRL
CPLL-SD03	71,700	3,520	17.0	1380.0	BRL
CPLL-SD04	31,700	587	28.9	116.0	BRL
CPLL-SD05	68,700	2,740	13.8	1750.0	5.28

BRL- Below Reporting Limit

2007 Stillwater Pond Sediment Data
Date: May 9, 2007

Station	Iron (mg/kg)	Total Phosphorus (mg/kg)	% Solids	Iron Bound Phosphorus (mg/kg)	Loosely Sorbed Phosphorus (mg/kg)
CPSP-SD01	65,300	4060.0	11.1	1,490	3.79
CPSP-SD02	43,100	976.0	19.3	179	BRL
CPSP-SD02D	38,900	919.0	23.0	219	BRL
CPSP-SD03	38,100	1570.0	12.8	1,070	BRL

BRL- Below Reporting Limit

Grain Size	CPLL-SDP1	CPLL-SDP2	CPSP-SDP
Fractional % Sieve #4 (>4750 um)	0	0	0
Fractional % Sieve #10	1.9	0.6	0.4
Fractional % Sieve #20 (2000-850 um)	15.6	10.5	10.9
Fractional % Sieve #40 (850-425 um)	16.1	21.1	22.8
Fractional % Sieve #60 (425-250 um)	9.3	14.4	15.1
Fractional % Sieve #100 (250-150 um)	11.4	15	11.9
Fractional % Sieve #200 (150-75 um)	22.6	21.1	20
Fractional % Sieve #230 (less than)	23.1	17.4	18.8

Figure 3-1a. Lovers Lake Deep Station Temperature Profile
5/9/07-8/1/07

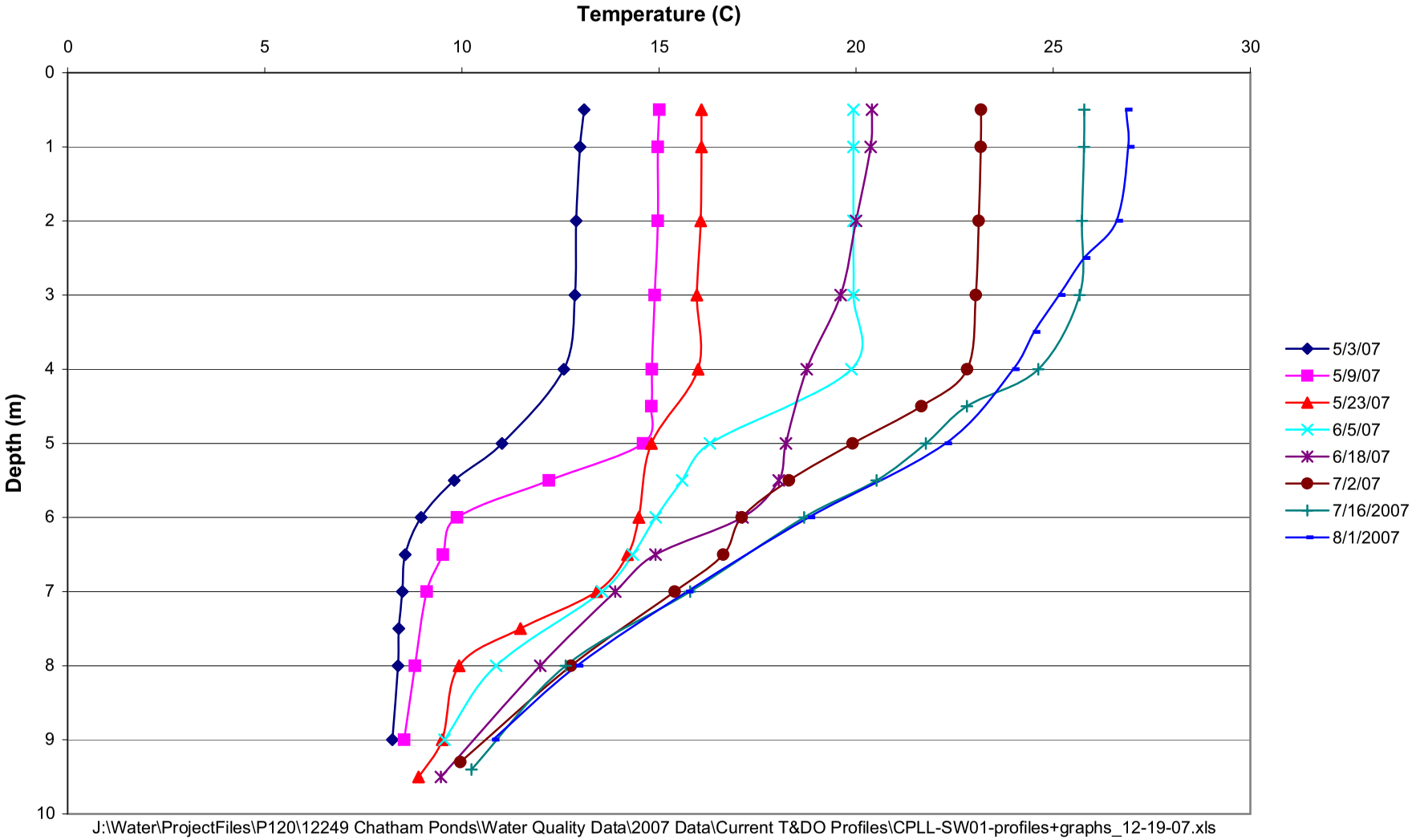

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Figure 3-1b. Lovers Lake Deep Station Temperature Profile
8/29/07-11/7/07

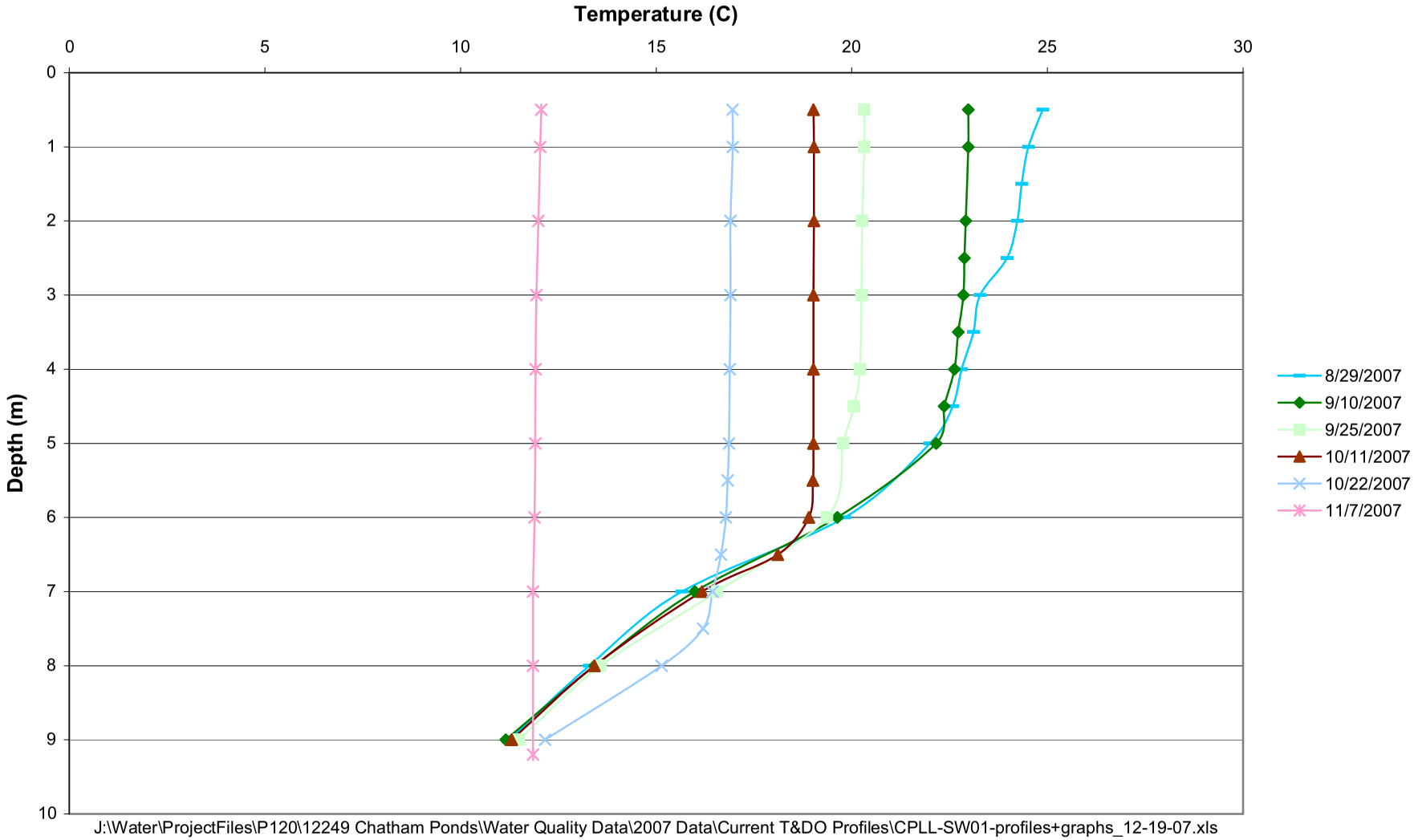

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Figure 3-2a. Lovers Lake Deep Station Dissolved Oxygen Profile
5/9/07-8/1/07

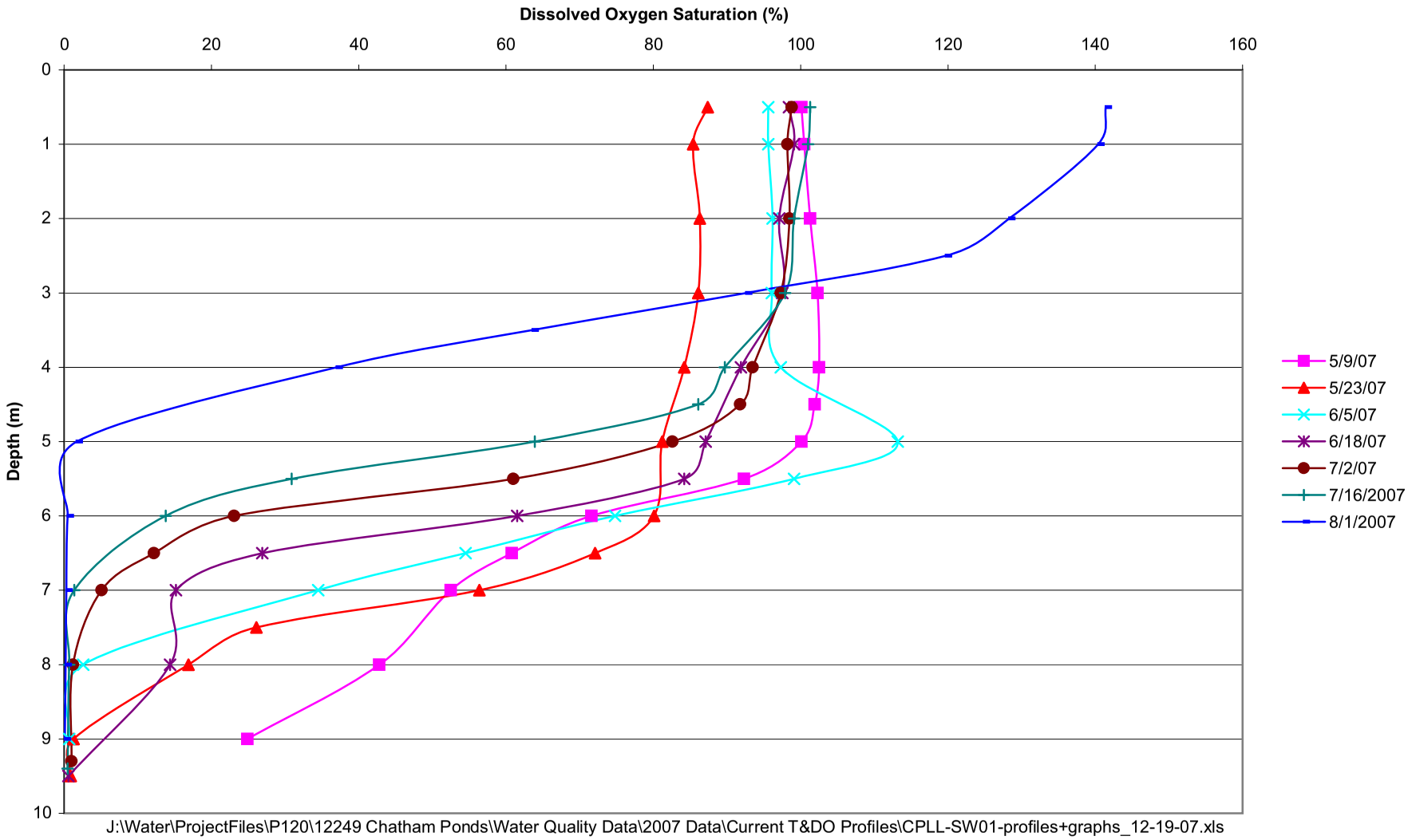

Figure 3-2b. Lovers Lake Deep Station Dissolved Oxygen Profile 8/29/07-11/7/07

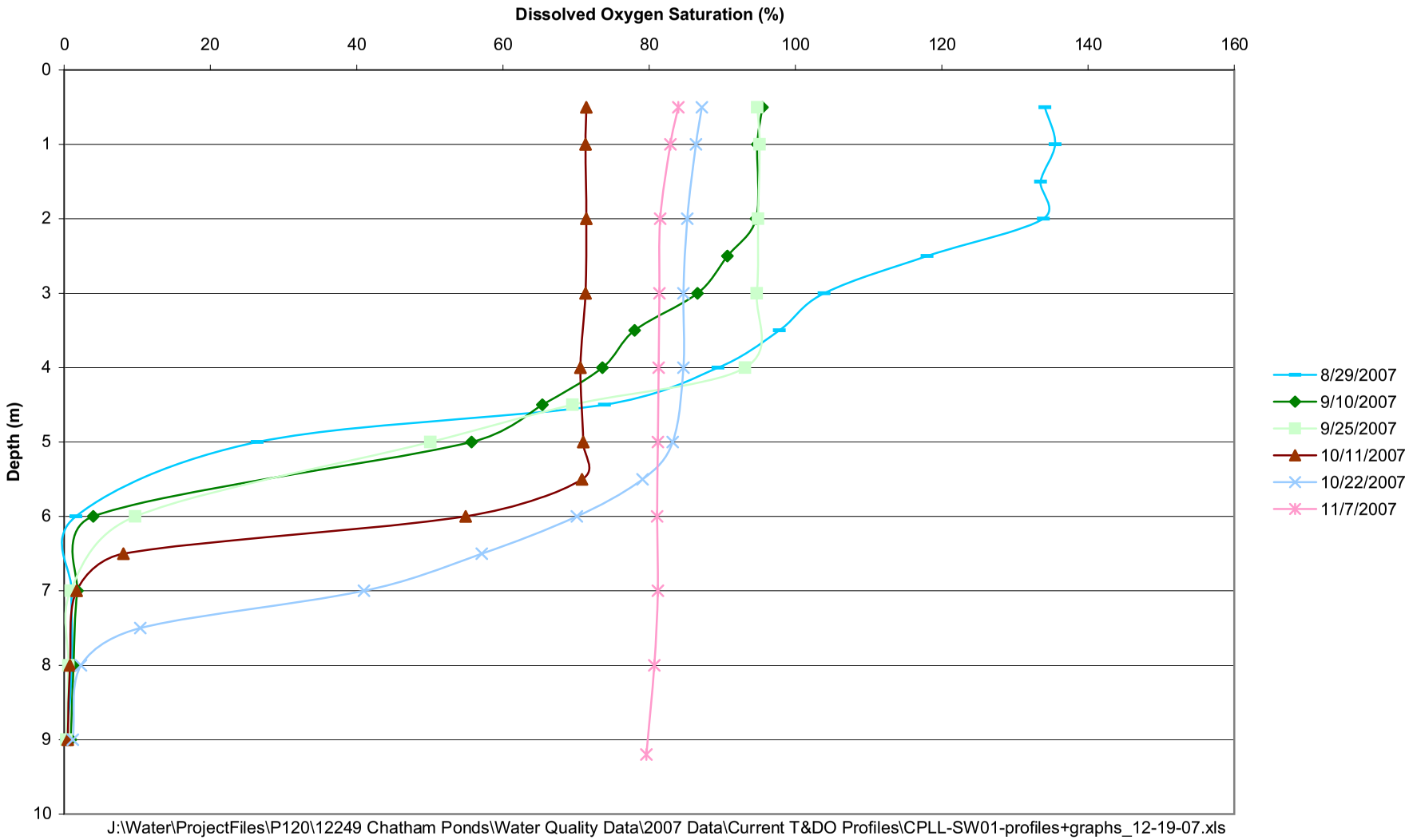

Figure 3-3. Lovers Lake Deep Site Secchi Disk Transparencies

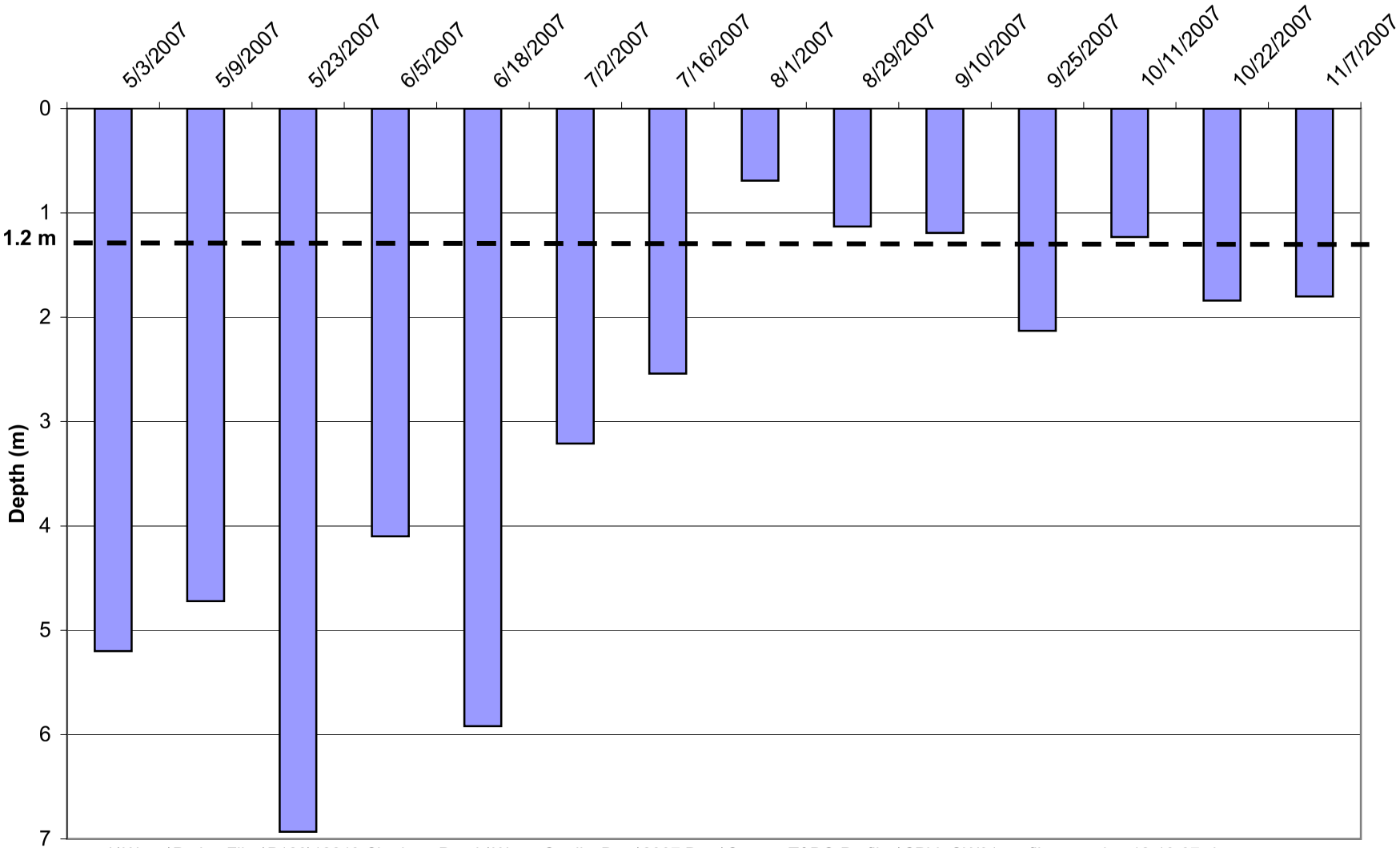

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Figure 3-4a. Stillwater Pond Deep Station Temperature Profile
5/3/07-8/1/07

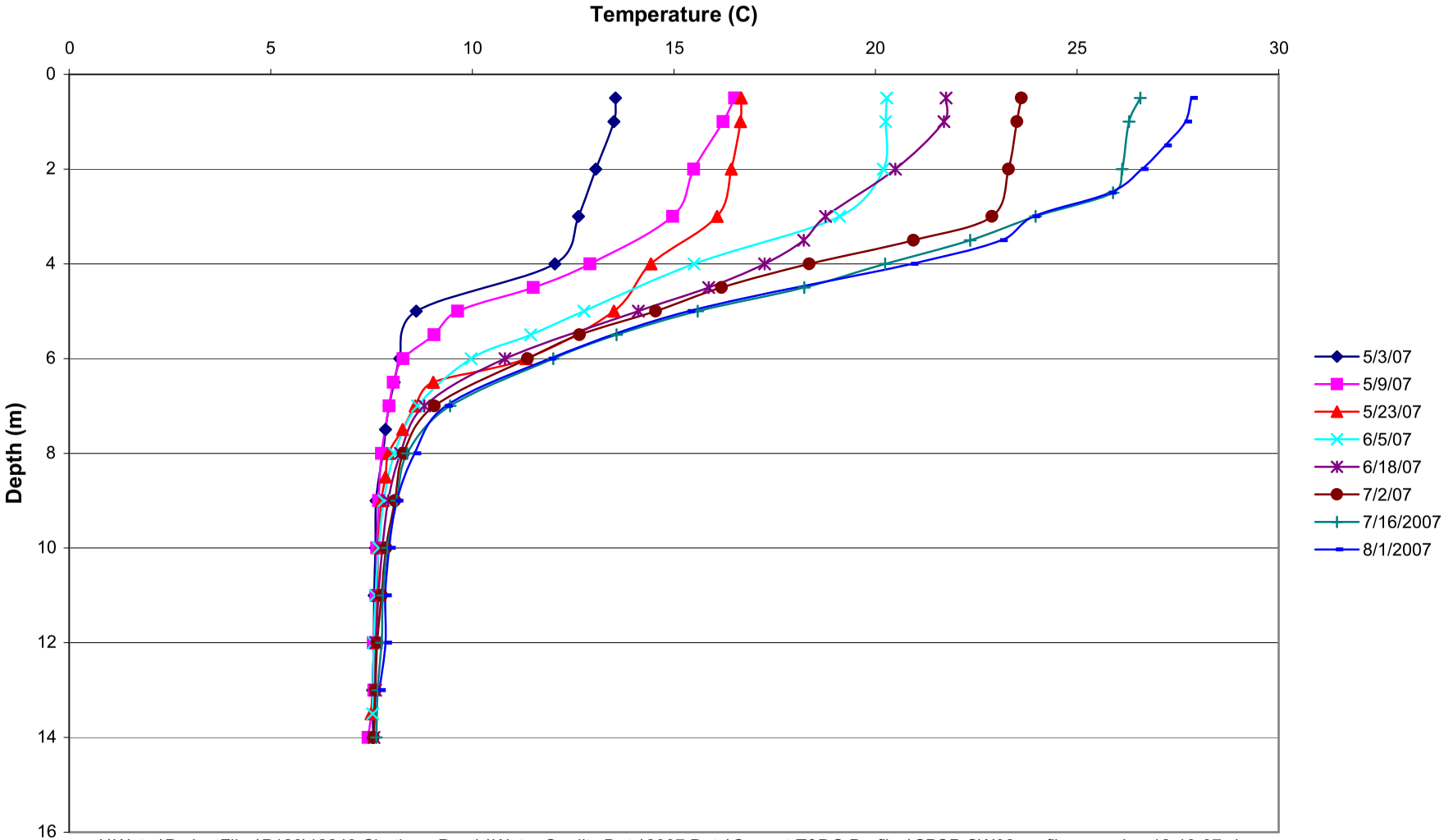

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Figure 3-4b. Stillwater Pond Deep Station Temperature Profile 8/29/07-12/7/07

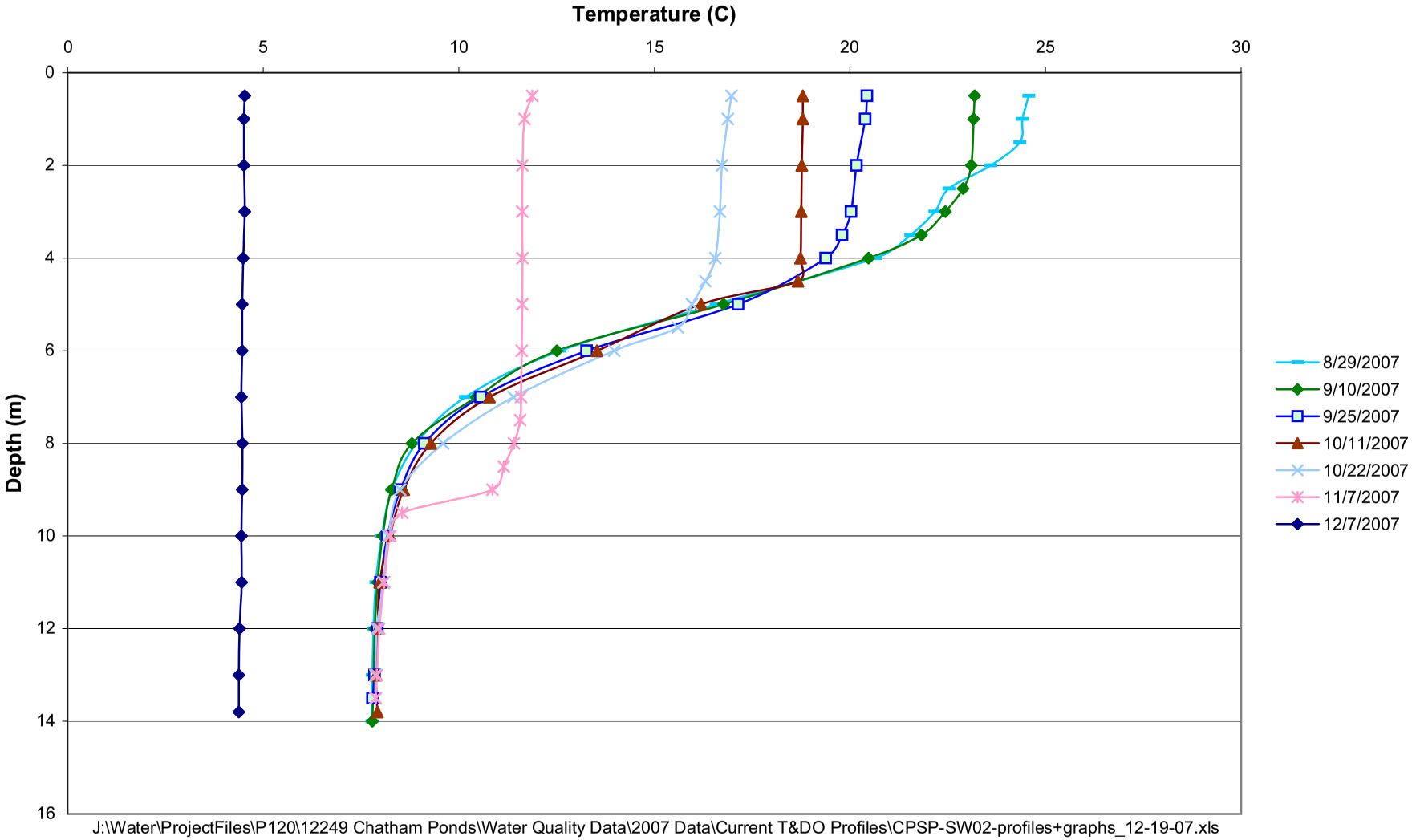

Figure 3-5a. Stillwater Pond Deep Station Dissolved Oxygen Profile 5/3/07-8/1/07

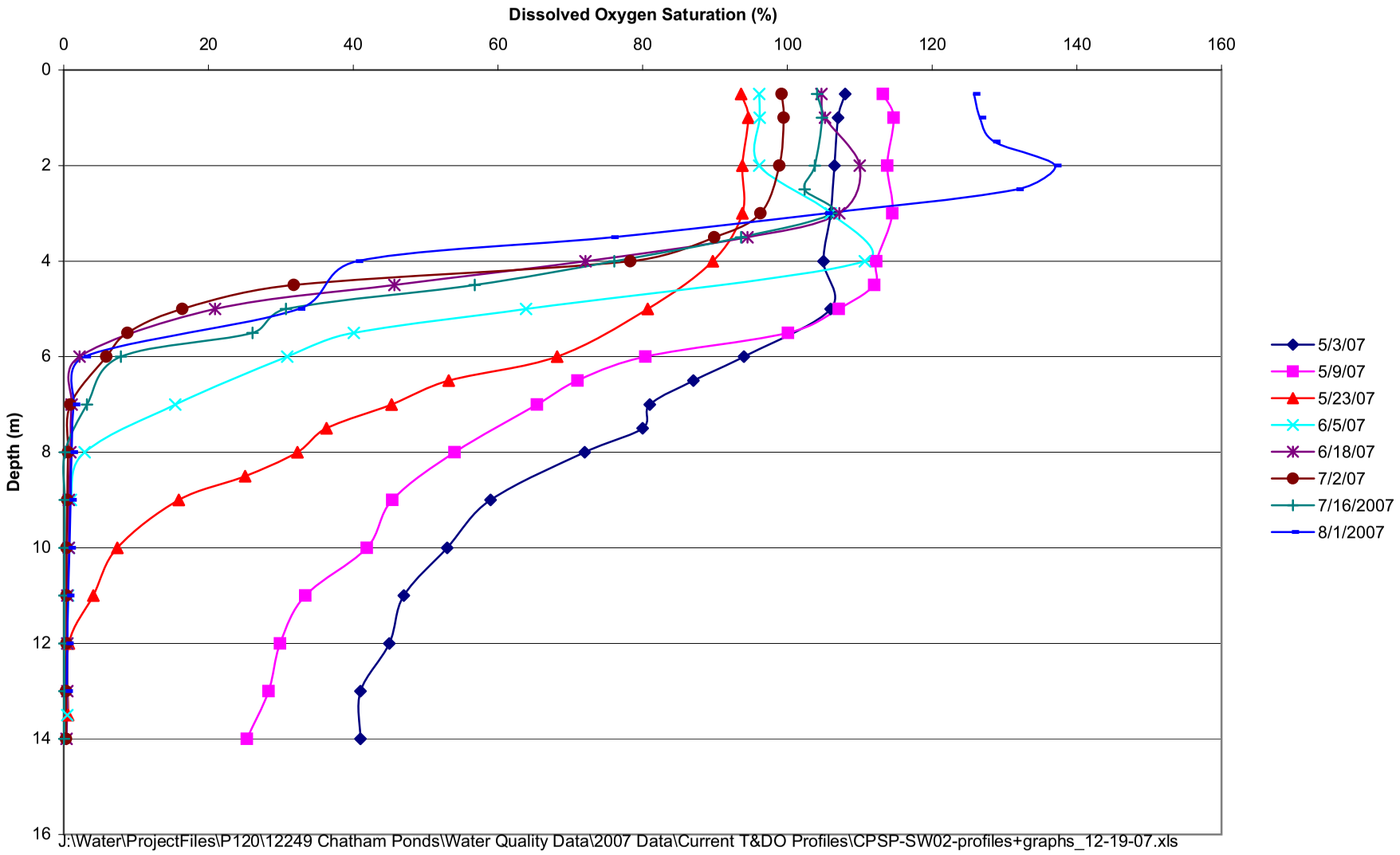

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Figure 3-5b. Stillwater Pond Deep Station Dissolved Oxygen Profile 8/29/07-12/7/07

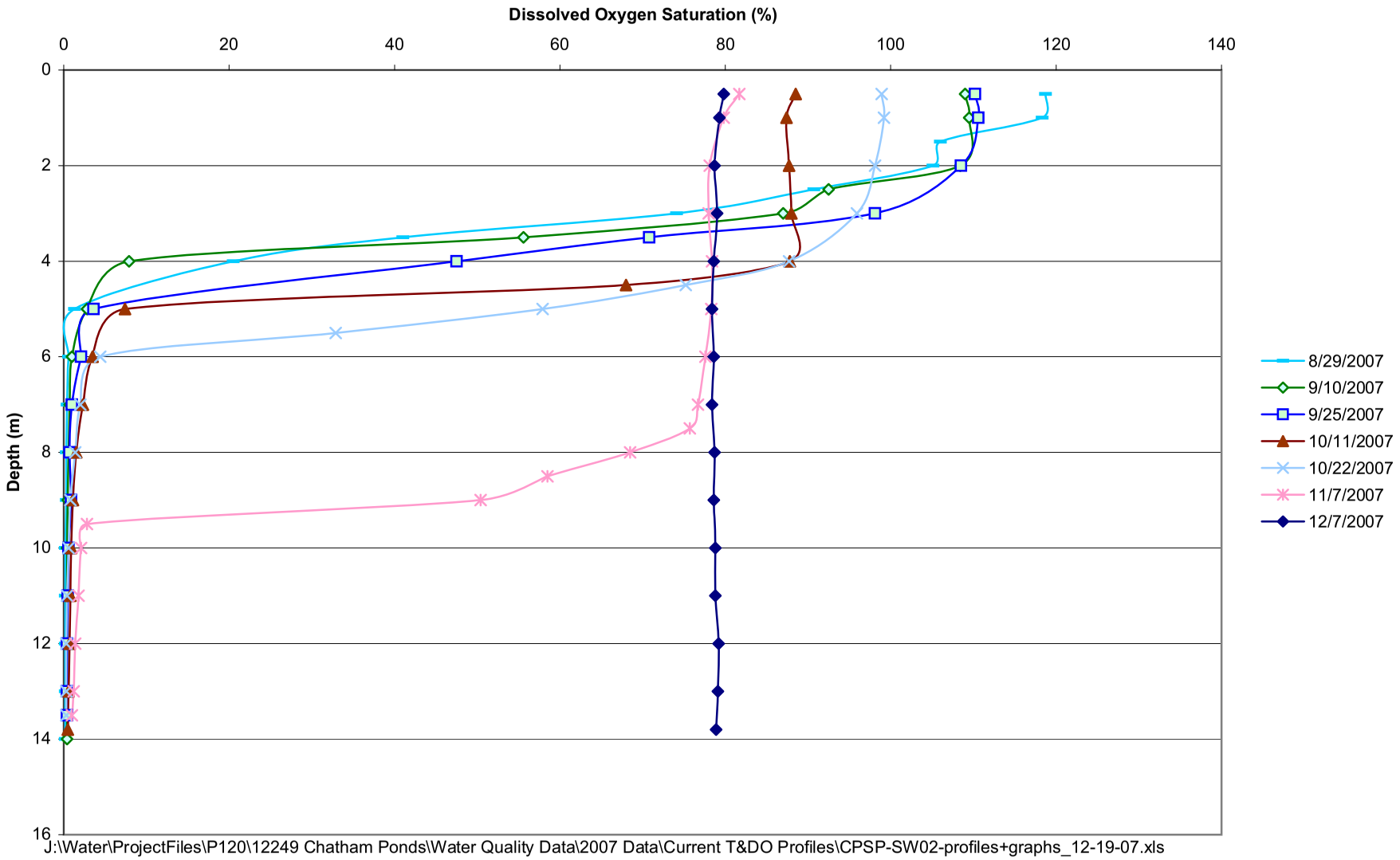

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Figure 3-6. Stillwater Pond Deep Site Secchi Disk Transparencies

