

SEDIMENTOLOGICAL AND GEOCHEMICAL CHARACTERIZATION OF EAST
POND, BELGRADE LAKES WATERSHED, CENTRAL MAINE

Robin H. Nesbeda, '04

A Thesis

Submitted to the Faculty of the Geology
Department of Colby College in Fulfillment
of the Requirements for Honors in Geology

Waterville, Maine

May 18, 2004

Table of Contents

List of Figures and Tables	iv
Abstract	1
Introduction	2
Lake eutrophication	2
Nutrient cycling in lakes	4
Phosphorus loading and cycling	9
Monitoring quality and remediation of lakes	14
Study Area	15
East Pond	18
Scope of this study	20
Procedures and Methods	21
Sediment analysis	22
Water quality and chemistry	25
Seasonal water quality.....	28
Results	30
Sediment characterization	30
Water quality and chemistry	48
Seasonal water quality	55
Discussion	65
Sediment characterization	66
Lake Dynamics	75
Precondition	76
Mixing trigger	78
Summary of lake dynamics	80
Water Chemistry	81
Comparison to other Maine lakes	84
Summary	86
Remediation	87
Recommendations for future studies	88

Conclusions	90
Acknowledgements	92
References	93
Appendix A: 2000 Water Quality Summary for East Pond, which is cited in this project (from PEARL, 2003)	99
Appendix B: Grain-size analysis data for all 59 sediment samples	100
Appendix C: Sediment chemistry data for all 59 sediment samples	103
Appendix D: Grain-size analysis data from suspended particulate	106

List of Figures and Tables

Table 1: Summary of the dominant sources, sinks, and forms of phosphorus, carbon, and nitrogen in non-calcareous lake sediments (based primarily on Williams et al., 1971; Kerr et al., 1973; Petterson & Bostrom, 1984; Forsberg, 1988; Hessen et al., 1997; Pettersson, 1998; Pearce, 2000; Sterner & Elser, 2002).

Figure 1: Phosphorus and other nutrients can cycle through water, sediments, and biota in an un-stratified lake. (a) Nutrients are incorporated into primary producers (often algae) in the photic zone of the lake. (b) Upon death, the organisms (or fecal matter of consumers) settle to the lake bottom where (c) nutrients are released through decay. (d) Overturn mixes the nutrients back up to the lake's surface to be re-incorporated into the biota (based on Forsberg, 1989; Levine & Schindler, 1992; de Montigny & Prairie, 1993; Bacon, 1996; Petterson, 1998).

Figure 2: Stoichiometric ratios of C:N:P reflect the origin of organic matter and nutrient conditions at a given site (based on Redfield, 1958; Forsberg, 1989; Levine & Schindler, 1992; Hecky et al., 1993; Hessen et al., 1997; Brown et al., 1998).

Figure 3: Two dominant mechanisms can describe the net movement of phosphorus from the sediments to the photic zone. Mechanism 1 controls the release of phosphorus from the sediments into the pore waters and/or anoxic bottom water. Mechanism 2 controls the movement of phosphorus within the water column, from the anoxic lake bottom to the oxygenated water and photic zone where it can be used by photosynthesizing organisms (based on Holdren, 1977; Bostrom & Pettersson, 1982; Forsberg, 1989; Pearce, 2000).

Table 2: A summary of the major reservoirs of phosphorus, the forms present in each reservoir, that two mechanisms that account for P-mobility, and the major factors contributing to each mechanism (based on Syers, 1973; Holdren, 1977; Bostrom & Petterson, 1982; Pettersson et al., 1988; Forsberg, 1989; Keizer & Sinke, 1992; Pearce, 2000; and others).

Figure 4: The Belgrade Lakes watershed located in central Maine consists of 7 interconnected lakes, which eventually empty into the Kennebec River.

Figure 5: Bathymetry of East Pond. Produced by Colby geochemistry studies, 2002.

Figure 6: East Pond bathymetry with locations of 59 sediment grab samples and two hand-driven cores. (A) Lake bathymetry and the location of all 23 water-profiles taken on 6/17/03, 8/11/03, 8/12/03, 8/15/03, and 8/20/03. (B) Lake bathymetry and the location of the 5 water-profiles discussed in depth as well as the location of the phosphorus profile taken 8/12/03.

Figure 7: Lake bathymetry and (A) the location of all 23 water-profiles taken on 6/17/03, 8/11/03, 8/12/03, 8/15/03, and 8/20/03; and (B) the location of the 5 water-profiles discussed in depth as well as the location of the phosphorus profile taken 8/12/03.

Figure 8: Locations for weekly water quality measurements. Temperature, dissolved oxygen concentration, and secchi depth were measured at 1 m intervals at each site, at least once a week throughout the summer and into the fall of 2003. (A) Measurements taken at each sample location. (B) To evaluate changing conditions across the lake, sample locations 1 through 8 were combined into transect A to A' and sample locations 9 through 14 were combined into transect B to B'.

Figure 9: Percent sand ($>4\Phi$), silt ($4-8\Phi$), and clay ($>8\Phi$) of each sample plotted on a ternary diagram.

Figure 10: Results of the grain-size analysis of lake-bottom sediment. (A) Distribution of median grain size in phi with sediment sample locations; (B) distribution of median grain size in phi with bathymetric contours at 0.5 m intervals; and (C) bottom depth at the sample location versus median grain-size.

Figure 11: The sand ($>4\Phi$) to silt ($4-8\Phi$) ratio indicates the coarseness or fineness of the sediment mixture. (A) Distribution of the sand-to-silt ratio, and (B) the sand-to-silt ratio excluding data from location 022, which was coarse and an outlier (sand:silt ≈ 126).

Figure 12: The distribution of (A) % TOC content of the sediments; and (B) the TOC:TON ratio, indicating the origin of organic matter (scale and organic matter origin based on Brown et al., 1998).

Figure 13: Bivariate plots of sediment chemistry versus bottom depth. (A) % TOC; (B) % TON; and (C) the TOC:TON ratio.

Figure 14: Bivariate plots of sediment chemistry versus the median sediment grain-size (Φ). (A) % TOC; (B) % TOC, minus the outlying samples 018 and 084; (C) TON (%); and (D) TOC:TON ratio.

Figure 15: The relative concentration of the different phosphorus fractions in East Pond sediments. (A) The three fraction's mean percent of total phosphorus, and (B) the relative concentration of EDTA inorganic (orange), NaOH (green), and HCl (blue) organic phosphorus in each sediment grab sample. Note: data are missing from samples 042 and 043 due to ICP malfunction; the total P concentration is known for those samples, but not the P fractionation.

Figure 16: Total Phosphorus (%) distribution throughout East Pond. (A) Distribution of total phosphorus, (B) distribution of total phosphorus (%) with bathymetric contours at 0.5 m intervals.

Figure 17: Phosphorus distribution throughout East Pond. (A) Distribution of inorganic, and (B) organic phosphorus.

Figure 18: Bivariate plots of sediment chemistry versus bottom depth. (A) % inorganic phosphorus, and (B) % organic phosphorus.

Figure 19: Bivariate plots of sediment chemistry versus the median sediment grain-size (Φ). (A) % inorganic phosphorus, and (B) % organic phosphorus.

Figure 20: Description and chemistry of the core extracted from Heron Cove (N 44.597°, E 69.766°). (A) A photograph of the core; (B) description of the Heron Cove core with locations of removed sub-samples; (C) TOC, TON, and TOC:TON values of the sub-samples versus depth; and (D) inorganic, organic, and total phosphorus concentrations of the sub-samples versus depth.

Figure 21: Description and chemistry of the core extracted from the Serpentine outlet (N 44.626°, E 69.801°). (A) A photograph of the core; (B) description of the Serpentine core with locations of removed sub-samples; (C) TOC, TON, and TOC:TON values of the sub-samples versus depth, and (D) inorganic, organic, and total phosphorus concentrations of the sub-samples versus depth.

Table 3: Summary of chemical characteristics before and during the 2003 algal bloom.

Figure 22: Temperature and dissolved oxygen water-column profile (A) from June 17, before the algal bloom; and (B) from August 12, during the algal bloom.

Figure 23: Temperature and conductivity water-column profile (A) from June 17, before the algal bloom; and (B) from August 12, during the algal bloom.

Figure 24: Temperature and pH water-column profile (A) from June 17, before the algal bloom; and (B) from August 12, during the algal bloom.

Figure 25: Temperature and fluorescence water-column profile (A) from June 17, before the algal bloom; and (B) from August 12, during the algal bloom.

Table 4: Summary of the summer's ORP and pH data.

Figure 26: The range of mean ORP and pH values of East Pond water, plotted on an Eh-pH diagram (Garrels & Christ, 1965).

Figure 27: August 12, 2003, phosphorus concentration (blue) throughout the water column compared to other chemical parameters (green): (A) temperature, (B) oxygen concentration, (C) conductivity, (D) pH, and (E) fluorescence.

Figure 28: The distribution of (A) temperature and (B) oxygen content along a north-to-south transect before the algal bloom.

Figure 29: The distribution of (A) temperature and (B) oxygen content along a west-to-east transect before the algal bloom.

Figure 30: The distribution of (A) temperature and (B) oxygen content along a north-to-south transect during the algal bloom.

Figure 31: The distribution of (A) temperature and (B) oxygen content along a west-to-east transect during the algal bloom.

Figure 32: The vertical distribution of (A) temperature and (B) oxygen throughout the summer of 2003, at sample site 12 (N 44.60539°, W 69.79177 °), located at the center of the lake.

Figure 33: The mean of all secchi measurements for each date, with 95% confidence interval.

Figure 34: The mean secchi depth (blue) and mean weekly air temperature (red) with 95% confidence interval plotted throughout the summer 2003.

Figure 35: The mean secchi depth with standard deviation (blue) and total weekly precipitation (green) plotted throughout the summer 2003.

Figure 36: The mean secchi depth (blue) and mean weekly lake water temperature at 3 m depth (red) with 95% confidence interval plotted throughout the summer 2003.

Figure 37: The mean secchi depth (blue) and mean weekly wind speed (green) with 95% confidence interval plotted throughout the summer 2003. Weekly wind direction is presented in the rose diagrams.

Figure 38: Distribution of the median sediment-grain diameter (Φ) with the dominant wind direction indicated by the red arrow. In the top right corner is a rose diagram of the wind direction from June 1 to August 31, 2003. The statistical mean direction and 95% C.I. are indicated by the maroon line. Note that the majority of the winds are from the southeast; however, the statistical mean is shifted to the southwest by several episodes of northwesterly winds over the summer months.

Figure 39: Comparison of nutrients in East Pond sediments (blue) to predicted Redfield mass ratios for algae (red line). (A) TOC:TON, predicted Redfield mass ratio for algae = 5.7; (B) TOC:Total phosphorus, predicted Redfield mass ratio for algae = 40; and (C) TON:Total phosphorus, predicted Redfield mass ratio for algae = 7.

Figure 40: Comparison of nutrients in the hand driven cores to predicted Redfield mass ratios for algae. (A) The Heron Cove core, from the southeast margin of the lake; and (B) the Serpentine outlet core, extracted from the bog-outlet (note the difference in scale).

Figure 41: A two-stepped dynamic is proposed to account for algal blooms in East Pond. (A) The early summer pre-condition – temperature-oxygen stratification below –5 m creates a thin, dysoxic lens in the deep center of the lake, into which sediment phosphorus can be released. This phosphorus-rich lens is trapped at depth. Thus, P is released into the water-column yet unavailable to algae restricted to the photic zone. (B) The wind shifts from the south-east, moving the water towards the islands to the north-west of the deep lake center. These barriers force the surface water to depth. (C) The P-rich, dysoxic water from below –5 m is mixed to the lake surface by a vertical gyre-type dynamic. Increased P concentrations within the photic zone cause increased photosynthesis/algal populations, resulting in the observed algal blooms.

Figure 42: Shifting wind direction is the proposed trigger for vertical mixing in East Pond. A rose diagram of the wind direction is presented to the right, the maroon line represents the mean direction and 95% C.I.. The mean wind direction is superimposed onto a map of East Pond (black arrow). (A) The wind direction from June 1 through July 13. (B) The wind direction from July 14 through August 31.

Table 5: A summary of the major reservoirs of phosphorus, the forms present in each reservoir, the two mechanisms the account for P-mobility, and the major factors contributing to each mechanism in East Pond.

Sedimentological and geochemical characterization of East Pond, Belgrade Lakes watershed, central Maine

Abstract

An interdisciplinary research program (Geology and Chemistry) at Colby College, Waterville, Maine, is developing a model for surface and groundwater interactions in the Belgrade Lakes watershed. The watershed is a system of seven glacially formed, interconnected lakes in central Maine. Surface and groundwater discharges from the area to the Kennebec River, which empties into the Gulf of Maine.

The present study focuses on East Pond, the head of the lake-chain system. East Pond is roughly oval in shape with several coves along the margins; it has an average depth of 4.5 m, a maximum depth of 7.3 m, and a total volume of $26.35 \times 10^6 \text{ m}^3$. The lake is surrounded by North temperate hardwood forest and a marshy outlet to the other lakes exists in the northwest corner. East Pond has suffered severe yearly algal blooms during the late summer and into the fall since 1993. This project aims to develop a baseline for the geological, geochemical, and hydrochemical parameters through spatial and temporal scales to better understand the lake's dynamics. It is suspected that changes in water chemistry over the summer may prohibit or promote phosphorus release from the lake bottom, leading to the observed algal bloom.

Analyses included: characterization of the lake-bottom sediments, measurement of water-chemistry parameters, and water-quality monitoring throughout the summer. Sediment analysis revealed a substrate that is characterized as an organic rich (mean TOC = 5.42%), moderately well sorted silt (mean grain-size = 4.51Φ). Total phosphorus concentration in the sediments was elevated with a mean of 0.048%. Total phosphorus

concentration in the water column during the algal bloom peaked at 64 ppb at 1.5 m depth. The basin morphology and coincidental orientation to local winds explain the sediment distribution and vertical mixing of the water column that released sediment phosphorus to the lake surface, leading to the worst algal bloom recorded in the lake's history.

Introduction

Lakes provide an historical record of the conditions of the environments that surrounds them (Ballinger & McKee, 1971; Bacon, 1996). Nutrient cycling throughout lakes is directly linked to processes operating within the lake and surrounding environs (Goulden, 1972; Forsberg, 1989; Hessen *et al.*, 1997; Ostrom *et al.*, 1998). As a result, lacustrine nutrient conditions reflect both the natural processes and human activity and their effects on the lake. Most notably, increases in nutrient loading in a lake can lead to eutrophication and a general decrease in water quality (Ballinger & McKee, 1971; Bacon, 1996; and others). Lake eutrophication is among the most widespread environmental concerns in Maine (Davis *et al.*, 1978; Nieratko, 1992; Bacon, 1996; Pearce, 2000; Maine DEP, 2001; Amirbahman *et al.*, 2003), where over 4,500 square miles, roughly 13% of the state, are covered with water (Netstate, 2003).

Lake Eutrophication

Eutrophication is a lacustrine trophic state typified by excessive growth and increased populations of primary producers – specifically phytoplankton and algae. Eutrophic waters are very rich in nutrients and can appear murky and stagnant. Because eutrophic lakes are nutrient rich, extensive algal blooms occur and a positive feedback loop begins that leads to the infilling of the lake with organic matter (Pearce, 2000;

Bacon, 1996; EPA, 2003). Decreased water quality aggravates lake-property owners; it also can negatively affect the entire lake's ecosystem – the phytoplankton can compete with other biota or block sunlight to deeper waters resulting in a net decrease in the macro-faunal diversity and overall lake health (Bacon, 1996; Ostrom *et al.*, 1998; Pearce, 2000; EPA, 2003). In Maine, most of the concern stems from property devaluation and lake usage deterrence, especially by summer camps and tourists.