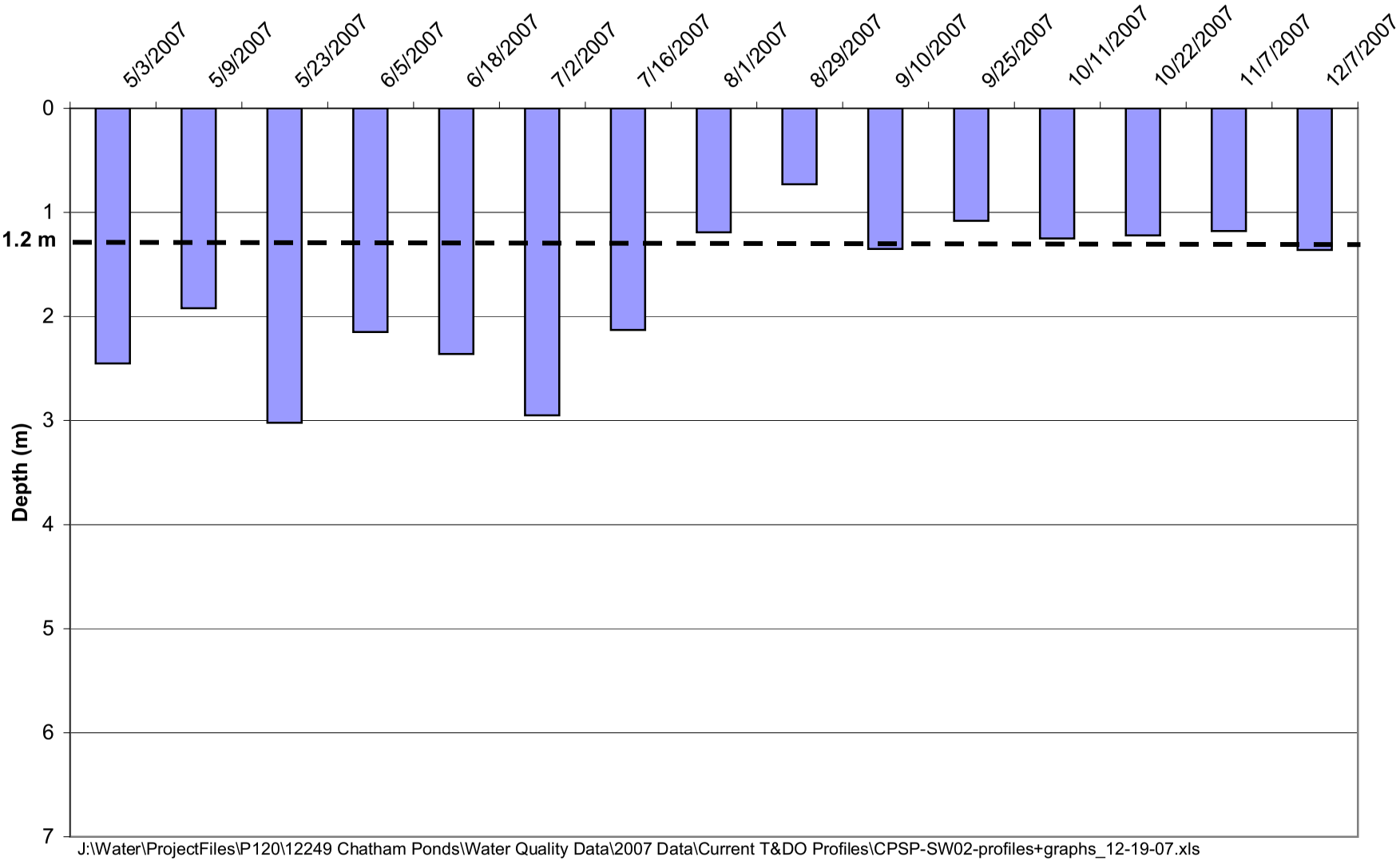


Figure 3-7. Total and Iron Bound Phosphorus in Lovers Lake

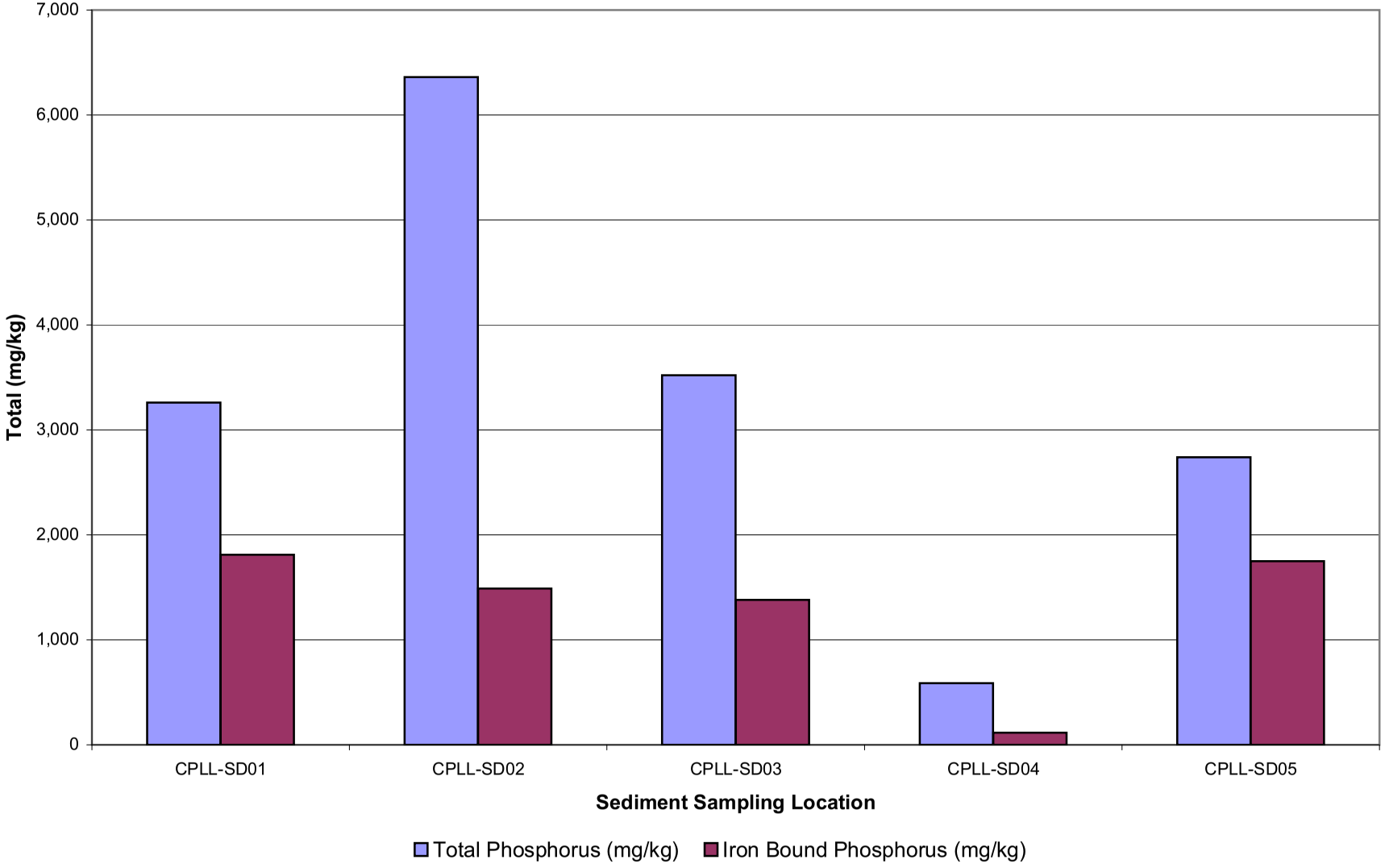
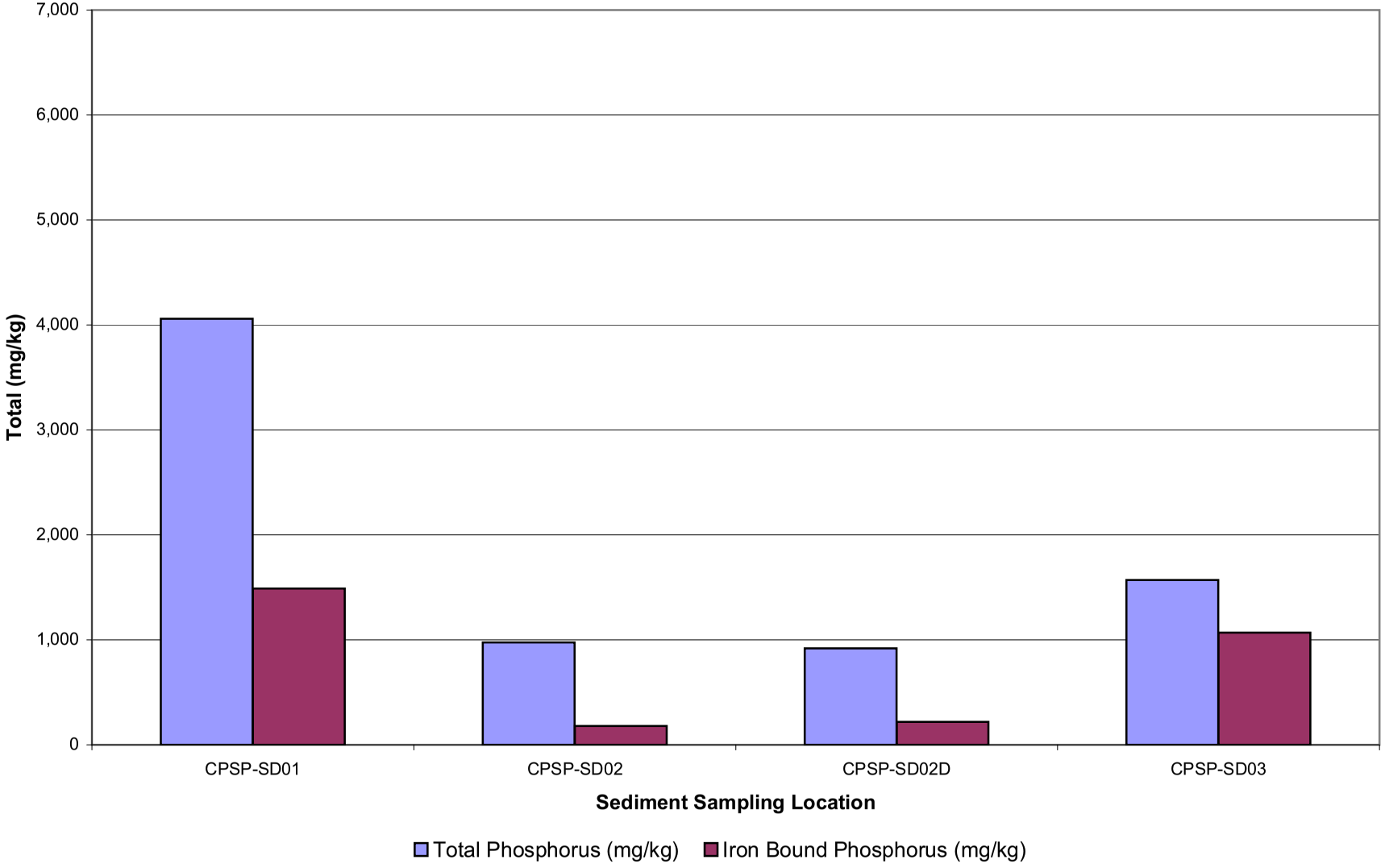


Figure 3-8. Total and Iron Bound Phosphorus in Stillwater Pond



4.0 Hydrologic budget

A hydrologic budget is a conceptual model of the various inputs and outputs of water into a waterbody that result in the current volume of water in the basin. A hydrologic budget is used to identify the major and minor sources of water entering and leaving the pond which can then be used to identify possible major sources or sinks of loads (e.g., nutrients, TSS) to the pond. The pond hydrology and nutrient loading are intricately linked as one can not determine the nutrient loads without considering the associated hydrologic load.

Typical hydrologic inputs for a pond include precipitation, surface tributary flow, groundwater, stormwater runoff, and direct overland flow. Typical outputs include evaporation, outlet flow, groundwater, and direct water withdrawals. Over the longterm, if the area and the surface elevation of the waterbody are stable, it is assumed that inputs equal the outputs, but this may not be the case in a shorter study (i.e., 1-2 years) due to climatic variation, timing of storms, and antecedent groundwater levels.

4.1 Background information

For kettlehole ponds in Cape Cod, hydrologic budgets are typically dominated by the influence of groundwater recharge entering the pond as in-seepage and discharge exiting the pond bottom as out-seepage. These type of waterbodies have been termed “flow-through” ponds (Walter et al., 2004) due to this pattern of groundwater influence. The major source of groundwater is through recharge by precipitation falling in the watershed, but it is also affected by water withdrawals (e.g., public drinking water wells) or localized recharge (e.g., influence of hydrologic inputs of on-site septic systems). As noted by Walter and Whealon (2005), groundwater flows away from regional water-table divides towards natural discharge boundaries at streams and coastal water bodies; some water flows through kettlehole ponds prior to discharging with some water removed from the system for water supply.

Determination of contributing groundwater watershed areas was based on models and maps originally developed by the USGS and divided into sub-watershed areas contributing to Pleasant Bay (see “Section III. Delineation of Watersheds”; MEP, 2003). The USGS three-dimensional, finite-difference groundwater model MODFLOW-2000 was used to simulate groundwater flow in the aquifer. The USGS particle-tracking program MODPATH4, which uses output files from MODFLOW-2000 to track the simulated movement of water in the aquifer, was used to delineate the area at the water table that contributes water to wells, streams, ponds, and coastal water bodies (MEP, 2003; EOEA & MADEP, 2004).

Both Lovers Lake and Stillwater watersheds are part of the Monomoy aquifer (flow lense) system, which is the sole source aquifer for Chatham and parts of surrounding towns. Flow within this aquifer has been well characterized regionally (Walter et al., 2004; Walter and Whealon, 2005) and refined by local study. Walter and Wheaton have produced estimates of groundwater travel time, which relates to the period of time that water stays in the aquifer before discharging to a surface water body, either freshwater pond or coastal system. Both watersheds are considered within the 10 year time-of-travel zone for discharge to Ryder’s Pond (MEP, 2003). In addition, the mapping of groundwater flows in the ponds’ watershed areas indicates that the current and potentially future pumping of upgradient wells in the Stillwater Pond watershed will need to be considered as part of the hydrologic budget.

Rainfall and wind records during the period of the 2007 field surveys (April – November) were obtained from summary *Quality Control Local Climatological Data* datasheets produced by the NOAA, National Climatic Data Center. Meteorological information is from the weather station maintained at the Chatham Municipal Airport; approximately ½ mile away from Lovers Lake and 1 mile from Stillwater Pond. The relevant NOAA datasheets are provided in Appendix F.

4.1.1 Influence of drinking water wells

The potential influence of the pumping of the drinking water wells in the Stillwater Pond watershed was quantified. Two drinking water wells (wells #5 and #8) are located in a small well field located off of Training Field Road. This wellfield area is due west of Lovers Lake but, despite the close proximity to that waterbody, the groundwater in this portion of the watershed recharges Stillwater Pond. Pumping data from 2004-2006 was obtained from the Town of Chatham and used to determine average annual pumping rates for Wells #5 and #8. The data for Well #5 had a missing value for May 2006; this omission was corrected by using the average May value from the 2004-2005 data.

The corrected three year average pumping rate for Well #5 was 50,328,100 gallons per year (range of 40,426,500- 57,802,500); while that for Well #8 was 59,766,110 gallons per year (range of 39,151,900 – 71,080,000). The combined pumping rate was 110,090,200 with a range of 80,078,400 - 126,680,900 gallons per year. This dataset was assumed to provide a reasonable estimate of current water demand from these wells

It is not certain to what extent these two wells' production removes groundwater from the portion of the aquifer that recharges Stillwater Pond. Well #5 is reportedly screened at 69-79 ft below ground surface (bgs), while well #8 has screens down at 102.5 – 110 ft bgs (pers. comm., Lynn Van Sant). The 2003 Chatham SWAP report notes that well #5 is located in an aquifer of high vulnerability to contamination due to the absence of a hydrogeologic barrier (i.e., a contiguous clay layer) (MA DEP, 2003). Typically, in this area of the watershed, the top of groundwater elevation (a.k.a. water table) is from 15 to 25 ft bgs, depending on season.

4.1.2 Previous studies of Lovers Lake and Stillwater Pond hydrology

As part of the nitrogen TMDL for Pleasant Bay, a longterm monitoring (November 2000 – December 2002) of the stage (water depth in streams) in the outflow streams leaving Lovers Lake and Stillwater Pond was conducted (MEP, 2003) (see Appendix F for map of locations). The upper gauging station was also used to evaluate the impact of the effect of additional water going into Stillwater Pond that had historically been discharged to Frost Fish Creek but which is currently blocked. The lower gauging station (outflow of Stillwater Pond) was used to evaluate the surface water flow to Ryder's Cove. At each site a continuously recording water level gauge was installed and calibrated to flow, which was periodically measured using a Marsh-McBirney flow meter (MEP, 2003). Despite difficulties with episodes of instrument failures, stream flow data for 470 days and 361 days were available for the outflows of Lovers Lake and Stillwater Pond, respectively.

From these data, a composite year was constructed for which the annual and average daily outflows for Lovers Lake and Stillwater Pond were estimated (MEP, 2003). This composite year showed a seasonal pattern of high flow in the spring time and lowest periods during summer. This seasonal pattern reflects the annual variation of groundwater level but is also influenced by the selected storage and release of water due to the surface water level manipulations due to management for the herring fishery (see Section 2.4.1.2). The estimated annual outflow of Lovers Lake was estimated at 0.44 cubic feet per second (cfs) while that for Stillwater Pond was 0.35 cfs. The MEP (2003) report concluded that most of the potential recharge (i.e., 91%) was exiting the pond as surface flow, based on contributing watershed size to Lovers Lake. This helps confirm that hydrologic loss to Frost Fish Creek is minimal and the historic outlet is functionally blocked, although some outseepage may drain towards the Creek. For Stillwater Pond, the outflow was significantly less than either the expected recharge based on watershed or even the inflow from Lovers Lake. This condition was taken to indicate that the pond is preferentially discharging to the groundwater.

4.2 Hydrologic budget calculations

The hydrologic budgets for Lovers Lake and Stillwater Pond were estimated using a combination of watershed characteristics as well as previously published data and information on pumping and outflow. Groundwater recharge watersheds were based on the prior USGS work described above. The average annual precipitation

value for both ponds was determined from combined data from the National Weather Service Chatham station and the Town of Chatham Water Quality Laboratory from 1985-2002 and is estimated at 44.3“ per year (MEP, 2003). [Note: this value is very comparable to the longer duration (1941-1995) average of 45” per year reported from Hatchville, MA (Walter et al., 2004)]. Recharge of the watershed groundwater in the Sagamore and Monomoy aquifer by precipitation has been previously estimated to be 27” per year (Walter et al., 2004).

There are no surface water tributaries to each pond (save the Lovers Lake outlet to Stillwater Pond). Due to the sandy soils of the watershed and the absence of large areas of impervious cover (land use is low density residential and forest), the amount of direct surface water runoff and stormwater flow was assumed to be negligible compared to other sources. Le Blanc et al. (1986) estimated that only one percent of annual precipitation becomes surface runoff due to the permeable nature of Cape Cod soils. Therefore, the surface watershed boundary is of limited importance to the condition of Lovers Lake and Stillwater Pond. Surface impacts for purposes of hydrologic estimation and for consistency with nutrient budget calculations were restricted to the 300 ft buffer zone area immediately around the pond.

Some provision for return of the water through septic system discharge was estimated using the number of residences within 300 ft upgradient of the ponds, an estimated occupancy rate of 2.3 and assumption of per capita daily use of 55 gallons/day, previously been used in the Pleasant Bay TMDL study (MEP, 2003) and for Chatham (Stearns and Wheler, 1999).

Direct precipitation entering the pond was estimated by multiplying average annual precipitation by the surface area for each pond. Evaporation was estimated to be somewhat less than two thirds of the average yearly precipitation (or 28” per year) (Higgins and Colonell, 1971). Outflow values measured in 2000-2002 were used to estimate the amount of water leaving each pond via the surface water route. Groundwater flux was not measured directly but was determined as the difference between estimated inputs and outputs, with the assumption that the pond is in steady state, which may not be true for any individual year due to fluctuations in pond elevation and storage volume.

4.2.1 Lovers Lake hydrologic budget

Lovers Lake has a relatively simple hydrologic budget. The hydrologic inputs include direct precipitation, groundwater in-seepage, and septic system inputs. The outputs include surface water outflow, groundwater out-seepage, and evaporation. A summary of the estimated hydrologic budget is provided in Table 4–1. Calculations used for derivation of the hydrologic budget are provided in Appendix F.

Review of the hydrologic inputs in Table 4-1 indicates that groundwater recharge is the most important factor (55%), followed by direct precipitation (39%), riparian runoff (5%), with minor contribution from septic recharge (1%). The total inputs equate to a combined flow of 0.49 cfs. The outputs are dominated by surface water outflow (78%) and evaporation (22%). As noted during the stream flow study the outflow represents about 93% of the expected contributions for watershed and atmospheric inputs. Since the outputs exceed the inputs, no groundwater out-seepage is assumed although a minimal amount may be exiting through the former outlet into Frost Fish Creek. The total outputs equate to a combined flow of 0.56 cfs.

The overall agreement between the estimated inputs and outputs (15.4 vs. 17.7 x 10^6 ft^3) is reasonably good (i.e., 87% agreement) and the absolute difference between the values is quantitatively minor (<0.07 cfs). One source of uncertainty is the natural seasonal and year-to-year variation in the surface elevation of Lovers Lake associated with shifts in the local groundwater table. As described by the Herring Warden, it is not unusual for the surface elevation of Lovers Lake to fluctuate about 10 inches during the course of a year or between years (St. Pierre, 2007). This volume (i.e., 10” x surface area or 1.37 x 10^6 ft^3) can represent about 8-9% of the total flow to the lake. Another source of uncertainty is the amount of recharge of the precipitation falling directly on waterbodies intermediate in the watershed (e.g., Mary’s Pond and Barclay Pond). Finally, the cranberry bog at the southern end of the watershed may be importing some water from outside of the watershed (e.g., from

Emery Pond) after application on the bog. With these potential natural and man-made sources of variability in mind, the hydrologic budget of Lovers Lake was still deemed sufficiently balanced to use for other loading analyses (e.g., phosphorus budget) for support of evaluation of potential restoration methods.

4.2.2 Stillwater Pond hydrologic budget

Stillwater Pond represents a more complex hydrologic budget. The hydrologic inputs include surface water inflow from Lovers Lake, direct precipitation, groundwater in-seepage, and septic system inputs. In the case of Stillwater Pond, it is necessary to reduce the amount of expected groundwater in-seepage to account for the amount removed for drinking water (see below). The outputs include surface water outflow, groundwater out-seepage, and evaporation. A summary of the estimated hydrologic budget is provided in Table 4–2. Calculations used for derivation of the hydrologic budget are provided in Appendix F.

Review of the hydrologic inputs in Table 4-2 indicates that surface water tributary is the most important factor (60%), followed by groundwater in-seepage (25%), direct precipitation (13%), riparian runoff (2%), with negligible contribution from septic recharge (<1%). The estimate of groundwater in-seepage was based on the amount of groundwater recharge expected from the Stillwater Pond watershed minus the amount of drinking water production at Well #5. Well #5 was considered to potentially draw on the aquifer contributing to Stillwater Pond since it is screened at about 69-79 feet bgs (Stillwater Pond is up to 51 ft deep) and it is located in an unconfined aquifer. In contrast, Well #8 was considered to be too deep to have an influence (also has a confining layer). This is a conservative assumption that could be refined further, as needed. Another source of uncertainty is the amount of recharge of the precipitation falling directly on Pinkwink Pond, sited in an intermediate location in the watershed (Figure 2-3).

The hydrologic outputs include surface water outflow (48%) and evaporation (8%). The inflows exceed the outflow, so groundwater out-seepage was assumed to balance the budget at 23.2 10^6 ft^3 (0.74 cfs) and is an important outflow component (44%). One source of uncertainty is the natural seasonal and year-to-year variation in the surface elevation of Stillwater Pond associated with shifts in the local groundwater table. As described by the Herring Warden, it is not unusual for the surface elevation of Stillwater Pond to fluctuate about 6 inches during the course of a year or between years (St. Pierre, 2007). This volume (i.e., 6” x surface area or 0.41 x 10^6 ft^3) can represent about 2% of the total flow to the lake. The hydrologic budget of Stillwater Pond was used for other loading analyses (e.g., phosphorus budget) for support of evaluation of potential restoration methods

4.3 Flushing rates and hydraulic residence time

One of the hydrologic characteristics that can influence the impact that nutrients have on the ecology of a pond is the flushing rate. The flushing rate is the number of times in a given year that the entire water column would be replaced by hydrologic inputs. The inverse of the flushing rate is the hydraulic residence time (HRT) or detention time which is the average period that water remains in the pond. Based on the hydrologic budget developed above and using the pond volumes calculated in Section 2.0, the flushing rate was calculated for Lovers Lake and Stillwater Pond (Appendix F).

For Lovers Lake, using the annual hydrologic inflow inputs, the average flushing rate is 0.63 exchanges per year with a corresponding HRT of 582 days. If the outflow is used, the average flushing rate is slightly quicker 0.72 exchanges per year with an associated HRT of 506 days. This means, on average, that water stays in Lovers Lake from 1.4 to 1.6 years. For Stillwater Pond, the amount of inflow is larger and the volume is less, resulting in a quicker average flushing rate of 1.32 exchanges per year with a corresponding HRT of 277 days.

It should be recognized that flushing rate and HRT are not seasonally constant and will depend on seasonal variation, precipitation history, the amount of water withdrawal (by pumping) in the watershed and the surface water manipulation for the herring run (see Section 4.4). During periods of stable thermal stratification, water

inputs to the epilimnion generally will not mix with the hypolimnion, thereby decreasing the effective volume of pond water being exchanged and therefore increasing the effective flushing rate.

Flushing rates are useful for evaluating if nutrients that reach the pond have sufficient residence in the water column to sponsor biological growth. This may not be the case for some rapidly flushed waterbodies, such as river impoundments. For both Lovers Lake and Stillwater Pond, the HRT is long enough that nutrients would be expected to be in the pond long enough to express their full potential impact (generally through internal recycling). Furthermore, the basic conceptual model of lake behavior predicts that it will take 3 to 5 times the flushing rate to dilute or remove persistent pollutants to a point below detection. This means that any impact on the pond could last for 5 to 10 years; activities of the last decade may be manifested today, and today's activities may still be impacting lake condition in the next decade.

4.4 Impact of the herring run

The hydrologic impact of maintaining the herring run was evaluated. As noted earlier, the Herring Warden manipulates the pond surface elevations by installation of flashboards in the late winter to store water and opens them in the early spring (St. Pierre, 2007). The flashboards are reinstalled around the Fourth of July to maintain pond levels during the summer and then removed again around Labor Day. This has the potential for changing the surface elevation of Stillwater Pond by up to 9" and for Lovers Lake by up to 18" (see Appendix B), although it appears the observed ranges are 6" and 10" respectively. Thus, the ponds have four stages (2 seasonal free-flowing periods and 2 periods of storage or impoundment), as briefly described below:

- **Stage 1 Early Fall – Early Winter** – free-flowing (juvenile alewife leave ponds) condition during period of moderate precipitation and slowly increasing groundwater tables. Ponds are fully mixing and entire two pond system is well flushed;
- **Stage 2. Early Winter – Early Spring** – storage of water during period of high precipitation and elevated groundwater tables. Ponds fully mixing but warming;
- **Stage 3. Early Spring – Mid-Summer** – free flowing conditions (adult alewife enter, spawn and leave), groundwater tables peak and begin to decline. Ponds stratify over this period; and
- **Stage 4. Mid-Summer – Early Fall** – storage of water during period of high evapotranspiration, groundwater tables are declining; recharge of groundwater maximized. Ponds well-stratified over this period; but eventually turnover and the system returns to Stage 1.

The flushing rate will be slowed during periods of storage and facilitated during free-flowing periods. The overall pattern of flushing/storage associated with maintenance of the herring run will tend to improve water quality during the early part of the summer (**Stage 3**) and decrease it during late summer (**Stage 4**). This is because the flow through the system is greatest in **Stage 3** and the artificially increased hydraulic head will increase or prolong outflow. This would result in a slightly greater siphoning off of the epilimnion and the vernal spring bloom that is developing then. The closure of the ponds for **Stage 4** tends to exacerbate the ponds' eutrophic conditions. A combination of increased evapotranspiration, reduced groundwater recharge, and possible higher watershed groundwater pumping, will tend to slow the through-flow. As the water stagnates in the full stratified ponds, the increased water temperature and turbidity would provide excellent conditions for outbreaks of BGA nuisance algal blooms. The removal of flashboards in early fall will tend at first to flush only the epilmnia of both ponds since ponds are still stratified. With autumnal turnover (first Lovers Lake, then Stillwater Pond) the system would eventually return to the **Stage 1** condition.

Table 4-1. Lovers Lake hydrologic budget

Input Source	Water (Million ft^3/yr)	% of Total water
Groundwater in-seepage	8.46	55
Direct Precipitation	6.06	39
Riparian Zone Runoff	0.76	5
Septic Discharge	0.13	1
Total	15.41	100
Output Source		
Surface Water Outflow	13.9	78
Evaporation	3.83	22
Groundwater Out-seepage	0	0
Total	17.7	100

Table 4-2. Stillwater Pond hydrologic budget

Input Source	Water (Million ft^3/yr)	% of Total water
Surface Water Tributary	13.9	60
Groundwater in-seepage	5.82	25
Direct Precipitation	3.01	13
Riparian Zone Runoff	0.41	2
Septic Discharge	0.07	<1
Total	23.2	100
Output Source		
Surface Water Outflow	11	48
Evaporation	1.9	8
Groundwater Out-seepage	10.3	44
Total	23.2	100

5.0 Oxygen demand and phosphorus budget

The field surveys conducted in 2007 (Section 3.1) and the historic data presented in Section 2.3 consistently show a pattern of seasonal hypolimnetic anoxia following stratification in the two ponds. Two important processes associated with this pattern is the progressive loss of oxygen (and fish and benthic habitat) in the lower waters, as well as the increasing amount of phosphorus being released from the sediments over the length of anoxic periods. For purposes of evaluating potential restoration techniques for Lovers Lake and Stillwater Pond (i.e., aeration, nutrient inactivation), both of this phenomena are described in detail and further quantified below.

5.1 Hypolimnetic oxygen demand

The hypolimnetic oxygen demand was based on the DO depth profile data collected this year, which appears to be representative of past profiles. The DO content of a pond for a particular date was determined using the depth-specific DO measurement for a sampling date multiplying it by the volume in the respective strata and then summed to produce a pond total DO (as kg O_2). The differences between DO concentrations for each date on which data were collected were then divided by the number of days between sampling events to estimate an oxygen demand rate (e.g., measured as $mgO_2/m^2/day$). ENSR considered two measures of oxygen demand: (1) the loss of total oxygen from the entire pond and (2) the loss of oxygen from the hypolimnion.

ENSR separated the pond into epilimnion and hypolimnion layers based on the observed pattern of temperature and DO. For Stillwater Pond, a depth of 6 meters provides a good approximation of this division between the two layers in the pond, since there was an extremely stable thermocline over the 2007 season. However, for Lovers Lake, the thermocline tends to decline with season. The cause of this variation (groundwater influx, internal seiches, etc.) is not known but it makes the hypolimnion volume increasingly small over the season. On the other hand, the depth of the anoxia did not stay confined to the hypolimnion but was also in metalimnion and lower epilimnetic waters. For purposes of this calculation, the volume in Lovers Lake below 6 m was used for the calculation as being representative of the anoxic zone. In addition, the bathymetry of Lovers Lake shows that it can be divided into two basins, separated by a shallower sill. For purposes of this calculation, an oxygen demand was calculated for each of the basins and the total summed.

Data from days when the DO concentration in the hypolimnion was <1 mg/L were not used for calculating oxygen demand rates as DO loss slows considerably at levels less than 1.0 mg/L. Use of data from these periods will underestimate the actual DO demand. This method requires that the oxygen concentration in a given depth layer be well above zero on the two dates for which the difference is calculated. Data were then averaged across dates and converted to an oxygen loss by multiplication by the volume of each depth layer.

To provide a full evaluation of the data, it is necessary to have as a starting point, the fully mixed and oxygenated water column shortly after vernal turnover. Even though the first sampling was early in the season (5/3/07), both ponds were already stratified and exhibited non-saturated oxygen levels in the hypolimnion. Accordingly, ENSR arbitrarily selected April 15th as a reasonable estimate of when vernal turnover should be occurring and assumed a water temperature of 7°C and a 100% saturated DO content of 12.14 mg/L on that date. The first estimate of oxygen loss was calculated by subtracting the 5/3/07 DO value from the assumed 12.14 mg/L on April 15th. Subsequent oxygen demand was calculated from comparison of observed data from the field surveys.

5.1.1 Lovers Lake

Lovers Lakes has two distinct deep basins separated by a shallow sill (Figure 2-1a).These two basins were sampled for dissolved oxygen, and the results combined to estimate oxygen loss for this pond. The amount of DO and the dynamics of its change over the season in these two basins are shown in Table 5-1 for the North Basin and Table 5-2 for the South Basin. Using the number of days between sampling dates and the amount of area of the basin allows calculation of the rate of oxygen loss (expressed in mg O_2/m^2/day) for the entire basin. Both Table 5-1b and 5-2b present similar types of calculations but only consider the oxygen content within the bottom waters, adjusted for the surface area associated with the hypolimnion, to estimate the rate of hypolimnetic oxygen loss (also expressed as mg O_2/m^2/day).

Looking first at the north Basin (CPLL-SW-01), it can be seen that oxygen is lost rapidly from the pond in late spring and early summer (Figure 5-1). This loss of oxygen is presumably due to a combination of the rapid heating of the epilimnion (i.e., DO at saturation is inversely related to temperature) and the influence of the sediment oxygen demand. This trend starts to slow in June (actually the pond has an increase in oxygen on 6/5/07) with lesser rates of oxygen loss in July and then starts to slowly increase in late summer and fall as the epilimnion expands downward. While this pattern is mirrored by the oxygen depletion rate expressed on an areal basis, the benthic oxygen demand is hard to isolate from this pattern.

Focusing just on the waters located below 6 m (Table 5-1b), provides a clearer picture. It can be seen that after an initial very rapid decrease (which may be an artifact of the assumed starting temperature), there is a fairly constant rate of loss ranging from 193 to 243 mg O_2/m^2/day over four consecutive dates (i.e., linear portion of Figure 5-1). By late June the rate of loss begins to slow as the hypolimnion becomes anoxic and no further DO decrease is possible. Using the period when oxygen was measurable, the maximum hypolimnetic oxygen demand rate for the North Basin averaged 219mg O_2/m^2/day.

These observed rates are likely to underestimate actual demand since the measured demand declines as the oxygen concentration decreases. Applying the aeration industry empirical “rule of thumb” of doubling the estimate of necessary oxygen for bottom aeration based on actual data, a predicted range of approximately 386 to 486 mg O_2/m^2/day is likely.

For comparison purposes, lakes with an oxygen demand >550 mg/m^2/day often experience hypolimnetic anoxia, and lakes with an oxygen demand >1000 usually experience severe anoxia. These values support the judgment that Lovers Lake has anoxic conditions in early spring but the fluctuations of the thermocline lead to some ventilation of the bottom waters during mid-summer.

The southern basin (CPLL-SW-02) shows a somewhat similar seasonal pattern for a loss of oxygen early in the year (Table 5-2a). However, the hypolimnetic oxygen reduction at this station has a very erratic pattern. This station is located near the depth of the seasonal thermocline which fluctuates considerably in this lake. Therefore, there is a periodic intrusion of oxygen into these waters (and mixing of these waters). This is also the mechanisms by which there is a transfer of released phosphorus (see Section 5.2). This information will be considered further for possible restoration options, particularly for aeration as discussed in Section 7.5.

5.1.2 Stillwater Pond

Stillwater Pond has a single central basin (Figure 2-1b) which exhibits a dramatic decrease in DO in late spring (Table 5-3a; Figure 5-2) which then slows as all available oxygen in the bottom waters is consumed. During the months of May and June, Stillwater Pond is losing hypolimnetic DO at the rate of about 920 O_2/m^2/day; with a range of 742– 1185 O_2/m^2/day (Table 5-3b). Doubling this estimate suggests that the maximal oxygen demand to be countered is between 1482 and 2370 mg/m^2/day.

As noted above, lakes with an oxygen demand >1000 usually experience severe anoxia, which is the case for Stillwater. Lakes with serious anoxia and internal recycling problems studied by ENSR in recent years have

had oxygen demands of 1200 to 4500 mg/m^2/day. For example, Hamblin Pond (Barnstable, MA) oxygen demand was estimated at 1720 mg/m^2/day, while Long Pond (Brewster, Harwich, MA) ranged from 1162 and 1628 mg/m^2/day. Stillwater Pond is in a similar category of having a strong hypolimnetic oxygen demand. This information will be considered further in evaluation of possible restoration options (e.g., aeration option discussed in Section 7.5).

5.2 Phosphorus budget and internal recycling

The phosphorus budget for a kettlehole pond is an approximate estimate of the amount of phosphorus entering a waterbody from surface tributaries, groundwater in-seepage, atmospheric inputs, wildlife and non-point and direct discharges. This is balanced against the amount of phosphorus that is leaving the waterbody by outlet flow, groundwater out-seepage, biological uptake (and removal), and storage (sedimentation). Phosphorus budgets were estimated for both Lovers Lake and Stillwater Pond based on the 2007 field survey results, watershed land use characteristics, number of residences within 300 ft of the shoreline, estimated waterfowl numbers, assumed atmospheric areal contributions, etc. The phosphorus budgets were then used to provide input parameters to simple lake models to see how well these input/output estimates predicted the observed phosphorus concentrations. In cases, where the fit was only approximate, further consideration of the input/outputs were evaluated, adjustment made and the models re-run to produce a better fit to the surface water concentrations. One of the key factors is the estimate of the functional contribution of internal recycling to the two pond systems, which is considered in detail in Section 5.2.2.

For easier tracking of phosphorus contributions from various watershed sources, a spreadsheet-based export coefficient model (SHED) was used (CT DEP and ENSR, 2004). The SHED methodology, developed by Dr. Kenneth Wagner (ENSR Corporation) for use in southern New England, allows the user to select yield coefficients and attenuation factors from a range appropriate to this area. Areal land use estimates were generated using the MA GIS database and imported into the model. Attenuation values and yield coefficients are based on those applied in the Long Island Sound Study, the compilation by Reckhow et al. (1980), and work by Frink and Norvell at the Connecticut Agricultural Station over many years (Norvell et al, 1979; Frink and Norvell, 1984). Generally, a range of export values is provided and the median value is used (in most situations) at the start, unless site-specific data indicate that another value within the expected range is appropriate. The export coefficient can be changed to calibrate the model based on site-specific data, within the known range for the land use. The generated load to the lake loads was processed through a series of empirical models (described below) and provides estimates of in-lake phosphorus concentrations and the associated effects on algal productivity and water clarity. This model is most effective when calibrated with water quality data for the target system. Loading was summed for each input to the pond including area of groundwater contribution and bordering areas that drain directly to the lake without entering a tributary.

Predictions of lake phosphorus dynamics and trophic indicators were based on the LAKEMOD spreadsheet (CT DEP and ENSR, 2004) which is a compilation of empirical lake input-output models (Bachman 1980, Kirchner-Dillon 1975, Vollenwieder 1968, Vollenweider 1975, Reckhow 1977, Larsen-Mercier 1976, and Jones-Bachmann 1976). These empirical models generate estimates of the load necessary to achieve observed in-lake conditions, based on system features such as pond morphometry (surface area, volume) and detention time. They are based on relationships derived from many other lakes.

There are many assumptions that go into loading predictions, including the accuracy and treatment of data, choice of models, selection of export coefficients, and assignment of attenuation factors. Furthermore, loading does not occur at a constant rate and can vary substantially among seasons and years. As a consequence, the uncertainty of such estimates can be quite large and no single number should be relied upon too heavily. Rather than rely on any one equation, the mean response and range of predictions is used. As such, they may not apply accurately to any one pond, but provide an approximation of current loading and a reasonable estimate of the direction and magnitude of changes that might be expected if loading is altered.

The models require concentrations of influent and effluent. For Lovers Lake, which has no true influent, we used the average surface concentration at the southern basin (CPLL-SW-02) as the surrogate value, while the northern basin (CPLL-SW-01) served as the outflow. This latter station also served as the input influent concentration for Stillwater Pond while the central station closest to the outlet served as the effluent value.

5.2.1 Phosphorus input assumptions

For both Lovers Lake and Stillwater Pond, a similar approach was taken for estimating phosphorus inputs arising from groundwater in-seepage, septic systems, waterfowl, and atmospheric inputs. These methods are described briefly below.

The amount of phosphorus entering the lake via groundwater in-seepage was estimated using the SHED spreadsheet model, which assigns land use classifications and uses area-weighted land use specific phosphorus yield coefficients to provide an estimate of phosphorus contribution. Land use classifications were based on the MA GIS files as described in Section 2.2.2. Surface runoff and baseflow (i.e., groundwater) land use P yield coefficients are provided in Appendix F. Due to the nature of the watershed and lack of tributaries, the surface runoff component for most of the watershed was assumed to be to zero so that the groundwater component is the significant contribution. The exception to this was land within 300 ft of the pond. Using an assumed recharge value of 27”/year (Walter et al., 2004) and the watershed area, the amount of groundwater in-seepage was estimated (see Section 4.0). An attenuation factor of 90% was used to estimate the amount of phosphorus delivered to the pond, based on the expected retention of phosphorus by soils through which the groundwater flows.

For estimation of the potential contribution of septic systems to the phosphorus budget, ENSR identified the number of upgradient houses within 300 ft of the pond (Figure 2-3; Google® Earth views) and used estimates of occupancy and water use (75% year-round, 25% seasonal, 2.3 occupants, and 55 gallons per capita). The 300 ft horizontal buffer was selected based on the general empirical consensus that phosphorus in groundwater outside of this zone is likely to be adsorbed or attenuated with passage through the soil from this distance. This rationale is the basis for the CCC minimal performance standard discouraging siting of septic systems with effluent discharge within 300 ft of freshwater ponds and is consistent with the Needs Assessment Report (NAR) for the Chatham CWMP Study (Stearns and Wheler, 1999; CCC 2003).

For purposes of evaluating potential watershed management options, a maximum “buildout” scenario was constructed. For this exercise, it was assumed that all of the developed lots, as well as all of the buildable lots in the watershed, were potentially contributing to groundwater going toward the ponds. Determination of the status and location of buildable lots was developed by the Town of Chatham and provided to ENSR.

Waterfowl phosphorus loading was estimated using the standard approach of estimating the number of “bird-years” spent at the pond (the average number of birds present at all times) and multiplying by an average P load per bird. Based on casual observations and size of the pond, we conservatively estimated about 20 resident waterfowl for Lovers Lake and 10 for Stillwater Pond. Resident Canada geese are present in both locations, along with mallard duck, mute swans and other waterfowl. This total may be an underestimate due to the seasonal presence of alewife in the ponds which would attract more piscivores such as black-crowned night heron, great blue heron, or cormorants. At the same time, the good abundance of local ponds and coastal waters may reduce the average amount of time that waterfowl would be found in any pond environment. More careful measurement of this input could be conducted by volunteers to ascertain how many birds are resident over longer periods of time, but this simple estimate is appropriate for this analysis.

For estimates of the contribution of atmospheric contribution, an average concentration of 14 µg/L of phosphorus in rainwater was used along with the average yearly precipitation of 43”/year and the area of the pond. Finally no permitted discharge is located in either of the ponds and therefore this value is set at zero for both waterbodies.

5.2.2 Internal recycling estimates

The current and historic pattern of significant seasonal anoxia and elevated concentrations of phosphorus in the bottom waters of both Lovers Lake and Stillwater Pond indicate that internal recycling (i.e., the release of bound-phosphorus from the sediments under low redox conditions) is likely to be an important component of the phosphorus budgets of both ponds. However, it is not intuitively clear how much of the phosphorus released to the hypolimnion will actually be transferred to the epilimnion, where light availability is good and where most phytoplankton growth would occur. This transfer can occur as diffusion through the metalimnion due to sharp chemical gradients of phosphorus concentration or through the physical mixing of water masses (e.g., entrainment of hypolimnetic water by turbulent mixing along the thermocline).

If the phosphorus is transferred during the middle-late summer, it can provide the nutritional basis for fall phytoplankton blooms; if transferred in late fall, it may have very little effect on algal growth due to the decreasing light levels and deeper mixing. Eventually, the return of DO to bottom waters during the fall turnover period will lead to an oxidative re-binding of phosphorus by iron again; with subsequent precipitation out of the water column back to the sediments. Therefore, it is a combination of the amount of phosphorus release and the timing of internal mixing that will determine the extent to which internal recycling drives the trophic state of a pond.

To evaluate the percentage of internal phosphorus available to sponsor biological growth, ENSR estimated the total amount of phosphorus accumulating in the hypolimnion over the stratified season. ENSR also estimated the amount of internal recycled P necessary to balance the surface water concentrations measured during 2007 sampling in lake models. Comparison between these two estimates will provide an approximation of how much of the released phosphorus is getting “entrained” (i.e., vertically mixed up) into the epilimnion.

5.2.2.1 Stillwater Pond internal recycling

In a departure from the usual order of discussion of the ponds, we considered internal recycling in Stillwater Pond first, since this pond has the simpler thermal structure. As shown in Figure 5-3, the phosphorus concentration in the hypolimnion of Stillwater Pond exhibits a nearly linear increase between the first and last samples, spanning 112 days, over the course of the period when oxygen is rapidly declining.

The seasonal course of phosphorus accumulation in both the epilimnion and hypolimnion in Stillwater Pond is displayed in Table 5-4. The mass in kilograms (kg) of phosphorus in each layer was calculated as the product of the phosphorus concentration times the volume of the water layer. These amounts are also expressed as a loading function normalized by the benthic area associated with each layer (as mg P /m^2). By comparing the change (either – or +) in the mass of phosphorus over the days between samplings and normalizing for surface area, the phosphorus release rate is calculated (as mg P/m^2/day). The average release rate based on the cumulative increase over the entire summer period of record was also calculated.

Examination of Table 5-4 indicates that the hypolimnion of Stillwater Pond accumulated phosphorus with an overall increase of 75.8 kg over the period between May 3 and August 29; with a large proportion present as dissolved inorganic phosphorus (Table 3-3). These values translate into benthic release rates ranging from 5.8 to 30 mg P/m^2/day; with an average of 18.1 mg P/m^2/day. It should also be noted that further phosphorus accumulation likely occurred well into the fall period due to the late turnover of Stillwater Pond, but that we have no water quality data during that period to confirm that.

In comparison, there is very little change in the epilimnetic total phosphorus which ranges between 9 to 23.57 kg, with no particular seasonal trend other than a low TP value in June which is probably related to some amount of washout or water release due to several days of preceding rainfall (see precipitation records in Appendix F). Regeneration of phosphorus from the epilimnion sediments is negligible (<0.1 mg P/m^2/day). Looking at the total (combined epilimnetic and hypolimnetic) phosphorus load provides a whole lake release rate of 6.08 mg P/m^2/day; the vast majority of which is due to hypolimnion release.

Despite this large hypolimnetic P reservoir, it appears that only a portion of this nutrient loading is making it into the epilimnion during a time period when it could sponsor algal growth. The extremely stable thermocline does not begin to seriously erode until well into November (Figure 3-4b), thus reducing the chance for phosphorus in the hypolimnion to enter the upper waters until a period when temperature and light levels are declining and mixing depth is deepening. However, it should be noted that the lower epilimnion/metalimnion of Stillwater Pond became anoxic (Figures 3-4b; 3-5b) and may be a source of phosphorus as well. Additional evidence for partial internal mixing is seen in the moderate amounts of dissolved inorganic phosphorus (Table 3-3) present in the upper waters.

The potential for vertical transport of phosphorus may be predicted through calculation of the Osgood Index (Osgood, 1988). The Osgood Index is a useful empirical estimate of the probability that deep mixing events will occur in a lake during summer stratification that brings P from the metalimnion and upper hypolimnion to surface waters (Cooke et al., 1993). The dimensionless index is the ratio of the mean depth (as m) to the square root of the surface area (as km^2). The Osgood Index for Stillwater Pond equals 24.0.

Observations indicate that lakes that have indices < 8 often have summer surface water TP concentrations that exceeded the concentration predicted from external loading and include polymictic or weakly stratified ponds (Osgood, 1988; 2007). These are ponds in which phosphorus released from bottom waters is more easily transferred to upper waters where light availability and algal populations are present. On the other hand, ponds with indices > 12 are considered strongly stratified dimictic waterbodies with reduced probability for vertical transport of phosphorus via deep mixing events, particularly if the pond is more sheltered from wind action due to surrounding landscape and/or vegetation (Ecologic, 2003; Osgood, 2007). Stillwater Pond would be considered a situation where vertical transport is likely to be minimal.

Based on these factors, we initially assumed that from 10-20% of the hypolimnetic TP load gets into the upper waters. For an estimate of total TP release, we extrapolated the stratified period to mid-November, based on the date of final turnover (late November). Using the average hypolimnetic phosphorus release of 18.1 mg P/m^2/day X 190 days (May 3 – November 15) X 3.747 ha = 128.6 kg; yielding estimates of 12.9 to 25.7 kg TP entering the upper water. Inclusion of this estimate of internal recycling led to a slight underestimate of in-lake phosphorus concentration in the lake models. Therefore, we refined this estimate to 27 kg/yr in the final Stillwater Pond phosphorus budget.

5.2.2.2 Lovers Lake internal recycling

Lovers Lake has a less emphatic pattern of phosphorus accumulation in the hypolimnion even in the deeper North Basin (Figure 5-4). There is not a significant build-up of phosphorus mass in the bottom waters in either the North or South Basin (Tables 5-5 and 5-6). This lack of phosphorus accumulation does not mean that benthic release is not occurring, since phosphorus may be entrained into the epilimnion or released by sediments above the thermocline. Entrainment is particularly likely during late summer and early fall due to the slow encroachment of the epilimnion on anoxic bottom waters (Figures 3-1a, b and 3-2a, b).The shape of the thermocline is much more gradual than in Stillwater Pond and the reduced density gradient would pose less of an obstacle for vertical mixing. It is possible that the most active depth of groundwater influx is near the metalimnion and it could be destabilizing the thermal structure. Comparison of the Osgood Index for Lovers Lake (11.8) indicates that its bathymetry should be somewhat conducive to vertical transport as well.

Another piece of evidence is the increasing concentrations of total and dissolved organic phosphorus in the upper water column during late summer during a period when there is reduced hydrologic (groundwater in-seepage) inputs and no outlet flow. Other than for the low June values (which appear to reflect some degree of washout), there is a slight increase in the phosphorus mass through August. The bottom sediments of Lovers Lake are enriched in phosphorus at concentrations above Stillwater Pond, so relatively similar rates of phosphorus release can be assumed. What appears to be the case for Lovers Lake is that the phosphorus is much more effectively transferred to the upper waters and does not accumulate at depth.

To estimate the amount of internal loading, we matched the amount of loading necessary to achieve the observed epilimnetic phosphorus concentration after subtraction of estimated inputs from other sources. Based on the modeling used for comparison with in-lake concentrations, an amount of 22 TP kg was estimated for the phosphorus release due to sediments in Lovers Lake.

5.2.3 Phosphorus budgets

The summary of phosphorus inputs and outputs for Lovers Lake and Stillwater Pond were estimated using a combination of site-specific water quality data, calculated watershed loadings, and modeling. These budgets were also the basis for estimates of potential improvement of water quality following restoration by various techniques.

5.2.3.1 Lovers Lake phosphorus budget

The total phosphorus load to Lovers Lake initially estimated from the average of several empirical models was 56 kg/yr. Differences among estimates from various empirical models can sometimes provide insights into lake function. The range of values for the five empirical models is 39-70 kg/yr. Some of the differences in estimates are derived mainly from variation in how the phosphorus retention coefficient (portion retained in the lake) is calculated. The Vollenweider retention coefficient value is roughly twice that of the Larsen-Mercier and Kirchner-Dillon retention coefficients. The Jones-Bachmann and Reckhow models use an implicit retention coefficient calculation based on hydraulic features of the lake (i.e., flushing rate and depth), while the others apply a retention coefficient based on measured phosphorus values. It is entirely possible that the year to year variation in phosphorus retention by Lovers Lake spans the range represented in these models.

The total phosphorus load predicted from the SHED model without internal loading was 17 kg/yr, suggesting that a contribution of phosphorus from internal recycling of approximately 39 kg/yr is possible. If a sediment release rate of this magnitude is used and re-input into the SHED model, the predicted TP concentration is 56 ug/L, which overestimates the surface water concentration (mean and median = 38 ug/L). If we adjust the internal recycling contribution for a phosphorus budget that meets the mean concentration; a value of 22 kg/yr is determined. The resulting phosphorus budget for Lovers Lake is provided in Table 5-7.

The overall budget for Lovers Lake is estimated at 42.5 kg / yr. This is apportioned between inputs and outputs as indicated. The largest input for the lake is the internal recycling component, providing about 43% of the phosphorus inputs. Considering that this internal load is added almost entirely during the summer season, it is clearly the most important source. The surface water runoff from shoreline properties, waterfowl, and atmospheric inputs provide an additional 40%, while groundwater sources (septic and background) are 27%.

Outputs include the outlet to Stillwater Pond (estimated at 35%) and storage (remaining 65%). Storage refers to phosphorus retained by the pond, typically as phosphorus stored in organic bottom sediments. Some amount of phosphorus may also exit the pond bottom as out-seepage. The phosphorus concentration of out-seepage has not been measured in the two ponds. However, it would be likely that P concentration in this component would be low since it passes through the pond bottom where a combination of uptake by the biofilm (bacteria and algal component) in the top layer of the sediment as well as passage through iron-rich sediments would make it unlikely that large amounts of phosphorus would travel downgradient. Due to this we conservatively assumed that all phosphorus not leaving as surface flow is retained in the pond within the sediment layer. A sizeable portion of the phosphorus inputs are being stored within the pond and are reflected by the very high phosphorus concentrations observed there (Table 3-5).

Chlorophyll and water clarity (as SDT) were predicted using the adjusted phosphorus load and predicted in-lake phosphorus concentrations from the empirical models. Predicted chlorophyll values ranged from 14 to 19 ug/L with an average of 16.9 ug/L and a predicted peak value of 56 ug/L. Observed chlorophyll values during the 2001-2006 PALS summer monitoring averaged 25.3 ug/L; with a peak observance of 68 ug/L. Water

clarity measured by SDT was predicted to average 1.4 m; while the PALS average observed water clarity in Lovers Lake was 1.1 m.

5.2.3.2 Stillwater Pond phosphorus budget

The total phosphorus load to Stillwater Pond initially estimated from the average of several empirical models was 53 kg/yr. Differences among estimates from various empirical models can sometimes provide insights into lake function. The range of values for the five empirical models was 46-56 kg/yr. The year to year variation in phosphorus retention by Stillwater Pond probably spans the range represented in these models.

The total phosphorus load predicted from the SHED model without internal loading was 21 kg/yr, suggesting a contribution of phosphorus from internal recycling of approximately 27 kg/yr is possible. This is slightly more than 20% of the full summer accumulation of TP in the hypolimnion (see Section 5.2.2.1). If a sediment release rate of this magnitude is used and re-input into the SHED model, the predicted TP concentration is 40 ug/L, representative of surface water concentration (mean = 40 and median = 35 ug/L). The resulting phosphorus budget for Stillwater Pond is provided in Table 5-8.

The overall budget for Stillwater Pond is estimated at 48.5 kg / yr. This is apportioned between inputs and outputs as indicated. The largest input for the lake is the internal recycling component, providing about 55% of the phosphorus inputs. The next largest contribution is the inlet stream (i.e., outlet of Lovers Lake) at about 31% of the budget. The surface water runoff from shoreline properties, waterfowl, and atmospheric inputs provide an additional 9%, while groundwater sources (both septic and background loading) are 5%.

Outputs include the outlet to Ryder's Cove (estimated at 26%) and storage (remaining 74%). As before, we conservatively assumed that all phosphorus not leaving as surface flow is retained in the pond within the sediment layer. A large amount of the phosphorus inputs are being stored within the pond and this is reflected by the very high phosphorus concentrations observed there (Table 3-5).

Chlorophyll and water clarity (as SDT) were predicted using the adjusted phosphorus load and predicted in-lake phosphorus concentrations from the empirical models. Predicted chlorophyll values averaged 17.9 ug/L; with a predicted peak value of 59 ug/L. Observed chlorophyll values during the 2001-2006 PALS summers monitoring averaged 22 ug/L; with a peak observance of 56 ug/L. Water clarity measured by SDT was predicted to average 1.4 m; while the PALS average observed water clarity in Lovers Lake was 1.6 m. During summer 2007 the SDT in Stillwater Pond averaged 1.8 m, with a median value of 1.6 m.

5.2.4 Nitrogen to phosphorus ratios

Phosphorus is typically the limiting nutrient (i.e., nutrient in shortest supply) in fresh water systems and generally dictates algal productivity, but this is not always the case. The amount of nitrogen to phosphorus ratio ("N:P ratio"), calculated as the atomic ratios of (TN / TP) X 2.21, indicates the relative availability of chemical resources critical to the primary producers. The N:P ratio has potential water quality implications for the lake and its phytoplankton community. Examination of the empirical relationship between N:P ratios suggest that at values lower than 15:1 (atomic ratio), the supply of nitrogen may limit phytoplankton growth (Smith, 1983; Hecky and Kilham, 1988; Fisher et al. 1995). Values greater than 50:1 are indicative of phosphorus deficient lakes, while those lakes whose ratios fall between these limits (i.e., > 15:1 and < 50:1) may show variable patterns of limitation (Smith, 1983).

With regard to Lovers Lake, the TN:TP ratio in the epilimnion at the northern basin ranged from 7 to 206 with a mean of 69:1; while that at the southern basin was 18 to 93 with a mean of 41:1 (Table 3-2). At first glance, these results seem to confirm that phosphorus will be limiting. However, the TN fraction in Lovers Lake is dominated by TKN, a form of nitrogen less likely to be available for uptake by phytoplankton. It can also be seen that the N:P ratios tend to decline from early to late summer. [Note: the June 5, 2007 sample appears

almost as an outlier, but there is not sufficient rationale to remove this datum; the high ammonia may reflect runoff of fertilizer].

Further, calculation of the more easily assimilated dissolved inorganic nitrogen (DIN) to dissolved inorganic phosphorus (DIP) ratio averaged 8:1 at the northern basin and was 14:1 at the southern basin. These ratios strongly suggest that the abundance of readily available phosphorus relative to nitrogen will preferentially select for nitrogen-fixing cyanobacteria in the pond, particularly later in the season.

Similar results are seen in the surface stations in Stillwater Pond (Tables 3-3) with TN:TP ratios that ranged from 12 to 123 with a mean of 59:1 in the central basin (CPSP-SW-01) and from 17 to 205 with a mean of 78:1 at the other station (CPSP-SW-02). However, the DIN:DIP ratio at the two stations averaged 8:1 and 25:1, respectively. These results suggest, particularly in the period of July – August, that BGA species, which also thrive during periods of low light availability, will be highly favored.

5.2.5 Impact of herring run

One of the major uncertainties of the phosphorus budgets described above is the potential effect of the alewife fishery on the ecology of Lovers Lake and Stillwater Pond. Zooplanktivorous fishes, such as alewife, can sometimes have profound impacts on lake water quality, largely through their influence on reducing the biomass and size structure of zooplankton communities, but also through their potential for transport, storage, and recycling of large quantities of nutrients (Brooks and Dodson, 1965; Carpenter et al., 1987; Vanni and Layne, 1997). High densities of zooplanktivorous fishes can potentially exacerbate the symptoms of eutrophication by extirpating populations of large bodied zooplankton, such as *Daphnia* spp. which may through grazing activities otherwise limit phytoplankton biomass to levels below that established by phosphorus limitation (Carpenter et al, 1995). This impact on freshwater systems is particularly well-documented in the case of alewife and is a cause for concern for resource managers considering removing dams that would allow reintroduction of herring runs into formerly isolated freshwater ponds (Post, 2006).

Independent of their grazing activities on zooplankton, alewife also have the potential for affecting nutrient dynamics in the two freshwater systems as a result of their spawning cycle. The three mechanisms by which this could happen include: (1) nutrient inputs by spawning adult mortality and egg production; (2) direct excretion of nutrients by spawning adults; and (3) the export of nutrients by young-of-the-year (YOY) alewife as they emigrate out of the ponds in the fall. Additional export of nutrients could also occur by harvest of adult alewife by birds taking the fish from the two ponds, but it appears that most bird feeding on alewife occurs at low tide at the Ryder's Cove entrance of the outlet stream fishway structure (St. Pierre, 2007).

As noted in Section 2.4.1, there is little quantitative information on the transient adult herring populations and YOY in the two ponds, such that the potential impact on the nutrient budgets is still speculative. However, it should be noted that the transparency (SDT depth) of Stillwater Pond is much less than that of Lovers Lake in late spring - early summer, with an average SDT of 2.5 m and no measurements over 3 m. During this period, which coincides with the period of greatest zooplankton feeding (termed the "clearwater phase"), Lovers Lake averages 5.0 m with some observations reaching 6.9 m. One possible explanation is that zooplankton grazing in Lovers Lake is more effective than in Stillwater Pond, possibly due to the lesser numbers of alewife reaching this more interior lake. Further work would be needed to substantiate this hypothesis, but a few zooplankton samples during early summer could quickly determine this.

One potential management option (biomanipulation) often contemplated for lakes with overabundant alewife populations is the stocking of predators to reduce the alewife population with the hopes of increasing zooplankton numbers and average size. It is very doubtful that this method would be instituted in the two ponds due to the relative scarcity and social significance of herring runs on Cape Cod and the current decline in regional herring numbers.

Table 5-1a. Water Column Oxygen Totals in Lovers Lake - North Basin

Date	Hypolimnetic Dissolved Oxygen (kg)	Upper Hypolimnetic Surface Area (ha)	Hypolimnetic Dissolved Oxygen (kg/ha)	Change in Hypolimnetic Oxygen (kg/ha)	Days	Rate of Hypolimnetic Oxygen Depletion ($mg/m^2/day$)
Deep Spot, North Basin-CPLL-SW-01						
4/15/2007	5913.65	9.07	651.93			
5/3/2007	4912.96	9.07	541.61	-110.32	18	-612.87
5/9/2007	4651.65	9.07	512.80	-28.81	6	-480.12
5/23/2007	3877.55	9.07	427.47	-85.34	14	-609.55
6/5/2007	3890.39	9.07	428.88	1.41	12	11.79
6/18/2007	3700.83	9.07	407.98	-20.90	13	-160.75
7/2/2007	3358.11	9.07	370.20	-37.78	14	-269.87
7/16/2007	2912.68	9.07	321.10	-49.11	14	-350.75
8/1/2007	2997.82	9.07	330.48	9.39	15	62.57
8/29/2007	3582.40	9.07	394.93	64.44	28	230.16
9/10/2007	2833.11	9.07	312.33	-82.60	11	-750.93
9/25/2007	3127.23	9.07	344.75	32.42	15	216.16
10/11/2007	2705.66	9.07	298.28	-46.47	16	-290.46
10/22/2007	4302.94	9.07	474.36	176.09	11	1600.78

Table 5-1b. Hypolimnetic Oxygen Totals in Lovers Lake - North Basin

Date	Hypolimnetic Dissolved Oxygen (kg)	Upper Hypolimnetic Surface Area (ha)	Hypolimnetic Dissolved Oxygen (kg/ha)	Change in Hypolimnetic Oxygen (kg/ha)	Days	Rate of Hypolimnetic Oxygen Depletion ($mg/m^2/day$)
Deep Spot, North Basin-CPLL-SW-01						
4/15/2007	963.58	3.67	262.28			
5/3/2007	508.49	3.67	138.41	-123.87	18	-688.19
5/9/2007	459.99	3.67	125.21	-13.20	6	**-220.02**
5/23/2007	360.60	3.67	98.15	-27.05	14	**-193.25**
6/5/2007	253.36	3.67	68.96	-29.19	12	**-243.26**
6/18/2007	147.99	3.67	40.28	-28.68	13	**-220.62**
7/2/2007	51.42	3.67	14.00	-26.29	14	-187.75
7/16/2007	32.16	3.67	8.75	-5.24	14	-37.45
8/1/2007	1.65	3.67	0.45	-8.30	15	-55.37
8/29/2007	7.06	3.67	1.92	1.47	28	5.26
9/10/2007	15.98	3.67	4.35	2.43	11	22.07
9/25/2007	22.79	3.67	6.20	1.85	15	12.35
10/11/2007	33.99	3.67	9.25	3.05	16	19.05
10/22/2007	236.08	3.67	64.26	55.01	11	500.08

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DO Depletion\CPLL-SW01_DO_Depletion_12-16-07.xls

Table 5-2a. Water Column Oxygen Totals in Lovers Lake - South Basin

Date	Hypolimnetic Dissolved Oxygen (kg)	Upper Hypolimnetic Surface Area (ha)	Hypolimnetic Dissolved Oxygen (kg/ha)	Change in Hypolimnetic Oxygen (kg/ha)	Days	Rate of Hypolimnetic Oxygen Depletion ($mg/m^2/day$)
South Basin-CPLL-SW-02						
4/15/2007	2538.11	6.19	410.33			
5/3/2007	2183.56	6.19	353.01	-57.32	18	-318.44
5/9/2007	2088.81	6.19	337.69	-15.32	6	-255.30
5/23/2007	1818.63	6.19	294.01	-43.68	14	-311.99
6/5/2007	1728.84	6.19	279.50	-14.52	12	-120.97
6/18/2007	1747.62	6.19	282.53	3.04	13	23.36
7/2/2007	1617.38	6.19	261.48	-21.06	14	-150.40
7/16/2007	914.39	6.19	147.83	-113.65	14	-811.79
8/1/2007	1587.72	6.19	256.68	108.86	15	725.70
8/29/2007	1884.92	6.19	304.73	48.05	28	171.60
9/10/2007	1470.87	6.19	237.79	-66.94	11	-608.54
9/25/2007	1622.71	6.19	262.34	24.55	15	163.66
10/11/2007	1311.51	6.19	212.03	-50.31	16	-314.44
10/22/2007	1567.63	6.19	253.44	41.41	11	376.42

Table 5-2b. Hypolimnetic Oxygen Totals in Lovers Lake - South Basin

Date	Hypolimnetic Dissolved Oxygen (kg)	Upper Hypolimnetic Surface Area (ha)	Hypolimnetic Dissolved Oxygen (kg/ha)	Change in Hypolimnetic Oxygen (kg/ha)	Days	Rate of Hypolimnetic Oxygen Depletion ($mg/m^2/day$)
South Basin-CPLL-SW-02						
4/15/2007	48.81	0.40	121.23			
5/3/2007	10.86	0.40	26.96	-94.27	18	-523.72
5/9/2007	14.19	0.40	35.25	8.29	6	138.14
5/23/2007	6.11	0.40	15.18	-20.07	14	-143.37
6/5/2007	1.29	0.40	3.20	-11.98	12	-99.86
6/18/2007	11.50	0.40	28.56	25.36	13	195.11
7/2/2007	1.09	0.40	2.70	-25.86	14	-184.74
7/16/2007	0.16	0.40	0.40	-2.30	14	-16.41
8/1/2007	0.08	0.40	0.20	-0.20	15	-1.33
8/29/2007	0.72	0.40	1.80	1.60	28	5.71
9/10/2007	0.68	0.40	1.70	-0.10	11	-0.91
9/25/2007	0.32	0.40	0.80	-0.90	15	-5.99
10/11/2007	0.44	0.40	1.10	0.30	16	1.87
10/22/2007	2.25	0.00	5.59	4.49	11	40.85

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DO Depletion\CPLL-SW01_DO_Depletion_12-16-07.xls

Table 5-3a. Total Oxygen Content in Stillwater Pond

Date	Pond Total Dissolved Oxygen (kg)	Pond Surface Area (hectares)	Pond Total Dissolved Oxygen (kg/ha)	Change in Pond Dissolved Oxygen (kg/ha)	Days	Rate of Total Oxygen Change (mg/m2/day)
4/15/2007	6009.09	7.57	794.12			
5/3/2007	5215.97	7.57	689.30	-104.81	18.00	-582.30
5/9/2007	4925.52	7.57	650.92	-38.38	6.00	-639.72
5/23/2007	3655.25	7.57	483.05	-167.87	14.00	-1199.07
6/5/2007	3063.54	7.57	404.86	-78.20	12.00	-651.63
6/18/2007	2698.39	7.57	356.60	-48.26	13.00	-371.20
7/2/2007	2371.33	7.57	313.38	-43.22	14.00	-308.73
7/16/2007	2536.95	7.57	335.27	21.89	14.00	156.34
8/1/2007	2656.81	7.57	351.10	15.84	15.00	105.60
8/29/2007	2058.25	7.57	272.00	-79.10	28.00	-282.50
9/10/2007	2099.83	7.57	277.50	5.49	11.00	49.95
9/25/2007	2457.98	7.57	324.83	47.33	15.00	315.54
10/11/2007	2435.83	7.57	321.90	-2.93	16.00	-18.30
10/22/2007	2948.72	7.57	389.68	67.78	11.00	616.19
11/7/2007	3707.24	7.57	489.92	100.24	15.00	668.27

Table 5-3b. Hypolimnetic Oxygen Totals in Stillwater Pond

Date	Hypolimnetic Dissolved Oxygen (kg)	Upper Hypolimnetic Surface Area (hectares)	Hypolimnetic Dissolved Oxygen (kg/ha)	Change in Hypolimnetic Dissolved Oxygen (kg/ha)	Days	Rate of Hypolimnetic Oxygen Change (mg/m2/day)
4/15/2007	1801.36	3.75	480.74			
5/3/2007	1195.13	3.75	318.95	-161.79	18.00	**-898.83**
5/9/2007	928.72	3.75	247.86	-71.10	6.00	**-1184.99**
5/23/2007	479.23	3.75	127.90	-119.96	14.00	**-856.85**
6/5/2007	145.58	3.75	38.85	-89.04	12.00	**-742.03**
6/18/2007	17.19	3.75	4.59	-34.27	13.00	-263.58
7/2/2007	40.92	3.75	10.92	6.33	14.00	45.24
7/16/2007	39.35	3.75	10.50	-0.42	14.00	-2.99
8/1/2007	21.59	3.75	5.76	-4.74	15.00	-31.60
8/29/2007	5.90	3.75	1.57	-4.19	28.00	-14.95
9/10/2007	9.52	3.75	2.54	0.97	11.00	8.78
9/25/2007	14.10	3.75	3.76	1.22	15.00	8.16
10/11/2007	27.32	3.75	7.29	3.53	16.00	22.05
10/22/2007	25.40	3.75	6.78	-0.51	11.00	-4.67
11/7/2007	733.08	3.75	195.64	188.87	15.00	1259.10

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Table 5-4. Epilimnetic and Hypolimnetic TP in Stillwater Pond.