Eutrophication due to nutrient loading is one of the most extensively studied global environmental concerns (e.g., Forsberg, 1989; Pearce, 2000). While eutrophication is a step in the natural process of lake maturation from clean (oligotrophic) waters to enclosed wetlands (Keenley, 1973; Bacon, 1996; EPA, 2003), human influences can accelerate this process resulting in artificial anthropogenic eutrophication. Nutrients derived from excessive anthropogenic organic matter that decays and is recycled through the water, biota, and sediments can accumulate in a lake and result in eutrophication and the deterioration of water quality (Lavine & Schnidler, 1992; Ostrom *et al.*, 1998; Nieratko, 1992; Pearce, 2000). Non-point pollution nutrient loading due to runoff from developed and agricultural land that is enriched with C, N, and P from fertilizers, septic systems, and detergents, is often the main culprit in anthropogenically accelerated eutrophication (Bacon, 1996; Pearce, 2000; Amirbahman *et al.*, 2003; EPA, 2003; and others). Changes in land-use patterns also affect the nutrient load of a lake. Runoff from the entire drainage basin increases when roads and lawns are installed, and deforestation along the lake's edge removes trees that normally would use nutrients before they reached the lake (Bostrom & Pettersson, 1982; Nieratko, 1992; Bacon, 1996; Pearce, 2000; EPA, 2003). In some cases, sewage and other waste have been piped directly into

watersheds, dramatically increasing the available phosphorus and nitrogen (Kramer *et al.*, 1972; Bengtsson, 1975).

Nutrient cycling in lakes

Major nutrients (C, N, P) have numerous sources, sinks, and chemical forms in natural waters. Table 1 presents the common forms seen in non-calcareous lake sediments, resulting from intrinsic and extrinsic processes. The distinction of inorganic versus organic forms is based on the type of material with which nutrients are associated in the sediments, not on the origin of the nutrients. Once released into the water column or otherwise made available, inorganic and organic nutrients have equal potential for assimilation by autotrophic organisms (Syers, 1973).

Carbon and nitrogen species are predominantly determined by the carbon and nitrogen cycle, respectively; several other processes are indicated in Table 1. Phosphorus, however, has a more complex speciation and dynamic. There are many forms of phosphorus in lacustrine systems (e.g., Willaims *et al.*, 1971; Pettersson *et al.*, 1988; Forsberg, 1989; Golterman, 1996). Inorganic phosphorus is defined as P that is released from easily-dissolvable inorganic material. This includes “discrete phosphates,” such as precipitated phosphate minerals, as well as phosphate molecules either sorbed onto or incorporated into the sediments. Fe-bound phosphorus is considered the major form of P in lake sediments. Phosphorus often complexes with Fe(III) in lake-bottom sediments and is released upon reduction of Fe(III) to Fe(II) (de Montigny & Prairie, 1993; Fuller & Wehrli, 1996; Pearce, 2000; Amirbahman *et al.*, 2003; Gächter & Müller, 2003).

The organic phosphorus fraction is that which is incorporated into or associated with organic material. It often accumulates as organic matter that settles to the bottom of

Table 1: Summary of the dominant sources, sinks, and forms of phosphorus, carbon, and nitrogen in non-calcareous lake sediments (based primarily on Williams et al., 1971; Kerr et al., 1973; Petterson & Bostrom, 1984; Forsberg, 1988; Hessen et al., 1997; Pettersson, 1998; Pearce, 2000; Sterner & Elser, 2002).

<u>Phosphorus Sources</u>		<u>Phosphorus Sinks</u>	
<u>Internal</u>	<u>External</u>	<u>Inorganic</u>	<u>Organic</u>
Decaying autochthonous organic matter	Accumulation and decay of extrinsic/terrestrial organic matter, allochthonous runoff	Minerals (e.g. apatite, vivanite)	Incorporated into biota or organic detritus
P released from sediments	Resulting from human activities – fertilizers, detergents, effluent from agricultural, developed, or deforested land	Incorporated into clay minerals in sediments	
		x-PO ₄ complexes (often with Fe(III))	
		Adsorbed to sediments	
<u>Carbon Sources</u>		<u>Carbon Sinks</u>	
<u>Internal</u>	<u>External</u>		
Decaying autochthonous organic matter	Dissolved organic and inorganic C in allochthonous runoff	Used by/incorporated into biota	
Inorganic C in the form of CaCO ₃ from shells	Accumulation and decay of extrinsic/terrestrial organic matter	Lost to the atmosphere as CO ₂ or CH ₃	
	Atmospheric CO ₂	Buried in the sediments	
<u>Nitrogen Sources</u>		<u>Nitrogen Sinks</u>	
<u>Internal</u>	<u>External</u>		
Decaying autochthonous organic matter	Accumulation and decay of extrinsic/terrestrial organic matter	Used by/incorporated into biota	
Deposited as urea		Lost to the atmosphere as N ₂ or NH ₃ ⁻	
N ₂ fixation		Buried in the sediments	

a lake. As the organic matter decays phosphorus is released. Once released, it can be re-incorporated into the biota in the water column (Holdren, 1977; Forsberg, 1989; Nieratko, 1992; Pearce, 2000). A nearly closed cycle can be envisioned (Fig. 1) where phosphorus is incorporated into photosynthesizing organisms, these organisms die and settle to the lake bottom where the phosphorus is trapped in the sediments until it is released, again, to be used by other phytoplankton.

Phosphorus that enters the system through anthropogenic sources, such as fertilizer-runoff, potentially could be incorporated into either inorganic or organic fractions. Once phosphorus accumulates within an lake, it can cycle through the water column and promote algal blooms indefinitely (Forsberg, 1989; Levine & Schindler, 1992; de Montigny & Prairie, 1993; Bacon, 1996; Petterson, 1998).

Different types of photosynthesizing organisms preferentially use and incorporate carbon, nitrogen, and phosphorus in different relative amounts (Reiners, 1986; Levine & Schindler, 1992; Hecky *et al.*, 1993; Brown *et al.*, 1998). For example, woody plants readily use phosphorus to build cell walls and are relatively depleted in nitrogen. Conversely, algal cells incorporate more nitrogen than phosphorus and their elemental C:N:P ratio is different from that of woody plants. The stoichiometric ratio of C:N:P in organic matter reflects its origin. Brown *et al.* (1998) assigned a C:N ratio >20 that indicates derivation woody plants. Redfield (1958) derived a theoretical C:N:P ratio of 106:16:1 for both lacustrine and marine algae (Reiners, 1986; Forsberg, 1989; Levine & Schindler, 1992; Hecky *et al.*, 1993). This “Redfield Ratio” has been used in many studies to determine the type and origin of organic matter, to constrain the source of nutrients (Fig. 2), and to evaluate the nutrient conditions present at any particular site

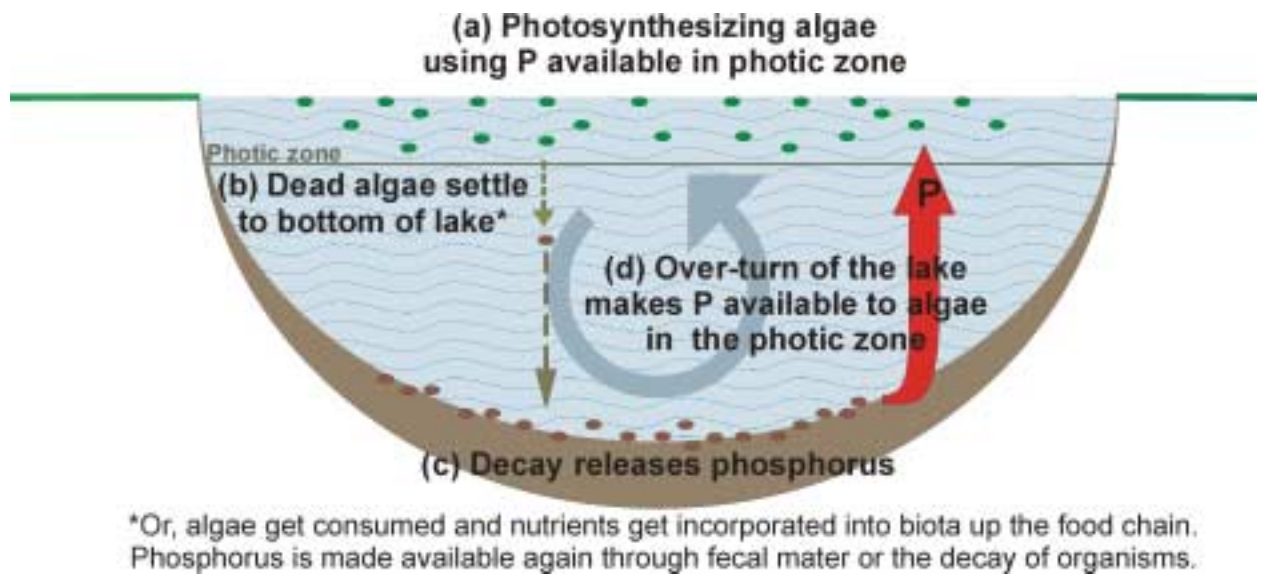


Figure 1: Phosphorus and other nutrients can cycle through water, sediments, and biota in an un-stratified lake. (a) Nutrients are incorporated into primary producers (often algae) in the photic zone of the lake. (b) Upon death, the organisms (or fecal matter of consumers) settle to the lake bottom where (c) nutrients are released through decay. (d) Overturn mixes the nutrients back up to the lake's surface to be re-incorporated into the biota (based on Forsberg, 1989; Levine & Schindler, 1992; de Montigny & Prairie, 1993; Bacon, 1996; Petterson, 1998).

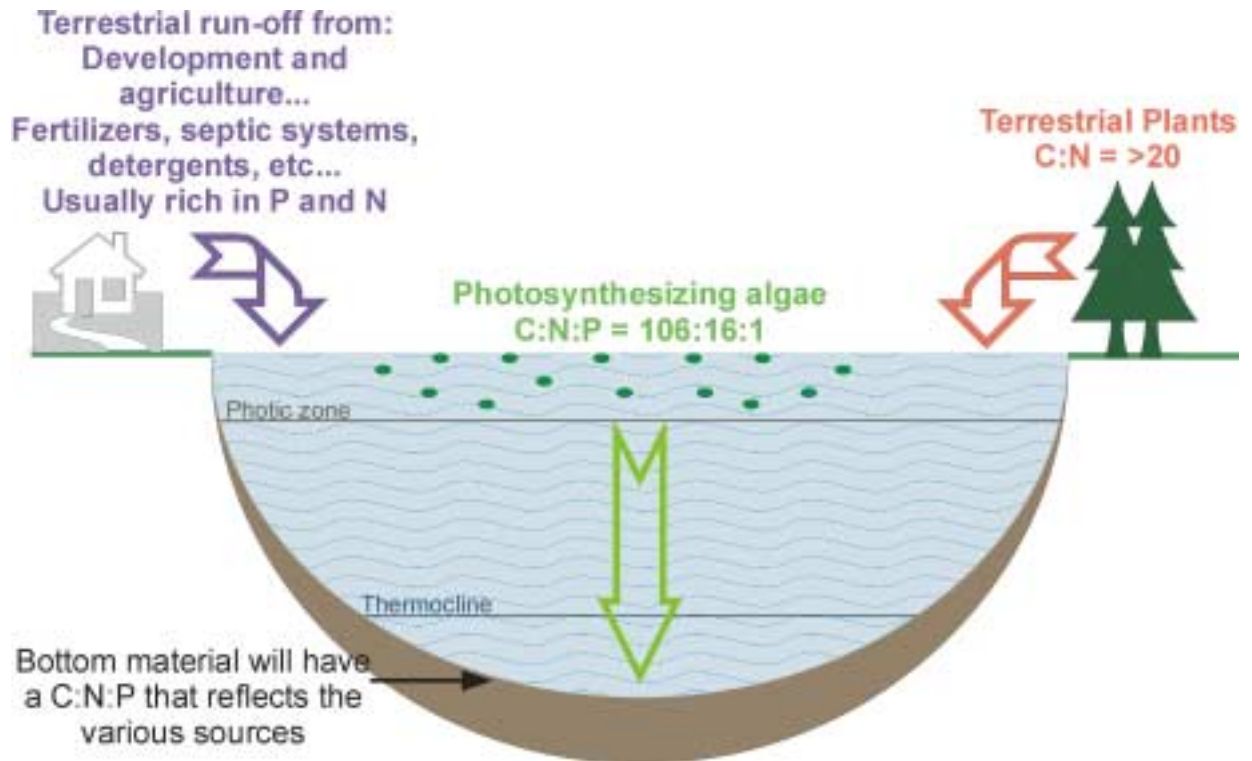


Figure 2: Stoichiometric ratios of C:N:P reflect the origin of organic matter and nutrient conditions at a given site (based on Redfield, 1958; Forsberg, 1989; Levine & Schindler, 1992; Hecky et al., 1993; Hessen et al., 1997; Brown et al., 1998).

(e.g., Levine & Schnidler, 1992; Hecky *et al.*, 1993; Hessen *et al.*, 1997; Brown *et al.*, 1998).

Phosphorus loading and cycling

In freshwater, phosphorus is the limiting nutrient and is, therefore, of greatest concern when evaluating a lake's nutrient status. Internal phosphorus loading is the accepted mechanism for lake eutrophication and algal blooms (e.g., Holdren, 1977; Nieratko, 1992; Pettersson, 1998; Pearce, 2000; Maine DEP, 2003). P-loading in lakes may be the result of time-averaged increases in organic matter and other nutrient-rich materials under either natural or anthropogenic processes. Phosphorus accumulates in the sediments primarily by particulate deposition; there are many factors that control the release of P back into the water column where it is available to biota. Because the phosphorus depositional rates usually far exceed release rates, there is a net increase in the sediments over time. Thus, these sediments can serve as both the source and sink for phosphorus and other nutrients (Holdren, 1977; Campbell, 1994; Pettersson, 1998; Carman *et al.*, 2000). Because nutrients are frequently incorporated into lake-bottom sediments, nutrient availability becomes a function of the geology (Holdren, 1977; Davis *et al.*, 1978; Lotse, 1973; Nieratko, 1992; Pearce, 2000). Furthermore, physical and chemical characterization of lake sediments is an important part of lake studies and potential for eutrophication (e.g., Williams *et al.*, 1971; Holdren, 1977; Davis *et al.*, 1978; Carignan & Lean, 1991; Peace, 2000).

While sediments may act as a phosphorus source within lakes, the movement of compounds from the sediments into the overlying water column where they can be used by biota is often an indirect process. Lakes can be functionally divided into three

reservoirs: (1) the sediments, (2) sediment-pore waters, which can be considered to be at equilibrium with anoxic lake-bottom water/hypolimnion (Pearce, 2000), and (3) the oxygenated, homogenized water column/epilimnion (Fig. 3). The primary producers who use the nutrients are constrained to the photic zone at the top of the water column where they can utilize sunlight for photosynthesis. Two mechanisms are needed to account for the net movement of phosphorus from the sediments to the photic zone where it can be incorporated into biological processes (Fig. 3). Mechanism 1 is the transfer of phosphorus from the sediments to the anoxic pore and lake-bottom waters. Mechanism 2 involves the mixing of phosphorus rich, anoxic bottom water and transfer to the lake's surface, where nutrients can be used by primary producers. The common phosphorus forms and factors affecting each transfer mechanism are summarized in Table 2.

Mechanism 1, phosphorus release from lake sediments, is primarily governed by chemical processes that determine the kinetic diffusion between phosphorus in the sediments and the overlying dysoxic water (Williams *et al.*, 1971; Ostrofsky *et al.*, 1989; Pettersson *et al.*, 1988; de Montigny & Prairie, 1993; Pearce, 2000). Chemical characterization of sediments and bottom waters generally focuses on identifying the reduction-oxidation conditions through measurements including temperature, oxygen content, and pH (Holdren, 1977; Furrer & Wehrli, 1996; Pearce, 2000; and others). The extent of vertical stratification of the water column determines many of these factors. Physical lake characteristics, including basin morphology, depth, and orientation, often effect the stratification of the water column and redox conditions throughout the lake (Holdren, 1977; Pettersson, 1998; Nieratko, 1992; and others).