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Epilimnetic Total Phosphorus Load in Stillwater Pond

Date	Julian Date	Epilimnetic TP (kg)	Upper Epi SA (m^2)	Upper Epi SA (ha)	Epi TP (kg/ha)	Epi TP (mg/m^2)	Interval (days)	Change in Epi TP (kg)	Epi TP Release (mg/m2/day)
5/9/2007	129	12.13	74940.62	7.49	1.62	161.875	-	-	-
6/5/2007	156	9.01	74940.62	7.49	1.20	120.250	27.00	-3.12	-1.54
7/2/2007	183	23.57	74940.62	7.49	3.15	314.500	27.00	14.56	7.19
8/1/2007	213	11.78	74940.62	7.49	1.57	157.250	30.00	-11.78	-5.24
8/29/2007	241	12.82	74940.62	7.49	1.71	171.125	28.00	1.04	0.50
						Over summer:	**112.00**	**0.69**	**0.08**

Hypolimnetic Total Phosphorus Load in Stillwater Pond

Date	Julian Date	Hypolimnetic TP (kg)	Upper Hypo SA (m2)	Upper Hypo SA (ha)	HypoTP (kg/ha)	Hypo TP (mg/m2)	Interval (days)	Change in Hypo TP (kg)	Hypo TP Release (mg/m2/day)
5/9/2007	129	8.01	37470	3.75	2.14	213.769	-	-	-
6/5/2007	156	18.25	37470	3.75	4.87	487.080	27.00	10.24	10.12
7/2/2007	183	48.52	37470	3.75	12.95	1294.920	27.00	30.27	29.92
8/1/2007	213	55.05	37470	3.75	14.69	1469.160	30.00	6.53	5.81
8/29/2007	241	83.84	37470	3.75	22.37	2237.400	28.00	28.79	27.44
						Over summer:	**112.00**	**75.83**	**18.07**

Combined Total Phopshorus Load in Stillwater Pond

Date	Julian Date	Combined TP (kg)	Pond SA (m2)	Pond SA (ha)	Combined TP (kg/ha)	Combined TP (mg/m2)	Interval (days)	Change in Total TP (kg)	Total TP Release (mg/m2/day)
5/9/2007	129	20.14	112411	11.24	1.79	179.173	-	-	-
6/5/2007	156	27.26	112411	11.24	2.43	242.527	27.00	7.12	2.35
7/2/2007	183	72.09	112411	11.24	6.41	641.307	27.00	44.83	14.77
8/1/2007	213	66.83	112411	11.24	5.95	594.553	30.00	-5.26	-1.56
8/29/2007	241	96.66	112411	11.24	8.60	859.883	28.00	29.83	9.48
						Over summer:	**112.00**	**76.52**	**6.08**

Table 5-5. Epilimnetic and Hypolimnetic TP - Lovers Lake North Basin.

Epilimnetic Total Phosphorus Increase in Lovers Lake-North Basin

Date	Julian Date	Epi TP (kg)	Upper Epi SA (m2)	Upper Epi SA (ha)	Epi TP (kg/ha)	Epi TP (mg/m2)	Interval (days)	Change in Epi TP (kg)	Epi TP Release (mg/m2/day)
5/9/2007	129	15.49	90711.52	9.07	1.7081	170.81	-	-	-
6/5/2007	156	5.30	90711.52	9.07	0.58435	58.44	27.00	-10.19	-4.16
7/2/2007	183	22.83	90711.52	9.07	2.5172	251.72	27.00	17.53	7.16
8/1/2007	213	23.65	90711.52	9.07	2.6071	260.71	30.00	0.82	0.30
8/29/2007	241	10.60	90711.52	9.07	1.1687	116.87	28.00	-13.05	-5.14
						Over summer:	**112.00**	**-4.89**	**-0.48**

Hypolimnetic Total Phosphorus for Lovers Lake- North Basin

Date	Julian Date	Hypo TP (kg)	Upper Hypo SA (m2)	Upper HypoSA (ha)	Hypo TP (kg/ha)	Hypo TP(mg/m2)	Interval (days)	Change in Hypo TP (kg)	Hypo TP Release (mg/m2/day)
5/9/2007	129	3.89	36738	3.67	1.06	105.86	-	-	-
6/5/2007	156	2.30	36738	3.67	0.63	62.65	27.00	-1.59	-1.60
7/2/2007	183	8.49	36738	3.67	2.31	231.17	27.00	6.19	6.24
8/1/2007	213	4.29	36738	3.67	1.17	116.67	30.00	-4.21	-3.82
8/29/2007	241	6.27	36738	3.67	1.71	170.68	28.00	1.98	1.93
						Over summer:	**112.00**	**2.38**	**0.58**

Combined Total Phosphorus Load for Lovers Lake- North Basin

Date	Julian Date	Combined TP (kg)	Pond SA (m2)	Pond SA (ha)	Combined TP (kg/ha)	Combined TP (mg/m2)	Interval (days)	Change in Total TP (kg)	Total TP Release (mg/m2/day)
5/9/2007	129	19.38	127449.52	12.74	1.52	152.09	-	-	-
6/5/2007	156	7.60	127449.52	12.74	0.60	59.65	27.00	-11.78	-3.42
7/2/2007	183	31.33	127449.52	12.74	2.46	245.80	27.00	23.72	6.89
8/1/2007	213	27.94	127449.52	12.74	2.19	219.19	30.00	-3.39	-0.89
8/29/2007	241	16.87	127449.52	12.74	1.32	132.38	28.00	-11.06	-3.10
						Over summer:	**112.00**	**-2.51**	**-0.18**

Table 5-6. Epilimnetic and Hypolimnetic TP in Lovers Lake South Basin.

ENSR

Epilimnetic Total Phosphorus Increase in Lovers Lake-South Basin

Date	Julian Date	Epi TP (kg)	Upper Epi SA (m2)	Upper Epi SA (ha)	Epi TP (kg/ha)	Epi TP (mg/m2)	Interval (days)	Change in Epi TP (kg)	Epi TP Release (mg/m2/day)
5/9/2007	129	10.05	61854.97	6.19	1.62	162.44	-	-	-
6/5/2007	156	1.03	61854.97	6.19	0.17	16.58	27.00	-9.02	-5.40
7/2/2007	183	6.36	61854.97	6.19	1.03	102.77	27.00	5.33	3.19
8/1/2007	213	9.02	61854.97	6.19	1.46	145.86	30.00	2.67	1.44
8/29/2007	241	5.95	61854.97	6.19	0.96	96.14	28.00	-3.08	-1.78
						Over summer:	**112.00**	**-4.10**	**-0.59**

Hypolimnetic Total Phosphorus Increase in Lovers Lake-South Basin

Date	Julian Date	Hypo TP (kg)	Upper Hypo SA (m2)	Upper Hypo SA (ha)	Hypo TP (kg/ha)	Hypo TP (mg/m2)	Interval (days)	Change in Hypo TP (kg)	Hypo TP Release (mg/m2/day)
5/9/2007	129	0.18	4020.57	0.40	0.46	46.00	-	-	-
6/5/2007	156	0.08	4020.57	0.40	0.21	21.00	27.00	-0.10	-0.93
7/2/2007	183	0.33	4020.57	0.40	0.83	83.00	27.00	0.25	2.30
8/1/2007	213	0.33	4020.57	0.40	0.83	83.00	30.00	0.00	0.00
8/29/2007	241	0.33	4020.57	0.40	0.81	81.00	28.00	-0.01	-0.07
						Over summer:	**112.00**	**0.14**	**0.31**

Combined Total Phosphorus Load for Lovers Lake- South Basin

Date	Julian Date	Combined TP (kg)	Pond SA (m2)	Pond SA (ha)	Combined TP (kg/ha)	Combined TP (mg/m2)	Interval (days)	Change in Total TP (kg)	Total TP Release (mg/m2/day)
5/9/2007	129	10.23	65875.54	6.59	1.55	155.33	-	-	-
6/5/2007	156	1.11	65875.54	6.59	0.17	16.85	27.00	-9.12	-5.13
7/2/2007	183	6.69	65875.54	6.59	1.02	101.56	27.00	5.58	3.14
8/1/2007	213	9.36	65875.54	6.59	1.42	142.02	30.00	2.67	1.35
8/29/2007	241	6.27	65875.54	6.59	0.95	95.21	28.00	-3.08	-1.67
						Over summer:	**112.00**	**-0.60**	**-0.08**

Table 5-7. Lovers Lake Total Phosphorus Load (5/9/07 - 8/29/07).

Date	Layer	South Basin (SW02) TP (kg)	North Basin (SW01) TP (kg)	Sub-Total TP (kg)	Total Pond TP (kg)
5/9/2007	Epilimnion	10.05	15.49	25.54	
	Hypolimnion	0.18	3.89	4.07	29.62
6/5/2007	Epilimnion	1.03	5.30	6.33	
	Hypolimnion	0.08	2.30	2.39	8.71
7/2/2007	Epilimnion	6.36	22.83	29.19	
	Hypolimnion	0.33	8.49	8.83	38.02
8/1/2007	Epilimnion	9.02	23.65	32.67	
	Hypolimnion	0.33	4.29	4.62	37.29
8/29/2007	Epilimnion	5.95	10.60	16.55	
	Hypolimnion	0.33	6.27	6.60	23.14

Table 5-8. Lovers Lake phosphorous budget

Input Source	TP Load (kg/yr)	% of TP
Atmospheric	3.8	9
Internal Recycling	18.3	43
Waterfowl	4	9
Septic Systems	4.6	11
Watershed GW Load	0.3	1
Watershed Runoff Load	11.5	27
Total	42.5	100
Output Source		
Surface Water Outflow	15	35
Out-seepage (assumed)	0	0
Storage	27.5	65
Total	42.5	100

Table 5-9. Stillwater Pond phosphorous budget

Input Source	TP Load (kg/yr)	% of TP
Inlet (LL Outlet)	15	31
Atmospheric	1.9	4
Internal Recycling	27	55
Waterfowl	2	4
Septic Systems	2.6	5
Watershed GW Load	0.002	<.01
Watershed Runoff Load	0.4	1
Total	48.5	100
Output Source		
Surface Water Outflow	12.5	26
Out-seepage (assumed)	0	0
Storage	36	74
Total	48.5	100

Figure 5-1. Lovers Lake Hypolimnetic Oxygen Depletion

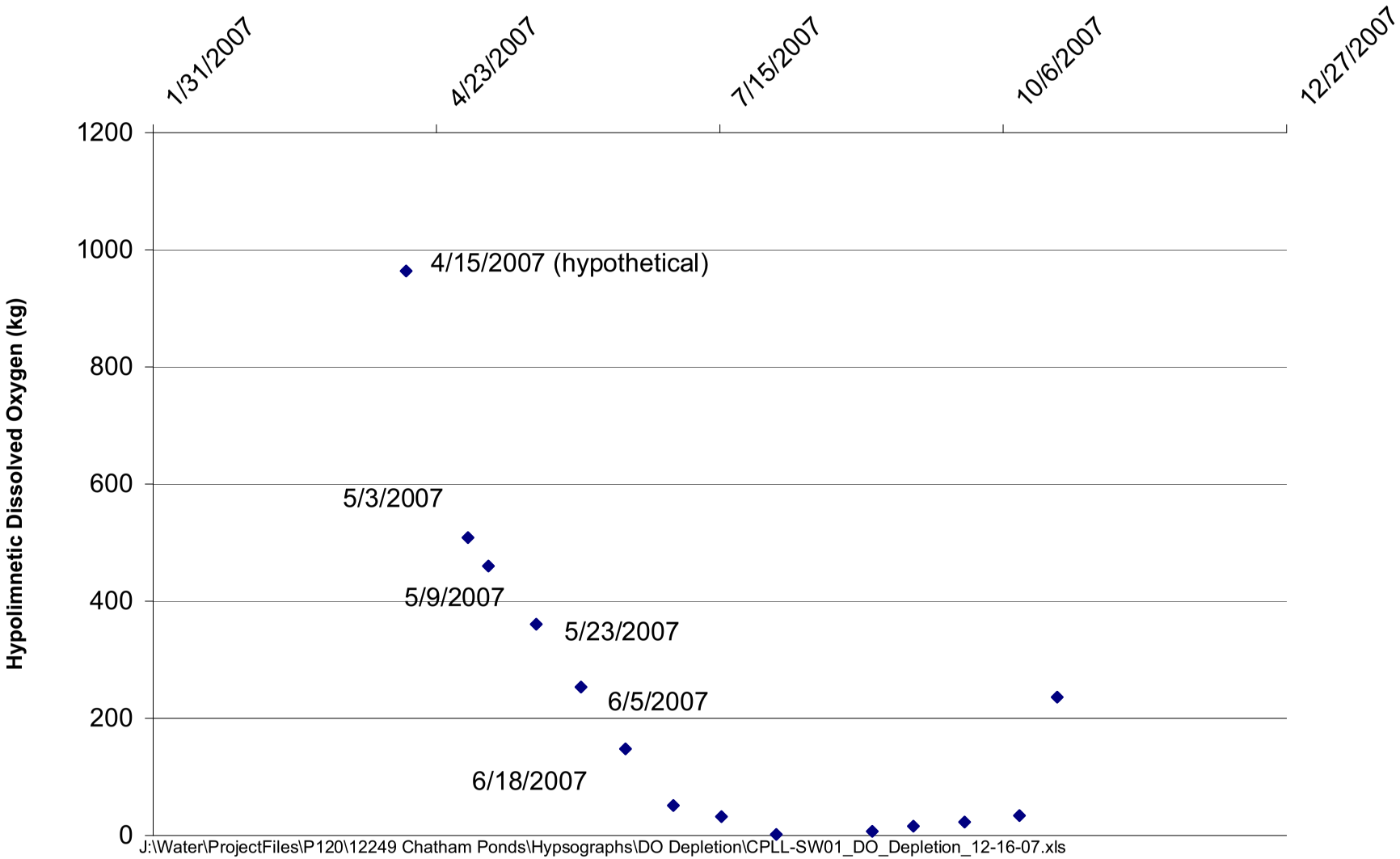


Figure 5-2. Stillwater Pond Hypolimnetic Oxygen Depletion

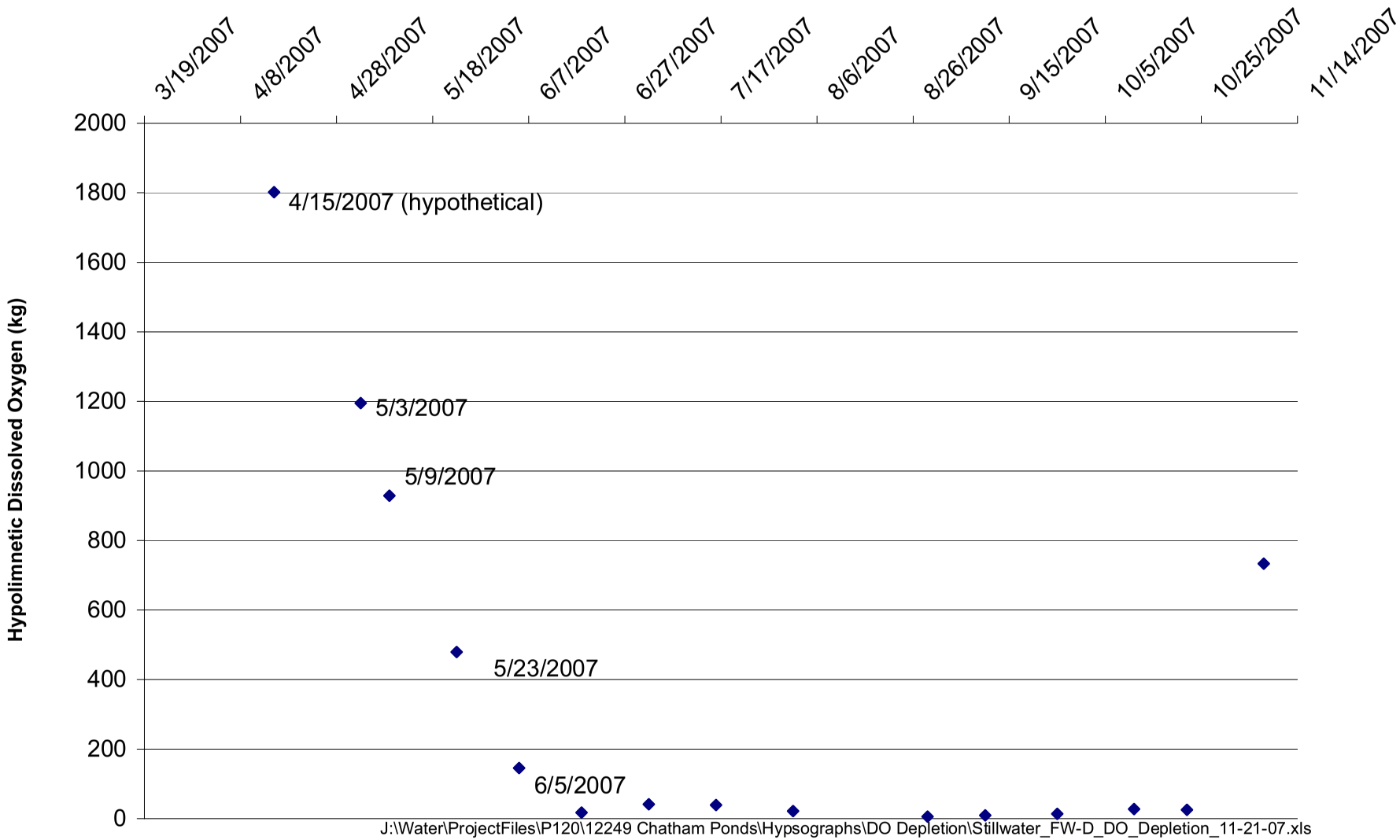


Figure 5-3. Stillwater Pond Central Basin - Hypolimnetic Phosphorus Increase

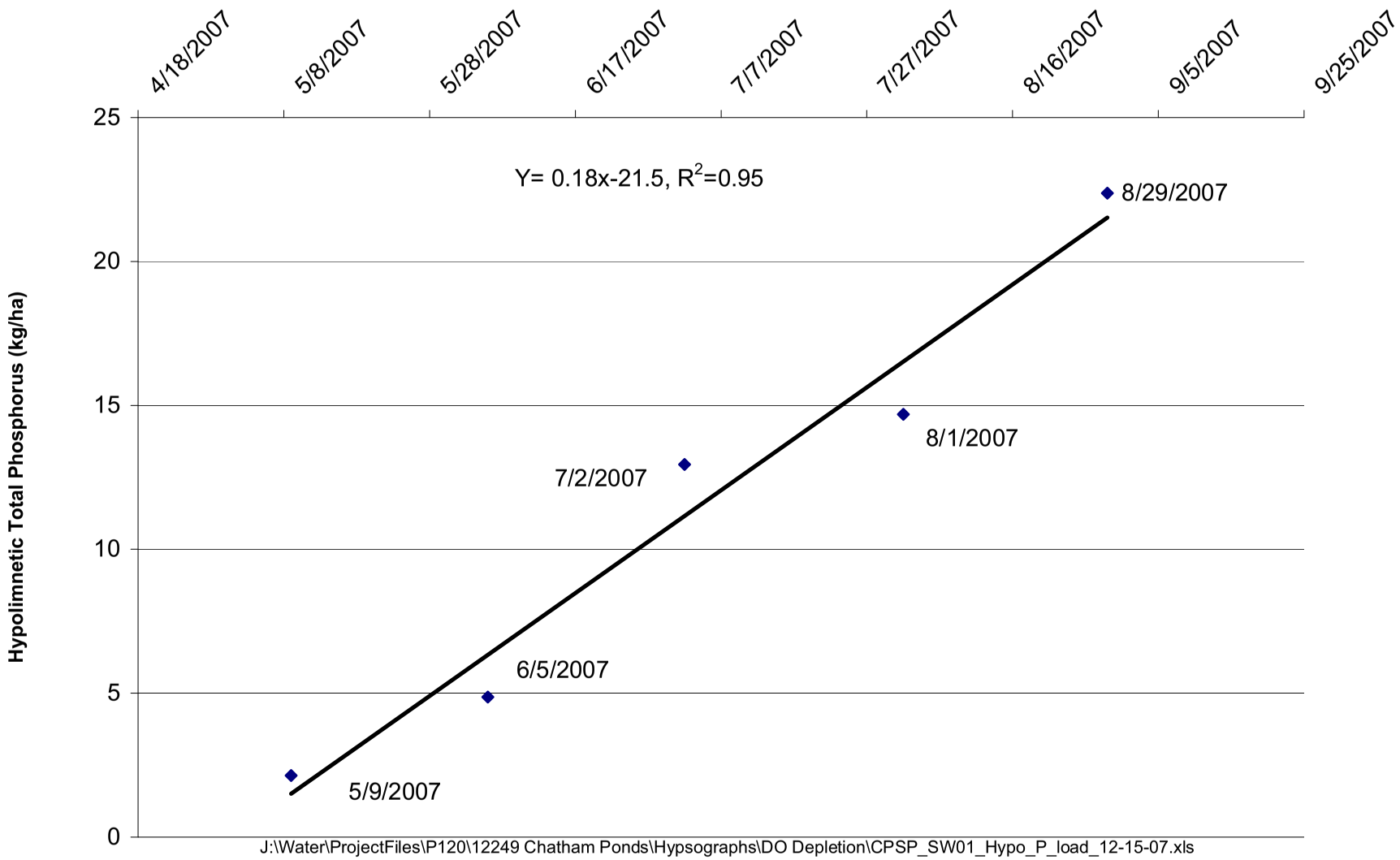
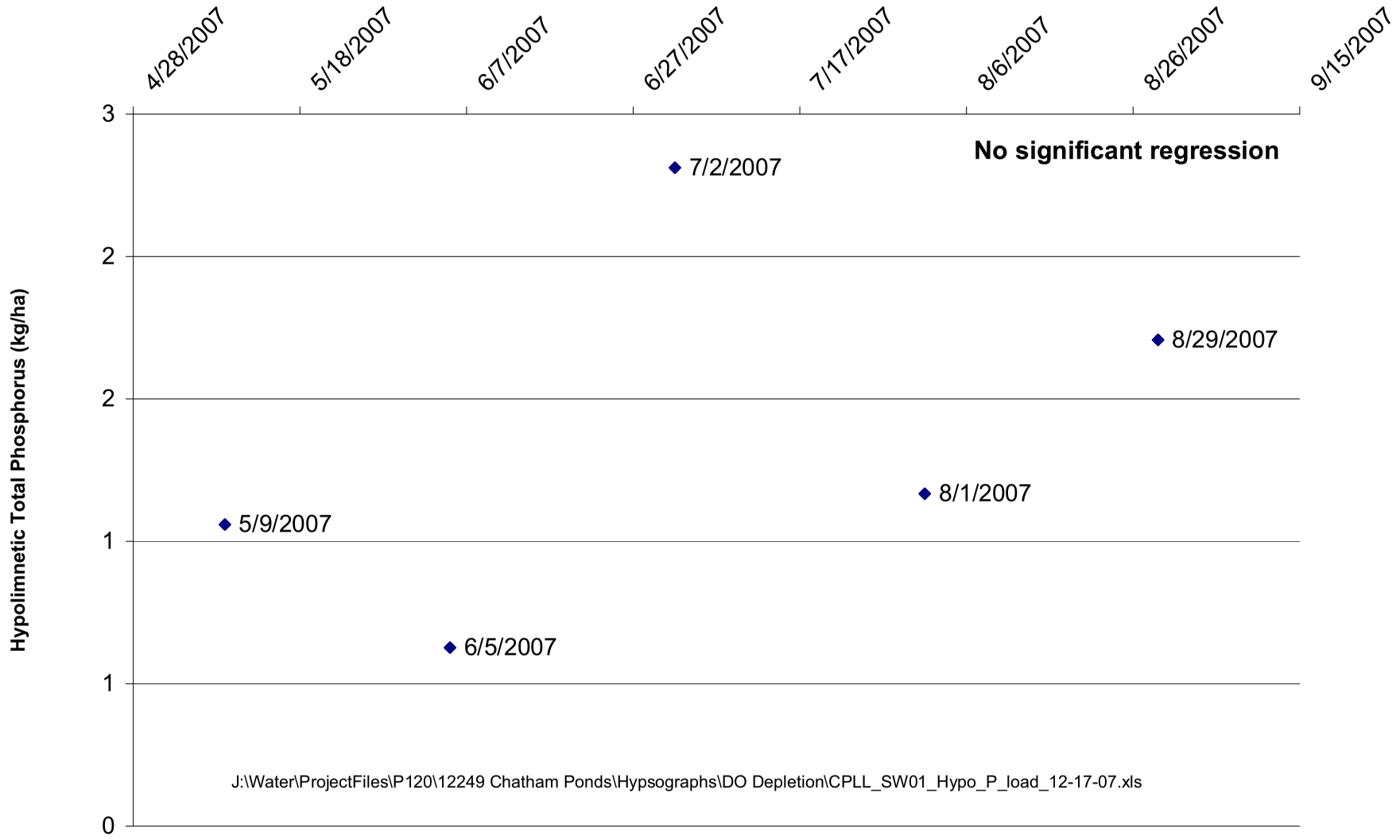


Figure 5-4. Lovers Lake Hypolimnetic Phosphorus Increase-North Basin



6.0 Summary of assessment phase

6.1 Summary of diagnostic findings

Lovers Lake (37.7 acres) and Stillwater Pond (18.7 acres) are two hydrologically connected kettlehole ponds located in Chatham, MA that outlet to coastal Ryder's Cove (Section 2.2.1). Lovers Lake (maximum depth = 11 m (36 ft); average depth = 4.6 m (15 ft)) has two deep basins located at ends of an approximate "L"-shaped configuration, while Stillwater Pond (maximum depth = 15.5 m (51 ft); average depth = 7.4 m (22 ft)) has a simple central deep basin. Water volume for Lovers Lake is about 695,000 m^3 and that for Stillwater pond is just slightly below 500,000 m^3.

Both ponds are characterized by small watersheds (Lovers Lake = 86 acres; Stillwater Pond = 128.3 acres). Land use in both watersheds is largely forested, low density residential, and open or protected land, with some cranberry production (Lovers Lake) and public drinking water wells (Stillwater Pond). There are approximately 21 upgradient residences and septic systems within 300 ft of Lovers Lake and 11 residences for Stillwater Pond (Section 2.2.2).

Both ponds are part of the Pleasant Bay ACEC and are classified as ORWs. Public use of both ponds includes swimming, fishing, and non-motorized boating. There is informal public access to Lovers Lake and undeveloped access to Stillwater Pond but there are no public swimming beaches or boat launches.

Both ponds support a warmwater fishery community and seasonal runs of anadromous alewife. The herring run is actively managed by water elevation manipulations through outlet structures and pipe conveyances maintained by the Chatham Herring Warden. Herring populations may be declining in these ponds, as elsewhere on the Cape. Suitable summer habitat for trout is very limited, as the surface waters are too warm and the bottom waters too low in oxygen (Section 2.4.1).

The ponds have diverse riparian shoreline vegetation which includes several protected or sensitive species. Emergent reeds, water lilies, and pickerelweed are reported. Submergent aquatic vegetation was not surveyed, but may be limited due to the sandy substrate, rapid depth dropoff, and low summer transparency of the lakes (Section 2.4.3).

Lovers Lake flows into Stillwater Pond which then flows into Ryder's Cover (marine environment); otherwise there are no surface tributaries to either pond (Section 4.2). Precipitation and groundwater in-seepage are the dominant sources of water, with a negligible amount of runoff from the very sandy watershed. It appears that some portion of the Stillwater Pond groundwater contribution is intercepted by pumping by Town Well #5 (Section 4.1.1). Most water leaves Lovers Lakes as surface overflow into Stillwater Pond. Water exits Stillwater Pond by a combination of outflow and groundwater out-seepage. Evaporation is a minor but significant exit route for water in summer. Total hydrologic through-flow was estimated for both ponds, suggesting an average annual detention time of 1.4 to 1.6 years for Lovers Lake and 1.3 years for Stillwater Pond; both ponds will flush more slowly in the summer (Section 4.3). Due to the management of water levels and flows to support the herring run, the two ponds have distinct periods of flow and storage (Section 4.4).

Inspection of the PALS monitoring database (2000-2006) (Section 2.3), pond assessments (CCC, 2003; EcoLogic, 2003)(Section 2.5), and additional investigation by ENSR and CDH&E in 2007 (Section 3.1) have documented consistent patterns of elevated nutrient conditions and poor transparency in summer and associated deep water anoxia with regeneration of phosphorus from bottom sediments in >20 ft of water. Binding of iron by sulfides is suspected of disrupting the natural iron-phosphorus binding cycle and allowing phosphorus to reach the upper waters in significant quantity.

It appears that phosphorus has accumulated in the deep organic sediments of both ponds over an extended time period, although the exact nature of the sources contributing to this nutrient reserve was not determined. It is possible that cranberry activities in the former bog formerly supplied by Lovers Lake may be a potential source. More likely, the natural features of both ponds (deep, groundwater-driven, slow flushing rate) are responsible for a net increase in sediment phosphorus each year. It may have simply taken many decades for the internal load to reach the threshold where it could supply sufficient phosphorus to cause the observed level of blooms.

Bottom sediments were collected and analyzed from both ponds. Most sediment samples were highly organic and contained large amounts of total phosphorus (Section 3.2). Analysis of the phosphorus fractions indicated that large amounts were contained in the iron-bound phosphorus fraction that would be susceptible to release under low redox conditions that occur each summer. Loosely-sorbed and iron-bound phosphorus represent the available phosphorus fraction within the sediment and range from 2.8 to 86.9 g/m^2 for Lovers Lake and from 5.3 to 71.7 g/m^2 for Stillwater Pond.

Examination of the conditions that promote phosphorus release included assessment of oxygen demand (Section 5.1). Average areal oxygen demand in Lovers Lake is estimated at a predicted range of approximately 386 to 486 mg O_2/m^2/day. This demand causes strong anoxia as soon as stratification sets in and bottom waters are denied further atmospheric oxygen inputs. Stillwater Pond loses hypolimnetic DO quickly over the season with a maximal oxygen demand between 1482 and 2370 mg/m^2/day.

Estimates of the levels of internal recycling were made on the basis of observations of the accumulation of hypolimnetic phosphorus and by modeling (Section 5.2). The hypolimnion of Stillwater Pond accumulated phosphorus with an overall increase of 75.8 kg over the period between May 3 and August 29; with a large proportion present as dissolved inorganic phosphorus (Table 3-3). These values translate into benthic release rates ranging from 5.8 to 30 mg P/m^2/day; with an average of 18.1 mg P/m^2/day. Redox reactions promoting the release of this phosphorus with only 10-20% reaching the epilimnion could still raise the phosphorus concentration sufficient to support the observed algal blooms in the pond.

Estimation of sediment phosphorus release from Lovers Lake sediments was not calculated from water quality data since little accumulation occurred in the hypolimnion. However, release from the sediments is assumed to have resulted in a transfer of phosphorus to upper waters via diffusion and vertical mixing. The contribution for internal loading was estimated through modeling (Section 5.2.2).

Phosphorus budgets were prepared for both lakes showing an estimated load of 42 kg/yr for Lovers Lake (Table 5-7) and 48 kg/yr for Stillwater Pond (Table 5-8) (Section 5.2.3). There are many assumptions in these budgets and further adjustments are possible (e.g., the runoff contribution may be lower and the ground water contribution might be higher), but it is apparent that the annual input from the watershed is not the dominant influence at this time. The potential influence of the herring run on the ponds' nutrient dynamics was noted but little or no data exist to evaluate this influence (Section 5.2.5). Clearly the internal load is the controlling factor in both ponds' phosphorus dynamics. This trend is unlikely to reverse itself without human intervention However, it should be kept in mind that the watershed is the ultimate source of the phosphorus and other pollutants and both in-lake and watershed management are needed.

6.2 Lovers Lake assessment

6.2.1 Current conditions

The current trophic state of Lovers Lake is eutrophic, based on the high levels of nutrients, early and pervasive anoxia in the hypolimnion, low summer SDT transparency, and evidence of internal recycling. The average phosphorus levels at the surface stations in summer 2007 (32-38 ug/L) are above the CCC criterion for impacted lakes, as well as most generally acceptable trophic classification of eutrophic (i.e., >25 ug/L) (Wetzel,

2001; CCC; 2003). These levels are consistent with the historic phosphorus data (Table 2-4). Although chlorophyll was not monitored in 2007, historic chlorophyll levels were elevated (>25 ug/L). In addition, based on photographs taken in 2005, a dense blue-green algal bloom occurred in Lovers Lake. The historic SDT record shows that transparency is limited to a less than a meter in summer observations, as is consistent with 2007 data (Table 3-2; Appendix A). The persistence of low SDT values into the fall, accompanied by observations of brownish-green or tea-colored water (Appendix D) suggests that phytoplankton blooms (possibly dinoflagellates or chrysophytes) are still occurring. These observations, taken together with the large sediment oxygen demand and seasonal hypoxia and elevated phosphorus in deep waters, clearly indicate that Lovers Lake is eutrophic.

6.2.2 Lovers Lake restoration objectives

Restoration objectives established earlier (Section 1.0) look to: reduce the amount of nutrients available for phytoplankton growth; improve the ecological health of Lovers Lake, including water clarity and dissolved oxygen levels; and enhance the pond's recreational and aesthetic qualities. As a means of establishing the amount of phosphorus reduction needed to achieve these restoration objectives, permissible and critical limits for phosphorus loading were estimated for Lovers Lake based upon an approach developed by Vollenweider (1975; 1978). The permissible load is the amount of phosphorus that could enter a system without obvious or continual detrimental effects (i.e., nuisance algal blooms should be rare). As values exceed the permissible load and get closer to the critical load, nuisance algal blooms often become a problem. Lakes exceeding the critical load usually experience serious productivity problems where algal blooms become common to continuous. Permissible and critical phosphorus loads were calculated for Lovers Lake at 26 kg/yr and 53 kg/yr, respectively. A summary of the various loads for Lovers Lake discussed in this section and their associated trophic indicators are provided in Table 6-1.

Under the hypothetical modeled critical loading, Lovers Lake in-lake TP concentrations are estimated at 46 ug/L; average chlorophyll at 21.5 ug/L with a maximum value of 71.5 ug/L; and average SDT at 1.2 m. The probability of algal bloom exceeding 10 ug/L chlorophyll in the summer months is 79.5%, while events exceeding 20 ug/L chlorophyll occur at a frequency of 46%. While the current state of Lovers Lake is below this state, with a projected phosphorus load of 42.5 kg/yr, Lovers Lake is already nearing this highly undesirable critical load. Comparison with the PALS data (Table 2-4) as well as the 2007 water quality data (Table 3-2) indicate that trophic conditions in Lovers Lake already approximate those expected under a critical load. The combination of modeled predictions and current measured data all consistently indicate that the nutrient loading and water quality of the Lovers Lake is unacceptable and needs to be improved. The phosphorus budget under future full "buildout" conditions (if and when the remaining buildable lots are developed in the watershed) do not look to be very different (38.5 kg vs. 38.2 kg) due to the low number (5) of additional buildable lots located mostly at distance from the pond (Table 2-3; Figure 2-3).

If possible, phosphorus should be reduced to levels below the permissible load or by 16.5 kg. If this 26 kg/yr load can be achieved, models predict an in-lake phosphorus concentration of 23 ug/L; average chlorophyll at 9 ug/L with a maximum value of 31 ug/L; and average SDT at 2.1 m. The probability of summer algal blooms exceeding 10 ug/L chlorophyll is reduced to 33%; that for events exceeding 20 ug/L chlorophyll reduced to 3%.

This level of phosphorus associated with the permissible load would be generally acceptable in many areas nationwide but would still be considered elevated for Cape Cod. A more ambitious restoration goal would be the CCC TP criterion for healthy ponds of 10 ug/L (CCC, 2003). To do so would require reduction to a loading of 11 kg/yr. If this is achieved, models predict average chlorophyll at 3 ug/L with a maximum value of 11 ug/L; and average SDT at 4.0 m. The probability of algal bloom exceeding 10 ug/L chlorophyll is reduced to 0.3%; that for events exceeding 20 ug/L chlorophyll reduced to >0.1%.

To achieve these restoration objectives (permissible, healthy levels), a significant amount of phosphorus reduction is necessary. For example, to get from current conditions to the permissible load, an overall

reduction of 38% of the current phosphorus load is required. However, it will be difficult, if not impossible, to significantly reduce atmospheric, waterfowl, or groundwater background loads, at least in the short term. This means that the amount of reduction that would be necessary in the remaining categories of internal recycling, septic system and riparian runoff is about 48%. To reach the CCC criterion, the amount of reduction necessary in the manageable categories is about 91%, an extremely ambition goal which may not be achievable with the restoration tools available.

Since Lovers Lake provides a good portion of Stillwater Pond's phosphorus, remedial action aimed at that internal load of the former should do much to restore desirable conditions in both ponds, and protective measures in the watershed will help slow down the accumulation of phosphorus and internal loading in the future. Further discussion of specific restoration efforts and the amount of phosphorus reduction is provided in Sections 7.0 and 8.0.

6.3 Stillwater Pond assessment

6.3.1 Current conditions

The current trophic state of Stillwater Pond is eutrophic, based on the high levels of nutrients, early and pervasive anoxia in the hypolimnion, low summer SDT transparency, and evidence of internal recycling. The average phosphorus levels at the surface stations in summer 2007 (40-43 ug/L) are above the CCC criterion for impacted lakes, as well as most generally acceptable trophic classification of eutrophic (i.e., >25 ug/L) (Wetzel, 2001; CCC, 2003). These levels show with some increase from the historic phosphorus data (Table 2-5; Appendix A). It is possible that the rerouting of water from Lovers Lake that used to outlet to Frost Fish Creek has increased the amount of phosphorus being delivered to the pond. Although chlorophyll was not monitored in 2007, historic chlorophyll levels were elevated (>25 ug/L). SDT transparency is limited to a less than a meter in late summer observations similar to previous monitoring years (Table 3-3; Appendix A). These observations, taken together with the large sediment oxygen demand and seasonal hypoxia and elevated phosphorus in deep waters, clearly indicate that Stillwater Pond is eutrophic.

6.3.2 Restoration objectives

The restoration objectives for Stillwater Pond are similar to those established for Lovers Lake: reduce the amount of nutrients available for phytoplankton growth; improve the ecological health of Stillwater Pond, including water clarity and dissolved oxygen levels; and enhance the pond's recreational and aesthetic qualities. As a means of establishing the amount of phosphorus reduction needed to achieve these restoration objectives, permissible and critical limits for phosphorus loading were estimated for Stillwater Pond. Permissible and critical phosphorus loads were calculated at 22 kg/yr and 44 kg/yr, respectively. A summary of the various loads for Stillwater Pond discussed in this section and their associated trophic indicators are provided in Table 6-2.

Under the critical loading, Stillwater Pond in-lake TP concentrations are estimated at 37 ug/L; average chlorophyll at 19 ug/L with a maximum value of 64 ug/L; and average SDT at 1.3 m. At a phosphorus load of 48 kg/yr, Stillwater Pond already exceeds the critical load. The phosphorus budget for Stillwater Pond under future full "buildout" conditions (if and when the remaining buildable lots are developed in the watershed) does not look to be very different (40 kg vs. 40.4 kg) due to the low number (3) of additional buildable lots located mostly at distance from the pond (Table 2-3; Figure 2-3). Comparison with the PALS data (Table 2-5) as well as the 2007 water quality data (Table 3-3) indicates that conditions in Stillwater Pond are heavily impaired, with severe impacts to water quality, ecological habitat, and recreational usage.

If possible, phosphorus should be reduced to levels below the permissible load or by 26 kg. If this 22 kg/yr load can be achieved, models predict an in-lake phosphorus concentration of 18 ug/L; average chlorophyll at 7 ug/L with a maximum value of 23 ug/L; and average SDT at 2.5 m. The probability of algal blooms exceeding 10

ug/L chlorophyll is reduced to 15%; and that for events exceeding 20 ug/L chlorophyll reduced to 5%. To have a TP loading that would result in an in-lake concentration approximating the CCC TP criterion of 10 ug/L would require reduction to a loading of 12 kg/yr. If this is achieved, models predict similar positive results to those predicted for Lovers Lake

To achieve these restoration objectives (permissible, healthy levels), a significant amount of phosphorus reduction is necessary. For example, to get from current conditions to the permissible load, an overall reduction of 54% is required. However, as noted earlier, management options can only really reduce loadings from internal recycling, septic system and watershed (riparian) runoff. This means the amount of reduction needed to reach the permissible loading is 90%. Under the current TP loading regime, it is not possible to reach the CCC criterion unless improvements are made to Lovers Lake.

On the other hand, if Lovers Lake is restored, benefits will also accrue to Stillwater Pond, as the inlet represents 31% of the phosphorus budget. For example, if Lovers Lake is brought to the permissible loading, the tributary inlet contribution is reduced by 6 kg; and the target reduction to get Stillwater Pond to its permissible loading is lowered to 67% effort.

Overall, the major source and sink for Stillwater Pond's phosphorus is the sediment. Therefore, while changes in other sources such as runoff and in-seepage may help decrease the phosphorus load to the pond, sediment recycling will continue to be the major contributor and the most significant factor controlling the condition of Stillwater Pond. Further discussion of specific restoration efforts and the amount of phosphorus reduction is provided in Sections 7.0 and 8.0.

Table 6 - 1. Lovers Lake Current Trophic Conditions and Potential Restoration Objectives.

Description	Total P Load (kg/yr)	Mean In-lake P (ug/L)	Mean In-lake chl a (ug/L)	Mean SDT (m)	Probability of bloom> 10 ug/L (%)
Observed Conditions (2007):	-	38	-	3	-
Current Modeled Conditions:	42	38	17	1.4	77
Modeled with Town Sewering:	40	36	16	1.5	74
Modeled Critical Load:	51	46	22	1.2	90
Modeled Permissible Load:	26	23	9	2.1	33
Modeled CCC Criteria:	11	10	3	4	0.3

Table 6 - 2. Stillwater Pond Current Trophic Conditions and Potential Restoration Objectives.

Description	Total P Load (kg/yr)	Mean In-lake P (ug/L)	Mean In-lake chl a (ug/L)	Mean SDT (m)	Probability of bloom> 10 ug/L (%)
Observed Conditions (2007):	-	40	-	1.8	-
Current Modeled Conditions:	48	40	18	1.4	82
Modeled with Town Sewering:	47	38	17	1.4	80
Current Critical Conditions:	45	37	16	1.5	74
Modeled Permissible Load:	22	18	7	2.5	14
Modeled CCC Criteria:	12	10	3	4	0.3

7.0 Potential lake treatment options

The purpose of the initial phase of the *Eutrophication Mitigation Plan* study of Lovers Lake and Stillwater Pond was to collect background watershed characteristics, conduct necessary water and sediment quality sampling, and seasonally monitor pond thermal structure. This data was used to develop and conduct associated analyses of the hydrologic and nutrient budgets to be able to evaluate four potentially applicable pond restoration methods (dredging, aeration, circulation, and nutrient inactivation) to reduce or eliminate the phosphorus recycling from the sediments. The 2007 data collection and analyses conducted and reported in Sections 3 – 4 and summarized in Section 6 form the basis for this diagnostic evaluation.

The diagnostic summaries show that both ponds are eutrophic with poor water quality due to enrichment by nutrients. Phosphorus levels are at excessive concentrations and nutrient ratios favor the development of undesirable blue-green algae These basins are slowly flushed due to the small watershed and dependency on groundwater discharge; with summer circulation being particularly poor due to increased evapotranspiration, the installation of flashboards at the outlets of both Ponds to store water, and the increased pumping of groundwater in the Stillwater Pond watershed. Due to very strong oxygen demand, the Ponds' bottom waters quickly become anoxic. Internal phosphorus recycling from the sediments forms an important but treatable portion of the phosphorus budget.

7.1 Eutrophication mitigation objectives

In terms of the restoration of desirable water quality for the users of the Ponds, the primary goal is to eliminate nuisance algae blooms, or at least to reduce their frequency and severity. Linked objectives include reducing the internal loading of phosphorus and improving the oxygen level in the hypolimnion of both Lovers Lake and Stillwater Pond. As a secondary goal, the watershed should be managed to minimize future pollutant inputs. The watershed is the ultimate source of contaminants in the pond, and while annual loading of phosphorus from the watershed does not currently appear to the primary driver, control of loading will protect the pond for future generations. Primary objectives under the watershed management goal would be best practical management of septic systems, preservation of open space, and riparian shoreline management. Summarized in outline form, the goals and objectives for Lovers Lake and Stillwater Pond are as follows:

Goal: Minimize the frequency and severity of nuisance algae blooms.

- **Objective:** Reduce internal loading until the permissible limit is not exceeded.
- **Objective:** Increase SDT depth to four feet to meet MA bathing criterion.
- **Objective:** Increase oxygen to the extent practical in conjunction with internal phosphorus load reduction.

Goal: Minimize future watershed inputs of contaminants to Lovers Lake and Stillwater Pond.

- **Objective:** Manage landscapes for minimized adverse impact (i.e., nutrients, bacteria) on the pond.
- **Objective:** Manage septic systems for minimized adverse impact (i.e., nutrients, bacteria) on the pond.
- **Objective:** Preserve open space within the contributory land area around the pond.

Methods for achieving these goals and objectives will be addressed in the subsequent sections.

7.2 Justification of candidate management options for controlling algal blooms

While a major purpose of the *Eutrophication Mitigation Plan* study of Lovers Lake and Stillwater Pond is to evaluate four potentially applicable pond restoration methods (dredging, aeration, circulation, and nutrient inactivation), there are other potential pond management options available to control in-lake populations of nuisance algal blooms. As a first step in the evaluation of the four management options it is useful to consider the alternative in-lake options that were not selected and why these are not appropriate for restoration of Lovers Lake and Stillwater Pond. These are provided in Table 7-1, taken from the *Eutrophication and Aquatic Plant Management in Massachusetts Final Generic Environmental Impact Review (FGEIR)* (EOEA, 2004), with a brief description of the mode of action, advantages and disadvantages of these various techniques. Watershed management for nutrient input reduction will be discussed separately in Section 7.6.

Physical controls not considered appropriate for Lovers and Stillwater Pond include: (1) dilution and flushing; (2) drawdown; (3) light-limiting dyes; (4) mechanical removal; (5) selective withdrawal; and (6) sonication. Dilution and flushing was not appropriate since there is not excess water in either of the ponds' watersheds to use to increase the flushing rate (actual it is likely that watershed pumping will increase In the future). Drawdown is not appropriate due to a lack of an effective outlet structure that will allow significant drawdown and is usually less feasible where groundwater is the major hydrologic input. Also, this method would increase groundwater recharge and might interfere with the operation of the public water wells. Light-limiting dyes are generally only used in small waterbodies where aesthetic considerations are the major concern (e.g., golf courses, reflecting pools), are not feasible for large waterbodies due to expenses and associated ecological effects (decreasing light availability). Mechanical withdrawal refers to the pumping and treatment of water generally for public water supplies which is not applicable to the two ponds. Selective withdrawal of anoxia bottom water might be considered for Lovers Lake (outlet into Frost Fish Creek) and Stillwater Pond (outlet to Ryder's Cove). However, in either case there is neither sufficient hydraulic head to facilitate this nor sufficient hydraulic input to replace the displaced water. There would also be the problem of the impact of the discharge of low-oxygen water (often accompanied by poor odor) on the receiving waterbodies. Sonication is generally reserved for application near the intake of drinking water supplies.

Chemical controls not considered appropriate for Lovers and Stillwater Pond include: (1) use of algaecides; (2) sediment oxidation; (3) settling agents, and (4) selective nutrient addition. Algaecides, as indicated by Table 7-1, come in many forms and most will provide short-term relief from phytoplankton blooms but do nothing to change the fundamental reasons (excess nutrients) for the algal blooms. Further, breakdown and decay of algal biomass in the poorly flushed ponds would lead to more organic oxygen demand in the water column (already a problem) and release and recycling of the nutrients to sponsor more growth. Sediment oxidants work to change the redox conditions in the sediments to help inactivate nutrients but would be considered an alternative to nutrient inactivation. For Lovers Lake and Stillwater Pond, the more conventional alum treatment of the sediments is simpler and more likely to work in the very low redox conditions found at the bottom. Settling agents are another form of alum-based nutrient inactivation. In this case, the alum material flocculates out phosphorus in the water column and binds it in the sediment layer. This method is useful for treating stormwater inputs or other flow-associated nutrients. However in the case of Lovers Lake and Stillwater Pond the nutrient issues are associated ultimately with the sediments and not the water column. Selective nutrient addition is rarely considered for eutrophic waterbodies as excess levels of nitrogen and phosphorus are already present. Further, addition of nitrogen would not be appropriate for these ponds given its potential impacts to the nitrogen-limited coastal waters.

Biological controls not considered appropriate for Lovers and Stillwater Pond include: (1) enhanced grazing; (2) bottom-feeding fish removal; (3) fungal/viral agents; and (4) other biological controls. Enhancement of grazing by biomanipulation is often unpredictable and requires repeated stockings. Stocking with predator fish to enhance a larger zooplankter size may be adverse to the herring that use the ponds as spawning and nursery grounds and which are considered a valuable regional resource. Bottom-feeding fish are not an issue in these ponds. Other suggested biological controls were considered too experimental and not as direct a method to deal with the underlying issues in these ponds.

Table 7-1 Options for control of algae (Adapted from Wagner 2001)

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
	WATERSHED CONTROLS		
1) Management for nutrient input reduction	♦ Includes wide range of watershed and lake edge activities intended to eliminate nutrient sources or reduce delivery to lake ♦ Essential component of algal control strategy where internal recycling is not the dominant nutrient source, and desired even where internal recycling is important	♦ Acts against the original source of algal nutrition ♦ Creates sustainable limitation on algal growth ♦ May control delivery of other unwanted pollutants to lake ♦ Facilitates ecosystem management approach which considers more than just algal control	♦ May involve considerable lag time before improvement observed ♦ May not be sufficient to achieve goals without some form of in-lake management ♦ Reduction of overall system fertility may impact fisheries ♦ May cause shift in nutrient ratios which favor less desirable algae
1a) Point source controls	♦ More stringent discharge requirements ♦ May involve diversion ♦ May involve technological or operational adjustments ♦ May involve pollution prevention plans	♦ Often provides major input reduction ♦ Highly efficient approach in most cases ♦ Success easily monitored	♦ May be very expensive in terms of capital and operational costs ♦ May transfer problems to another watershed ♦ Variability in results may be high in some cases
1b) Non-point source controls	♦ Reduction of sources of nutrients ♦ May involve elimination of land uses or activities that release nutrients ♦ May involve alternative product use, as with no phosphate fertilizer	♦ Removes source ♦ Limited or no ongoing costs	♦ May require purchase of land or activity ♦ May be viewed as limitation of “quality of life” ♦ Usually requires education and gradual implementation

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
1c) Non-point source pollutant trapping	♦ Capture of pollutants between source and lake ♦ May involve drainage system alteration ♦ Often involves wetland treatments (detention/infiltration) ♦ May involve stormwater collection and treatment as with point sources	♦ Minimizes interference with land uses and activities ♦ Allows diffuse and phased implementation throughout watershed ♦ Highly flexible approach ♦ Tends to address wide range of pollutant loads	♦ Does not address actual sources ♦ May be expensive on necessary scale ♦ May require substantial maintenance
IN-LAKE PHYSICAL CONTROLS			
2) Circulation and destratification	♦ Use of water or air to keep water in motion ♦ Intended to prevent or break stratification ♦ Generally driven by mechanical or pneumatic force	♦ Reduces surface build-up of algal scums ♦ May disrupt growth of blue-green algae ♦ Counteraction of anoxia improves habitat for fish/invertebrates ♦ Can eliminate localized problems without obvious impact on whole lake	♦ May spread localized impacts ♦ May lower oxygen levels in shallow water ♦ May promote downstream impacts
3)Dilution and flushing	♦ Addition of water of better quality can dilute nutrients ♦ Addition of water of similar or poorer quality flushes system to minimize algal build-up ♦ May have continuous or periodic additions	♦ Dilution reduces nutrient concentrations without altering load ♦ Flushing minimizes detention; response to pollutants may be reduced	♦ Diverts water from other uses ♦ Flushing may wash desirable zooplankton from lake ♦ Use of poorer quality water increases loads ♦ Possible downstream impacts

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
4) Drawdown	♦ Lowering of water over autumn period allows oxidation, desiccation and compaction of sediments ♦ Duration of exposure and degree of dewatering of exposed areas are important ♦ Algae are affected mainly by reduction in available nutrients.	♦ May reduce available nutrients or nutrient ratios, affecting algal biomass and composition ♦ Opportunity for shoreline clean-up/structure repair ♦ Flood control utility ♦ May provide rooted plant control as well	♦ Possible impacts on non-target resources ♦ Possible impairment of water supply ♦ Alteration of downstream flows and winter water level ♦ May result in greater nutrient availability if flushing inadequate
5) Dredging	♦ Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering ♦ Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system ♦ Nutrient reserves are removed and algal growth can be limited by nutrient availability	♦ Can control algae if internal recycling is main nutrient source ♦ 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
5a) “Dry” excavation	♦ Lake drained or lowered to maximum extent practical ♦ Target material dried to maximum extent possible ♦ Conventional excavation equipment used to remove sediments	♦ Tends to facilitate a very thorough effort ♦ May allow drying of sediments prior to removal ♦ Allows use of less specialized equipment	♦ Eliminates most aquatic biota unless a portion left undrained ♦ Eliminates lake use during dredging

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
5b) "Wet" excavation	♦ Lake level may be lowered, but sediments not substantially exposed ♦ Draglines, bucket dredges, or long-reach backhoes used to remove sediment	♦ Requires least preparation time or effort, tends to be least cost dredging approach ♦ May allow use of easily acquired equipment ♦ May preserve aquatic biota	♦ Usually creates extreme turbidity ♦ Normally requires intermediate containment area to dry sediments prior to hauling ♦ May disrupt ecological function ♦ Use disruption
5c) Hydraulic removal	♦ Lake level not reduced ♦ Suction or cutterhead dredges create slurry which is hydraulically pumped to containment area ♦ Slurry is dewatered; sediment retained, water discharged	♦ Creates minimal turbidity and impact on biota ♦ Can allow some lake uses during dredging ♦ Allows removal with limited access or shoreline disturbance	♦ Often leaves some sediment behind ♦ Cannot handle coarse or debris-laden materials ♦ Requires sophisticated and more expensive containment area
6) Light-limiting dyes and surface covers	♦ Creates light limitation	♦ Creates light limit on algal growth without high turbidity or great depth ♦ May achieve some control of rooted plants as well	♦ May cause thermal stratification in shallow ponds ♦ May facilitate anoxia at sediment interface with water
6.a) Dyes	♦ Water-soluble dye is mixed with lake water, thereby limiting light penetration and inhibiting algal growth ♦ Dyes remain in solution until washed out of system.	♦ Produces appealing color ♦ Creates illusion of greater depth	♦ May not control surface bloom-forming species ♦ May not control growth of shallow water algal mats ♦ Altered thermal regime

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
6.b) Surface covers	♦ Opaque sheet material applied to water surface	♦ Minimizes atmospheric and wildlife pollutant inputs	♦ Minimizes atmospheric gas exchange ♦ Limits recreational use
7) Mechanical removal	♦ Filtering of pumped water for water supply purposes ♦ Collection of floating scums or mats with booms, nets, or other devices ♦ Continuous or multiple applications per year usually needed	♦ Algae and associated nutrients can be removed from system ♦ Surface collection can be applied as needed ♦ May remove floating debris ♦ Collected algae dry to minimal volume	♦ Filtration requires high backwash and sludge handling capability for use with high algal densities ♦ Labor and/or capital intensive ♦ Variable collection efficiency ♦ Possible impacts on non-target aquatic life
8)Selective withdrawal	♦ Discharge of bottom water which may contain (or be susceptible to) low oxygen and higher nutrient levels ♦ May be pumped or utilize passive head differential	♦ Removes targeted water from lake efficiently ♦ Complements other techniques such as drawdown or aeration ♦ May prevent anoxia and phosphorus build up in bottom water ♦ May remove initial phase of algal blooms which start in deep water ♦ May create coldwater conditions downstream	♦ Possible downstream impacts of poor water quality ♦ May eliminate colder thermal layer that supports certain fish ♦ May promote mixing of remaining poor quality bottom water with surface waters ♦ May cause unintended drawdown if inflows do not match withdrawal

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
9) Sonication	♦ Sound waves disrupt algal cells	♦ Supposedly affects only algae (new technique) ♦ Applicable in localized areas	♦ Unknown effects on non-target organisms ♦ May release cellular toxins or other undesirable contents into water column
	IN-LAKE CHEMICAL CONTROLS		
10) Hypolimnetic aeration or oxygenation	♦ Addition of air or oxygen at varying depth provides oxic conditions ♦ May maintain or break stratification ♦ Can also withdraw water, oxygenate, then replace	♦ Oxic conditions promote binding/sedimentation of phosphorus ♦ Counteraction of anoxia improves habitat for fish/invertebrates ♦ Build-up of dissolved iron, manganese, ammonia and phosphorus reduced	♦ May disrupt thermal layers important to fish community ♦ Theoretically promotes supersaturation with gases harmful to fish
11) Algaecides	♦ Liquid or pelletized algaecides applied to target area ♦ Algae killed by direct toxicity or metabolic interference ♦ Typically requires application at least once/yr, often more frequently	♦ Rapid elimination of algae from water column , normally with increased water clarity ♦ May result in net movement of nutrients to bottom of lake	♦ Possible toxicity to non-target species ♦ Restrictions on water use for varying time after treatment ♦ Increased oxygen demand and possible toxicity ♦ Possible recycling of nutrients

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
11a) Forms of copper	♦ Cellular toxicant, suggested disruption of photosynthesis, nitrogen metabolism, and membrane transport ♦ Applied as wide variety of liquid or granular formulations, often in conjunction with chelators, polymers, surfactants or herbicides	♦ Effective and rapid control of many algae species ♦ Approved for use in most water supplies	♦ Possible toxicity to aquatic fauna ♦ Ineffective at colder temperatures ♦ Accumulation of copper in system ♦ Resistance by certain green and blue-green nuisance species ♦ Lysing of cells releases nutrients and toxins
11b) Synthetic organic herbicides	♦ Absorbed or embrane-active chemicals which disrupt metabolism ♦ Causes structural deterioration	♦ Used where copper is ineffective ♦ Limited toxicity to fish at recommended dosages ♦ Rapid action	♦ Non-selective in treated area ♦ Toxic to aquatic fauna (varying degrees by formulation) ♦ Time delays on water use
11c) Oxidants	♦ Disrupts most cellular functions, tends to attack membranes ♦ Applied most often as a liquid.	♦ Moderate control of thick algal mats, used where copper alone is ineffective ♦ Rapid action	♦ Non-selective in treated area ♦ Toxic to zooplankton/fish at possible dosage

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
12) Phosphorus inactivation	♦ Typically salts of aluminum, iron or calcium are added to the lake, as liquid or powder ♦ Phosphorus in the treated water column is complexed and settled to the bottom of the lake ♦ Phosphorus in upper sediment layer is complexed, reducing release from sediment ♦ Permanence of binding varies by binder in relation to redox potential and pH	♦ Can provide rapid, major decrease in phosphorus concentration in water column ♦ Can minimize release of phosphorus from sediment ♦ May remove other nutrients and contaminants as well as phosphorus ♦ Flexible with regard to depth of application and speed of improvement	♦ Possible toxicity to fish and invertebrates, especially by aluminum at low pH ♦ Possible release of phosphorus under anoxia or extreme pH ♦ May cause fluctuations in water chemistry, especially pH, during treatment ♦ Possible resuspension of floc in shallow areas ♦ Adds to bottom sediment, but typically an insignificant amount
13) Sediment oxidation	♦ Addition of oxidants, binders and pH adjustors to oxidize sediment ♦ Binding of phosphorus is enhanced ♦ Denitrification is stimulated	♦ Can reduce phosphorus supply to algae ♦ Can alter N:P ratios in water column ♦ May decrease sediment oxygen demand	♦ Possible impacts on benthic biota ♦ Longevity of effects not well known ♦ Possible source of nitrogen for blue-green algae

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
14) Settling agents	♦ Closely aligned with phosphorus inactivation, but can be used to reduce algae directly too ♦ Lime, alum or polymers applied, usually as a liquid or slurry ♦ Creates a floc with algae and other suspended particles ♦ Floc settles to bottom of lake ♦ Re-application typically necessary at least once/yr	♦ Removes algae and increases water clarity without lysing most cells ♦ Reduces nutrient recycling if floc sufficient ♦ Removes non-algal particles as well as algae ♦ May reduce dissolved phosphorus levels at the same time	♦ Possible impacts on aquatic fauna ♦ Possible fluctuations in water chemistry during treatment ♦ Resuspension of floc possible in shallow, well-mixed waters ♦ Promotes increased sediment accumulation
15) Selective nutrient addition	♦ Ratio of nutrients changed by additions of selected nutrients ♦ Addition of non-limiting nutrients can change composition of algal community ♦ Processes such as settling and grazing can then reduce algal biomass (productivity can actually increase, but standing crop can decline)	♦ Can reduce algal levels where control of limiting nutrient not feasible ♦ Can promote non-nuisance forms of algae ♦ Can improve productivity of system without increased standing crop of algae	♦ May result in greater algal abundance through uncertain biological response ♦ May require frequent application to maintain desired ratios ♦ Possible downstream effects

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
	IN-LAKE BIOLOGICAL CONTROLS		
16) Enhanced grazing	♦ Manipulation of biological components of system to achieve grazing control over algae ♦ Typically involves alteration of fish community to promote growth of large herbivorous zooplankton, or stocking with phytophagous fish	♦ May increase water clarity by changes in algal biomass or cell size distribution without reduction of nutrient levels ♦ Can convert unwanted biomass into desirable form (fish) ♦ Harnesses natural processes to produce desired conditions	♦ May involve introduction of exotic species ♦ Effects may not be controllable or lasting ♦ May foster shifts in algal composition to even less desirable forms
16.a) Herbivorous fish	♦ Stocking of fish that eat algae	♦ Converts algae directly into potentially harvestable fish ♦ Grazing pressure can be adjusted through stocking rate	♦ Typically requires introduction of non-native species ♦ Difficult to control over long term ♦ Smaller algal forms may be benefitted and bloom
16.b) Herbivorous zooplankton	♦ Reduction in planktivorous fish to promote grazing pressure by zooplankton ♦ May involve stocking piscivores or removing planktivores ♦ May also involve stocking zooplankton or establishing refugia	♦ Converts algae indirectly into harvestable fish ♦ Zooplankton response to increasing algae can be rapid ♦ May be accomplished without introduction of non-native species ♦ Generally compatible with most fishery management goals	♦ Highly variable response expected; temporal and spatial variability may be high ♦ Requires careful monitoring and management action on 1-5 yr basis ♦ Larger or toxic algal forms may be benefitted and bloom

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
17) Bottom-feeding fish removal	♦ Removes fish that browse among bottom deposits, releasing nutrients to the water column by physical agitation and excretion	♦ Reduces turbidity and nutrient additions from this source ♦ May restructure fish community in more desirable manner	♦ Targeted fish species are difficult to eradicate or control ♦ Reduction in fish populations valued by some lake users (human/non-human)
18) Pathogens	♦ Addition of inocula to initiate attack on algal cells ♦ May involve fungi, bacteria or viruses	♦ May create lakewide "epidemic" and reduction of algal biomass ♦ May provide sustained control through cycles ♦ Can be highly specific to algal group or genera	♦ Largely experimental approach at this time ♦ May promote resistant nuisance forms ♦ May cause high oxygen demand or release of toxins by lysed algal cells ♦ Effects on non-target organisms uncertain
19) Competition and allelopathy	♦ Plants may tie up sufficient nutrients to limit algal growth ♦ Plants may create a light limitation on algal growth ♦ Chemical inhibition of algae may occur through substances released by other organisms	♦ Harnesses power of natural biological interactions ♦ May provide responsive and prolonged control	♦ Some algal forms appear resistant ♦ Use of plants may lead to problems with vascular plants ♦ Use of plant material may cause depression of oxygen levels

OPTION	MODE OF ACTION	ADVANTAGES	DISADVANTAGES
19a) Plantings for nutrient control	♦ Plant growths of sufficient density may limit algal access to nutrients ♦ Plants can exude allelopathic substances which inhibit algal growth ♦ Portable plant "pods" , floating islands, or other structures can be installed	♦ Productivity and associated habitat value can remain high without algal blooms ♦ Can be managed to limit interference with recreation and provide habitat ♦ Wetland cells in or adjacent to the lake can minimize nutrient inputs	♦ Vascular plants may achieve nuisance densities ♦ Vascular plant senescence may release nutrients and cause algal blooms ♦ The switch from algae to vascular plant domination of a lake may cause unexpected or undesirable changes
19b) Plantings for light control	♦ Plant species with floating leaves can shade out many algal growths at elevated densities	♦ Vascular plants can be more easily harvested than most algae ♦ Many floating species provide valuable waterfowl food	♦ At the necessary density, the floating plants will be a recreational nuisance ♦ Low surface mixing and atmospheric contact promote anoxia
19c) Addition of barley straw	♦ Input of barely straw can set off a series of chemical reactions which limit algal growth ♦ Release of allelopathic chemicals can kill algae ♦ Release of humic substances can bind phosphorus	♦ Materials and application are relatively inexpensive ♦ Decline in algal abundance is more gradual than with algaecides, limiting oxygen demand and the release of cell contents	♦ Success appears linked to uncertain and potentially uncontrollable water chemistry factors ♦ Depression of oxygen levels may result ♦ Water chemistry may be altered in other ways unsuitable for non-target organisms

7.3 Dredging

7.3.1 Introduction

One of the four in-lake methods for reduction of nutrients and algal blooms selected for evaluation in the *Eutrophication Mitigation Study* is dredging. Dredging may be an effective restoration technique since the release of algae-stimulating nutrients from lake sediments can be reduced or controlled by removing layers of enriched materials. This removal may produce significantly lower in-lake nutrient concentrations and lessen algal production, assuming that there has been adequate diversion or treatment of incoming nutrient, organic

and sediment loads from external sources. Even where incoming nutrient loads are high, dredging can reduce benthic mat formation and related problems with filamentous green and blue-green algae, as these forms may initially depend on nutrient-rich substrates for nutrition. Dredging also removes the accumulated resting cysts deposited by a variety of algae. Although recolonization would be expected to be rapid, some changes in algal composition can result.

While removing the entire nutrient-rich layer of sediment can control algae, dredging is most frequently done to deepen a lake, remove accumulations of toxic substances, or to remove and control macrophytes. Algal control benefits are largely ancillary in these cases. In most cases, the expense of complete soft sediment removal and the more pressing need for watershed management are the primary reasons that dredging is not used more often for algal control. Sediment removal to retard nutrient release can be effective, however.

The FGEIR provides a number of case studies where dredging results in reduction of algal biomass (EOEA, 2004). An example is provided by Lake Trummen in Sweden (Andersson 1988) where the upper 3.3 feet of sediments were extremely rich in nutrients. This layer was removed and the total phosphorus concentration in the lake dropped sharply and remained fairly stable for at least 18 years. Phytoplankton production was reduced as a result.

Algal abundance also decreased and water clarity increased in Hills Pond in Massachusetts after all soft sediment was removed and a storm water treatment wetland was installed in 1994 (Wagner 1996). Dredging of 6-acre Bulloughs Pond in Massachusetts in 1993 has resulted in abatement of thick green algal mats for over a decade, despite continued high nutrient loading from urban runoff (Wagner, pers. obs.). These mats had previously begun as spring bottom growths then they floated to the surface in mid-summer. Additional dredging case studies are provided in the FGEIR (EOEA, 2004).

Table 7-2 provides a summary of the potential issues and concerns associated with dredging. Accordingly, because of the need for mobilization of large equipment, adequate dewatering and disposal areas, transportation concerns, engineering design, and environmental permitting, the long-term benefits of the sediment removal have to be carefully weighed against the feasibility, costs and short and long-term impacts. The following sections consider the technical feasibility, expected water quality improvements, longevity, cost-effectiveness and potential permitting issues associated with Lovers Lake and Stillwater Pond.

7.3.2 Technical feasibility

Based on the pond and sediment characteristics, hydraulic dredging or wet dredging (see Table 7-1) would be the only viable dredging options for Lovers Lake and Stillwater Pond. Technically infeasible alternatives (i.e., dry dredging under drawdown conditions) were not further considered for selection. The first step in scoping such a project is the determination of the total amount of sediment to be removed. Therefore, the depth and area of proposed dredging need to be selected. In many cases, these parameters are based on a relative optimization of the benefits of decreased nutrient levels vs. cost and environmental concerns.

Table 7-2. Key considerations for successful dredging

Reasons for Dredging:
Increased depth/access
Removal of nutrient reserves
Control of aquatic vegetation
Alteration of bottom composition
Habitat enhancement
Reduction in oxygen demand

Volume Of Material To Be Removed:
In-situ volume to be removed
Distribution of volume among sediment types
Distribution of volume over lake area (key sectors)
Bulked volume (see below)
Dried volume (see below)

Nature of Underlying Material To Be Exposed:
Type of material
Comparison with overlying material

Dewatering Capacity of Sediments:
Dewatering potential
Dewatering timeframe
Methodological considerations

Protected Resource Areas:
Wetlands
Endangered species
Habitats of special concern
Species of special concern
Regulatory resource classifications

Equipment Access:
Possible input and output points
Land slopes
Pipeline routing
Property issues

Potential Disposal Sites:
Possible containment sites
Soil conditions
Necessary site preparation
Volumetric capacity
Property issues
Long term disposal options

Existing and Proposed Bathymetry:
Existing mean depth
Existing maximum depth
Proposed distribution of lake area over depth range
Proposed mean depth
Proposed maximum depth
Proposed distribution of area over depth range

Physical Nature of Material To Be Removed:
Grain size distribution
Solids and organic content
Settling rate
Bulking factor
Drying factor
Residual turbidity

Chemical Nature of Material To Be Removed:
Metals levels
Petroleum hydrocarbon levels
Nutrient levels
Pesticides levels
PCB levels
Other organic contaminant levels
Other contaminants of concern (site-specific)

Flow Management:
System hydrology
Possible peak flows
Expected mean flows
Provisions for controlling water level
Methodological implications

Relationship To Lake Uses:
Impact on existing uses during project
Impact on existing uses after project
Facilitation of additional uses

Dredging Methodologies:
Hydraulic (or pneumatic) options
Wet excavation
Dry excavation

Table 7-2. Key considerations for successful dredging (continued).

Applicable Regulatory Processes:
MEPA review (Environmental Notification Form)
Environmental impact reporting (EIR if needed)
Wetlands Protection Act (Order of Conditions)
Dredging permits (Chapter 91)
Aquatic structures permits (Chapter 91)
Drawdown notification (to DFWELE)
Water Management Act (diversion/use permits)
Clean Water Act Section 401 (WQ certification)
Clean Water Act Section 404 (USACE wetlands statute)
Dam safety/alteration permit (DEM)
Waste disposal permit (DEP)
Discharge permits (NPDES, USEPA/DEP)

Removal Costs:
Engineering and permitting costs
Construction of containment area
Equipment purchases
Operational costs
Contract dredging costs
Ultimate disposal costs
Monitoring costs
Total cost divided by volume to be removed

Uses Or Sale Of Dredged Material:
Possible uses
Possible sale
Target markets

Other Mitigating Factors:
Necessary watershed management
Ancillary project impacts
Economic setting
Political setting
Sociological setting

The target depth of the dredging would be the removal of nutrient rich sediments to a hard bottom or as deep as is technically feasible or may be conducted with available funding. The second element determining total sediment to be removed is the area to be dredged – with a potential range of options from the entire pond to a lesser portion of the sediment underlying the hypolimnion. Determination of this target area depends on many factors such as the potential impacts to lake biota and ecosystem function, potential impacts to adjacent areas (including wetlands), impacts to water quality, the size and capacity of the dewatering and disposal areas, interference with other uses of the Pond, distance to neighboring residences, truck traffic, and overall costs and benefits.

As a starting point, the extreme example of dredging the top two feet of sediment of the entire pond was considered. For Lovers Lake, this would entail removal of a minimum of >120,000 cubic yards (CY); while for Stillwater Pond this total would be approximately 57,000 CY. Dredging of the entire pond bottom is not advisable, however, since not all sediments are nutrient rich. Removal of sandy substrate should be avoided since these sediments are relatively low in phosphorus. Based on the occurrence of phosphorus-rich organic sediments and the depth of seasonal anoxia, sediments under the 20 ft contour would be targeted as the primary target, with expansion into shallower depths possible.

Therefore, a more appropriate sediment target goal might be the removal of the top two feet of benthic material in the portions of the deeper sections of northern and southern basin of Lovers Lake and the central portion of Stillwater Pond. For Lovers Lake the amount of material would be about 32,850 CY; while for Stillwater Pond a total of 28,500 CY is reached. While these are more manageable sediment volumes, this would still be a relatively difficult management technique for either pond.

One major concern is to what extent the project is technically feasible without specialized equipment. It is unusual to dredge in inland waters at depths of greater than 15 ft water depth. Most lake restoration dredging projects are typically aimed at increasing water depth from <10 to 15 ft for light limitation of rooted aquatic plants) (Cooke et al, 2005). The greater depth would likely be problematic for use of most conventional hydraulic cutterhead dredges that rely on maintaining strong suction at the head digging into the bottom

material and to pump the resultant slurry material up and to the dewatering areas. The greater depth would at least require a larger dredge type with a more powerful pump; which would cost more to operate.