P diffusion from lake-bottom sediments is also a function of the phosphorus

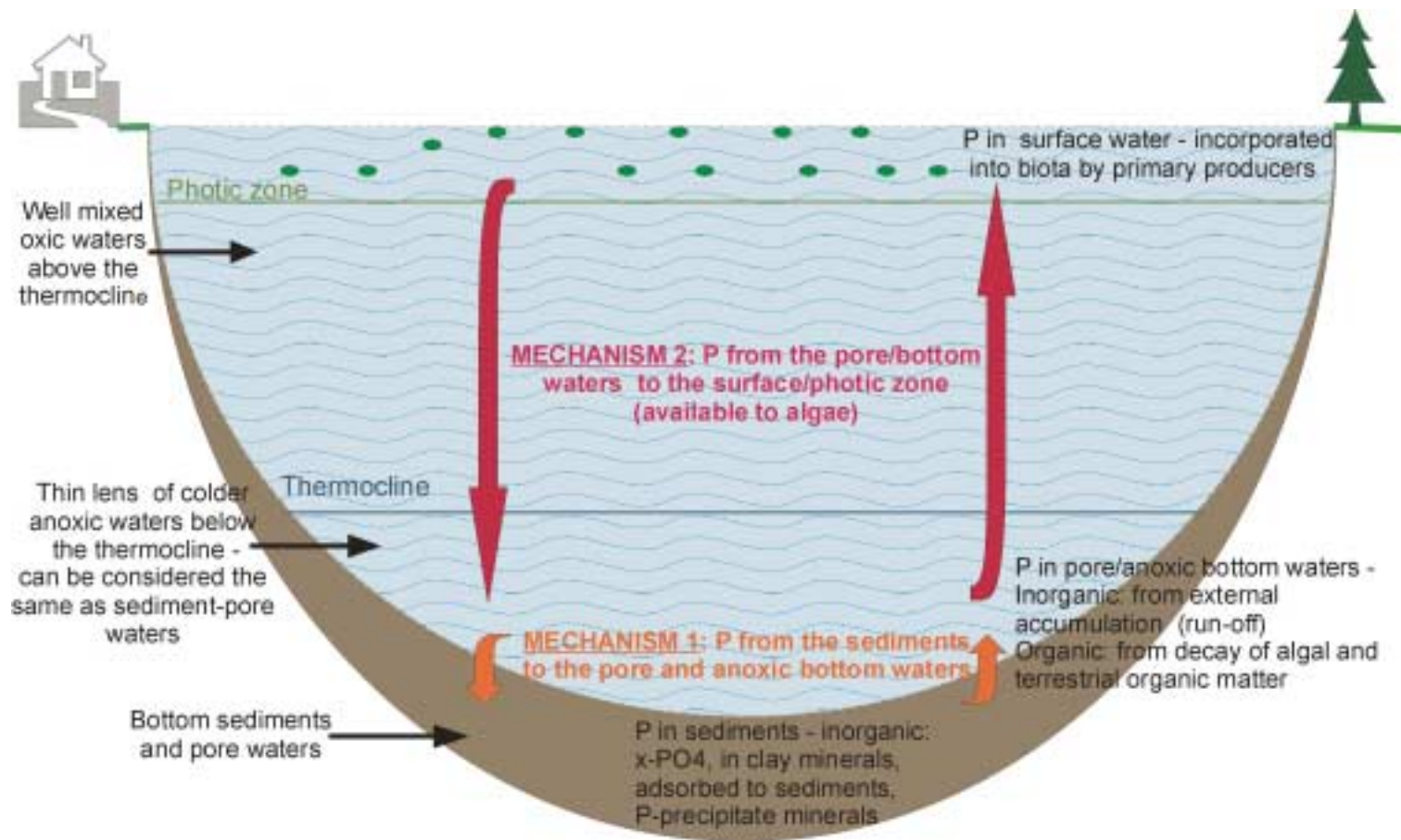


Figure 3: Two dominant mechanisms can describe the net movement of phosphorus from the sediments to the photic zone. Mechanism 1 controls the release of phosphorus from the sediments into the pore waters and/or anoxic bottom water. Mechanism 2 controls the movement of phosphorus within the water column, from the anoxic lake bottom to the oxygenated water and photic zone where it can be used by photosynthesizing organisms (based on Holdren, 1977; Bostrom & Pettersson, 1982; Forsberg, 1989; Pearce, 2000).

Table 2: A summary of the major reservoirs of phosphorus, the forms present in each reservoir, that two mechanisms the account for P-mobility, and the major factors contributing to each mechanism (based on Syers, 1973; Holdren, 1977; Bostrom & Petterson, 1982; Pettersson et al., 1988; Forsberg, 1989; Keizer & Sinke, 1992; Pearce, 2000; and others).

Location within Lake	Forms of Phosphorus		Mechanism of P-Transfer	Factors Effecting P-Transfer
	Organic	Inorganic		
Mixed/oxygenated waters including the photic zone, generally where planktonic and nektonic organisms live, often the majority of the water column	Incorporated into biota	Suspended particulate	<u>MECHANISM 2:</u> Phosphorus from the pore water/anoxic bottom waters to mixed/oxygenated water column where it can be used by photosynthesizing organisms	Physical lake dynamics – turnover/mixing, temperature-oxygen stratification, mechanical mixing, the location of the biota (depth of photic zone, phytoplankton concentration, etc.)
Anoxic bottom waters (hypolimnion), sediment pore waters	Decay of terrestrial and algal material	Accumulation of external anthropogenic P	<u>MECHANISM 1:</u> Phosphorus from the sediments to the pore water/anoxic bottom waters	Physical and Chemical factors – diffusion, redox conditions, bacterial activity, pH, amount of turbulent mixing/re-suspension of sediments, P concentration gradient, forms of P
Incorporated in sediments	Incorporated into buried organic matter	x-PO ₄ (often Fe(III)), in clay minerals; sorbed to sediments; P-precipitated minerals		

species present (Fe or Al complexes, precipitate minerals, etc., Table 1). The availability of species (such as Fe and Al) to bind with phosphorus and the capacity of phosphorus to sorb onto sediments are, in part, determined by the local lithology, mineralogy, and sediment grain-size (e.g., Bostrom & Pettersson, 1982; Davis *et al.*, 1978; Pearce, 2000). The extent of P-loading in the sediments and the P-concentration gradient between the sediments and overlying water also can effect the rate and amount of release. Turbulent mixing and bioturbation can results in re-suspension of sediments, thus increasing P-release (de Montigny & Prairie, 1993; Furrer & Wehrli, 1996; Pearce, 2000; Gächter & Müller, 2003).

Biological activity also plays a key role in the mobility of phosphorus in lake-bottom settings. Deposition of organic detritus transports nutrients into lake-bottom sediments and bacterial decomposition of organic matter effects the oxygen content of the sediments and overlying water (e.g., Holdren, 1977; and others). Furthermore, recent studies (e.g., Pearce, 2000; Amirbahman *et al.*, 2003; Gächter & Müller, 2003) have implicated anaerobic bacterial activity in determining P release from sediments by affecting electron acceptors present.

Mechanism 2, the movement of phosphorus from anoxic bottom waters to the oxygenated water column and ultimately biota within the photic zone, is primarily governed by physical lake dynamics that promote or prohibit vertical mixing of the water column. Loading of organic detritus at the lake-bottom leads to increased activity of aerobic bacteria, increasing the oxygen demand of the sediments and resulting in dysoxic bottom water. Physical mixing dynamics within a lake can be determined by the basin morphology, depth, and orientation. Local weather patterns, such as temperature, amount

of precipitation, and wind, can promote homogenization of the water column (Davis *et al.*, 1978; Carignan & Lean, 1991; Nieratko, 1992; Preace, 2000). Many studies have been published on the factors controlling mechanism 1 (e.g., Ballinger & McKee, 1971; Holdren, 1977; Bengtsson, 1975; Bostrom & Pettersson, 1982; Forsberg, 1989; Nieratko, 1992), but few have discussed mechanism 2 in detail (e.g., Nieratko, 1992).

The specific environmental factors and geochemical relationships governing phosphorus release from lake sediments and the dynamics making phosphorus available to biota are thought to be unique to individual lakes (Holdren, 1977; Bostrom & Pettersson, 1982; Pettersson *et al.*, 1988). While numerous studies have been conducted on lake-nutrient loading and cycling, as well as human-induced eutrophication (e.g., Williams *et al.*, 1971; Bostrom & Pettersson, 1982; Twinch & Peters, 1984), there is a distinct absence of first-order principles on the subject. Pearce (2000, p. 10) states: “attempts to find a simple comprehensive model for P release from sediments have been unsuccessful.” Simply, each lake is unique and needs to be evaluated individually (Williams *et al.*, 1971; Holdren, 1977; Ostrofsky *et al.*, 1989; de Montigny & Prairie, 1993; Nieratko, 1992; Pearce, 2000).

Monitoring water quality and remediation of lakes

The DEP/EPA defines algal blooms to be present in any lake, pond, or river with a Secchi depth less than 2 m (Maine DEP, 2001). Waters that have a concentration of phosphorous greater than 6 ppb are considered at risk for algal blooms (Maine DEP, 2001). According to the Public Educational Access to Environmental Information in Maine online database (PEARL, 2003), phosphorus concentrations in the water column of Maine lakes ranges from 0.1 to 1500 ppb. Pearce (2000) reports sediment phosphorus

concentrations ranging from 0.001 to 8.5×10^{-4} moles of phosphorus per cubic meter (1.04×10^{-4} to 8.5×10^{-4} $\mu\text{M/L}$) in seven Maine lakes, and Lotse (1973) reports sediment phosphorus concentrations ranging from 0.06 to 0.12 % in four Maine lakes.

Remediation procedures for reducing or removing the causes of anthropogenic eutrophication have been a primary focus of environmental research in the past thirty years. Currently, most U.S. federal and state environmental agencies, as well as local lake associations, are primarily concerned with monitoring water quality to predict or prevent algal blooms (Maine DEP, 2003; Belgrade Lakes Association, 2002). Many European countries have focused on diverting in-flowing waste and remediating eutrophic lakes (Bengtsson, 1975; Pettersson & Bostrom, 1984; Forsberg, 1989). Remediation strategies have included several methods of preventing P-release from lake-bottom sediments. Aeration of the lake bottom creates conditions that are not favorable for P-release, effectively trapping the phosphorus in the sediments. Capping the bottom sediments with clay or alum (aluminum sulfate) also traps phosphorus in the lake-bottom sediments. Dredging the lake, removing the P-rich sediments, ultimately removes the internal nutrient source for algal blooms (Maine DEP, 2003; PEARL, 2003; Wisconsin Dept. of Natural Resources, 2003). Before an appropriate remedial strategy can be derived for a lake, the specific dynamics of phosphorus release and cycling present within the lake must be understood.

Study area

The Belgrade Lakes watershed is a system of seven interconnected glacial lakes located in central Maine (Fig. 4). The system is situated within a north temperate hardwood forest and is associated with several bogs and streams. The lakes are fed by

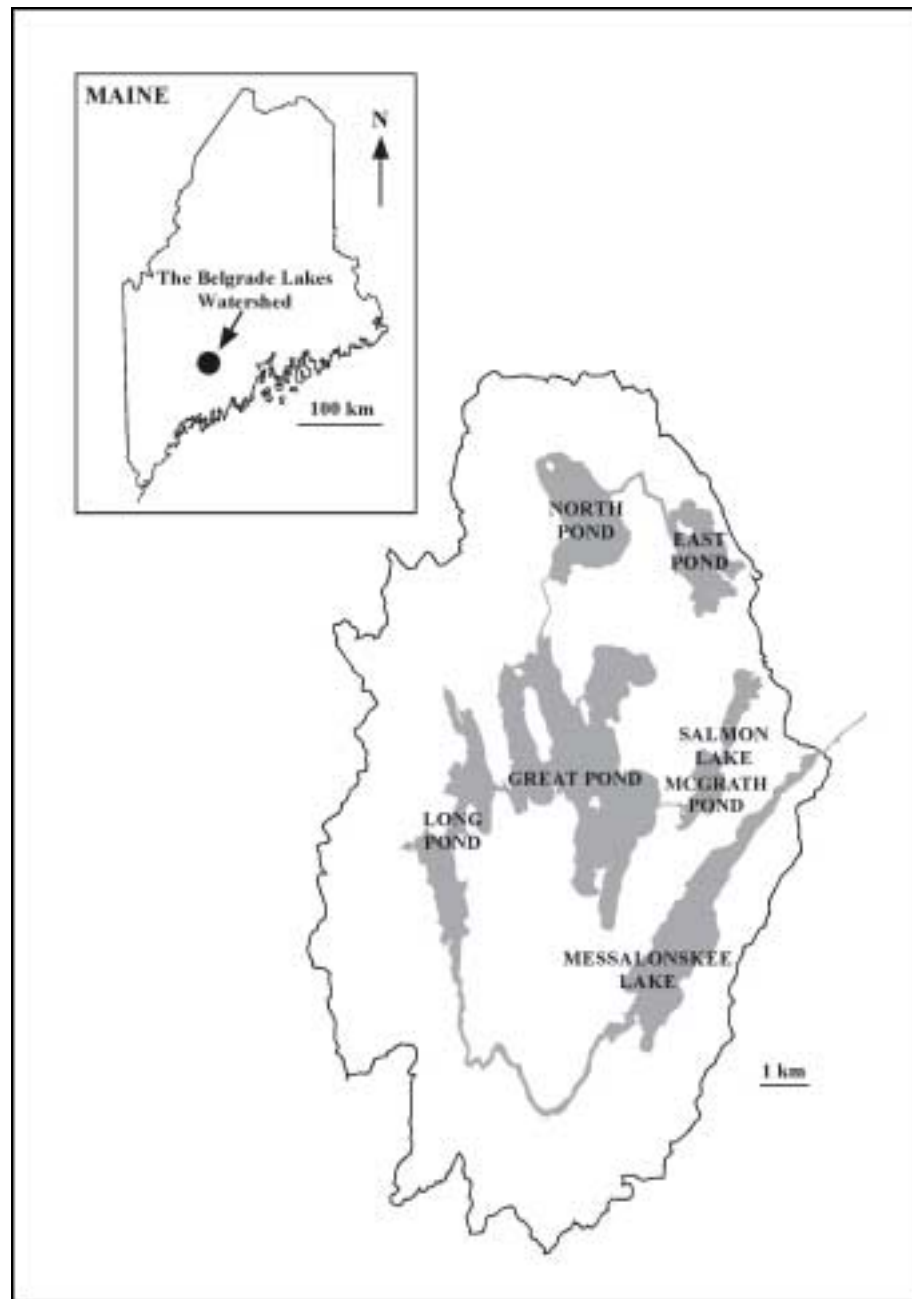


Figure 4: The Belgrade Lakes watershed located in central Maine consists of 7 interconnected lakes, which eventually empty into the Kennebec River.

surface and groundwater discharge from the area. The chain eventually empties into the Kennebec River, which empties into the Gulf of Maine (Davis *et al.*, 1978).

Human activity has heavily affected the lakes in the past century (Davis *et al.*, 1978). Activities include, but are not limited to damming, agricultural and real estate development, and increasing motorboat traffic (BI493, 2000; Maine DEP, 2001). Damming not only has drastically altered the lake-water levels but also has changed the dynamics of sediment, nutrient, and detritus accumulation within the impoundments (Twinch & Breen, 1982; BI493, 2000). Development has resulted in deforestation and road building, with run-off from roads, fields, lawns, and improperly maintained septic systems enriched in phosphorus-rich materials (such fertilizers and detergents) being washed into the lakes. This has elevated the phosphorus concentrations (Maine DEP, 2001). In the past several decades, pressures on the lake have lessened as land once used for agriculture has been converted to private homes and the forests have recovered (Maine DEP, 2001).

Degradation of water quality, changes in wildlife populations, and the threat of invasive plants have been the concerns of local conservation and lake associations for the past decade. This has led to an increased awareness among residents and has been noted by the Maine Department of Environmental Protection (Maine DEP, 2001; Belgrade Lakes Association, 2002). However, in light of these changes and concerns, little investigative science has been done on this watershed. Davis *et al.* (1978) conducted a scientific survey of Maine Lakes, including North Pond and Messalonskee Lake, with a particular focus on eutrophication. Phosphorus dynamics resulting in eutrophication within Maine lakes has been the subject of several additional studies conducted by the

University of Maine, Orono (e.g. Lotske, 1973; Niertko, 1992; Pearce, 2000). Also, over the past fifteen years, the Colby Biology Department's BI493 class has conducted environmental assessment projects on individual lakes. Two such studies have been conducted on East Pond (BI493, 1991; BI493, 2000). The Maine DEP has conducted a sampling program, as have the local pond associations, and a Total Maximum Daily Loads (TMDL) report was published recently about East Pond by the Maine DEP (2001). Many of EPA and DEP reports either are unpublished or are public bulletins lacking scientific detail (Maine DEP, 2001; Belgrade Lakes Association, 2002; Maine DEP, 2003; East Pond Association, 2003). In the past two years, the Colby College Geology and Chemistry departments have initiated several studies within the Belgrade Lakes (e.g., Allen *et al.*, 2003; Dushman & Shosa, 2003; King *et al.*, 2002; Ossolinski *et al.*, 2002; Shosa *et al.*, 2002).