Depth limitation is less of a challenge for a barge-mounted clamshell dredge, but this type of equipment is not the method of first choice when removing flocculent, fine organic sediments due to leakage of material from the bucket and silt resuspension when bringing up the bottom material up through the water column. If not carefully managed by silt curtains or outlet barriers this could lead to the potential for silt being transported downstream to either Stillwater Pond and/or Ryder's Cove. There is also the need for an additional work barge to temporarily store and then offload the dredged material taken from shoreline areas.

Another major technical constraint for dredging in either pond is the lack of large, adjacent areas for dewatering of the sediments. The pumped slurry or excavated load is likely to have 80-90% water content that must be drained and usually treated to meet water quality standards prior to its return to the lake. This procedure sometimes takes multiple basins to achieve. For the volume of material considered, a dewatering basin of 3-5 acres is probably required, depending on how fast the material could be decanted and disposed of or whether the dredging is conducted over several seasons. Ideal candidate locations for such basins would have a sufficiently-sized, level or gently sloped area, cleared of vegetation, not too high above lake surface elevation, with good access for trucks (for transporting dried material) and not adjacent to residential areas.

Inspection of the shoreline areas for both Lovers Lake and Stillwater Pond does not show good candidate areas. The shoreline and adjacent area next to Stillwater Pond show little promise for siting a dewatering basin. For Lovers Lake, the most promising areas would be in the conservation lands to the west of the pond. However, locating basins here would require removal of existing vegetation, pumping the slurry upslope, and proximity issues with the town drinking water wells. This area does have the advantage of being a securable site, with potential access for truck traffic, and in having upland sandy soils that would aid in the draining of the dewatering material. Otherwise, the use of the former cranberry bog located on the northeast corner for dewatering and possible disposal might be technically feasible but this would be considered filling of a wetland area and would be highly unlikely under the Massachusetts Wetland Protection Act.

Since there are no good candidate locations for the dewatering basins at either pond, it is likely that mechanical dewatering would be selected as the method of choice for the dewatering of dredged materials from the ponds. This selection was also based on the effectiveness of mechanical dewatering in handling fine silty material and the assumed availability of a location for several filter belt press units. This also assumed that final disposal would be away from the ponds.

Assuming no limitations on the disposal of dredged material, potential disposal/reuse options include use as topsoil or topsoil amendment, use in compositing or as construction fill, and daily cover at landfills. [Note: we assumed that the sediments are non-hazardous due to environmental setting and historic land use, but if dredging is considered further additional testing would be required]. Potential usage is often dependent on the amount and timing of the material available. Given the uncertain schedule of funding for implementation of dredging, identification of potential disposal destinations is somewhat uncertain. Based on typical disposal plans elsewhere, local facilities that could be contacted for potential disposal include the local contractors and landscape firms, the Chatham Department of Public Works, and local landfills. Other potential destinations could include local golf courses or remediation projects with a need for clean fill. Further information and identification of the final disposal destination would be finalized as part of the design, specifications and environmental permitting.

Other practical concerns include locating a suitable mobilization point for accessing large equipment to the lake, aesthetic issues (noise, sight, and odor) associated with dredging and potential for restrictions on areas of lake use. Mobilization areas and embarkation points for such equipment would also have to be located. Given that there are no large public boat launches on either pond, alternative access would have to be secured. A small blacktopped access easement to Lovers Lake is located off Lake Shore Drive at the south basin, but is narrow, and would present problems for mobilization of large equipment. The easement access to

Stillwater Pond, located off Valley Road, is somewhat larger and has a greater shoreline expansion. Other access via private roads could be sought, but this is highly uncertain. The use of mechanical dewatering would also require a large volume of truck traffic into and out of the area. This raises the question of traffic impacts, both in terms of increased congestion, the transit of large, dripping trucks through mostly residential areas, and wear and tear on local roadways.

Additional major environmental concerns would be water quality impacts to the herring run and potential impacts to riparian wetland areas. As will be discussed below, there is an extensive amount of environmental permitting required for any dredging operation, regardless of the amount of material removed.

7.3.3 Expected water quality or recreational improvements

Removal of phosphorus-enriched sediments would be expected to reduce the amount of internal phosphorus cycling. It could be expected that the topmost sediments are richer in phosphorus since they reflect recent loadings that have been most affected by anthropogenic influences, but since we do not know the exact source or timing of elevated phosphorus in the sediments, this assumption may or may not be true. The exact level of phosphorus reduction would be uncertain until the sediment quality underneath the excavated layer was sampled, say if further investigation of dredging was proposed. The maximum benefit would assume that the sediments beneath the dredged level are largely sand with low phosphorus content. The minimum benefit would occur if the sediments below are equally rich in phosphorus sediment. For purposes of this evaluation we assumed 50% reduction in phosphorus recycling. This level of reduction would reduce the phosphorus loading for both ponds (26-28% reduction) but would not get either below the permissible load. Therefore, while some modest improvement in water quality and recreational improvement could be expected, it is not as extensive or predictable as would be other means of reducing the internal recycling.

7.3.4 Longevity

The short-term impact of dredging should be an immediate (i.e., next growing season) reduction in the amount of phosphorus released from the sediments. The longevity of dredging to remove sediment depends on the rate of sedimentation and/or the potential for resuspension or shifting/slumping of sediments from upgradient locations downslope into excavated areas. For these two ponds, bulk sedimentation would be low due to the lack of surface runoff and erosion from the two watersheds. The watershed is largely forested or developed with little chance of large soil disturbance. Future de novo sedimentation would be expected to be limited to small organic inputs from the phytoplankton and other organic materials (e.g., riparian vegetation). However, the flocculent nature of the sediments and steep basin slopes could lead to resuspension and transfer of organic materials into deeper regions, which may result in increasing release of phosphorus. Based on these factors, the longevity of dredging as a means to suppress phosphorus release would be considered average to poor; with longevity of reduced phosphorus recycling estimated at a decade or less.

7.3.5 Cost-effectiveness

Dredging is generally an expensive proposition due to its many components (i.e., sediment removal, dewatering, sediment disposal, etc). The FGEIR cites a potential range of $10-20/CY sediment removed, based on several case studies (EOEA, 2004). Costs tended to be lower when there was a large volume of sediment to be removed, a good supply of adjacent flat land for dewatering basins, and dewatered sediments were either left in place in the basins or in local demand. Considering the small-moderate volume of dredged materials, sediment characteristics, depth of both ponds and lack of good candidate disposal options, together with the effect of cost inflation (some of the cases studies in the FGEIR are 20 years old), it was assumed that the upper end of the range was appropriate.

Based on the factors noted above, ENSR estimated $16/ CY for in-lake removal cost for this alternative. The costs associated with transporting the sediments to a potential reuse site were not included in the removal cost

due the uncertainty of its locations, but were estimated at an additional $6/CY. This provides an overall planning estimate of $22/CY. Based on the removal of the top two feet in areas greater than 20 ft, the amount to be removed for Lovers Lake would be 32,850 CY while that for Stillwater Pond would be 28,500 CY. At a cost of $22/cy, the in-lake sediment removal cost would be about $723,000 and $627,000, respectively for the two ponds. Engineering and environmental permits are likely to be an additional $100,000 for an estimated combined project total of $1.45 M. This number could be further refined during preliminary design and permitting, but provides an informed order-of-magnitude estimate.

7.3.6 Permitting issues

Dredging is a complicated and highly regulated activity (see Table 7-2), and the proposed project is no exception. Factors which increase permitting activity for dredging the ponds include, but are not restricted to: it would involve two ponds, both are located in the Pleasant Bay ACEC, the ponds have a valued herring run, the watersheds have identified NHESP habitats in and around the pond shoreline, and Stillwater Pond has a direct outlet to coastal marine resources in Ryder's Cove.

At a minimum it would require a full Notice of Intent from the Chatham Conservation Commission, a Massachusetts Department of Environmental Protection (MA DEP) Chapter 91 license, a CWA Section 401 Water Quality Certificate, and a potential discharge permit. Significant state regulatory review would be expected from MA DEP, MA Natural Heritage, and MA Division of Fish and Wildlife. Local involvement could involve the Chatham DPW, Herring and Shellfish Wardens. It is assumed that under MEPA, an ENF would be sufficient since a full EIR is not required, due to adoption of the FGEIR as the generic impact statement for such lake restorations. Once disposal options have been determined, testing and certification of dredged material quality as non-hazardous would likely be required. It is expected that the cost of obtaining these environmental permits is likely to cost up to $100,000.

7.3.7 Evaluation of potential applicability of method for Lovers Lake and Stillwater Pond

The applicability of dredging for restoration of Lovers Lake and Stillwater Pond was evaluated, specifically the potential for dredging to reduce internal recycling. The factors used for this evaluation were technical feasibility, expected water quality improvement, longevity, cost-effectiveness, and permitting issues.

The technical feasibility review indicates that removal of sediments provides a very direct way of removing a significant amount of phosphorus mass from the pond. However, sediment recycling is more dependent on the surface area of enriched phosphorus than the entire mass. Therefore, if removal of the top sediment simply exposes a new layer of phosphorus-enriched sediments then there will be little reduction in the phosphorus regeneration, despite the removal of a large amount of phosphorus mass. This technique is not well suited for either pond due to the depth involved, the lack of readily accessible dewatering and disposal areas, and residential setting.

Dredging could reduce the phosphorus loading (26-28% reduction) but would not get below the permissible load for either pond. Modest improvements in water quality might be expected. Longevity is expected to be lower than average in these ponds due to lack of knowledge of underlying sediment structure and potential refilling of dredged areas; it does not require a thick muck layer to release substantial phosphorus.

If both ponds are dredged, costs will approach $1.5M or more. These high costs reflect the technical difficulties described earlier. As noted earlier, environmental permitting will be extensive and there may be a large set of conditions (e.g., it is possible that MA DFW will want to schedule dredging to avoid critical periods of herring runs; thus reducing output during spring and summer) and extensive monitoring costs.

Taken these factors together, ENSR does not recommend dredging for restoration of Lovers Lake and Stillwater Pond. Other pond restoration options to address internal recycling appear more appropriate, more probable for success, and less costly.

7.4 Artificial circulation

7.4.1 Introduction

The second of the four in-lake methods for reduction of nutrients and algal blooms selected for evaluation in the *Eutrophication Mitigation Study* is artificial circulation. Whole lake circulation, like hypolimnetic aeration discussed next, involves the introduction of more oxygen into the bottom waters of ponds to limit the amount of phosphorus recycling, thereby controlling phytoplankton blooms. There is a sharp distinction between the two methods, however. Circulation strategies work to minimize stratification effects (e.g., destratification), while hypolimnetic aeration relies on the maintenance of the stratified state. Another difference is that the temperature of the whole lake is raised with circulation, with the greatest temperature difference observed in the depths previously part of the hypolimnion (Cooke et al., 2005). The type of equipment that is used to produces these types of aeration states varies, as illustrated in Figure 7-1. In some instances, surface-based, wind driven pumps have also been used to move water.

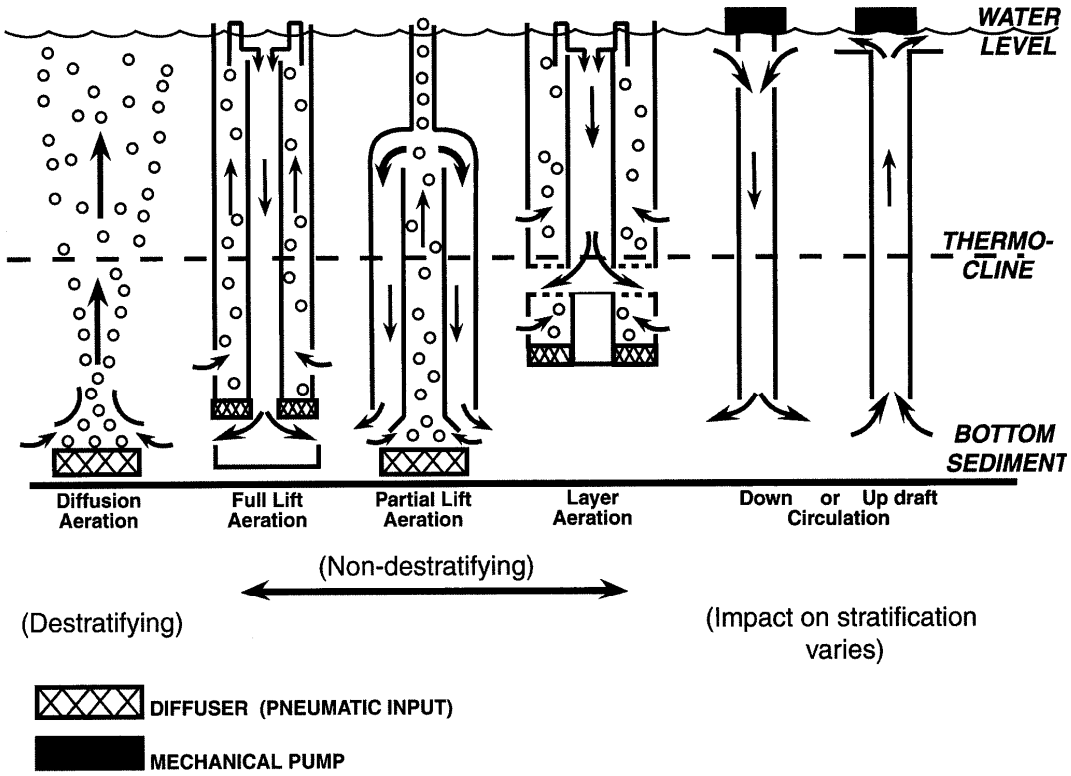
Circulation provides for complete mixing and homogenization of pond conditions. Thermal stratification and features of pond morphometry such as coves create stagnant zones that may be subject to loss of oxygen, accumulation of sediment, or algal blooms (EOEA, 2004). Artificial circulation, if vigorously applied, can prevent or eliminate thermal stratification. Movement of air or water is normally used to create the desired circulation pattern in shallow (<20 ft) waterbodies. Surface aerators, bottom diffusers, and water pumps have all been used to mix small ponds and shallow lakes, although the effect may be largely cosmetic in many instances; algae are simply mixed more evenly in the available volume of water.

In deeper lakes, thermal stratification is broken or prevented through the injection of compressed air into lake water from a diffuser at the lake bottom. The rising column of bubbles, if sufficiently powered, will produce lakewide mixing at a rate that eliminates temperature differences between top and bottom waters (EOEA, 2004). The use of air as the mixing force also provides some oxygenation of the water, but the efficiency and magnitude of this transfer are generally low.

Artificial circulation would be used in Lovers Lake and Stillwater Pond to provide sufficient oxygen to prevent low redox conditions and reduce or inhibit phosphorus release from sediments, with the ultimate goal of reducing algal blooms. Related benefits for algal control are hypothesized for this method include: suppression of algal growth through light limitations, as the mixing depth would greatly increase (and would somewhat counteract the buoyancy advantage of some cyanophytes); increase of the carbon dioxide content of the water to lower pH, which is thought to favor development of green algae over blue-green algae, and better distribution and survivorship of grazing zooplankters (EOEA, 2004).

This method has had a mixed record with regard to control of algal blooms. As discussed by Cooke et al. (2005), in more than half the cases, water quality conditions did not improve: total phosphorus increased or remained the same (65% of studies), SDT depths became more shallow (53%) and phytoplankton did not decrease (>50%). The most common failure of circulation to achieve the desired objective may be caused by improper sizing or faulty placement of equipment. Underdesign of the mixing system is the major equipment-related cause of failure for this technique.

Figure 7-1. Methods of artificial circulation and aeration (from Wagner, 2001).



While the end points for operation of diffusers are usually the beginning of stratification in the spring and the onset of autumnal turnover in the fall, it may be useful to supply oxygen to the ponds during ice-cover to prevent winterkills of fish in eutrophic lakes that become anoxic during the winter. On a smaller scale, artificial circulation can be used to prevent ice formation around docks or other structures. The technique is also used to maintain acceptable water quality in drinking reservoirs as the oxic conditions created by the circulation reduce concentrations of nuisance substances such as hydrogen sulfide, ammonia, iron and manganese (Wagner, 2004). For these types of problems artificial circulation has been very successful.

7.4.2 Technical feasibility

This method was considered technically feasible for Lovers Lake and Stillwater Pond. These waterbodies have many of the elements that favor this technique including: a large fraction of the phosphorus budget is due to internal recycling of the sediments, there are relatively low external phosphorus sources, and there is a high sediment oxygen demand (range of 200-1100 mg/m^2/day). Due to the high amount of iron in the sediments (Lovers Lake organic sediments have a total iron: total phosphorus (tFe:TP) ratio of 23:1, while Stillwater Pond's ratio is 27:1), so there is an adequate supply of inactivators present under oxidized conditions. They are also both sufficiently deep so that if total mixing is achieved there will be lesser light availability as the phytoplankton spend greater periods at depths with little or no light. Finally, the ponds do not support a coldwater fishery so maintenance of cooler bottom waters is not required.

The air-lift method, through diffusion of compressed air, is generally considered the least expensive and easiest to operate. Lorenzen and Fast (1977) suggested that a threshold air flow of about 1.3 ft^3/min per acre

(9.2 m^3/min/km^2) of lake surface is required to maintain mixing and oxygen within the lake. Review of many case studies, covering a variety of surface areas, depths, and volumes, indicated that an air flow equal to or greater than the 1.3 ft^3/min per acre level consistently achieved destratification (Cooke et al., 2005). Mixing may be induced with lower air flow through careful engineering design, but undersizing of mixing devices remains a common problem. On the other hand oversizing the system may lead to sediment resuspension. There are many engineering details to be considered in the design of a circulation system, and knowledge of site conditions is essential; professionally designed systems should be required despite the appealing simplicity of the concept.

Due to the morphometry of the two kettlehole ponds, it would be necessary to put a diffuser in each of the three major basins to achieve destratification. The diffuser is generally a pipe with multiple orifices that is suspended about 9" - 18" off the bottom to reduce sediment entrainment. Orifice spacing is dictated by the depth of air release, as the rising water plume will spread horizontally during the rise. To support the in-lake diffuser will require location of a shore-based air compressor and power source. There will be required maintenance needed during the period when the diffusers are operational. In most cases it will not be necessary that they are taken out during the winter.

The thermal structure of the two ponds has to be taken into consideration in the design of an artificial circulation. Lovers Lake should be easier to destratify as it is shallower, has less hypolimnetic volume, and a more gradual thermocline. It is likely that the much greater thermal stability and depth of Stillwater Pond would require a greater amount of airflow to destratify. As noted above, design and placement of the diffusers would need to be carefully designed as the generic "rule-of-thumb" may be an underestimate for Stillwater Pond.

Given the large oxygen demand and depth, it appears that artificial circulation would not be feasible solely through the placement of surface-based, wind-driven circulators (e.g., Solar Bees®). These devices do apparently provide some degree of circulation for a waterbody, particularly when placed in arrays. However, their ability to pull water from 40+ feet would be very limited, particularly since the small dimensions of the basins involved would prohibit a large number of such devices from being deployed simultaneously. Recent evaluations of the performance of surface circulators to aerate waterbodies have noted very sharp gradients of oxidized conditions such that measurements taken at 25 - 50 ft away have often failed to detect measurable change from ambient conditions (Anderson, 2007; Schafran et al., 2007).

While artificial circulation is feasible for Lovers Lake and Stillwater Pond, there are some concerns regarding this process, as it does induce an unnatural limnological state in these waterbodies during summer. The large amount of organic material and oxygen demand seen in the bottom waters in these ponds could be entrained into the upper waters and reduce the surface water DO. This may already be currently happening to a certain degree. As indicated by Figures 3-2b and 3-5b when the thermocline erodes in the fall there is a noticeable decrease in the DO percent saturation throughout the epilimnion of both ponds.

If the internal mixing is not complete, partial stratification may occur or there may be isolated areas or sediments where anoxic conditions prevail. In such cases, the artificial circulation would provide the means for redistributing phosphorus released from the sediments into the upper water column during summer, thus facilitating algal growth. This also might be true for ammonia, which has the possibility of being toxic at high concentrations. Other materials (reduced iron, sulfides) could also be brought up from the depths if mixing is not complete and would impact taste and odor.

If successful, the artificial circulation would likely disrupt the current plankton community (both algal and zooplankton) due to changes in mixing depth, removal of natural gradients, and changes in available nutrient resources. While it is presumed that these changes would shift the phytoplankton community away from dominance by blue-green algae this may not be realized or other effects could be seen. Entrainment of zooplankton by rising bubbles could lead to increased mortality to these grazers. The presence of a constant upwelling area may or may not attract the herring or other fish in ponds, again with uncertain results.

Other practical concerns associated with this method include locating two or three suitable and secure sites for long-term seasonal (or permanent) placement of air compressor and shoreline piping, with suitable access to high voltage (three-phase) power (getting access to adequate power supplies can be costly). Equipment could be placed on a gravel pad, placed in a pre-fabricated structure, or located inside a more permanent building (e.g., concrete block). The size requirements would be on the order of 50-100 ft^2. To reduce piping and power requirements, these should be sited reasonably close to each of the target basins but be suitably screened from local residences to prevent aesthetic issues (noise, sight) and placed in a silenced enclosure.

The most favorable site for Lovers Lake would be on the small peninsula on the central eastern shoreline since it could possibly access both basins, but the residential nature of that area makes siting compressors there infeasible. The most likely location for an equipment pad/building for would be along the western shoreline on the conservation foundation parcel (see Figure 2-3) since it has shoreline access, is located further from residences, and could probably access power from town well support buildings. There are less desirable siting options for an equipment site for southern Lovers Lake due to its proximity to residential areas, but is some town-owned land at the southern end of the pond. Stillwater Pond does not have good candidate sites, but since the amount of land required is small it may be possible to site equipment near the small easement that allows shoreline access at the western end of the pond. Selection of the final site would be part of the implementation planning and permit phase, but the amount of land required is small and it was assumed that this could be obtained at little or no cost to the Town.

7.4.3 Expected water quality or recreational improvements

The ability of artificial circulation to improve water quality has been proven, but the results have varied greatly between waterbodies. In most instances, chemical problems due to low dissolved oxygen have been solved. When destratification is properly used in a water supply reservoir, problems with iron and manganese can be eliminated. Where very small temperature differences from top to bottom have been maintained all summer, algal blooms seem to be reduced. Circulation should at least prevent the formation of distinct surface scums, although total algal biomass may not be reduced, there is typically a shift away from blue-green algal-dominated phytoplankton.

Systems that bring deep water to the surface can be inexpensive, but unless enough water is moved to prevent anoxia near the sediment-water interface, the quality of water that is brought to the surface may cause deterioration of surface conditions. Systems that pump surface water to the bottom may improve the oxygen level near the bottom, but may also present unfavorable circulation patterns and deterioration of surface water quality and/or impact to biotic communities.

Cooke et al. (2005) reviewed a number of examples of aeration and noted that available phosphorus tends to decline by one to two thirds during aeration. For Long Pond, ENSR estimated between 60-80% effectiveness in phosphorus reduction. One of the difficulties with aeration is that it can provide DO to the main water column but, due to sharp diffusion gradients near the bottom, may not affect the redox conditions of the benthic sediments and immediate overlying water such that phosphorus release is reduced but not abated. However, if the overlying water is kept well-oxygenated, it would be expected that any phosphorus released would tend to be bound up again with available iron.

There is some uncertainty regarding the amount of predicted improvement to water quality of this treatment between the ponds. It is assumed that the two basin morphometry of Lovers Lake and shallow sill between would result in two well-aerated basins with some stagnant zones during periods when wind is not present. While a simpler basin, the depth and stability of the Stillwater Pond thermocline may also provide a technical challenge due to the energy requirement. Based on best professional judgment, we conservatively assumed 60% reduction in phosphorus recycling. This level of reduction would reduce the phosphorus loading for both ponds but would not get either well below the permissible load. We would expect an increase in SDT and the increase in oxygen in the hypolimnia from 3 to 7 mg/L above present anoxic conditions.

7.4.4 Longevity

Since artificial circulation is an active treatment, the compressor, pumps, and diffuser must be kept continual running during the summer months or the oxygenation and associated positive benefits cease. There are negligible residual positive effects when the power is turned off as the pond will start to restratify almost immediately. Some shifts in algal communities may persist over several weeks, but the system will eventually return to its currently impacted state unless circulation is maintained. However, there should be no loss in efficiency of such a system operated for several years. Well-maintained systems can last for many years, as evidenced by several locations (primarily drinking water reservoirs) where this method has been successfully used for 20 years or more (EOEA, 2004).

7.4.5 Cost-effectiveness

Artificial circulation is one of the least expensive whole-lake treatments. Capital costs include the purchase and installation of the compressor, pumps, piping, diffusers, etc. The largest expense is for a properly sized compressor, whose horsepower takes into account the amount of air required, which is related to oxygen demand, surface area and volume. Installation of piping is relatively easy and can be accomplished by boat. There will be costs for land purchase (if needed), site preparation, building or structure construction, and possibly, extension of power to site (can be surprisingly costly). The major operating cost is the electrical demand, but there are also annual maintenance costs to keep equipment in good repair and between seasons. Equipment failure and vandalism are the most commonly reported maintenance issues.

To initially estimate cost-of-magnitude dollars, we used cost factors near the median of values cited in the FGEIR (EOEA, 2004), with an initial estimate of $1,800/acre for capital costs and $135 /acre for annual operational costs. Environmental permitting costs were estimated at $10,000. For purposes of comparison among various pond restoration methods, we used an expected duration of treatment of 15 years. For operation of an artificial circulation system in Lovers Lake for 15 years, an approximate cost of about $154,000 was determined, that for Stillwater Pond is about $78,000.

To provide a more informed estimate for Lovers Lake, a highly qualified vendor of aeration equipment was consulted (R.Geney of General Environmental Systems, NC - pers. comm.). Use of this costing information does not constitute an endorsement of a particular brand or type of equipment by ENSR, but does provide a more realistic cost estimate for comparison purposes. As before, we used the 15 year period of treatment for comparative purposes and estimated an average 150 day period of treatment (i.e., mid-June through mid-October). Due to our understanding of current electrical costs, the estimate of $40/day for power requirement was based on two compressors with a combined output of 15 horsepower (HP). Due to the expected rise in the cost of electrical power, we assumed an inflation rate for electrical power of 2%/yr.

The cost of the diffused aeration system (diffusers, anchoring system, compressors, air flow meters, pressure gauges, drain values, other ancillary equipment) was approximately $50,000. Preparation cost for two sites (assuming land does not need to be purchased) was at $5,000, initial installation costs at $3,000; and environmental permitting at $10,000 Operational costs for 15 years were estimated at $111,000 (electricity plus $500/yr for equipment maintenance) to provide a rounded estimate of $180,000. This estimate does not include permanent structures for the shore-based equipment or a cost for extending power. While we did not go through a similar exercise for Stillwater Pond, the excellent agreement of initial and refined costs (before assuming inflation) for Lovers Lake suggests that the initial estimate for Stillwater Pond is representative.

7.4.6 Permitting issues

Permits are generally required for aeration projects, but the positive benefits from circulation are easily comprehended by agencies and it would likely be one of the easier lake management processes to get approved. For this restoration option, the likely requirements for environmental permitting are a full Notice of Intent from the Chatham Conservation Commission and a MA DEP Chapter 91 license. State regulatory

review would be expected from MA DEP, MA Natural Heritage, and MA DFW. It is assumed that under MEPA, an ENF or less would be required, due to adoption of the FGEIR as the generic impact statement for such lake restorations. It is our understanding that the location of the pond within an ACEC will likely not change this regulatory position. Environmental permitting costs were estimated at approximately $10,000.

7.4.7 Evaluation of potential applicability of method for Lovers Lake and Stillwater Pond

The applicability of artificial circulation for restoration of Lovers Lake and Stillwater Pond was evaluated. The factors used for this evaluation were technical feasibility, expected water quality improvement, longevity, cost-effectiveness, and permitting issues.

The technical feasibility review indicates that artificial circulation or destratification would be a potential option for restoring deep water oxygen levels in Lovers Lake and Stillwater Pond and reducing internal phosphorus recycling. Similar installations have shown that, given sufficient airflow, a waterbody can be made to circulate. However, based on the morphometry, depth, and thermal structure of the two ponds, it was judged that the conditions of Lovers Lake make it much more conducive to mixing by aeration than Stillwater Pond.

Lovers Lake is shallower, has a more gradual thermocline, and a small hypolimnion volume (Figures 3-1a,b; Figures 3-2a,b). Anoxia is not restricted to the hypolimnion, but is present in a considerable portion of the upper water. The increase of phosphorus in surface waters of this pond in the summer time indicates that phosphorus release from “epilimnetic” sediments is an important factor. Finally, this pond is subject to intense blue-green algal blooms that might be dissipated by circulation.

In contrast, Stillwater Pond has a deep basin capable of producing a strong, persistent thermocline that provides a larger energetic barrier. Disrupting and maintaining destratification would take much more energy (airflow) and the pond may be prone to partial stratification due to its poor vertical transfer (i.e., indicated by the high Osgood number). Its very high oxygen demand suggests a great reservoir of organic substrate in the bottom waters that could also be problematic in the short-term for successful assimilation in upper water when mixed.

Review of the literature indicates some uncertainty as to how well the water chemistry and ecosystem would respond to this unnatural limnological state and whether it would be beneficial. Lovers Lake appears less unpredictable than Stillwater Pond in this regard. This level of uncertainty led to a conservative assumption of a 60% reduction of the internal phosphorus load, with lesser expectations for Stillwater Pond. However, this treatment provides the additional benefit of greatly increasing the amount of habitat for fish and other aquatic organisms and likely shifting the ponds away from dominance by blue-green algae.

There is no substantial longevity associated with this technique since the positive benefits start to decline as soon as the diffuser is taken off-line. Costs are relatively low compared to other restoration techniques, ranging between $180,000 for Lovers Lake and about $78,000 for Stillwater Pond for operation over a 15 year period, but this assumes that sites near the basins for installing the compressors and ancillary equipment will be secured. Environmental permitting is expected to be relatively simple and straight-forward.

Taken these factors together, ENSR recommends further consideration of artificial circulation for restoration of Lovers Lake and this is discussed further in Section 8.0 but does not recommend application of this technique in Stillwater Pond; mostly due to concerns over technical feasibility due to depth and thermal structure of the latter, the potential for the resuspension of high-oxygen demand organic sediments, and unpredictable impacts to lake biota. The relatively low costs of this method are attractive for Stillwater Pond, but the alternative method of hypolimnetic aeration (discussed below) appears to provide many of the same benefits without some of the potential risks of full circulation.

7.5 Hypolimnetic aeration

7.5.1 Introduction

The third of the four in-lake methods for reduction of nutrients and algal blooms selected for evaluation in the *Eutrophication Mitigation Study* is hypolimnetic aeration. In general, aeration puts air into the aquatic system, increasing oxygen concentration by transfer from gas to liquid and generating a controlled mixing force. Aeration is commonly used to mix shallow lakes, and is sometimes used as a mixing force for artificial circulation and destratification (see Section 7.4). This section looks specifically at hypolimnetic aeration as a technique intended to add oxygen to the bottom of deep lakes without disrupting stratification.

The oxygen transfer function is targeted to prevent hypolimnetic anoxia. By keeping the hypolimnion from becoming anoxic during stratification, hypolimnetic aeration should minimize the release of phosphorus, iron, manganese and sulfides from deep bottom sediments as well as decrease the build-up of undecomposed organic matter and compounds (e.g., ammonium) (Wagner, 2001; EOEA, 2004). Hypolimnetic aeration is also used to increase the volume of water suitable for habitation by zooplankton and fish, especially coldwater forms. In some applications, pure oxygen has been used in place of air to maximize transfer. Hypolimnetic aeration is usually not recommended if the maximum depth of a waterbody in less than 12 – 15 m and/or the hypolimnetic volume is relatively small due to the risk of destratification (Cooke et al., 2005).

Like artificial circulation, the effectiveness of aeration in controlling algae is linked to reducing available phosphorus, which in turn depends on benthic oxygen demand and the chemical content of the water and bottom sediment. Enough oxygen must be added to meet the hypolimnetic demand, and there must be an adequate supply of phosphorus binders present. If phosphorus binding agents are naturally insufficient, results can be improved by adding reactive aluminum or iron compounds to the process. The literature indicates that a tFE:TP ratio of 10:1 has been successful in facilitating the effects of aeration (EOEA, 2004). Another means of controlling algae is possible if the hypolimnetic aeration leads to the better survivorship of larger-sized zooplankton that are more effective grazers.

There are several approaches to hypolimnetic aeration that maintain stratification (see Figure 7-1 for illustrations). A full lift approach moves hypolimnetic water to the surface, aerates it, and replaces it in the hypolimnion. Another hypolimnetic aeration system is the partial lift system, in which air is pumped into a submerged chamber in which exchange of oxygen is made with the deeper waters (i.e., water and air bubbles are separated at depth and the air released back to the surface. The newly oxygenated waters are released back into the hypolimnion without destratification. An alternative approach involves a process called layer aeration (Kortmann et al., 1994) which provides depth-specific, stable oxygenated layers formed anywhere from the upper metalimnetic boundary down to the bottom of the lake. Each layer acts as a barrier to the passage of phosphorus, reduced metals and related contaminants from the layer below. Any of these three aeration systems can make a marked improvement in lake conditions, but it should be noted that practical experience has demonstrated that zones of minimal interaction can occur, possibly resulting in localized anoxia and possible phosphorus release.

7.5.2 Technical feasibility

This method was considered technically feasible for Lovers Lake and Stillwater Pond. These waterbodies have many of the elements that favor this technique including: a large fraction of the phosphorus budget due to internal recycling of the sediments, relatively low external phosphorus sources, high sediment oxygen demand (range of 200-1100 $mg/m^2/day$), and a relatively simple basin morphometry. It has previously been noted that the Lovers Lake and Stillwater Pond sediments have tFE:TP ratios between 23:1 - 27:1 (Table 3-5), so no additional binding agents are needed.

The most critical information for designing an aeration system is determining the oxygen demand that must be met by the system. To successfully aerate a hypolimnion, the continuous oxygen demand of the sediments

must be met, and experience dictates that the system should be slightly oversized to compensate for unpredicted variation in oxygen consumption, changes in hypolimnion volume, and mechanical breakdown. The oxygen demand may be reduced over time under long-term aeration as some of the organic material is broken down, but is unlikely to be eliminated.

For stratified lakes, the hypolimnetic oxygen demand can be calculated as the difference in oxygen levels at the time stratification formed and one or more points in time later during stratification. The compensatory water flow necessary to meet the oxygen demand is calculated based on the aerator input DO concentration (usually a little less than saturation). The oxygen input should be about double that of the measured oxygen demand, to allow for unmeasured and increased DO demand. There are a number of other factors complicating the assessment of oxygen demand; calculations and related interpretation for design purposes must consider all influences.

As described in Section 5.1, average areal oxygen demand in Lovers Lake is estimated at a predicted range of approximately 386 to 486 mg O_2/m^2/day (this value already includes the 2X safety factor). Stillwater Pond loses hypolimnetic DO at a maximum oxygen demand between 1482 and 2370 mg/m^2/day (includes the 2X safety factor). These demands were coupled with the volume of the hypolimnetic to evaluate the amount of total oxygen demand.

Necessary airflow is estimated by the following equation:

$$\textbf{Airflow}\ (m^3/\text{day}) = \frac{\textbf{Oxygen demand}\ (\text{mg } O_2/m^2/\text{day})\ \textbf{x}\ \textbf{Hypo SA}\ (m^2)\ \textbf{x}\ 2\ \textbf{x}\ 10^{-6}(\text{kg/mg})}{1.205(\text{kg}/m^3\ (\text{=air at 1 atm})\ \textbf{x}\ 0.2\ (\text{fraction of air as } O_2)}$$

However, the success of hypolimnetic aeration is more related to the effectiveness of oxygen transfer than simply a function of water mixing. A general rule is that 2.5% of the oxygen is transferred for each vertical meter of contact (Kortmann et al., 1994: EOAE, 2004). This dictates that there should be sufficient depth of hypolimnion to allow an effective transfer of oxygen. The required airflow is further adjusted upward to account for the depth of the hypolimnion by the factor = 100 / (Z (m) x 2.5).

The depth of Stillwater Pond is about 8 meters in July producing a factor of 100 / (8 x 2.5) = 5. This represents the amount of additional airflow needed to meet oxygen demand. In contrast, Lovers Lake has a shallower summer hypolimnion estimated at about 3.5 m in the northern basin, so there would be a factor of increased airflow greater than 11. Further calculation of final airflow design also takes into account other design factors such as the depth of air injection, orifice size in the diffuser tube, as well as friction losses and pressure requirements.