East Pond

East Pond is the first lake in the Belgrade Lakes chain. It is small, shallow, and oval-shaped with several coves along its margin. Bathymetry data collected by Colby College during the summer of 2002 revealed that East Pond has an average depth of 4.5 m, with a maximum depth of 7.3 m. The total lake volume was calculated to be $26.35 \times 10^6 \text{ m}^3$. The surface area of the lake basin (the sediment-water interface) is $6.8 \times 10^7 \text{ m}^2$ (6,800 ha). There is no distinct inlet into East Pond, and water flows out to North Pond through the Serpentine Bog on the northwestern end of the lake (Fig. 5). The estimated flushing rate of the lake is 0.25 flushes per year, meaning a 4-year residence time of water within the lake (Maine DEP, 2001). While the lake is classified as un-stratified to weakly stratified, slight thermal stratification has been reported (Appendix A; PEARL,

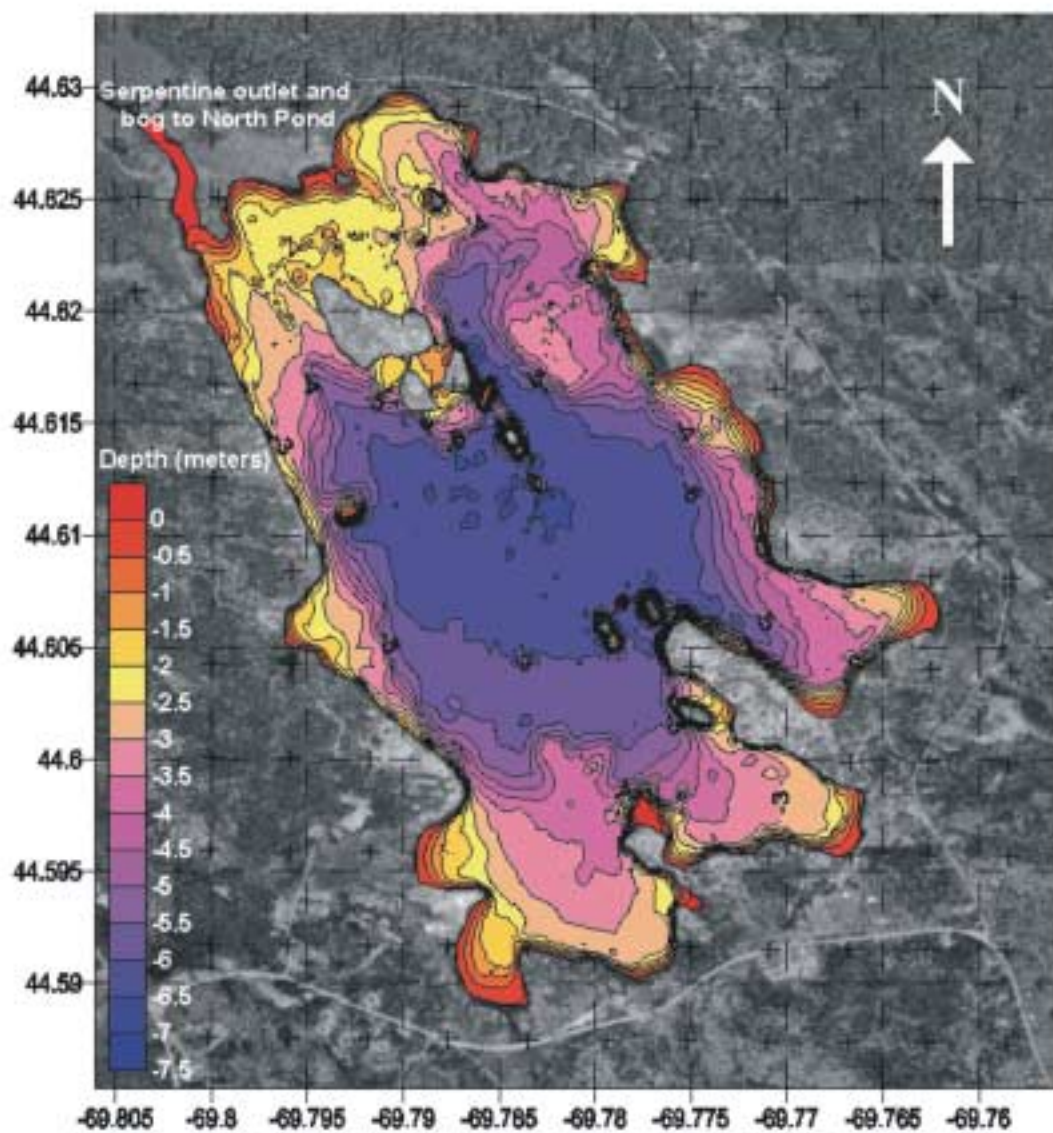


Figure 5: Bathymetry of East Pond. Produced by Colby geochemistry studies, 2002.

2000; PEARL, 2003).

One of the Pond's most notable features is that it suffers severe yearly algal blooms during the summer months (Appendix A; Maine DEP, 2001; PEARL, 2000; Maine DEP, 2003, PEARL, 2003). The overall water quality has significantly decreased and succumbed to eutrophication since 1993. Specifically, in recent years, residents have noted an "overnight" change in the water quality sometime between late July and early September. The lake will remain clear for most of the summer and then abruptly will turn green (J. Tipper, pers. comm. 2002). Both the severity and abruptness of the blooms have raised questions about the chemical, physical, and biological processes operating within East Pond.

Scope of this study

An interdisciplinary geological-geochemical study began on East Pond in the summer of 2003. The aim of this project, a collaboration between the Geology and Chemistry departments, is to develop a baseline for the geological, geochemical, and hydrochemical parameters over both spatial and temporal scales to better understand the processes operating within this lake.

Historical phosphorus loading in East Pond is believed to be human induced (Maine DEP, 2001; PEARL, 2003), and it is suspected that changes in the water chemistry over the summer may prohibit or promote phosphorus release from the lake bottom. This hypothesized sediment-water dynamic leads to the algal blooms and predicts a specific relationship between physical and chemical properties, lake dynamics, and productivity. It is suspected that early in the ice-free months, a high concentration of phosphorus is trapped in the sediment and overlying anoxic water by temperature

stratification that makes it unavailable for biologic consumption. A cooling event sometime between late July and early September eliminates the lake's stratification and allows vertical mixing, releasing phosphorus to the algae at the lake's surface. This abrupt increase in available nutrients in the photic zone promotes a rapid increase in photosynthesizing populations, which, in turn results in an algal bloom. The hypothesis tested in this study is that phosphorus storage and release in the sediments can be correlated to changing water quality parameters over the course of summer months. Hence, a predictive model can be constructed using high-resolution data acquired both spatially and temporally.

This project consists of a synthesis of the sedimentological and chemical parameters found in East Pond over the summer and fall of 2003. Analysis of the data results in a model to describe the lake's sediment-water chemical dynamics throughout this time period, including an assessment of the changes in the lake preceding this year's algal bloom. This project provides an unique picture of lake sediment-water dynamics because it includes both spatial and temporal scales. Comparably complete geochemical and hydrochemical systems for non-carbonate lakes are rarely described in the published literature. Thus, this project presents a model for future lake geo-chemical and hydro-chemical studies, and is a critical starting point for future research of the Belgrade Lakes watershed.

Procedures and Methods

Some general characteristics of East Pond, including depth, volume, and surface area, were calculated using bathymetry data collected by Colby College Geology and Chemistry departments during the summer 2002. To address the processes and dynamics

in East Pond, three protocols were used throughout the summer and fall of 2003. This study is subdivided into three parts – (1) sediment characterization, (2) detailed measurement of the water chemistry prior to and during the algal bloom, and (3) water quality monitoring throughout the summer.

Sediment analysis

Characterization of bottom sediments across the lake was accomplished by taking 59 grab samples (Fig. 6) using a Wilco sampling device from the Colby Compass, a pontoon boat equipped as a sampling platform owned by Colby College. Thirty-five samples evenly distributed across the lake (samples 016 through 061) were collected in June. In July, twenty-four additional samples (sample 062 through 085) were taken from specific locations to refine our understanding of the sediment distribution. Sample locations were identified and recorded using differential GPS; water depth was determined by sonar. Roughly 1-2 kg (wet weight) of sediment were collected at each site; samples were stored in sealed Ziploc-bags with lake water. Sub-samples were placed into beakers and dried for at least twenty-four hours in a 100°C oven before analysis.

Each sample was analyzed for grain-size distribution by dry sieving at half-phi intervals using standard U.S. testing sieves. The fine fraction ($<4\Phi$) was analyzed using a Spectrex PC-2000 Laser Particle Counter with data also collected at half-phi intervals. Folk and Snead statistics (Prothero & Schwab, 1996) were calculated using the grain-size data. Calculations included mean grain size (grain diameter), median grain size, standard deviation, skewness, and kurtosis. The percent sand ($>4\Phi$), silt ($4-8\Phi$), and clay ($<8\Phi$) fractions were tallied for each sample and graphed on a ternary diagram using Golden Grapher-4 software.

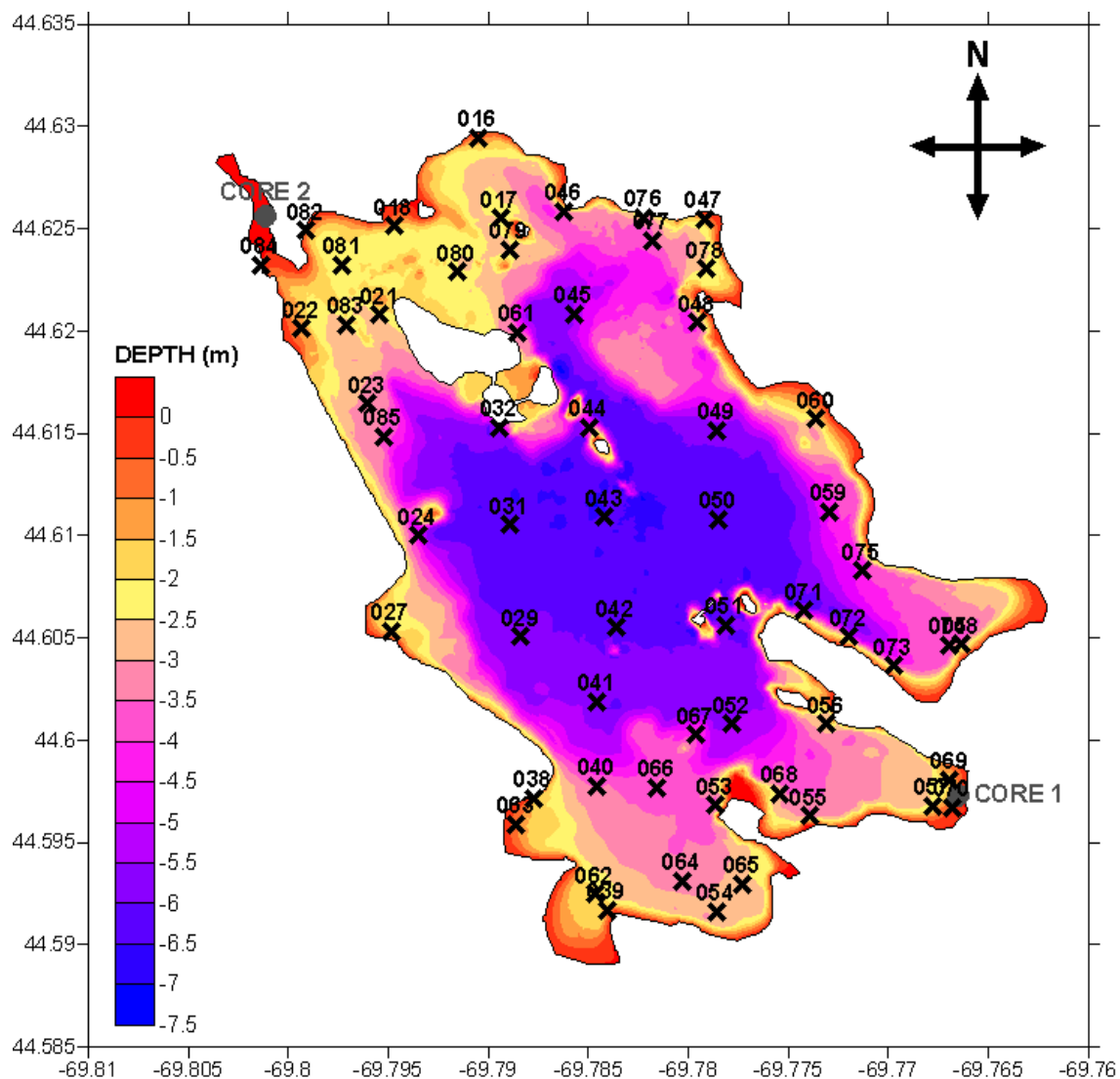


Figure 6: East Pond bathymetry with locations of 59 sediment grab samples and two hand-driven cores.

To ensure that organic particulate matter was not measured by the LPC during the grain-size analysis, two sub-samples also were treated for organics and re-analyzed. Samples 016 and 024 were selected because they were representative of mean grain size and TOC content. Wet sub-samples were treated in 30% hydrogen peroxide for at least 2 weeks (until the reaction no longer continued with agitation). The treated samples were then dried and analyzed using the LPC; the treated and untreated results were compared.

Grain-size analysis of the inorganic particulate matter suspended in the water-column also was evaluated. Water samples were taken at depths of 0.5 m, 3.0 m, and 5.5 m and analyzed in triplicate using the LPC.

The basic sediment mineralogy was analyzed for one representative sample (085) using a Rigaku Pmax 11B power X-ray diffractometer. Sample 085 was used because it is typical in grain-size, TOC, and TON content. The XRD analysis also allowed for the identification of any clay minerals and phosphorus precipitates.

Bottom-sediment chemistry also was analyzed for each sample to evaluate the stoichiometric ratios of carbon, nitrogen, and phosphorus. Total organic carbon (TOC) and total organic nitrogen (TON) were measured for dried sub-samples using an Exeter 440 CHNO analyzer. At least three repetitions were analyzed and averaged for each sample. The TOC:TON ratio was calculated for each sample because TOC:TON ratios are used as a proxy for determining the relative percent of organic matter that is of algal versus terrestrial origin (Brown *et al.*, 1998).

There are many ways to describe different phosphorus fractions; most of these distinctions are defined operationally. Here, the phosphorus fractionation as described by Golterman (1996) was used. Kassila *et al.* (2000) provide an in-depth comparison and

discussion of various phosphorus extraction schemes, including the Golterman method. Phosphorus is partitioned into three fractions through a series of digestions; the P concentration of each fraction was measured using Leeman Labs Inc. model PS1000UV Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES). The operationally defined fractions in the Golterman scheme are: (a) inorganic material extracted with EDTA, phosphorus associated with easily extractable inorganic material including iron-bound P; (b) HCl (acid) extractable organic phosphorus; and (c) NaOH (base) extractable organic P. Phosphorus results are presented in two categories: organic (HCl-extractable and NaOH-extractable organic phosphorus fractions) and inorganic P.

The distributions of bottom-sediment parameters were plotted throughout the lake, using the GPS localities of each sampling site and Golden software Surfer v.8 on default settings. In addition, relationships between grain-size, depth, and chemical composition, as well as the stoichiometric ratios of carbon, nitrogen, and phosphorus, were evaluated using x-y scatter plots.

In addition to the grab samples, two hand-driven cores, taken in one meter of water using a sharpened section of clear acrylic pipe, were obtained from the southern (N 44.597°, E 69.766°) and northern (N 44.626°, E 69.801°) margins of the lake to detail the stratigraphic changes in the recent lake-bottom sediments (Fig. 6). The cores were described while intact, then sediment sub-samples were taken at one centimeter intervals throughout the cores for chemical analyses (TOC, TON, and phosphorus contents) using the same methodologies described above.

Water quality and chemistry

The second part of the study consists of a spatial description of water quality and

chemistry accomplished through a series of vertical and lateral lake profiles completed before and during the summer algal bloom. An array of YSI sensors attached to an Endeco/YSI fiberglass fin were suspended off the Colby Compass. The array was connected directly to a laptop and data were recorded using Labview software programmed by Dr. Whitney King (King *et al.*, 2003). The position of each collection site was marked using differential GPS, measured bottom depth was determined by sonar, and fin/sensor depth was determined by pressure. The sensor array measured water temperature using a thermistor, conductivity using a 4-electrode cell, dissolved oxygen concentration using a Angdon electrode, pH and ORP using electrodes, and fluorescence as an estimate of primary productivity.

A total of 23 vertical profiles were conducted throughout the summer (Fig. 7A). Eleven profiles were completed on June 17, before the algal bloom. Four were completed on August 11, another four on August 12, three on August 15, and one on August 20, all during the algal bloom. One representative profile from each date was used for analysis (Fig. 7B). For each profile, the above parameters were measured at roughly 0.1 m intervals. Lateral profiles also were conducted at various depths on June 18, August 15, and August 20.

A series of water samples were collected at 1 m intervals along a vertical profile on August 12, during the algal bloom (Fig. 7B). These samples were analyzed in the laboratory for phosphorus content using standard methodologies. The relationships between the various chemical parameters were evaluated using x-y scatter plots. Due to many, minor fluctuations in ORP, these data were summarized for the entire lake and throughout the summer; the range of ORP and pH values were plotted on an Eh-pH

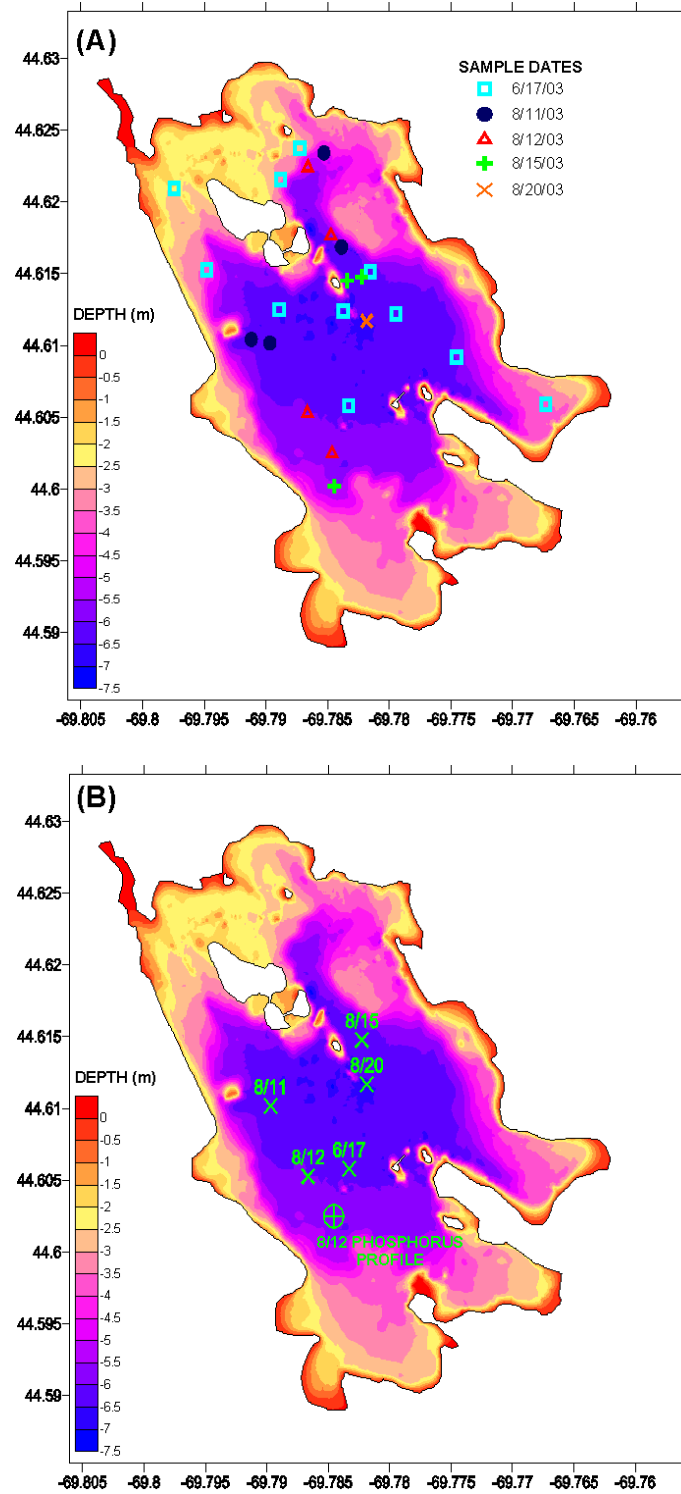


Figure 7: Lake bathymetry and (A) the location of all 23 water-profiles taken on 6/17/03, 8/11/03, 8/12/03, 8/15/03, and 8/20/03; and (B) the location of the 5 water-profiles discussed in depth as well as the location of the phosphorus profile taken 8/12/03.

diagram.

Seasonal water quality

Weekly readings of temperature, dissolved oxygen concentration, and secchi depth were measured at 1 m intervals at sixteen points across the lake (Fig. 8A). Liz Andrews, an East Pond resident and local high-school student, was hired by the East Pond Lake Association to collect these data from mid-June into the Fall.

The temperature and oxygen data were plotted throughout the lake versus depth to establish the extent of stratification. Sample point locations were converted into UTM coordinates and temperature and oxygen plotted along two transects across the lake (Fig. 8B). Secchi depths were averaged across the lake for each date and plotted for the entire summer. The lake-water temperature at 3 m depth also was averaged across the lake and plotted against secchi-depth data.

To establish first-order relationships between the observed water characteristics and seasonal variation, secchi depth, temperature, and oxygen data were correlated to NOAA records of climate conditions. Unedited local climatological data (LCD) measured at the Augusta State Airport in Augusta, Maine, were downloaded from the NOAA National Climatic Data Center (from the URL: <http://www.ncdc.noaa.gov/servlets/ULCD>) for June through November, 2003. The weekly air temperature was averaged and plotted on an x-y scatter plot with secchi depth data. The weekly wind speed also was averaged and plotted against secchi depth data; weekly wind direction was plotted in rose diagrams using Oriana software, and the weekly and cumulatively over the summer, and plotted with secchi-depth data.

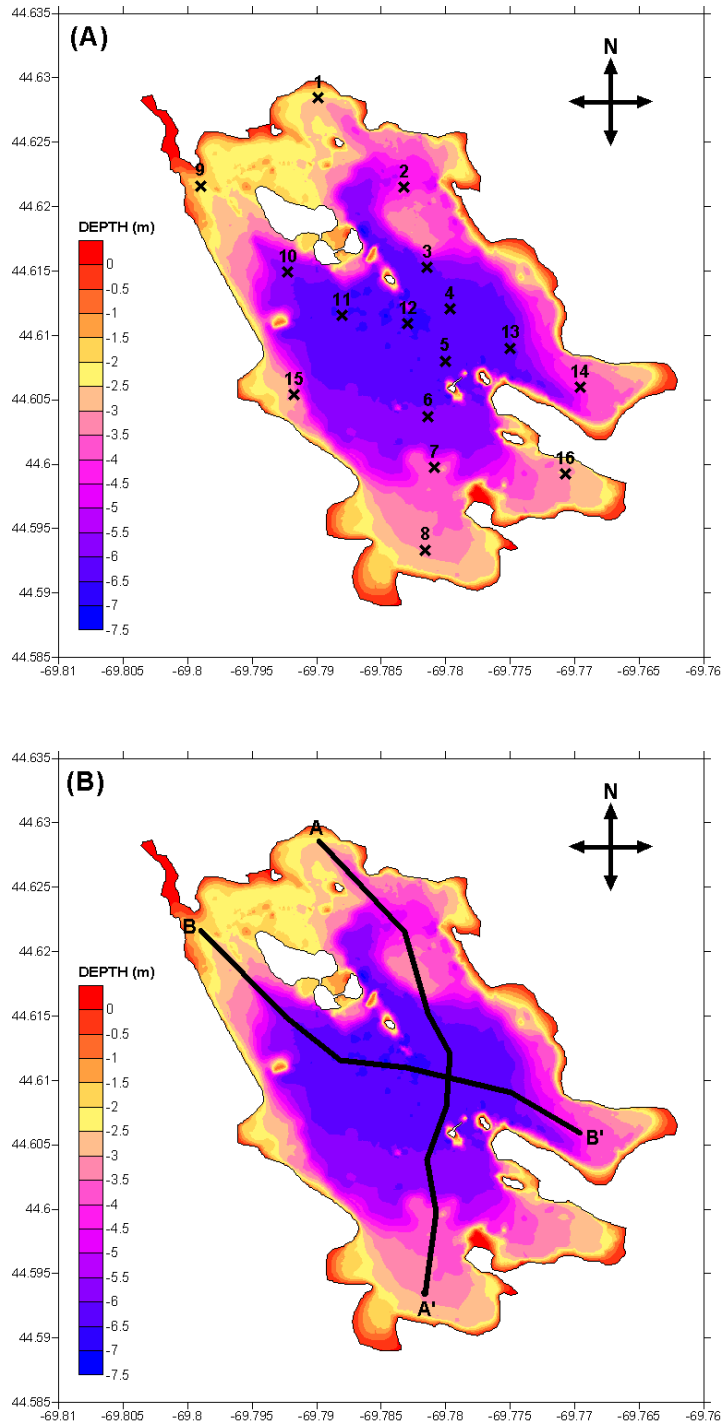


Figure 8: Locations for weekly water quality measurements. Temperature, dissolved oxygen concentration, and secchi depth were measured at 1 m intervals at each site, at least once a week throughout the summer and into the fall of 2003. (A) Measurements taken at each sample location. (B) To evaluate changing conditions across the lake, sample locations 1 through 8 were combined into transect A to A' and sample locations 9 through 14 were combined into transect B to B'.

Results

Sediment characterization

The grain-size analysis of the 59 sediment grab samples indicates that East Pond is typified by silt-sized clasts. Median grain size ranged from medium sand (1.00 Φ) to fine silt (6.15 Φ); the average median grain-size was coarse silt (4.51 Φ). Clay-sized particles ($<8 \Phi$) were notably absent in the sediments and water column. Figure 9 depicts the percent sand, silt, and clay of each sample plotted on a ternary diagram.

The distribution of the sediments across the lake roughly follows a fining-inwards bulls-eye pattern with the finest sediments in the lake center; the coarse sediments occur at the lake margin and Serpentine outlet (Fig. 10A). While the finest sediments are restricted mostly to the deeper lake center, within the 4.5 m contour (Fig. 10B), there appears to be little correlation between grain size and depth (Fig. 10C). The distribution of the sand-to-silt ratio indicates that much of the sediment is a silt-rich mixture (Fig. 11A). There is one very sandy sample near the Serpentine outlet, sample 022 (Fig. 11A); excluding this datum provides a more detailed picture of the distribution (Fig. 11B).

The Folk and Snead statistics described several other sediment characteristics of the sample suite. The standard deviation ranged from 0.22 to 2.00, indicating that the sediments are very well sorted to poorly sorted. The average standard deviation (0.62) indicates moderately well sorted sediment. Skewness ranged from -0.51 to 6.77 with an average of 3.07 (strongly skewed towards fine); kurtosis ranged from 0.66 to 2.23 with an average of 1.05 (excessively peaked). The measurement for grain-size for samples treated for organics were similar to the measured grain-size of untreated samples. A summary of data for all of the sediment samples is presented in Appendix B.

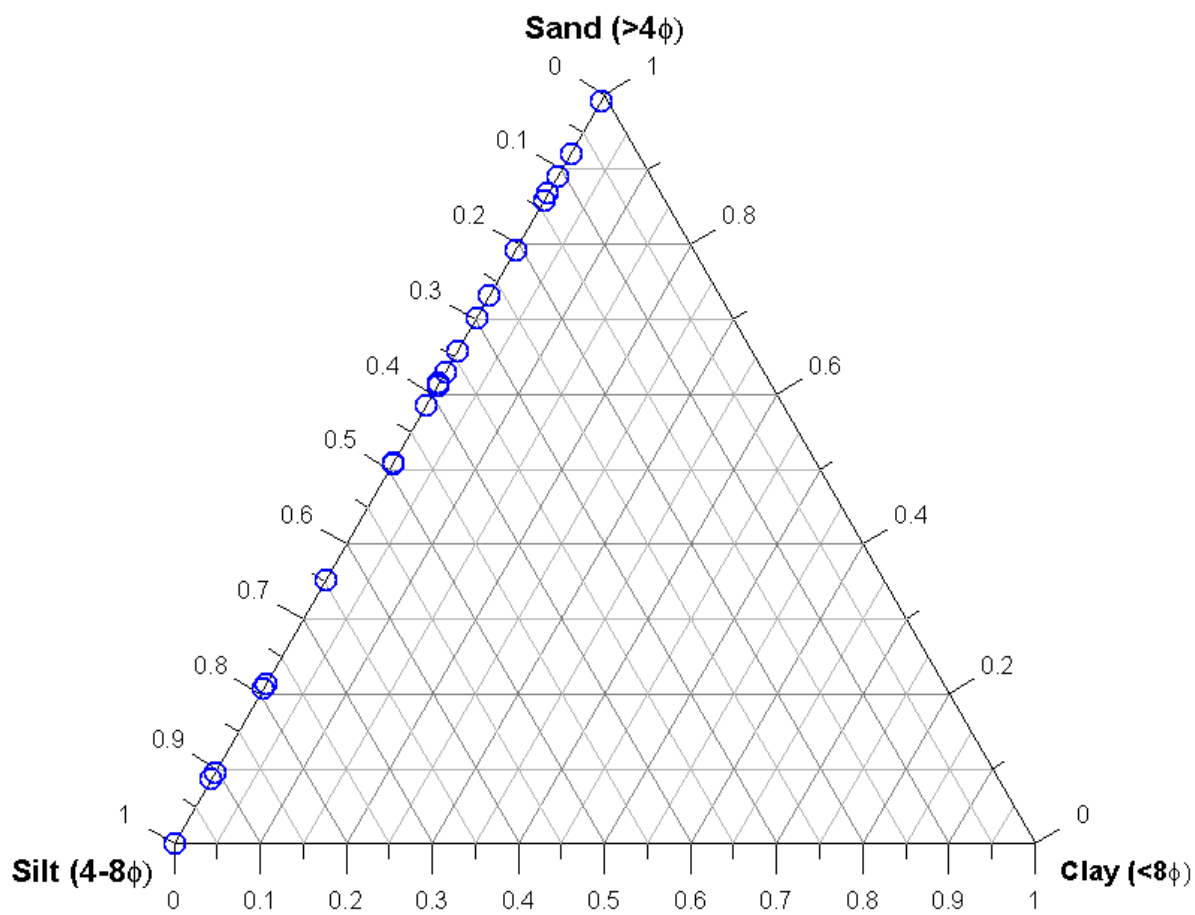


Figure 9: Percent sand ($>4\Phi$), silt ($4-8\Phi$), and clay ($<8\Phi$) of each sample plotted on a ternary diagram.