In the Chatham ponds, it is likely that hypolimnetic aeration would be achieved better with a partial-lift aeration device suspended at depth, usually extending from below to just above the thermocline. This sub-surface device provides less aesthetic concerns for sight and odor, and does not provide a barrier to surface recreation. Based on the available hypolimnetic depth, a structure about 8 m could be installed in Stillwater Pond with a shorter (3.5 m) device in Lovers Lake. Siting and installing this device will require the assistance of divers and a diver would also be necessary for annual maintenance activities.

Once installed, the hypolimnetic aerator would be operated from the beginning of thermal stratification until the autumnal turnover. To make sure that it effectively operating it will be necessary to monitor the water column regularly and, in particular, the oxygen content in the hypolimnion. The desire is to match the oxygen demand to keep the hypolimnion oxic (minimum of 5-6 mg/L would be sufficient to meet all habitat needs), but not provide too much airflow to inadvertently destratify the lake. Again, careful design and size of the equipment are essential.

As with the artificial circulation, there is a need for suitable and secure sites for long-term seasonal (or permanent) placement of air compressor and shoreline piping, with suitable access to high voltage (three-

phase) power (getting access to adequate power supplies can costly). Equipment could be placed on a gravel pad, placed in a pre-fabricated structure, or located inside a more permanent building (e.g., concrete block). The size requirements would be on the order of 50-100 ft^2. To reducing piping and power requirements, these should be sited reasonably close to each of the target basins but be suitably screened from local residences to prevent aesthetic issues (noise, sight) or placed in a silenced enclosure. Candidate site assessment was identical to that conducted for artificial circulation (see discussion of potential sites in Section 7.4.2). As before, selection of the final site would be part of the implementation planning and permit phase and it was assumed that this could be obtained at little or no cost to the Town.

7.5.3 Expected water quality or recreational improvements

The ability of hypolimnetic aeration to improve water quality has worked in many but not all waterbodies. Unacceptable results have typically been traced to inadequate equipment or operational measures (EOEA, 2004). A review of case studies indicated that 14 of 15 lakes for which this application was installed showed an increase in hypolimnetic DO (usually up to 7 mg/L) following aeration and 8 out of the 9 were data were available showed some decrease in TP ranging between 30-70% (Cooke et al., 2005). In previous similar analyses, ENSR has estimated between 60-80% effectiveness in phosphorus reduction (ENSR, 2001). Based on these factors, ENSR assumed 70% reduction in phosphorus recycling. This level of reduction, if achieved, would reduce the phosphorus loading for both ponds but would not get either well below the permissible load. For Stillwater Pond, there may be an increase in SDT associated with the long-term phosphorus reduction, but this may not be seen if Lovers Lake is left untreated.

7.5.4 Longevity

Hypolimnetic aeration, similar to artificial circulation, is an active treatment, and must be kept continual running during the summer months or the associated positive benefits cease. There are negligible residual positive effects when the power is turned off. Indeed, given the small volume of the hypolimnion for both ponds, it will start to return to ambient (anaerobic) conditions relatively rapidly.

Cooke et al. (2005) reviewed a number of examples of aeration and noted that available phosphorus tends to decline by one to two thirds during aeration, but quickly rises to pre-aeration levels when treatment is ceased. Aeration promotes binding activity and bound phosphorus does not necessarily become immediately available after aeration ceases, but can be released again under low redox conditions.

7.5.5 Cost-effectiveness

Hypolimnetic aerators are sophisticated devices (often custom-built) that are anchored and suspended in the water column, so the application of generic per acre costing factors for aeration available in the FGEIR seemed less reliable. Accordingly, a more informed estimate was sought from a highly qualified vendor of aeration equipment (R.Geney – pers. comm.). Use of this information does not constitute an endorsement of a particular brand or type of equipment by ENSR, but provides a more realistic cost estimate for comparison purposes. As before, we used the 15 year period of treatment for comparative purposes and estimated an average 150 day period of treatment. Due our understanding of current electrical costs, the estimate of $20/day for power requirement was based on one compressor with a 7.5 HP output. Due to the rising cost of electrical power, we assumed an inflation rate for electrical power of 2%/yr.

The capital cost of the hypolimnetic aeration system (diffuser device, anchoring system, air supply lines, compressors, and other ancillary equipment) was approximately $71,000. Site preparation costs (assuming land does not need to be purchased) were at $3,000, initial installation costs at $5,000 and environmental permitting at $10,000. Operational costs for 15 years were estimated at $74,000 including annual maintenance by divers ($1,000/yr), equipment replacement at ($500/yr) to provide a rounded estimate of $165,000. This

estimate does not include a permanent structure for the shore-based equipment nor a cost for extending power.

7.5.6 Permitting issues

Permits are required for aeration projects, but hypolimnetic aeration is a generally approved lake management processes, having few adverse side effects. For this restoration option, the likely requirements for environmental permitting are a full Notice of Intent from the Chatham Conservation Commission and a MA DEP Chapter 91 license. State regulatory review would be expected from MA DEP, MA Natural Heritage, and MA Division of Fish and Wildlife. It is assumed that under MEPA, an ENF or less would be required, due to adoption of the FGEIR as the generic impact statement for such lake restorations. It is our understanding that the location of the pond within an ACEC will likely not change this regulatory position. Environmental permitting costs were estimated at $10,000.

7.5.7 Evaluation of applicability of method for Lovers Lake and Stillwater Pond

The applicability of hypolimnetic aeration for restoration of Lovers Lake and Stillwater Pond was evaluated. The factors used for this evaluation were technical feasibility, expected water quality improvement, longevity, cost-effectiveness, and permitting issues.

The technical feasibility review indicates that hypolimnetic aeration would be a good potential option to reduce internal phosphorus recycling in Stillwater Pond. The characteristics of this basin and thermal structure are conducive to reduction of the amount of phosphorus generated there. Even though the pond does not turn over until late in the season, the very large phosphorus concentration gradient is likely to lead to some transfer via diffusion through the thermocline. The low SDT in the fall also suggests that phosphorus is being supplied and is supporting an algal bloom. The depth of the hypolimnion and the stability of the thermocline would also provide a better transfer of oxygen and little risk of destratification.

On the other hand, it was judged that Lovers Lake would not be a good candidate as it is shallower and lacks significant hypolimnetic volume during summer. Internal mixing events in Lovers Lake apparently reduce accumulation of phosphorus in this layer, so hypolimnetic aeration will provide little reduction if employed in this zone. Oxygen transfer would be poor due to the shallow depth of hypolimnion and there is a greater risk of destratification.

An estimate of 70% reduction of the internal phosphorus load ins Stillwater Pond was made by comparison to the range of reduction noted in the literature and best professional judgment (BPJ). This was based on the simple morphometry, adequate depth for oxygen transfer, and very stable thermal structure. It appears to be a good setting for this type of device. In addition, this treatment provides the additional benefit of providing an additional amount of habitat for fish and other aquatic organisms.

There is no real longevity associated with this technique since the positive benefits start to decline as soon as the aerating device is taken off-line. The cost for operation of a hypolimnetic aerator for Stillwater Pond over a 15 year period was estimated at $165,000, but this assumes that a site near the basins for installing the compressors and ancillary power requirements be secured. Environmental permitting is expected to be relatively simple and straight-forward. Taken these factors together, ENSR recommends further consideration of hypolimnetic aeration for restoration of Stillwater Pond but not for application in Lovers Lake.

7.6 Nutrient inactivation

7.6.1 Introduction

The last of the four in-lake methods for reduction of nutrients and algal blooms selected for evaluation in the *Eutrophication Mitigation Study* is nutrient inactivation. Phosphorus inactivation typically involves some amount of short-term phosphorus precipitation (flocculation) during or just after application, but mainly aims to achieve long-term control of phosphorus release from lake sediments by adding as much phosphorus binder to the lake as possible, within the limits dictated by environmental safety. This technique is most effective after other nutrient loadings from the watershed are sufficiently reduced, as it acts only on existing phosphorus reserves, not new ones added post-treatment.

Good candidate lakes for this procedure are those that have had low levels of external nutrient loads and have demonstrated a high internal phosphorus load (release from sediment). High alkalinity is also desirable (but not essential) to provide buffering capacity. Highly flushed impoundments are usually not good candidates because of an inability to limit phosphorus inputs. Treatment of lakes with low doses of alum may effectively remove phosphorus from the water column, but may be inadequate to provide long-term control of phosphorus release from lake sediments.

Aluminum has been widely used for phosphorus inactivation, mostly as aluminum sulfate and sometimes as sodium aluminate, as it binds phosphorus well under a wide range of conditions, including anoxia. In practice, aluminum sulfate (often called alum) is added to the water and colloidal aggregates aluminum hydroxide ($Al(OH)_3$)are formed. These aggregates rapidly grow into a visible, brownish white floc, a precipitate that settles to the sediments in a few hours to a few days, carrying sorbed phosphorus and bits of organic and inorganic particulate matter in the floc. The floc settling through the water column typically has a very immediate clearing effect on water transparency. After the floc settles to the sediment surface it is incorporated into the sediment matrix where it will continue to bind with phosphorus. If enough alum is added, a layer of 1 to 2 inches of aluminum hydroxide will cover the sediments and significantly retard the release of phosphorus into the water column as an internal load. In lakes where sufficient reduction of external nutrient loading has occurred, this can create a phosphorus limitation on algal growth.

Alum applications for pond restorations are generally made from specially designed barges that can support the dual chemical injection system that extends into the water as well as the large chemical storage tanks (one for alum, one for sodium aluminate). Application of the alum mixture is generally best done by rapid injection and mixing at 10-15 ft depth (if achievable with the injection system). This minimizes the amount of drift of floc material by wind or wave action and also provides a potential refuge for fish in case of aluminum toxicity.

Nutrient inactivation has received increasing attention over the last two decades as long lasting results have been demonstrated in multiple projects, especially those employing aluminum compounds (Welch and Cooke, 1999). The FGEIR provides several examples of New England lakes where alum application has resulted in significant reductions in internal phosphorus loading and subsequent increases in desirable water quality parameters such as SDT depth or amount of hypolimnetic DO including: Annabessacook Lake, ME; Kezar Lake, NH; and Lake Morey, VT (EOEA, 2004). Phosphorus inactivation has been successful in treating some shallow lakes (Welch et al., 1988; Gibbons, 1992; Welch and Schrieve, 1994), but has been unsuccessful in cases where the external loads were not been controlled prior to inactivation (Barko et al., 1990; Welch and Cooke, 1999).

More locally, alum treatment has been conducted at several lakes on Cape Cod including Hamblin Pond, Barnstable; Ashumet Pond, Mashpee and Falmouth; and Long Pond, Harwich and Brewster. Both Ashumet Pond and Hamblin Pond have shown positive responses to alum treatment in reducing internal phosphorus recycling. Application of alum to the latter resulted in a short-term fish-kill, but is widely recognized as one of the most effective pond restoration on the Cape (CCC, 2006). Long Pond was treated with alum in September

2007 so evaluation of the effectiveness of the treatment in reducing phosphorus will need to await current monitoring results.

Despite major successes, addition of aluminum salts to lakes does have the potential for serious negative impacts, and care must therefore be exercised with regard to dosage and buffering capacity. The potential for toxicity problems is directly related to the alkalinity and pH of the lake water. In soft (low alkalinity) water, only very small doses of alum can be added before alkalinity is exhausted and the pH falls below 6.0.

At pH 6.0 and below, $Al(OH)_2$ and dissolved elemental aluminum (Al^{+3}) become the dominant forms. Both can be toxic to aquatic species. Soft water lakes must be buffered, either with sodium aluminate or other compounds, to prevent the undesirable pH shift while allowing enough $Al(OH)_3$ to be formed to control phosphorus release. A ratio of aluminum sulfate to sodium aluminate of 2:1 is expected to cause no change in system pH where buffering is needed. Maintenance of the ambient pH is an appropriate goal, unless the pH is especially high as a consequence of excessive algal photosynthesis, In many cases, alum treatment is often applied near the thermocline depth (even before stratification) in deep lakes, providing a precautionary refuge for fish and zooplankton that could be affected by dissolved reactive aluminum.

Other potential indirect adverse impacts relate to the spread of macrophytes and changes in water chemistry after addition of aluminum compounds. Although the sharp increase in water transparency is viewed as desirable in most cases, it may allow an existing rooted plant infestation to spread into new areas or deeper water. Aluminum sulfate treatments that reduce the pH may cause decalcification in sensitive organisms and may also limit calcium control of phosphorus cycling. Aluminum toxicity to humans has created substantial public controversy as regards treatment of lakes with aluminum, but concerns have not been supported by the bulk of scientific investigations (Harriger and Steelhammer 1989).

7.6.2 Technical feasibility

Treatment of lakes with alum to inactivate phosphorus is an accepted lake remedial strategy and this method is considered very feasible for Lovers Lake and Stillwater Pond. These two waterbodies have many of the elements that favor this technique including: a large fraction of the phosphorus budget due to internal recycling of the sediments, relatively low external phosphorus sources, high sediment oxygen demand (range of 200-1100 $mg/m^2/day$), and a relatively simple basin morphometry. It has previously been noted that the Lovers Lake and Stillwater Pond sediments have tFE:TP ratios between 23:1 - 27:1 (Table 3-5), so no additional binding agents are needed.

A ratio of aluminum sulfate to sodium aluminate of approximately 2:1 (usually closer to 1.8:1) is expected to cause no change in system pH where buffering is needed. This type of buffering mixture would be required in both Lovers Lake and Stillwater Pond, where surface alkalinities range from 16 to 20 mg/L (as $CaCO_3$) and those in the hypolimnion from 17 – 35 mg/L. As with other alum applications in low alkalinity waters, a comprehensive and well-designed monitoring plan will be required to make sure that both pH and aluminum levels are kept in acceptable ranges.

Effectiveness of alum treatment is strongly related to proper assessment of available phosphorus in the sediment, its flux into the overlying water column, and calculation of an appropriate dose of the aluminum binder. Current methods suggest that the dose should be at least ten times and preferably up to 100 times the measured available sediment phosphorus content methods (Rydin and Welch, 1998; 1999).

The amount of alum/aluminate mixture needed to treat the extremely phosphorus-rich sediments of Lovers Lake and Stillwater Pond was estimated by consideration of the total mass of phosphorus in the top 2 – 4 cm of the sediments (Table 3-5). As noted in Section 3.2.2, sediments in Lovers Lake's northern basin have 33 - 86 g available P/m^2 while sediments in the southern basin have 36 to 85 g available P/m^2. In Stillwater Pond, there was from 26 to 72 g available P/m^2. These phosphorus concentrations are higher than concentrations

from lakes where alum application has been previously applied on Cape Cod. Based on the amount of aluminum need to achieve the desired 10:1 stoichiometry, an unusually large amount of the alum mixture would be required.

This amount of required alum would exceed that delivered by a single application within the common dose range used for New England lakes, ranging from 25-50 g. Completely matching the 10:1 alum ratio would result in the need for up to seven times the upper range of the dosages. ENSR suspects that a much lower absolute amount will be sufficient to bind up the phosphorus securely in the upper portions of the sediment. Accordingly, we calculated the amount of the alum mixture to create a final application of approximately 100 g Al^+/m2 at the sediment interface. This approach was used to provide chemical requirements to provide an interim dosage goal to allow for an approximate cost estimate. This total treatment is half of that recently delivered to a lake in Oregon (200 g Al^+/m2), but alkalinities were higher there.

ENSR recommends using the 50 g Al^+/m^2 (approximately that used at Ashumet Pond) and requiring more than one "pass" of the alum applicator, with sufficient time between applications to prevent buildup of unacceptable level of aluminum in the water column. Additional testing will be required as means of refining the process during the permit process, and we recommend sediment testing to determine more accurately whether a 10:1 ratio is required to fully inactive the available phosphorus or if lesser amounts are sufficient or more cost-effective.

The area of application was determined for each pond. For Lovers Lake, it appears that hypoxia is not confined to the thermally determined hypolimnion, but can extend as shallowly as 4 m during mid-summer conditions. This pond is likely getting epilimnetic phosphorus regeneration. We selected the area corresponding to the lake bottom greater than 4 m, which constitutes about 51% of the lake bottom or 19 acres total. For Stillwater Pond, we simply targeted the well-defined hypolimnion area under 6 m that is equal to 52% of the lake bottom or 9.25 acres.

One critical requirement is for a hard-surface access point for the mobilization of the specialized work barge and for periodic resupply of the barge's chemical storage tanks. Ideally, a large paved boat launch with a parking area is sought, since these units are brought on trailers by large trucks. As discussed earlier, there are size and legal access questions regarding the launch areas available. These may limit the size of the work barge deployable, require significant site preparation work, or require seeking private access elsewhere. Other possible solutions for application of alum mixtures could be considered, including shore-based tanks and a lighter boat being used to deploy the chemical injection lines over the pond surface. It may also be possible use the proposed whole-lake aeration system (and possibly the hypolimnetic aerator) to distribute the alum. At this time, it is assumed that these are challenging but surmountable obstacles. To account for these potential uncertainties, we added a 15% contingency fee to the cost estimates for alum treatment.

Timing of the application should be phased to avoid potential conflicts with ecological resources and recreational users of the pond but should be conducted during the period when the pond is stratified. A stable water column provides a better environment for settling, is conducive to more controlled placement of alum treatment at desired locations, and provides additional safety for aquatic receptors since the aluminum will be confined to certain locations and depth. Due to the timing of the herring run cycles and other spring spawners, the typical summer residence and recreation patterns, and the late autumnal turnover of these ponds, an alum application in mid-September to mid-October would be optimal.

7.6.3 Expected water quality or recreational improvements

Nutrient inactivation has the potential to significantly reduce internal loading, reduce algal densities and provide increased water clarity in Lovers Lake and Stillwater Pond. The range of reduction of release from the sediments can range from 60-90%. While this does not directly translate into a comparable reduction in the overall phosphorus budget (because internal loading is not 100% efficient in transfer), a significant portion of

the pond phosphorus budget can be eliminated in either pond. Moreover, the magnitude of reduction is such that either pond would be near or below permissible load presented in Tables 6-1 and 6-2. By reducing the significant internal load, Lovers Lake and Stillwater Pond should experience reduced algal blooms unless other watershed inputs increase, which is unlikely to be the case for either Lovers Lake or Stillwater Pond. Phosphorus inactivation presents a valid alternative to either destratification or hypolimnetic aeration for reducing sediment releases of phosphorus from the sediment.

7.6.4 Longevity

Longevity of alum treatments has generally been excellent where external inputs of phosphorus to the system are minimal or have been controlled (Payne et al. 1991). A review of 21 well-studied phosphorus inactivation treatments using aluminum (Welch and Cooke 1999) indicates that longevity of effects is typically 15 years or more for dimictic (summer stratified) lakes and about 10 years for shallow, polymictic (unstratified) lakes. Application of alum to Hamblin Pond in 1995 continues to be effective in providing greatly improved water quality (CCC, 2006) and after 12 years post-implementation shows no sign of abatement. Ashumet Pond's phosphorus levels have also been reduced and water quality and SDT conditions have also improved considerably (AFCEE, 2007), but since additional phosphorus control measures are also in place at this pond, it cannot be strictly ascribed to the alum treatment.

Overall, ENSR believes that the potential longevity of the alum treatment to provide relief from problems related to internal phosphorus inputs is between 15 – 20+ years depending on the pond. For purposes of direct comparison to other pond restoration options, ENSR conservatively assumed a 15 year period of duration.

7.6.5 Cost-effectiveness

The cost of alum treatment was estimated based on ENSR's recent experience with alum treatment at Long Pond. Costs are based on a number of factors, including: the alum required (based on the proposed final treatment dose of 100 mg Al^{+}/m^{2}), area/depth of application, equipment mobilization, on-lake application days, monitoring and water quality sampling, design and planning, and environmental permits. Four quarters of post-implementation monitoring is included. For application to Lovers Lake, an area of 19 acres (lake bottom > 4 m) was estimated and in Stillwater Pond, an area of 9.25 ac was used. As noted above, there are challenges regarding access and ease of mobilization (basically trying to get big equipment into small ponds), while we feel these challenges are resolvable we accounted for this uncertainty by including a contingency fee of 15% to produce a higher value for the probable range of costs. This will also help account for some uncertainty regarding the future cost of chemicals as bulk alum has become more expensive (e.g., approximate 15% increase in price of bulk alum between 2007 and 2008 prices). For direct comparison with other pond restoration methods (see Section 7.7), we took an approximately median value from this range.

ENSR estimated that the costs associated with an "extended hypolimnion" alum treatment for Lovers Lake would range from approximately $122,500-$141,000, with a rounded median of $132,000. Costs for a hypolimnetic alum treatment of Stillwater Pond would range from approximately $76,000-$87,500, with a rounded median of $82,000.

7.6.6 Permitting issues

For this restoration option, the likely requirements for environmental permitting are a full Notice of Intent from the Chatham Conservation Commission, Permit to Apply Chemicals from MA DEP. State regulatory review would be expected from MA DEP, MA Natural Heritage, and MA Division of Fish and Wildlife. Environmental permitting costs were estimated at $12,000. It is assumed that under MEPA, an ENF would be sufficient since a full EIR is not required, due to adoption of the FGEIR as the generic impact statement for such lake restorations. It is our understanding that the location of the pond within an ACEC will likely not change this regulatory position. Environmental permitting was estimated at $12,000.

7.6.7 Evaluation of applicability of method for Lovers Lake and Stillwater Pond

The applicability of nutrient inactivation for restoration of Lovers Lake and Stillwater Pond was evaluated. The factors used for this evaluation were technical feasibility, expected water quality improvement, longevity, cost-effectiveness, and permitting issues.

The technical feasibility review indicates that nutrient inactivation by alum treatment would be a very effective option to reduce internal phosphorus recycling in both Lovers Lake and Stillwater Pond. Alum treatment provides one of the few ways to permanently reduce the root cause of internal recycling by binding up the phosphorus in the sediments. The low alkalinity found in the ponds dictates an alum mixture (estimated at around 2:1) and careful monitoring during the application period and periodically (estimated at quarterly) during the following year. Assays and jar tests with a finer range of ratios than usually employed are recommended for verification prior to any treatment, but the 2:1 ratio appears appropriate when high doses are applied.

Application of alum in Lovers Lake was expanded from just the hypolimnion to the lake bottom > 4 m to provide a more effective level of reduction. The potential for substantial phosphorus reduction may be less in Stillwater Pond since we do not observe significant mixing of bottom phosphorus into the water column during summertime (as predicted by its high Osgood number (Cooke et al., 2005)). However, in lakes that have strong anoxia, a substantial portion of the hypolimnion phosphorus (10% or greater) can diffuse across the thermocline and into the epilimnion. Other factors which increase this transfer include wind action and internal mixing along the thermocline which are in evidence in Lovers Lake.

Application of alum should provide a rapid short-term clearing of the water column and a long-term reduction in sediment recycling. While there is little question that the alum applied will bind up phosphorus in both lakes, the large mass of phosphorus in the sediments suggests that additional alum treatments may be required if the 100 mg Al^{+}/m^{2} is completely used up by the available sediment phosphorus. The effectiveness of lesser doses to sponsor excellent phosphorus reduction in other Cape Cod lakes (Hamblin, Ashumet) is encouraging, however, such that additional treatments may not be required.

An estimate of 75% reduction of the internal phosphorus load was made by comparison to the range of reduction (60-90%) noted in the literature and BPJ. It should be noted that treatment does not prevent development of hypolimnetic anoxia and will not directly result in a significant amount of habitat for fish and other aquatic organisms. Increases in the SDT depth and the amount of DO with depth have been noted at both Hamblin and Ashumet Pond following alum treatment, however.

Longevity associated with this technique was conservatively estimated at 15 years but could be longer. The cost for nutrient inactivation at Lovers Lake was approximately $122,500-$141,000, with a rounded median of $132, 000. Estimated costs for hypolimnetic alum treatment of Stillwater Pond were approximately $76,000-$87,500, with a rounded median of $82,000.

Environmental permitting is critical not complex (WPA NOI and chemical application permits were required at Long Pond), with the caveat that the ACEC status does not expand regulatory review. Of particular concern for the NOI Order of Conditions will be a detailed list of monitoring requirements, both for activities during and after applications.

In summary, ENSR recommends further consideration of nutrient inactivation for restoration of Lovers Lake and Stillwater Pond. The treatment is highly appropriate and should be very effective for both lakes.

7.7 Comparisons between in-lake management options

ENSR fully evaluated the four methods of interest for pond restoration for Lovers Lake and Stillwater Pond. The recommended in-lake options that should be considered further for the two pond systems include:

- Installation of a diffused air system for artificial stratification of Lovers Lake;
- Installation of a hypolimnetic aerator for Stillwater Pond;
- Application of alum for nutrient inactivation to the "extended hypolimnion" of Lovers Lake; and
- Application of alum for nutrient inactivation to the hypolimnion of Stillwater Pond.

For each of the ponds, two options were selected as appropriate. A summary of the costs and benefits of the two options for Lovers Lake is shown in Table 7-3 and in Table 7-4 for Stillwater Pond. All of these options have been standardized for a 15 year period of performance.

Table 7.3 – Comparison of pond restoration options – Lovers Lake

Feature	Artificial Circulation	Nutrient Inactivation
Capital cost (equip, site prep, install. permit)	$68,000	$122,500-141,000
Operational cost	$6,900/yr	$0
Maintenance cost	$500 /yr	$0
Total Cost /15 years	$180,000	$132,000
Area of Pond Treated	37.7 acres (100%)	19 acres (51%)
Internal P load reduction	60%	60-90%
Hypolimnetic Oxygen increase	2-7 mg/L	0-4 mg/L
Potential toxicity	None	Possible short-term aluminum toxicity if pH is <6 or >8.0

Table 7.4– Comparison of pond restoration options – Stillwater Pond.

Feature	Hypolimnetic Aeration	Nutrient Inactivation
Capital cost (equip, site prep, install. permit)	$89,000	$76,000-87,500
Operational cost	$3,500/yr	$0
Maintenance cost	$1,500/yr	$0
Total Cost /15 years	$165,000	$82,000
Area of Pond Treated	9.25 acres (52%)	9.25 acres (52%)
Internal P load reduction	70%	60-90%
Hypolimnetic Oxygen increase	2-6 mg/L	0-4 mg/L
Potential toxicity	None	Possible short-term aluminum toxicity if pH is <6 or >8.0

7.8 Reduction of future watershed inputs

Even where in-lake management is applied, watershed management is often necessary and certainly protects the investment made through in-lake techniques. Developed areas are normally the primary target of watershed management. Development of a watershed creates impervious surface that changes the hydrology of the area and tends to increase loading of pollutants to waterways. Pollutants falling from the sky as atmospheric deposition are not incorporated into soils as in forests or meadows, but rather are transported into the aquatic environment. Additional pollutants from human activities in developed areas include solids from exposed soils, nutrients from fertilizers and waste disposal, bacteria from waste disposal and pets, hydrocarbons from automotive and other machine use, and metals from a variety of sources. These are also carried into the aquatic environment and can cause water quality degradation and use impairment.

In the Lovers Lake and Stillwater watersheds, there is generally mixed land use with a large portion already in forested or protected status. Potential watershed management is particularly targeted at residential land close to the lake since it is more likely to impact water quality in the ponds. While nutrient loading analysis indicate that internal loading is the primary cause of water quality problems in Lovers Lake and Stillwater Pond, reductions in external watershed loading can preserve long-term water quality. Source reduction controls are methods used to reduce the amount of pollutants generated in the watershed, or to prevent their release to the environment. Techniques for reducing pollutant loads and associated impacts are discussed below.

7.8.1 Land use conversion

Land use conversion involves purchasing properties that contribute excessive amounts of pollutants and converting these properties to less deleterious land uses. For example, the Town or local Conservation Foundation may decide to purchase a residential property and convert the land to open space or simply buy

developable property and convert it to a protected status, thus reducing or preventing pollutant generation from this parcel of land. There does not appear to be any strong need for additional effort at Lovers Lake and Stillwater Pond, but opportunities sometimes arise and should be considered on a case-by-case basis.

7.8.2 Zoning and land use planning

This is a very important component in controlling watershed inputs to aquatic resources where development is not yet extensive. A strong relationship exists between land use type and pollutant generation, with developed lands typically generating greater pollutant loads than non-developed lands. Preserving undeveloped land in the Lovers Lake and Stillwater Pond watershed is highly recommended, with particular emphasis on preserving areas of land that form buffer zones along the lake. This is a very expensive proposition but already has been successfully pursued within the Lovers Lake and Stillwater Pond watersheds. The zoning ordinances in Chatham should be reviewed with maintenance of buffer strips along lakeshore properties in mind. As most of the developable shoreline properties have already been developed in accordance with current zoning regulations, however, the need for such action is greatly diminished.

With regard to future phosphorus loadings, an estimate of the potential impact of the hypothetical “build-out” of all buildable lots within the Lovers Lake and Stillwater Pond watersheds was developed. Based on discussion with Town staff, both existing conforming zoned lots and “grandfathered” (i.e., established before 1987) non-conforming lots were considered. The total number of buildable lots located within the entire watershed and those located within the 300 ft buffer zone around the upgradient shoreline were estimated for the ponds. The impact of these additional residences is discussed further in Section 8.0.

7.8.3 Bank and slope stabilization

Erosion control is an important component of an overall management plan designed to decrease pollutant loading to aquatic ecosystems. This is especially important in areas of new development or re-development, where soils are both exposed and susceptible to erosion. Stabilization of steep slopes and any exposed shoreline is also important. This is a recommended management technique in the Lovers Lake and Stillwater Pond watersheds, and the Town should maintain lists of susceptible areas and check them periodically. Property owners must take responsibility for stabilization after clearing, or not perform such clearing. The Cape Cod Commission has a model clearing and grading bylaw that the towns should consider. Inspection of the shoreline did not indicate large areas of unstable or failing slopes. Some erosion is occurring near the access points at both Ponds and small deposition areas are forming. Luckily, the amount of undeveloped shoreline is reasonably good with well-established riparian vegetation.

7.8.4 Behavioral modifications

Behavioral modifications involve changing the actions of watershed residents and pond users to improve water quality. Such changes may include conversion to non-phosphate detergents, elimination of garbage grinders, proper inspection and maintenance of septic systems, limits on lawn fertilization, and eliminating illegal dumping. Behavioral modifications can be brought about in two principal ways, through education and/or the implementation of local bylaws and bans. Education is a critical first step and should precede any attempt at regulation.

Education can be accomplished by mailing informative brochures addressing watershed management topics to all residents in the watershed, through the use of video programs on local access television, by placing informative signs in high access areas, or by holding public meetings for watershed residents. Public education relies heavily upon cooperation from residents and other lake users, and is not likely to result in major improvements in water quality by itself. However, some level of improvement has been noted in other studies and the education process sets the stage for community involvement and cooperation. Public

education is a recommended management technique for Lovers Lake and Stillwater Pond, and should focus on landscape management (buffer strips), waste water management, and waterfowl control.

7.8.4.1 Buffer strips

Buffer strips (or vegetated filter strips or grassed buffers) are areas of grass or other dense vegetation that separate a waterway from an intensive land use. These vegetated strips allow overland flow to pass through vegetation that filters out some percentage of the particulates and decreases the velocity of the storm water. Particulate settling and infiltration of water often occurs as the storm water passes through the vegetation.

Based on work done elsewhere and especially in Maine (Dennis et al. 1989), buffer strips need to be at least 25 ft wide before any appreciable benefit is derived, and superior removal requires a width >100 ft. Lesser widths may provide pollutant removal benefits in sandy Cape Cod soils, but evidence is scant and a minimum width of 25 ft is recommended for areas with slopes <2%. As the slope increases, the minimum should also increase; a 100 ft minimum is appropriate for slopes in excess of 20%. This will provide a minimum of 25% reduction in phosphorus transport. Creative planting and use of buffer strips can be a low cost, low impact means to minimize inputs to the aquatic environment. Requiring buffer strips for all new construction is not unreasonable and is workable in most cases. This regulation should include provisions to allow docks, limited beach areas, and winding paths to the pond. Establishing buffer strips for existing residential land is more difficult, and would best be accomplished through a combination of education and incentive (funding) programs.

The Town of Chatham currently requires a 50 ft “No Disturb Zone” as part of its local wetland bylaws and recognizes and regulates up to 100 ft of “Adjacent Upland Resource” area (Chatham Wetland Regulations Part IV. *Regulations for Adjacent Upland Resource Area*. Section 4.01-4.03).The adjacent upland resource areas is a protected resource area considered best left in an undisturbed and natural state, with permanent alterations to be avoided, if possible, and any disturbance temporary, minimal, or subject to mitigation.

This regulation provides additional protection to Lovers Lake and Stillwater Pond, but application is restricted to those properties and activities coming before the Chatham Conservation Commission due to a need for a permit or Notice of Intent (NOI) for activities in the buffer zone. Therefore, the town may also want to consider providing technical assistance to homeowners interested in retrofitting natural revegetation into the buffer areas of existing properties.

7.8.4.2 Waste water management

A properly functioning on-site waste disposal (septic) system can be an effective means of reducing pollutant loading to an aquatic ecosystem, but does not trap all pollutants and requires inspection and maintenance as do larger public systems. While many pollutants will be removed during passage through 100 ft of suitable soil, the concentration of phosphorus in septic system leachate is much higher than can be tolerated by lakes and ponds, so the greatest possible setback is desired. Title V requirements relate mainly to human health, and may not be restrictive enough for maintaining pond health over the longer term, especially in sandy soils.

The CCC has been imposing a setback of 300 ft for major projects, and has encouraged the towns to impose similar setbacks where feasible. Setting a target of 300 ft would appear sufficiently protective of the ponds, but it can not be definitively stated that a lesser setback is inadequate. Other considerations will undoubtedly play a role in setback determination, and the towns are advised to work with the Cape Cod Commission to establish a reasonable process for reviewing site-specific plans. Applying the greatest possible setback, to a limit of 300 ft, is desired within the constraints of property boundaries and site features.

As many residences are seasonal, another threat is from conversion to year round residency, a problem at many other Massachusetts lakes with dense communities around them. This is more difficult to regulate, but highlights the importance of adequate control of wastewater systems.

Maintenance and inspection of on-site waste disposal systems is a recommended management technique for the Lovers Lake and Stillwater Pond watershed. Education is the first step in alerting residents to this need. . Some effort should be made to educate septic system users of the limitations of those systems, and how users can minimize strain on system capabilities.

7.8.4.3 Waterfowl control

As discussed in the phosphorus budget section (Section 5.2), one currently “unmanaged” phosphorus source is waterfowl. Waterfowl, including ducks, geese, and seabirds, are a valuable natural resource and a source of recreation to the general public, bird watchers, and hunters. However, they are also a source of nutrients, bacteria, and avian diseases.

Of all the waterfowl, Canada geese are particularly opportunistic and can easily become accustomed to urban settings. In New England, resident Canada goose populations have increased dramatically since the 1960's. In urban areas, Canada geese populations have responded explosively to landscape features that provide expanses of short grass for food, lack of natural predators, absence of hunting, and hand feeding by some people.

Although most people find a few geese acceptable, problems develop if local flocks grow and the droppings become excessive (a goose produces a pound of droppings per day). Problems include over-grazed lawns, accumulations of droppings and feathers on play areas and walkways, nutrient loading in ponds, public health concerns at beaches and drinking water supplies, aggressive behavior by nesting birds, and safety hazards near roads.

At this stage, waterfowl impacts on either pond are not excessive, but given that a small amount of phosphorus sponsors a significant amount of algal growth, it is recommended that waterfowl should be tolerated but not encouraged to reside at the two ponds. This would include discouraging feeding by residents (see below), managing adjacent riparian shoreline areas to reduce access or attractive features (e.g., lawns right at water’s edge), and, as needed, more direct control methods. Watershed residents should be reminded that the feeding of wild waterfowl was prohibited by the Chatham Board of Health (BOH) in 2007 under its Animal Regulation. Section 11. *Ban on the Feeding of Waterfowl*. A compendium of useful geese management techniques is provided by Managing Geese in Urban Environments (Berryman, 1999).