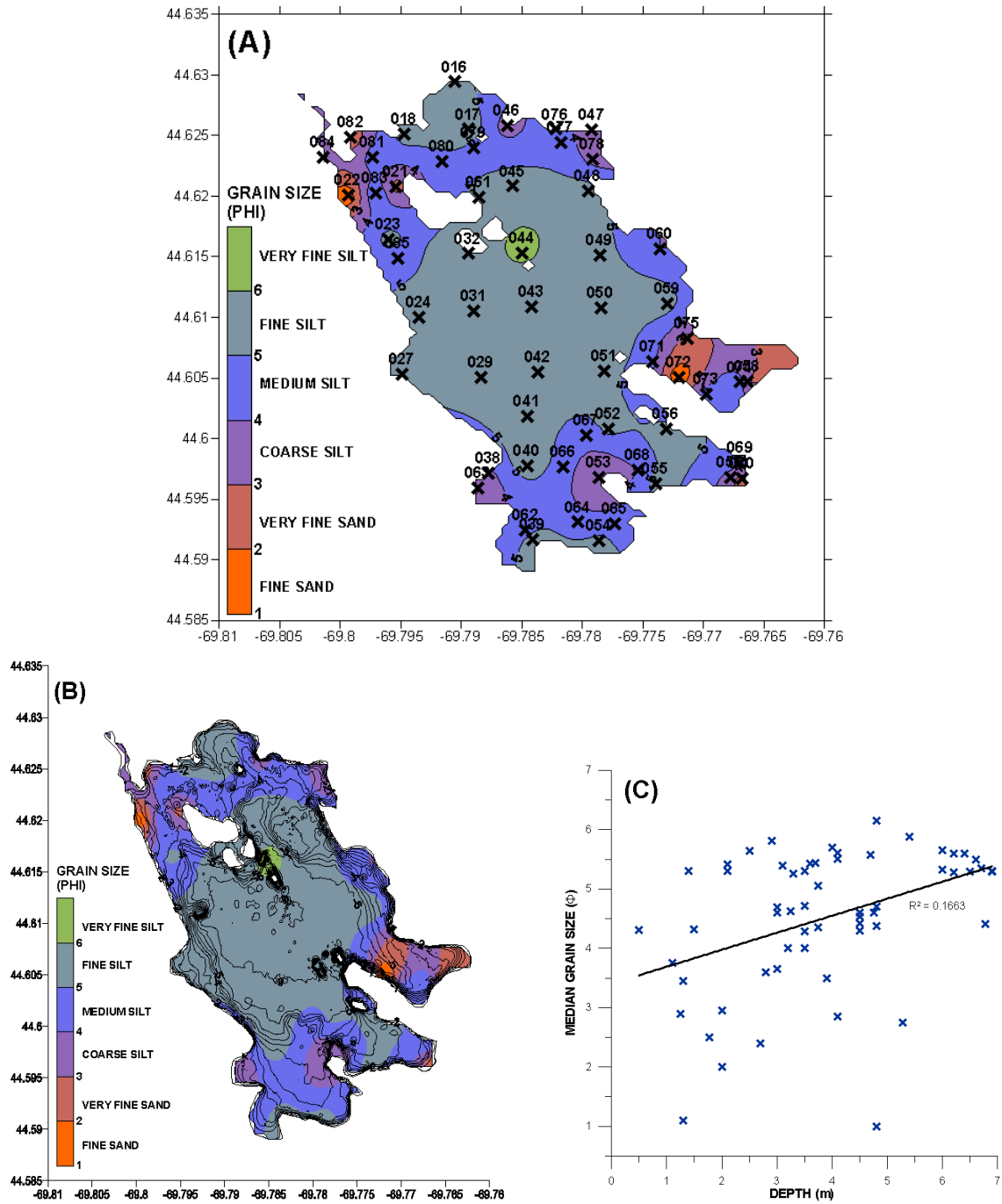


Figure 10: Results of the grain-size analysis of lake-bottom sediment. (A) Distribution of median grain size in phi with sediment sample locations; (B) distribution of median grain size in phi with bathymetric contours at 0.5 m intervals; and (C) bottom depth at the sample locations versus median grain-size.

Chemical analysis of the grab samples yielded a wide range in carbon, nitrogen, and phosphorus concentrations. TOC ranged from 0.47% along the lake's eastern margin (sample 072) to 30.64% in the Serpentine outlet (sample 084). Mean TOC was 5.42%. TOC distribution was fairly homogenous across the lake, except for much higher values at the northern end and into the Serpentine (Fig. 12A). TON ranged from 0.08% (sample 022) to 2.08% (sample 084) with a lake average of 0.57%. The ratio of TOC to TON for most samples was between 10 and 20, several samples were <10, and only sample 018 was >20 (Fig. 12B). Neither TOC, TON, nor the TOC:TON ratio show any correlation to depth (Figs. 13A, 13B, 13C). With the exception of two outlying samples, TOC has a very slight positive correlation to median grain size (Figs. 14A, 14B). However, TON and the TOC:TON ratio show no such relationship (Figs. 14C, 14D).

Phosphorus concentrations were elevated in East Pond sediments. The mean total phosphorus concentration was 0.048%. This comprises the phosphorus pool within the lake that could potentially be used by biota. Overall, 63% of phosphorus in the lake sediments was organic; the sediments contained more NaOH-extractable organic phosphorus than HCl-extractable organic or EDTA-extractable inorganic phosphorus (Figs. 15A, 15B). Organic phosphorus (NaOH plus HCl-extractable fractions) ranged from 0.005% (sample 022) to 0.052% (sample 059) and had a mean value of 0.029%. Inorganic phosphorus ranged from 0.002% (sample 082) to 0.048% (sample 031) and had a mean value of 0.018%. Total phosphorus distribution throughout the lake roughly follows a bulls-eye pattern with the highest P concentration in the lake's deep center and the lowest concentration at the Serpentine outlet (Fig. 16). Organic phosphorus had a more even distribution than inorganic P (Figs. 17A, 17B). While there is a slight positive

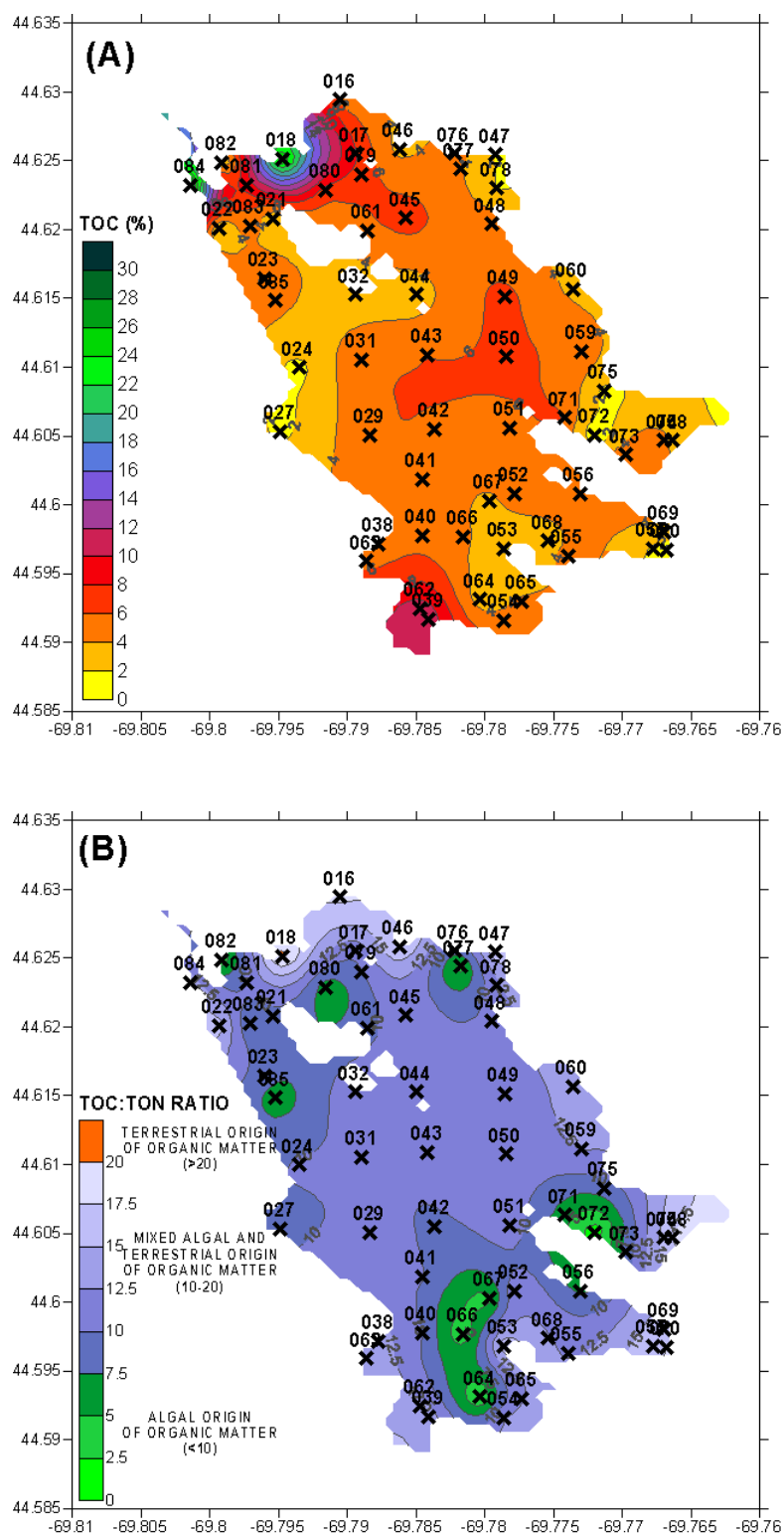


Figure 12: The distribution of (A) % TOC content of the sediments; and (B) the TOC:TON ratio, indicating the origin of organic matter (scale and organic matter origin based on Brown et al., 1998).

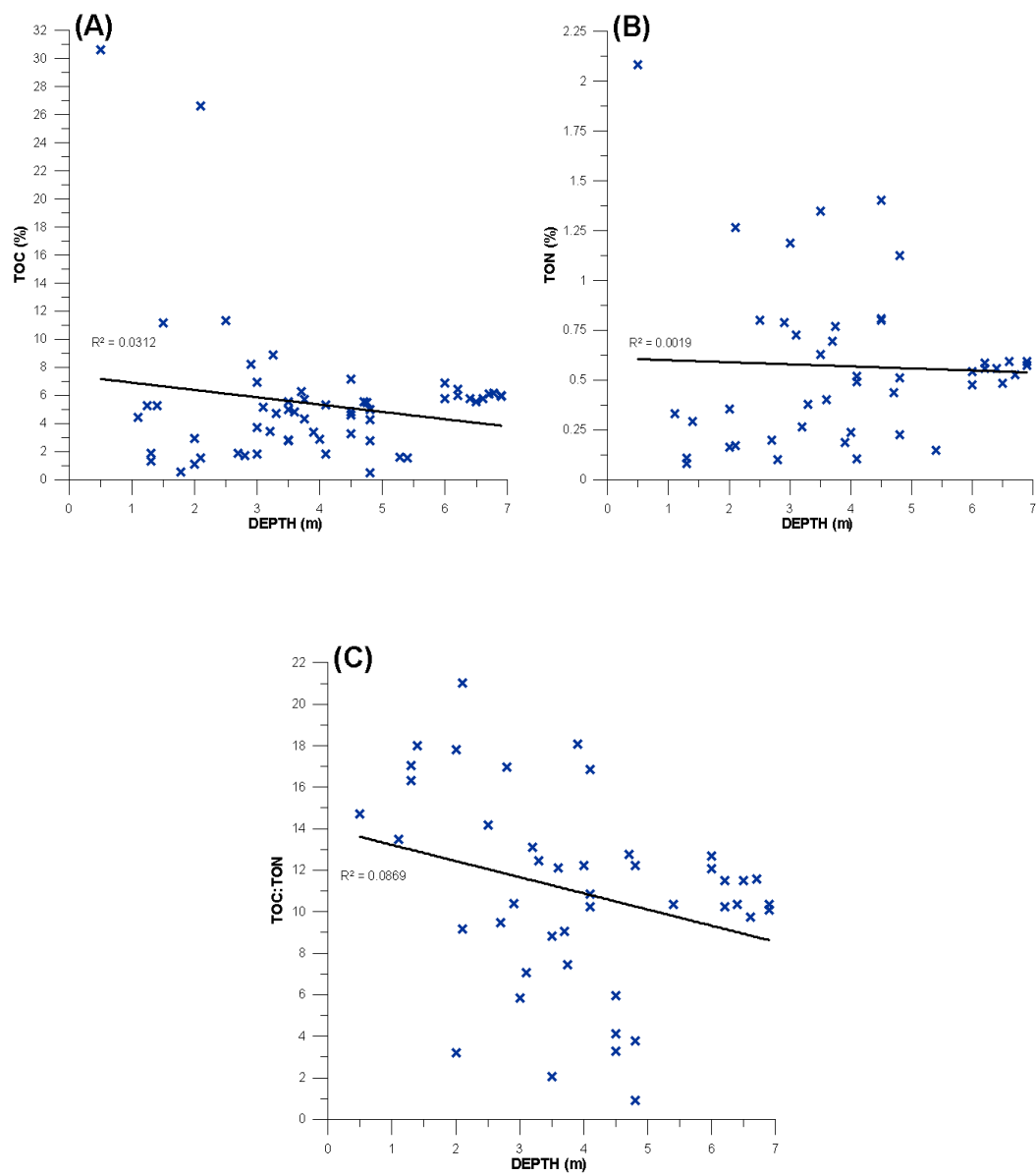


Figure 13: Bivariate plots of sediment chemistry versus bottom depth. (A) % TOC; (B) % TON; and (C) the TOC:TON ratio.

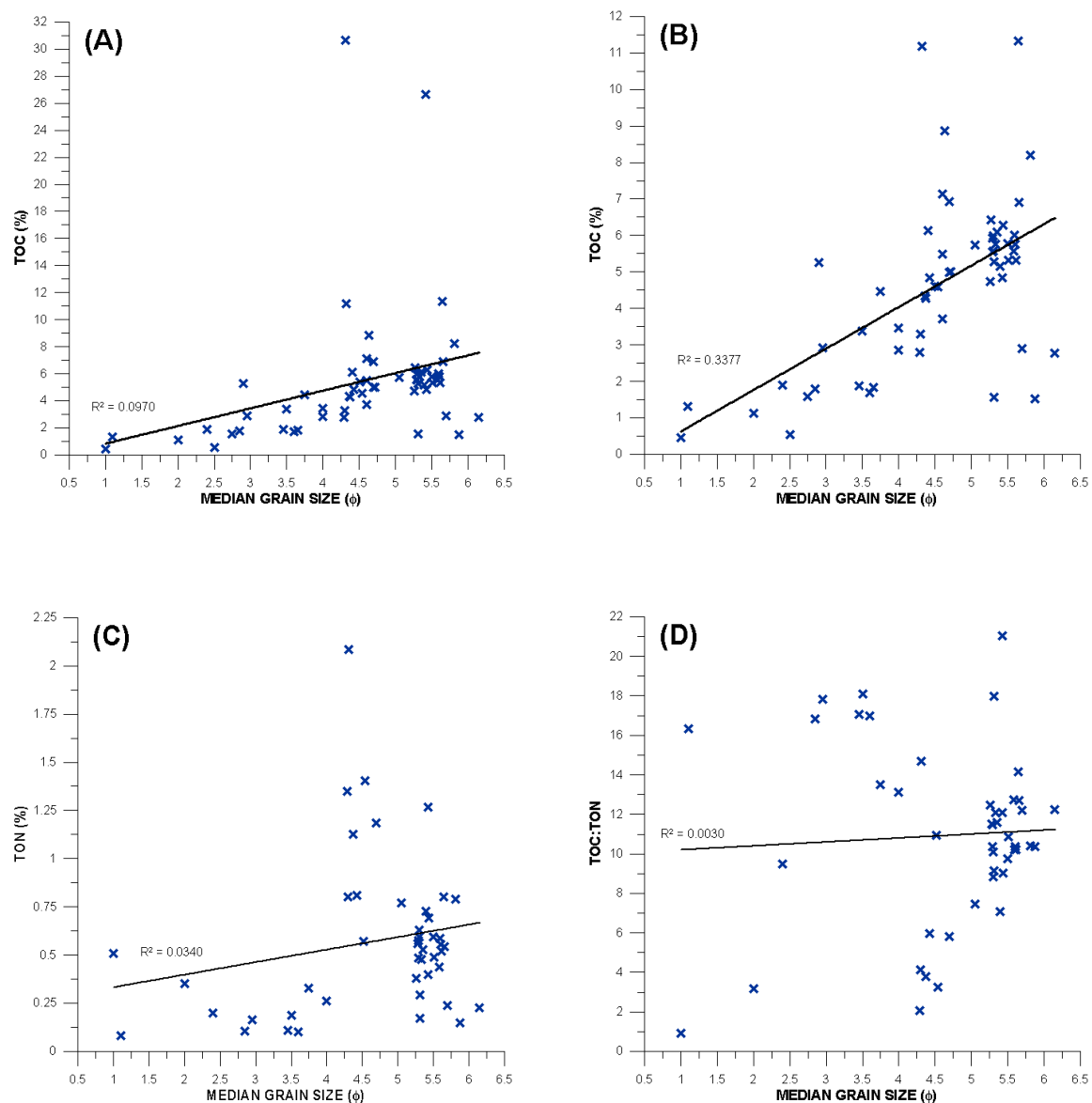


Figure 14: Bivariate plots of sediment chemistry versus the median sediment grain-size (Φ). (A) % TOC; (B) % TOC, minus the outlying samples 018 and 084; (C) TON (%); and (D) TOC:TON ratio.

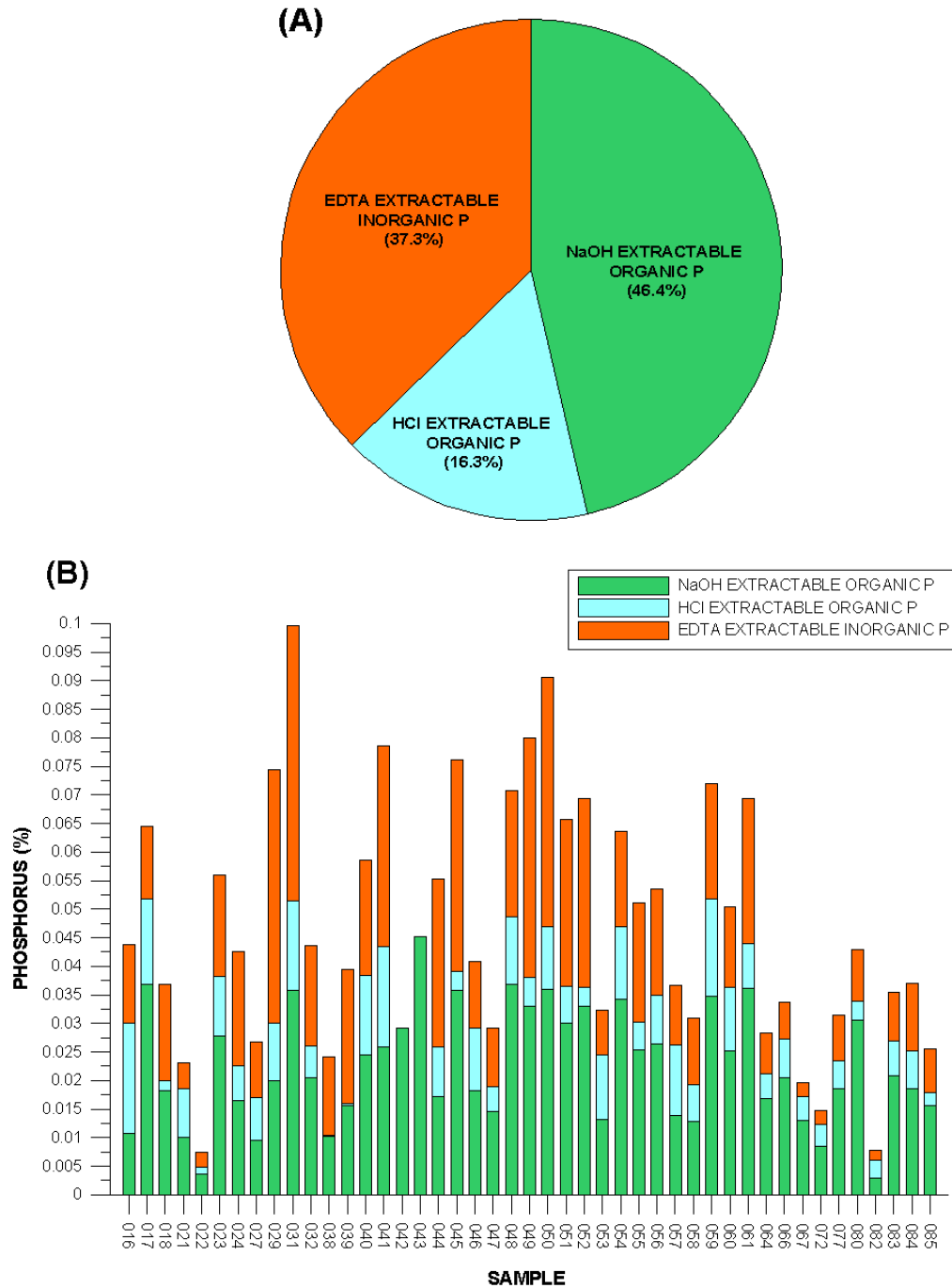


Figure 15: The relative concentration of the different phosphorus fractions in East Pond sediments. (A) The three fraction's mean percent of total phosphorus, and (B) the relative concentration of EDTA inorganic (orange), NaOH (green), and HCl (blue) organic phosphorus in each sediment grab sample. Note: data are missing from samples 042 and 043 due to ICP malfunction; the total P concentration is known for those samples, but not the P fractionation.

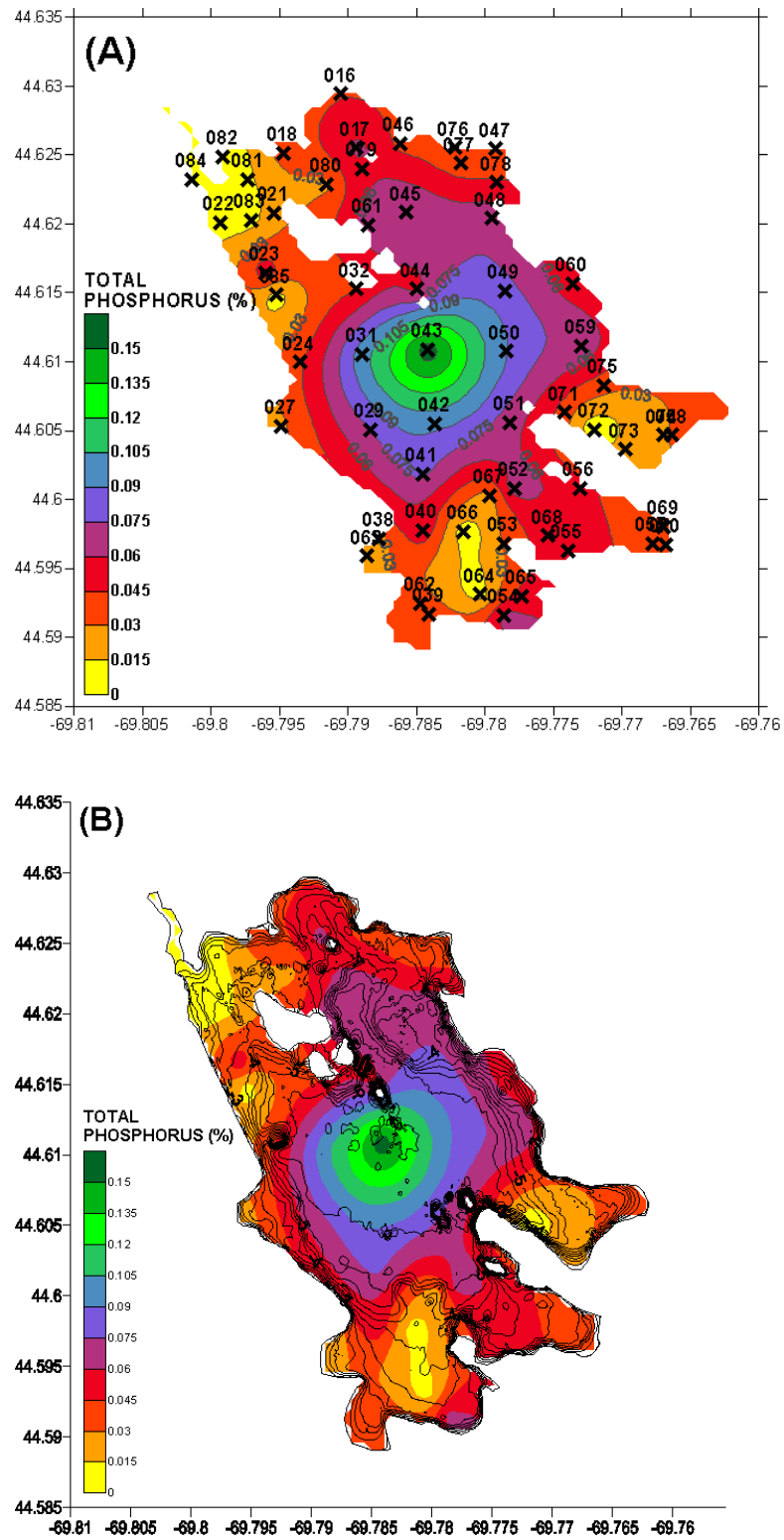


Figure 16: Total Phosphorus (%) distribution throughout East Pond. (A) Distribution of total phosphorus, (B) distribution of total phosphorus (%) with bathymetric contours at 0.5 m intervals.

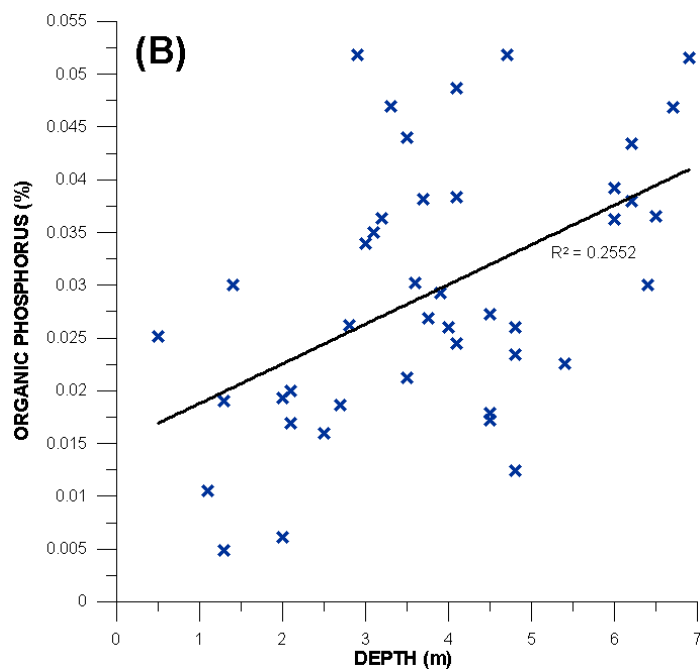
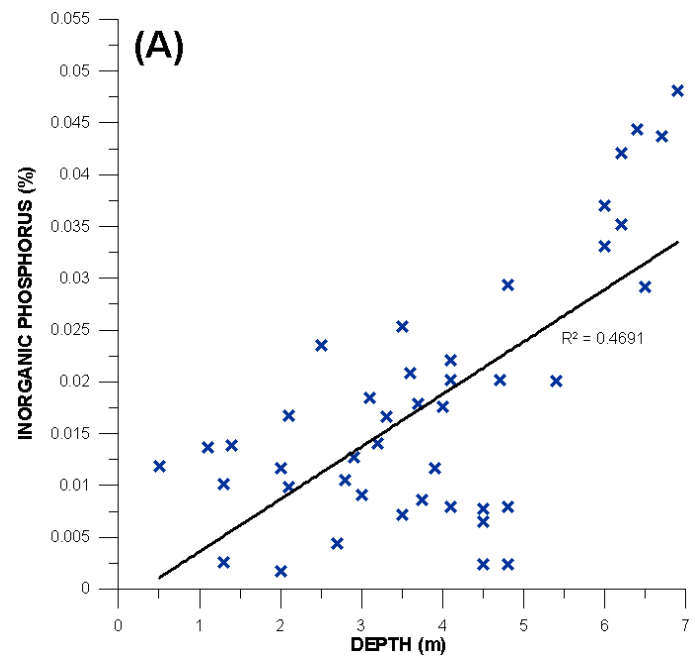


Figure 18: Bivariate plots of sediment chemistry versus bottom depth. (A) % inorganic phosphorus, and (B) % organic phosphorus.

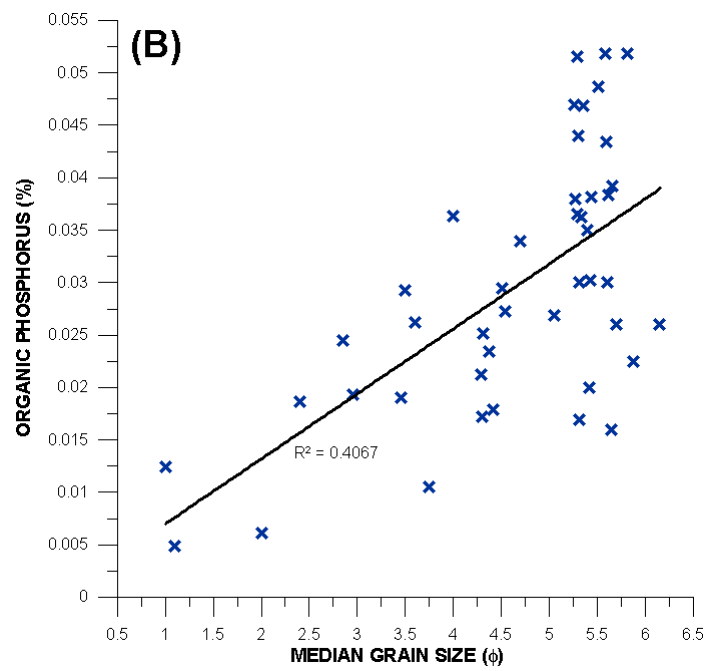
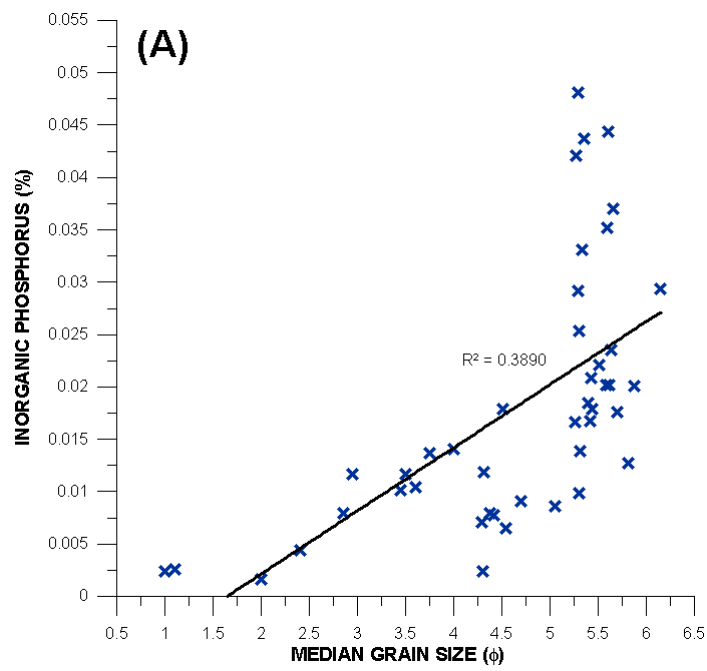


Figure 19: Bivariate plots of sediment chemistry versus the median sediment grain-size (Φ). (A) % inorganic phosphorus, and (B) % organic phosphorus.

correlation between inorganic phosphorus and depth (Fig. 18A), there is no such correlation between organic P and depth (Fig. 18B). Both inorganic and organic phosphorus show a slight positive correlation to median grain size (Figs. 19A, 19B). The complete sediment-chemistry data set is presented in Appendix C.

XRD analysis of sample 085 revealed a mineralogy dominated by quartz (~95%), with some albite, chlorite, and muscovite. There was a notable absence of clay minerals, as well as a lack of phosphate and phosphorus precipitate minerals.