8.0 Recommended eutrophication management restoration plan

The overall goals of the Eutrophication Mitigation Plan Study are to identify appropriate pond restoration treatments to: (1) eliminate, reduce or mitigate the release of phosphorus from the sediments; (2) improve the ecological health of the ponds; and (3) enhance the recreational and aesthetic qualities of the Lovers Lake and Stillwater Pond. To achieve these goals, restoration will require a significant reduction in the amount of phosphorus available from internal recycling. While many of the potential pond and watershed restoration options are not feasible or appropriate for use in the ponds (Section 7.2), four restoration methods were selected for detailed investigation of their potential applicability and effectiveness: dredging (Section 7.3); artificial circulation (7.4); hypolimnetic aeration (Section 7.5) and nutrient inactivation (Section 7.6). Of the four methods evaluated, only dredging was eliminated for application in either pond. The remaining three methods remain viable for application in one or both ponds. These potential applications are directly compared, by pond, in Tables 7-3 and 7-4.

8.1 Development of pond restoration options

Due to the effort and expense of conducting pond restoration, application of all of these pond restoration options is unlikely. Therefore selection among these options is necessary with a goal of optimizing potential water quality and recreation benefits against cost, effort, and schedule. ENSR has provided a series of potential options in Table 8-1. These are not the only options available but they provide the Town with a range of applications, a range of costs, and, hopefully, an understanding of the likely vision of the local stakeholders.

Some of the guiding principles that were used in the construction of the options were:

- **Restoration of Lovers Lake should precede Stillwater Pond** – restoration should begin in Lovers Lake since improvements in water quality there will benefit both ponds. It is still uncertain as to what extent internal recycling of phosphorus in Stillwater Pond is transported to the upper waters. On the other hand, surface flow from Lovers Lake directly affects water quality conditions in both ponds. Accordingly, the effectiveness of restoration conducted solely in Stillwater Pond without addressing Lovers Lake will be limited;
- **Protection of the herring fishery** – given the scarcity of viable herring runs on Cape Cod and regional declining numbers, it was assumed that protection of the fishery will be an important interest not only of the regulatory agencies but for the Town. We see this as a critical resource not only ecologically, but for enhancing the local citizenry's interest and support of restoration of the ponds. Ironically, management for herring may be responsible for some of the water quality issues there;
- **Reduction in internal recycling will provide the quickest improvement in water quality** – the historic and 2007 data strongly identify the dominant role of internal recycling and makes it the restoration target of choice. Application of either alum treatment or aeration/destratification should yield tangible improvements in water quality; and
- **Ecological expectations for the ponds are for a good quality mesotrophic pond** – pond restoration is targeted to reduce the frequency and magnitude of summer cyanobacteria (i.e., BGA) blooms and improve the ecological habitat, However, these ponds will still likely maintain a mesotrophic (intermediately productive) status even after restoration. This status should be appropriate for current uses.

8.2 Potential pond restoration options

Based on the principles identified in Section 8.1, ENSR developed a series of potential pond restoration options for Lovers Lake and Stillwater Pond, sorted in order of ascending estimated costs for implementation.

Table 8.1 provides the specific restoration tasks, an estimated cost, and a rationale for the development of the option to restore Lovers Lake and Stillwater Pond. As shown on Table 8-1, there are five options given for potential pond restoration, including the No Action Alternative. These options encompass a variety of approaches, management strategies and costs. All are appropriate but none is clearly superior since they all have advantages and drawbacks, different costs, or may represent choices between short-term vs. long-term approaches. Although not described explicitly on Table 8-1, watershed source control (Section 7.8) best management practices (BMPs) should be included as part of all options.

Two major concerns that have the potential to affect all of the restoration options are the lack of sizeable access for mobilization of large equipment to the ponds and the availability of three phase voltage to remote areas that would serve for equipment (compressor) pads or buildings. The small size of the ponds relative to other pond restoration means that they are less likely to benefit from the economy of scale that often characterizes costs in other larger lake. Finally, the nature and timing of potential funding sources may dictate the desirability of a restoration option. Lake whole-lake treatments such as alum are often supported by specific grants or budgeted as one-time events conducted over 1-2 seasons. Use of aeration would require lesser initial capital expenses but continued levels of funding for long periods, which may mean a yearly challenge for the town or pond associations to raise funds.

As identified in Table 8-1, Option #1, the No Action Alternative, describes the current management of the ponds. Based on the observations of local residents, the frequency and intensity of BGA blooms are increasing, however. At some stage of pond degradation, the diurnal cycle in DO caused by excessive algae could cause impairment or fishkills of the YOY alewife.

The first active pond restoration (Option #2) is termed the “Maintenance Approach” and calls for installation of an artificial circulation system in Lovers Lake. This option provides modest levels of water quality improvement but should be effective in shifting the conditions which favor BGA, thus increasing aesthetic qualities of the lake. This should also improve water clarity in Lovers Lake and improve swimming conditions somewhat. However, this option does not make a significant and permanent change to the phosphorus pools and is dependent on active aeration. This option does not call for active pond restoration in Stillwater Pond.

The “Phased Approach” describes two alternatives in which there is early management effort in Lovers Lake followed by an assessment period of 2-3 years to see water quality improvements in Lovers Lake, and then, as needed, implementation of additional pond restoration to Stillwater Pond. Both alternatives termed #3a and #3b start with an alum treatment in about half of the bottom area of Lovers Lake to bind phosphorus in the sediments. Following this application, a significant improvement in water quality is expected for Lovers Lake and some improvement in Stillwater Pond. A delay of up to 2-3 years might be used to see how this removal of influent phosphorus affects nutrient dynamics in Stillwater Pond. If the desired level of water quality is not attained, then two alternatives are suggested. In Option #3a, the second phase will be to conduct an alum treatment of Stillwater Pond. For Option #3b, the second phase would be to install a hypolimnetic aerator in the bottom of that pond. In considering Options #3a and #3b, the Town might view whether a large capital cost for a single activity (i.e., alum treatment) is more desirable than a smaller capital cost accompanied by long-term maintenance costs (i.e., installation and operation of an aerator).

The last option (#4) suggested is the “Aggressive Approach” which includes alum treatment for both basins as well as the installation of a circulation system in Lovers Lake. This incorporates options for reduction of historic phosphorus stored in the sediment and management of any residual phosphorus entering Lovers Lake. In this option, no evaluation period for the Lovers Lake treatment is assumed.

There are additional possibilities for various combinations of options not listed in Table 8-1, but those selected were considered among the most cost-effective and in accordance with our guiding principles.

8.3 Effectiveness of potential pond restoration options

The relative effectiveness of the various pond restoration options with regard to removal of phosphorus from Lovers Lake and Stillwater Pond is provided in Table 8-2. By comparison to Option #1 (No Action or Current Conditions) as the baseline condition, it can be seen how much the various options differ in the level and nature of phosphorus removal. Increasing phosphorus reduction is also related to the increasing cost of the treatment options (Table 8-1).

For Table 8-2, it was assumed that watershed runoff BMPs would achieve the high end of 60% effectiveness and aggressive behavioral modification could lead to 50% reduction in septic system inputs. We also conservatively assumed no changes in atmospheric or wildlife inputs, although there is some potential for reductions in the latter. By and large, the most conspicuous phosphorus budget decreases are due to reductions in the internal loading.

As discussed earlier, the improvements in the phosphorus budget of Lovers Lake also translate into reduction in the phosphorus budget of Stillwater Pond, since the export of phosphorus from the outlet of Lovers Lake is reduced. Note for Lovers Lake there is no difference in the phosphorus budget between Scenarios #3a and #3b, since the two options differ only in the nature of pond treatment in the downstream Stillwater Pond.

Table 8-3 translates the reduction in phosphorus achieved by the various options into the predicted water quality parameters associated with the resulting phosphorus budget. For reference, Table 8-3 includes the current modeled conditions and the modeled permissible load (see also Table 6-1), which represents the minimum amount of phosphorus reduction that should be achieved.

For informative purposes, we also predicted the amount of phosphorus reduction that would occur if sewering of the watershed occurred, but no other pond or watershed restoration options were implemented. It can be seen that sewering alone doesn't significantly alter the current phosphorus budget for either pond nor does it achieve the reduction of load necessary to meet the permissible conditions. Sewering, while a positive benefit for the trophic state of both ponds, is not sufficient, in itself to restore the ponds.

Looking at the amount of phosphorus loads resulting from Options #2, #3a, #3b, and #4 indicates all should push Lovers Lake down to an acceptable loading level. For Stillwater Pond, Option #2 provides limited relief but does not meet permissible phosphorus loading limits. All the other options (#3a, # 3b, #4) should place Stillwater Pond under the permissible condition.

8.4 Recommended eutrophication management restoration options

All of the candidate pond restoration scenarios (#2, #3a, #3b, and #4) provide significant phosphorus relief to one (#2) or both (#3a, #3b, and #4) ponds, but they represent very different options in terms of cost, ease of implementation, and the trade-off between capital cost and operational costs. ENSR evaluated the four candidate pond restoration scenarios as to which is most likely to be both technically and fiscally feasible, given the environmental setting and financial circumstances of the watershed and Town. Based on this evaluation, ENSR recommends that the Town select Option #3a as the restoration course of action.

ENSR recognizes that Town officials, shoreline residents, and pond watershed stakeholders will need review this report and these options carefully to reach consensus on how best to chart the future course of these important ecological resources, but we feel that Option #3a has the following advantages:

- It provides sufficient phosphorus reduction to significantly improve water quality and reduce the frequency and magnitude of nuisance algal blooms in both ponds. The additional investment represented by Options #3b or #4 do not provide a commensurate amount of improvement (e.g., mean SDT depth would increase by a few inches);

- Option #3a will improve the ecological health of the ponds, increase the amount of dissolved oxygen in lower depths, and be protective of the herring fishery;
- Nutrient inactivation, if conducted correctly, provides a simple and dependable treatment which can be finished in a short timeframe and has been shown to have a longevity of 15-20 years or more;
- Aeration options, while technically viable, represent a long-term commitment of personnel and labor for the foreseeable future. This has been successfully pursued in situations where institutional staff e.g., water supply staff) are available to operate, maintain, and repair equipment, but would likely be less successful in the case of Lovers Lake or Stillwater Pond due to limits of Town or watershed stakeholders resources;
- Installation of anchored aeration devices could lead to potential impairments of fishing or boating due to snagging or fouling of anchors or fishing gear. Power supply (both accessibility and rising costs) are also a concern. Nutrient inactivation would lead to a short-term disruption to recreational activities but would not leave a tangible obstacle;
- Option #3a represents a single expenditure for a Town budget or applicable grant rather than a continuing operations and maintenance expenditure to be considered annually. Failure to pass such an item would set the ponds back to the current, unimproved conditions. Alternative financial arrangements can be made but may also be complicated; and
- Nutrient inactivation appears to be an acceptable option with regard to some potential funding grants (see below).

There are possible concerns regarding Option #3a namely, access for treatment vessels, the accelerating cost of alum and aluminate, and the potential for lay public fears regarding introduction of “chemicals” to the waterbodies. However, none of these appears insurmountable and the advantages greatly outweigh these concerns.

While recommending Option #3a, ENSR also firmly believes that watershed protection measures should also be implemented, as this will be the best means to prevent future eutrophication of the ponds. ENSR recommends incorporating the selected pond restoration and watershed management into a comprehensive watershed eutrophication mitigation plan to address nutrients in the two ponds and downstream resources (e.g., Ryder’s Cove) as well as related outcomes of cultural eutrophication (e.g., increased pathogens) in Ryder’s Cove and Frost Fish Creek.

8.5 Funding sources for pond restoration

Pond restoration is imperative to improve the water quality and recreational usage of Lovers Lake and Stillwater Pond, but such activities are expensive and may be beyond the resources of the Town and local stakeholders. Therefore, potential funding sources for pond restoration were identified, including:

- Town Budget;
- Legislative Budget funding
- MA DCR Water Quality Grants;
- Clean Water Act Section 319 Watershed Grants;
- Coastal Zone Management Grants; and
- Other grants or funding sources.

8.5.1 Town budget

It is possible to fund pond restoration activities through the Town's annual budget. This would be possible by introduction of a specific set-aside or line item associated with a pond restoration task. ENSR's experience indicates that passage of such items through Town budget process is usually uncertain unless strongly championed by stakeholders and interested Town officials. In addition, there is often more success in the timely funding of a large, one-time request than in making an appreciable annual budget request over many years.

8.5.2 Legislative budget

It is possible to fund pond restoration activities through the inclusion of a line item on the State's annual budget. This could be possible by introduction of the funding on a bill by the local State legislator. Typically, watershed stakeholder need to contact and educate local and State elected officials to provide them with the information and political motivation to enact such legislation bills. While this is not easily nor swiftly done, it has been successfully pursued for lake restoration (e.g., Long Pond alum treatment).

8.5.3 MA DCR lake and ponds grant program

One important source of state funding for pond restoration has been the MA DCR Lake and Ponds grant program. This grant program awards grants for the protection, preservation and enhancement of public lakes and ponds in the Commonwealth. A maximum grant of $25,000 is available to eligible applicants on a 50/50 cost sharing basis (i.e., the applicant must match the State grant with an equivalent amount of money or "in-kind" services). The grant program is intended to help municipalities and local organizations that are struggling to meet the challenges of providing long term solutions for lake and ponds management. Information on this program is available at: http://www.mass.gov/dcr/grants.htm

Discussion with the MA DCR Acting Director, Office of Water Resources (Ms. Anne Monnelley) in March 2008 indicates that the current (2007-2008) MA DCR budget does not contain grant money. However, MA DCR has earmarked $2M in the upcoming Massachusetts Environmental Bond Act to be voted on in June 2008. This would result in the availability of grants in 2009 in the $25-$50,000 range, with a focus on invasive species (not a large issue at either of the two ponds). Overall, this represents a potential future funding option but it requires passage of the Bond Act.

8.5.4 Section 319(h) non-point source pollution grant program.

Another source of funding is the Clean Water Act (CWA) Section 319(h) Non-Point Source Pollution grant program administered by the MA DEP. The majority of section 319(h) funding is designated for funding implementation projects in impaired waters. The grants have a 40% non-federal match of the total project cost. The match may be cash or in-kind, and must meet the same eligibility criteria as the federal funds.

Project evaluation of the competitive proposals substantially favor work that is consistent with the Massachusetts Watershed-based Plan (a tool for project development and implementation) and that will result in meeting Massachusetts water quality standards and/or restoring beneficial uses (i.e., in removal of the waterbody from the 303d list, Category 4 or 5 of the Massachusetts 2006 Integrated List of Waters). Projects should be of manageable size, but should strive to be comprehensive projects addressing all major identified nonpoint sources affecting water quality in the watershed or subwatersheds. All 319 projects are required to provide quarterly reporting as well as a Final Report. Details on the grant program are provided at: http://www.mass.gov/dep/water/319rfr09.htm

Discussion with the MA DEP Section 319 Program Coordinator (Ms. Jane Peirce) indicated that previous watershed non-point source granting cycles have allowed (and encouraged) alum treatment as a fundable

option As indicated above, the grant proposal needs to involve watershed and pond restoration activities in response to a defined TMDL process. As noted earlier in this report, Ryder's Cove is listed for nutrients and pathogens and Frost Fish Creek is listed for pathogens. Overall, the Section 319 grant program provides an excellent opportunity for funding some of the pond restoration options in Lovers Lake and Stillwater Pond.

8.5.5 Coastal zone management non-point source pollution (Coastal NPS) grants

Coastal Zone Management (CZM) provides funding through the Coastal Nonpoint Source Pollution (Coastal NPS) grant program. This program assists public and non-profit entities in implementing nonpoint source pollution control efforts. Coastal NPS grant funding can be used for watershed- or subwatershed-scale NPS assessments, development of local planning tools, public education and outreach, design and/or implementation of Smart Growth and Low-Impact Development (LID) strategies for NPS control, and efforts to eliminate or manage pollution from septic systems and publicly owned marinas. Applicability of the Lovers Lake and Stillwater Pond restoration options is not an easy fit. Further, CZM did not have funding available through the Coastal NPS Grant Program in FY 2008 and its status for 2009 is uncertain. Details on the grant program are provided at: http://www.mass.gov/czm/coastalnpsgrants.htm.

8.5.6 Other grants or funding options

Funding of restoration activities can be done at a local level by stakeholder groups, but typically such funds are used as a local match for state of federal grants. Other potential funding opportunities may arise due to the inherent characteristics of Lovers Lake and Stillwater Pond, namely the anadromous herring run. This may qualify for such programs as the Community-Based Habitat Restoration Projects funded through the FishAmerica Foundation (FAF) and the National Oceanographic and Atmospheric Administration (NOAA) Restoration Center. Eligible projects must result in on-the-ground habitat restoration, clearly demonstrate benefits to marine, estuarine or anadromous fish resources, and must involve community participation through an educational or volunteer component tied to the restoration activities. Details on the FAF/NOAA grant program are provided at: http://www.fishamerica.org/images/grants/noaa08_rfp.pdf.

Table 8.1. Review of Potential Pond Restoration Options for Lovers Lake and Stillwater Pond, Chatham, MA.

#	Category	Specific Restoration Tasks	Est.($)	Rationale for Selection
1.	No Action	No in-pond restoration.	$0	Current conditions are impaired, but the Ponds are presumed to provide minimal ecological and recreational function. Conditions will not improve but should not degrade significantly over the next decade. Watershed & shoreline phosphorus source reduction where possible.
2.	Maintenance Approach	**LL**: install artificial circulation. **SP**: no in-pond restoration.	$180,000	Destratification in Lovers Lake will provide least costly means of reducing internal P recycling. Pond still very productive, but less BGA and fishery/benthic habitat is improved and expanded. Modest water quality improvements will extend into Stillwater Pond epilimnion. Watershed & shoreline phosphorus source reduction where possible.
3a.	Phased Approach Alternative 1	**LL**: "expanded" hypolimnetic pond alum treatment and monitoring. **SP**: hypolimnetic alum treatment and monitoring.	$214,000	Large reduction in both deeper epilimnetic and hypolimnetic sediment P-recycling. Significant improvement in water quality expected with respect to DO and SDT. A 2-3 year delay allows evaluation of the positive WQ impact on Stillwater Pond. If needed, alum treatment in SP will greatly reduce P-budget. Watershed & shoreline phosphorus source reduction where possible.
3b.	Phased Approach Alternative 2	**LL**: "expanded" hypolimnetic pond alum treatment and monitoring. **SP**: delayed (3 yr) installation of hypolimnetic aeration.	$297,000	Large reduction in both deeper epilimnetic and hypolimnetic sediment P-recycling. Significant improvement in water quality expected with respect to DO and SDT. A 2-3 year delay allows evaluation of the positive WQ impact on Stillwater Pond. If needed, install hypolimnetic aerator in SP central basin. Watershed & shoreline phosphorus source reduction where possible.
4	Aggressive Approach	**LL**: "expanded" hypolimnetic alum treatment and monitoring; followed by artificial circulation. **SP**: hypolimnetic alum treatment and monitoring.	$474,000	Large reduction in sediment P-recycling for both ponds. Significant improvement in water quality in entire system expected with respect to DO and SDT and shift of N:P ratios. Destratification in LL to keep basin oxic and reduce organic build-up, good water quality is exported to epilimnion of SP where herring fishery resources benefit. Alum treatment in SP will greatly reduce P-budget. Watershed & shoreline phosphorus source reduction where possible.

Table 8-2. Lovers Lake and Stillwater Pond - Restoration Option Phosphorus Reduction

Lovers Lake

	Scenario 1: Modeled Current Conditons	Option #2		Option#3a		Option #3b		Option #4	
Phosphorus Inputs	TP Load (kg/yr)	% TP Reduction	TP Load (kg/yr)	% TP Reduction	TP Load (kg/yr)	% TP Reduction	TP Load (kg/yr)	% TP Reduction	TP Load (kg/yr)
ATMOSPHERIC	3.8	0	3.8	0	3.8	0	3.8	0	3.8
INTERNAL	18.3	60	7.3	75	4.6	75	4.6	90	1.8
WATERFOWL	4.0	0	4.0	0	4.0	0	4.0	0	4.0
SEPTIC SYSTEM	4.6	50	2.3	50	2.3	50	2.3	50	2.3
GROUNDWATER LOAD	0.3	0	0.3	0	0.3	0	0.3	0	0.3
WATERSHED RUNOFF	11.5	60	4.6	60	4.6	60	4.6	60	4.6
TP Total Load:	**42.5**		**22.3**		**19.6**		**19.6**		**16.8**

Stillwater Pond

	Scenario 1: Modeled Current Conditons	Option #2		Option#3a		Option #3b		Option #4	
Phosphorus Inputs	TP Load (kg/yr)	% TP Reduction	TP Load (kg/yr)	% TP Reduction	TP Load (kg/yr)	% TP Reduction	TP Load (kg/yr)	% TP Reduction	TP Load (kg/yr)
ATMOSPHERIC	1.9	0	1.9	0	1.9	0	1.9	0	1.9
INTERNAL	26.6	0	26.6	75	6.7	70	8.0	75	6.7
WATERFOWL	2.0	0	2.0	0	2.0	0	2.0	0	2.0
SEPTIC SYSTEM	2.6	50	1.3	50	1.3	50	1.3	50	1.3
TRIBUTARY FROM LL	15.0	48	7.9	54	6.9	54	6.9	60	5.9
GROUNDWATER LOAD	0.0	0	0.0	0	0.0	0	0.0	0	0.0
WATERSHED RUNOFF	0.4	60	0.2	60	0.2	60	0.2	60	0.2
TP Total Load:	**48.5**		**39.8**		**18.9**		**20.2**		**17.9**

Table 8 - 3. Current Trophic Conditions and Potential Restoration Objectives.

Lover's Lake

Description	Total P Load (kg/yr)	Mean In-lake P (ug/L)	Mean In-lake chl a (ug/L)	Mean SDT (m)
Scenario 1: Current Modeled Conditions:	42.5	38.2	17.1	1.4
Modeled Permissible Load:	26.0	23.4	9.1	2.1
Modeled with Town Sewering:	38.0	34.0	15.0	1.6
Option #2	22.3	21.5	8.2	2.2
Option #3a	19.6	19.1	7.0	2.4
Option #3b	19.6	19.1	7.0	2.4
Option #4	16.8	16.5	5.8	2.7

Stillwater Pond

Description	Total P Load (kg/yr)	Mean In-lake P (ug/L)	Mean In-lake chl a (ug/L)	Mean SDT (m)
Scenario 1: Current Modeled Conditions:	48.5	40.0	18.0	1.4
Modeled Permissible Load:	22.0	18.4	6.7	2.5
Modeled with Town Sewering:	46.0	38.0	17.2	1.4
Option #2	39.8	33.1	14.3	1.6
Option #3a	18.9	15.7	5.4	2.8
Option #3b	20.2	16.8	5.9	2.7
Option #4	17.9	14.9	5.1	2.9

9.0 References

Ahrens T.D. and P.A. Siver, 2000. *Trophic conditions and water chemistry of lakes on Cape Cod, Massachusetts*. Lake and Reservoir Management 16: 268-280.

Anderson, L. 2007. Personal communication with Dr. Lars Anderson, research scientist (University of California –Davis and U.S. Dept. of Agriculture Research Station) regarding his observations o performance of surface circulators in South Lake Tahoe, CA.

Babin, J., E. Prepas, T. Murphy and H. Hamilton 1989. A test of the effects of lime on algal biomass and total phosphorus concentrations in Edmonton stormwater retention lakes. Lake Reserv. Manage. 5:129-135.

Bachmann, R.W. 1980. Prediction of Total Nitrogen in Lakes and Reservoirs. In: *Proceedings of an International Symposium on Lake and Reservoir Management*, pp. 320-323, EPA, Washington, D.C.

Barko, J., W.F. James, W.D. Taylor and D.G. McFarland 1990. Effects of alum treatment on phosphorus and phytoplankton dynamics in Eau Galle Reservoir: A synopsis. Lake Reserv. Manage. 6:1-8.

Brooks, J.L. and S.I. Dodson. 1965. Predation, body size, and the composition of plankton. Science 150:28-35. Washington, D.C.

Cape Cod Commission (CCC). 2003. *Cape Cod Pond and Lake Atlas. Final Report*. CCC Water Resources Office, Massachusetts Executive Office of Environmental Affairs, University of Massachusetts School of Marine Sciences and Technology (SMAST). May 2003.

Cape Cod Commission (CCC). 2006. *First Order Assessment of the Indian Ponds. Final Report*. CCC Water Resources Office, Barnstable, MA. March 2003

Carpenter, S.R., Kitchell, J.F., Hodgson, J.R., Cochran, P.A., Elser, J.J., Elser, M.M., Lodge, D.M., Kretchmer, D., He, x., and C.N. Von Ende. 1987. Regulation of lake primary productivity by food web structure. Ecology 68:1863-1876.

Carpenter, S.R., Christensen, D.L., Cole, J.J., Cottingham, K.L., He, X., Hodgson, J.R., Kitchell, J.F., Knight, S.E., Pace, M.L., Post, D.M., Schindler, D.E., and n. Voichick. 1995. Biological control of eutrophication in lake. Environmental Science and Technology 29:784-786.

Chatham Department of Health and Environment (CDH&E). 2007. Geographic Information System (GIS) map files, water quality data, paper maps, well locations and data, and other assorted technical information.

Connecticut Department of Environmental Protection and ENSR. 2004. A Total Maximum Daily Load Analysis for Kenosia Lake in Danbury, Connecticut.

Cooke, G.D., E.B. Welch, A.B. Martin, D.G. Fulmer, J.B. Hyde, and G.D. Schrieve. 1993. Effectiveness of Al, Ca, and Fe salts for control of internal phosphorus loading in shallow and deep lakes. Hydrobiologia 253:323-335.

Cooke, G.D., R.T. Heath, R.H. Kennedy, and M.R. McComas. 1982. Change in lake trophic state and internal phosphorus release after aluminum sulfate application. Water Resources Bulletin 18(4):699-705.

Cooke, G.D., Welch, E.B., Peterson, S.A. and P.R. Newroth. 2005. Restoration and Management of Lakes and Reservoirs. 3rd edition. Lewis Publishers, Boca Raton, FL.

Dennis, J., J. Noel, D. Miller and C. Eliot. 1989. Phosphorus Control in Lake Watersheds. Maine Department of Environmental Protection, Augusta, ME.

Duncanson, R. 2000. Letter from Robert Duncanson to Technical Advisory Committee, CWMP RE: Lovers Lake; dated October 17, 2000.

EcoLogic, LLC and Stearns and Wheler (S&W). 2003. *Action Plan for Town of Chatham Ponds. Final Report*. November 2003. Hyannis, MA.

Eichner, E. 2007. Personal communication – updated PALS water quality database for Lovers Lake and Stillwater Pond (2001-2006). CCC Water Resources Office.

ENSR International. 2001. Management Study of Long Pond, Brewster and Harwich, Massachusetts. Prepared for Cape Cod Commission and Towns of Brewster and Harwich, MA.

Executive Office for Environmental Affairs (EOEA). 2003a. *Cape Cod Watershed Assessment and Action Plan – Pleasant Bay Watershed*. Boston, MA. February 2000.

Executive Office for Environmental Affairs (EOEA). 2003b. *Pleasant Bay Area of Critical Environmental Concern (ACEC) Factsheet.* Boston, MA. Summer 2003.

Executive Office for Environmental Affairs (EOEA). 2004. *Eutrophication and Aquatic Plant Management in Massachusetts Final Generic Environmental Impact Report (FGEIR).*prepared for MA DEP, MA DCR, and EOEA, June 2004.

Executive Office for Environmental Affairs (EOEA) and Massachusetts Department of Environmental Protection (MA DEP). 2004. *Stage Harbor, Sulphur Springs, Taylors Pond, Bassing Harbor, and Muddy Creek. Total Maximum Daily Loads for Total Nitrogen*. Report #MA96-TMDL-3. November 2004.

Fisher, T.R., Melack, J.M., Grobbelaar, J.A. and R.W. Howard. 1995. Nutrient limitation of phytoplankton and eutrophication of inland, estuarine, and marine waters. from: Phosphorus in the Global Environment. H. Tiessen (ed.). John Wiley and Sons, Ltd. London.

Frink, C.R. and W.A. Norvell. 1984. Chemical and physical properties of Connecticut Lakes. Conn. Agricultural Experimental Station Bulletin 817.

Harriger, R.D., and J.C. Steelhammer. 1989. Alzheimer's Disease, Aluminum and Drinking Water Treatment: A Review. General Chemical Corporation, Syracuse, New York.

Hecky R.E. and P. Kilham. 1988. Nutrient limitation in freshwater and marine environments: a review of recent evidence on the effects of enrichment. Limnol. Oceanogr. 33:796-822.

Higgins, G. R. and J.M. Colonell, 1971 Hydrologic Factors in the Yield of Watersheds. University of Massachusetts Water Resources Research Center Publication # 20 (PB-204 974). Amherst, MA 125 pp.

Horsley and Witten (H&W). 2003. *A Qualitative Survey of Pond Shoreline Vegetation and Anthropogenic Threats at Eleven Freshwater Ponds in the Pleasant Bay Area of Critical Environmental Concern*. February 2003.

Hurley, S. 2007. Personal communication – assorted information from MDFW project files for Lovers Lake and Stillwater Pond. Massachusetts Division of Fisheries and Wildlife. Barnstable, MA.

Jones, J. and R. Bachmann. 1976. Prediction of Phosphorus and Chlorophyll Levels in Lakes. JWPCF 48:2176-2184.

Kalff, J. 2002. *Limnology. Inland Water Systems.* Prentice-Hall Publishers. Upper Saddle River, NJ.

Kirchner, W. and P. Dillon. 1975. An Empirical Method of Estimating the Retention of Phosphorus in Lakes. Water Resourc. Res. 11:182-183.

Kortmann, R.W., Knoecklein, G.W. and C.H. Bonnell. 1994. Aeration of stratified lakes: theory and practices. Lake and Reservoir Management. 8:99-120.

Larsen, D. and H. Mercier. 1976. Phosphorus Retention Capacity of Lakes. J. Fish. Res. Bd. Can. 33:1742-1750.

LeBlanc, D.R., Guswa, J.H., Frimpter, M.H., and Lonquist, C.J., 1986, Ground-water resources of Cape Cod, Massachusetts: U.S. Geological Survey Hydrologic Investigations Atlas 692, 4 pls.

Lorenzen, M.W. and A.W. Fast. 1977. A Guide to Aeration/Circulation Techniques for Lake Management. EPA-600-3-77-04.

Massachusetts Department of Environmental Protection (MA DEP). 2003. Source Water and Protection (SWAP) Report for Chatham Water Department.

Massachusetts Department of Environmental Protection (MA DEP) 2007. Great Ponds of Massachusetts according to study by DEP/Waterways Regulation Program. Revised October 17, 2007. Available at http://www.mass.gov/dep/water/greatpon.doc.

Massachusetts Estuaries Program (MEP). 2007. *Linked Watershed-Embayment Model to Determine Critical Nitrogen Loading Thresholds for Stage Harbor, Sulphur Springs, Taylors Pond, Bassing Harbor, and Muddy Creek. Final Report.* Massachusetts Department of Environmental Protection (MA DEP) and the University of Massachusetts at Dartmouth. School of Marine Science and Technology (SMAST). February, 2007.

Massachusetts Division of Marine Fisheries. 2004. *A survey of Anadromous Fish Passage in Coastal Massachusetts. Part 2. Cape Cod and the Islands*. MA Department of Fish and Game and EOEA, May 2004.

Massachusetts Geographic Information System (GIS). 2007. Executive Office of Energy and Environmental Affairs. Maps and datalayers provided at: http://www.mass.gov/mgis/.

Massachusetts Natural Heritage and Endangered Species Program. 2006. Massachusetts Natural Heritage Atlas. 12th edition.

Norvell, W.A., Frink, C.R., and D.E. Hill. 1979. Phosphorus in Connecticut Lakes Predicted by Land Use. Proceedings of the National Academy of Sciences 76:5426-5429.

Pleasant Bay Resource Management Alliance. 2003. *Pleasant Bay Resource Management plan Update.* April 2003.

Post, D.M. 2006. The dual influences of alewife, *Alosa pseudoharengus*, on inland water quality: nutrient fluxes and food web effects. Project Summary. Connecticut Institute of Water Resources. Annual Report 2005-2006.

Reckhow, K. 1977. Phosphorus Models for Lake Management. Ph.D. Dissertation, Harvard University, Cambridge, MA.

Reckhow, K.H., M. Beaulac, and J. Simpson. 1980. Modeling Phosphorus Loading and Lake Response Under Uncertainty: A Manual and Compilation of Export Coefficients. U.S. Environmental Protection Agency, EPA-440/5-80-011, 214 pp.

Rydin, E. and E.B. Welch. 1998. Aluminum dose required to inactivate phosphate in lake sediments. Water Res. 32:2969-2976

Rydin, E. and E.B. Welch. 1999. Dosing alum to Wisconsin lake sediments based on in vitro formation of aluminum bound phosphate. Lake Reserv. Manage. 15:324-331.

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. Platform presentation at National NALMS Conference. Orlando, FL.

Smith, A.E., Craven, S.R. and P.D. Curtis. 1999. Managing Canada geese in urban environments. A technical guide. Jack Berryman Institute Publication No. 16 and Cornell University Cooperative Extension, Ithaca, NY.

Smith, V. 1983. Low nitrogen to phosphorus ratios favor dominance by blue-green algae in lake phytoplankton. Science 221:669-671.

Stearns & Wheler, LLC. 1999. Needs Assessment Report for Town of Chatham Comprehensive Wastewater Management Plant (CWMP) Study. Hyannis, MA August,1999.

St. Pierre, D. 2007. Personal communication regarding status of Stillwater Pond/Lovers Lake herring run, outlet structures and operation of weirs.

Tompkins, W.A. 1958. Fisheries report for some southeastern Massachusetts lakes, ponds, and reservoirs, 1951-1952. Bureau of Wildlife Research and Management, MA DFW, Boston, MA. 87 pp.

United States Environmental Protection Agency. 2001. *Ambient Water Quality Criteria Recommendations. Lakes and Reservoirs in Nutrient Region XIV*. Office of Water. Washington, D.C. EPA 822-B-01-011. December 2001.

United States Geological Survey (USGS).1974. 7.5 minute Topographic Quadrangle Map. Chatham, MA, Reston, VA.

Vanni, M.J. and C.D. Layne. 1997. Nutrient recycling and herbivory as mechanisms in the “top-down” effect of fish on algae in lake. Ecology 78:21-40.

Vollenweider, R.A. 1975. Input-Output Models with Special Reference to the Phosphorus Loading Concept in Limnology. Schweiz. Z. Hydrol. 37:53-62.

Vollenweider, R.A. 1968. Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Nitrogen and Phosphorus as Factors in Eutrophication. Tech. Rept. to OECD, Paris, France.

Wagner,K.J. 2001. Management Techniques Within the Lake or Reservoir. Chapter 6 in Managing Lakes and Reservoirs. Holdren, Jones and Taggard (eds). USEPA/NALMS, Madison, WI.

Wagner, K.J. 2004. The Practical Guide to Lake Management in Massachusetts. A Companion to the Final Generic Environmental Impact Report on Eutrophication and Aquatic Plant Management in Massachusetts. prepared for MA DEP, MA DCR and EOEA. Westford, MA.

Walter D. A., Masterson, J.P, and K.M. Hess. 2004. *Ground-Water Recharge Areas and Traveltimes to Pumped Wells, Ponds, Streams, and Coastal Water Bodies, Cape* Cod, Massachusetts. Scientific Investigations Report 2004-2857.

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

Welch, E.B. and G.D. Cooke. 1999. Effectiveness and longevity of phosphorus inactivation with alum. Lake Reserv. Manage. 15:5-27.

Welch, E.B., C.L. DeGasperi, and D.E. Spyridakis. 1986. Effectiveness of alum in a weedy, shallow lake. Water Resources Bulletin 22(6):921-926.

Welch, E.B., C.L. DeGasperi, D.E. Spyridakis and T.J. Belnick 1988. Internal phosphorus loading and alum effectiveness in shallow lakes. Lake and Reservoir Management 4:27-33.

Welch, E.B. and G.D. Schrieve. 1994. Alum treatment effectiveness and longevity in shallow lakes. Hydrobiologia 276:423-431.

Wetzel, R.G. 2001. *Limnology. Lake and River Ecosystems* (3rd edition). Academic Press, San Diego, CA.