Analysis of the non-organic particulates suspended in the lake indicates that the suspended load in the water column is very low. Grain-size analysis of suspended particles at 0.5 m, 3.0 m, and 5.5 m depths all revealed characteristics similar to those found in the bottom sediments. Notably, no clay-sized particles were detected. The complete data set can be found in Appendix D.

The cores extracted from Heron Cove and the Serpentine outlet recovered 17.8 and 26.4 cm of sediment, respectively. The base of the Heron Cove core was a hemic peat, overlain by a fine sand with a mottled contact (Figs. 20A, 20B). This fine sand graded up-section into an organic rich silt, which dominated the sediment column. Sparse aquatic vegetation was rooted in this silt at the sediment-water interface. The top 2 mm of core consisted of organic litter from suspension load. The Serpentine core was composed entirely of hemic peat, mottled with a layer of silt or fine sand near the top (Figs. 21A, 21B). Large organic debris and rooting structures were found throughout the column.

The Heron Cove core had very low TOC and TON concentrations, with an increase within 4 cm of the sediment-water interface. The TOC:TON ratio has one excursion to >20 at 3 cm, and is characterized with a ratio between 10-20 through the rest

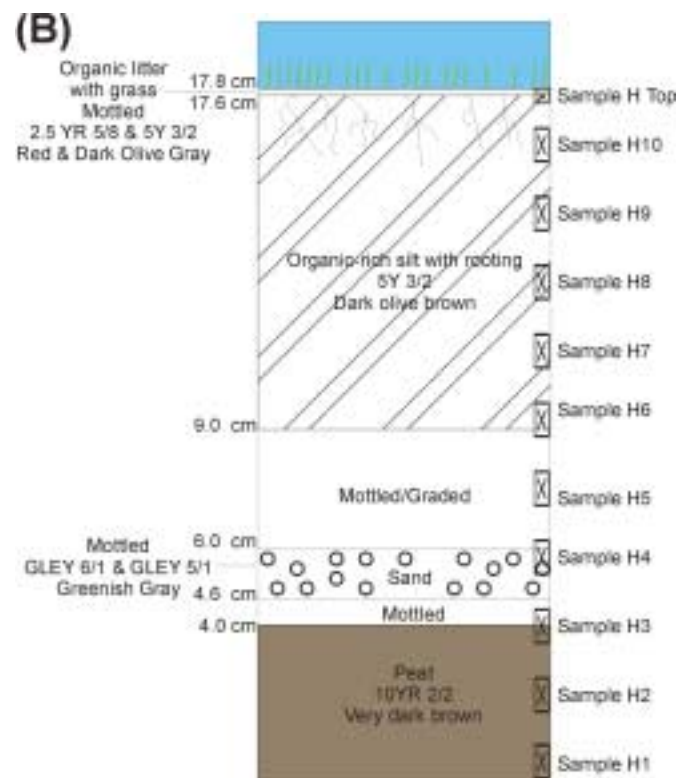


Figure 20: Description and chemistry of the core extracted from Heron Cove (N 44.597°, E 69.766°). (A) A photograph of the core; (B) description of the Heron Cove core with locations of removed sub-samples.

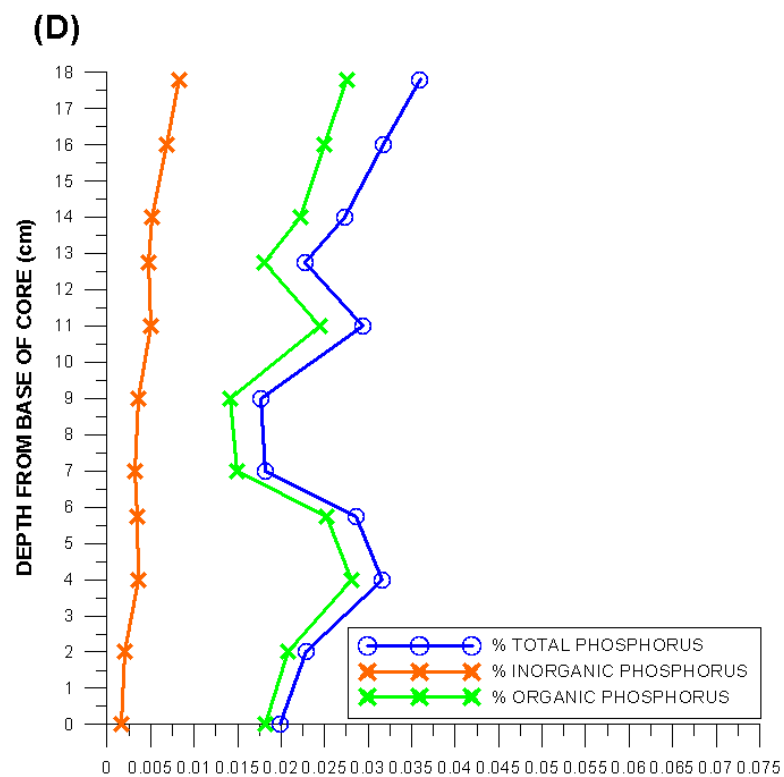
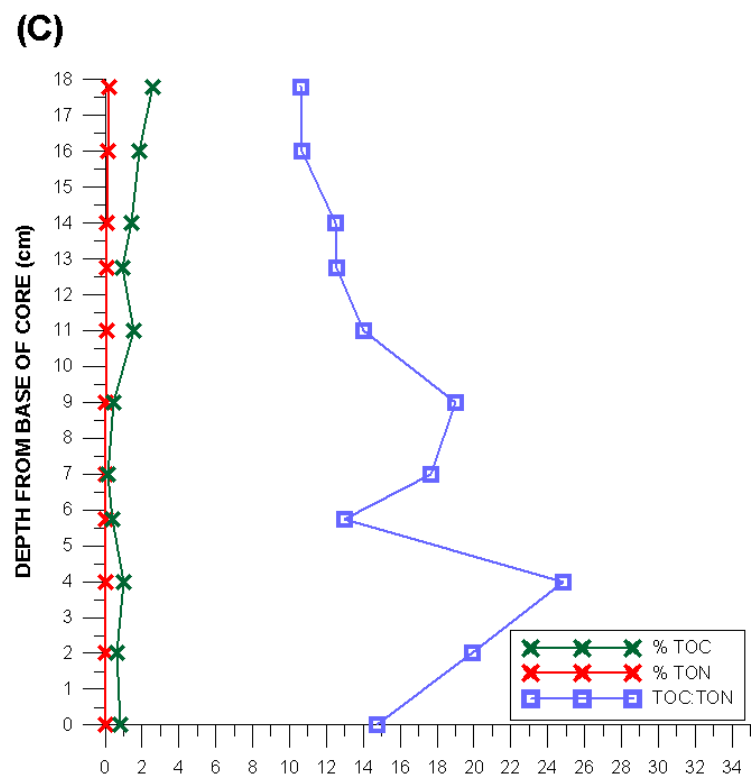


Figure 20 (continued): Description and chemistry of the core extracted from Heron Cove (N 44.597°, E 69.766°). (C) TOC, TON, and TOC:TON values of the sub-samples versus depth; and (D) inorganic, organic, and total phosphorus concentrations of the sub-samples versus depth.



Figure 21: Description and chemistry of the core extracted from the Serpentine outlet ($N 44.626^\circ$, $E 69.801^\circ$). (A) A photograph of the core; (B) description of the Serpentine outlet core with locations of removed sub-samples

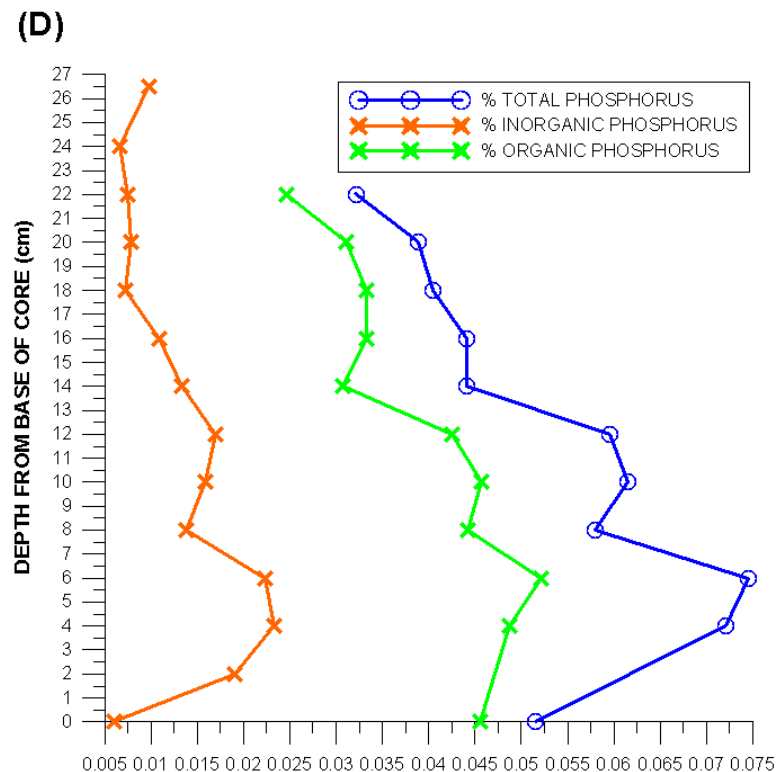
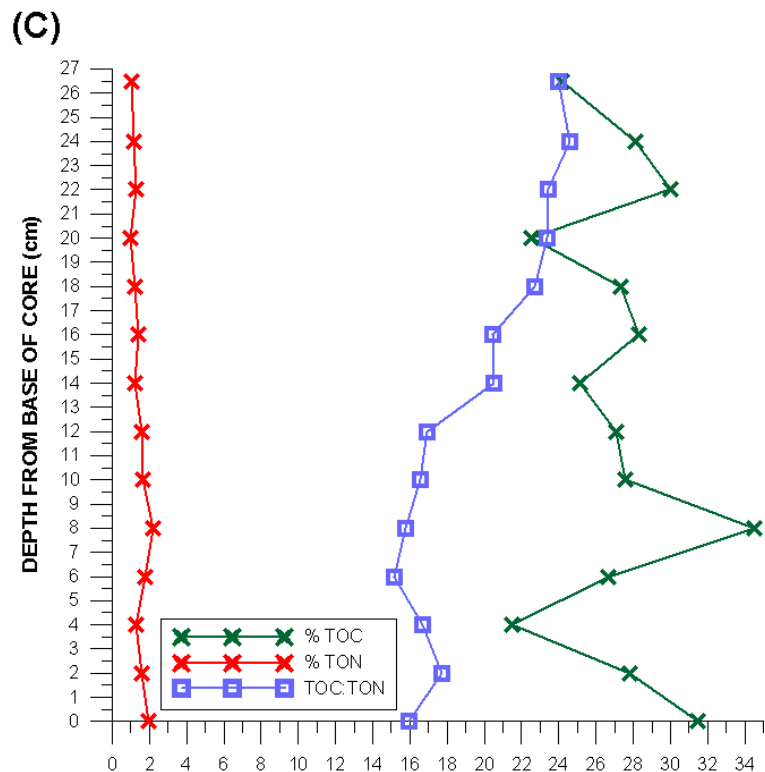


Figure 21 (continued): Description and chemistry of the core extracted from the Serpentine outlet (N 44.626°, E 69.801°). (C) TOC, TON, and TOC:TON values of the sub-samples versus depth, and (D) inorganic, organic, and total phosphorus concentrations of the sub-samples versus depth.

of the core (Fig. 20C). Phosphorus concentrations at the sediment-water interface of the cores were comparable to the values measured in the grab samples. Up section, there were increased phosphorus concentrations between 4 and 6 cm; above 13 cm, P concentration increases steadily to the sediment-water interface (Fig. 20D). The Serpentine core has TOC and TON concentrations much higher than those of the Heron Cove core. TOC fluctuates throughout the column and decreases near the sediment-water interface. The TOC:TON ratio increases downward, reaching values >20 at 14 cm (Fig. 21C). Phosphorus concentrations were elevated throughout the core compared to other sediment samples. Phosphorus increased from the base of the core to a depth of 6 cm, then decreased upwards to the sediment-water interface (Fig. 21D).

Water quality and chemistry

The water chemistry changed before and during the algal bloom of 2003. The maximum, minimum, and mean values for each variable are summarized in Table 3. On June 17, before the bloom, the temperature steadily decreased with depth; oxygen saturation was nearly constant from top to bottom, but sharply decreased at 5.5 m depth (Fig. 22A). On August 12, during the bloom, the lake as a whole, was warmer. The temperature was relatively low in the first 0.5 m of water (21 to 23° C), was constant at ~25° C to approximately 3 m depth, and then decreased steadily with depth (Fig 22B). After the bloom, the oxygen content was slightly lower than pre-bloom conditions. Dissolved oxygen generally decreased with depth, but this decline was not constant (Fig. 22B). Both before and during the algal bloom, conductivity roughly followed the same pattern as temperature – before the bloom it was low with increasing depth (Fig. 23A); during the bloom it was elevated from pre-bloom conditions and declined steeply below 3

Table 3: Summary of chemical characteristics before and during the 2003 algal bloom.

	<u>Pre Bloom (6/17/03)</u>			<u>During Bloom (8/12/03)</u>			<u>Units</u>
	Mean	Minimum	Maximum	Mean	Minimum	Maximum	
Temperature	18.35	18.01	19.67	24.57	22.78	25.62	°C
Dissolved O ₂	7.34	6.68	8.34	7.04	5.91	8.25	ppm
Conductivity	35	35	37	46	43	50	mS
pH	6.77	6.60	7.07	8.10	6.25	9.35	-log[H ⁺]
Fluorescence	0.63	0.00	1.00	0.86	-0.30	1.80	Arbitrary units
ORP	249.4	233.4	259.4	223.36	178.0	282.4	mV

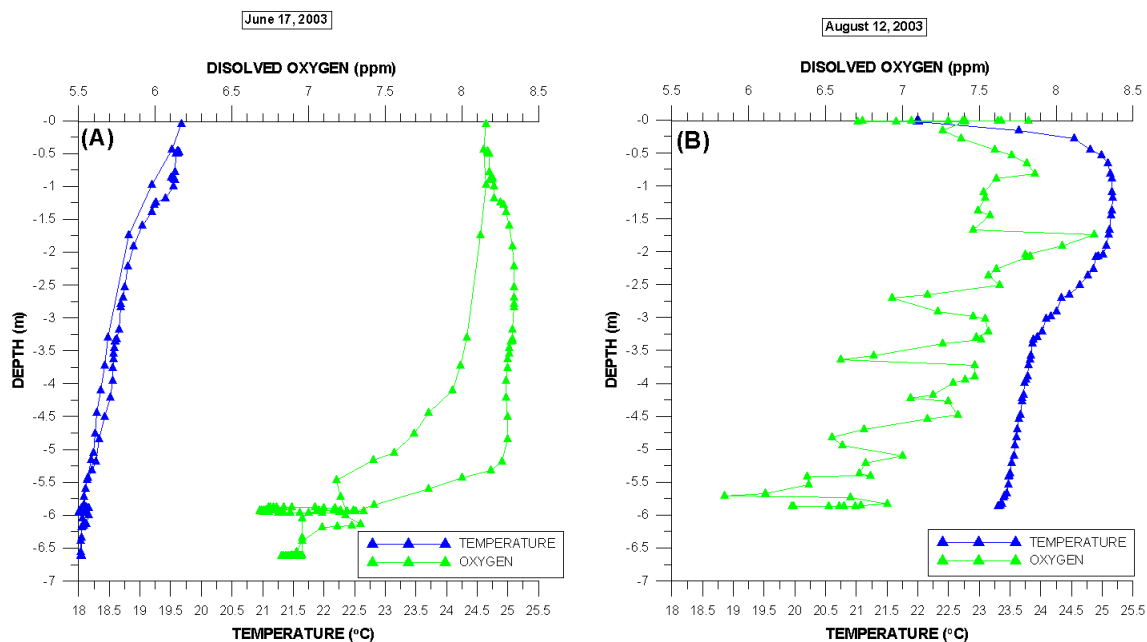


Figure 22: Temperature and dissolved oxygen water-column profile (A) from June 17, before the algal bloom; and (B) from August 12, during the algal bloom.

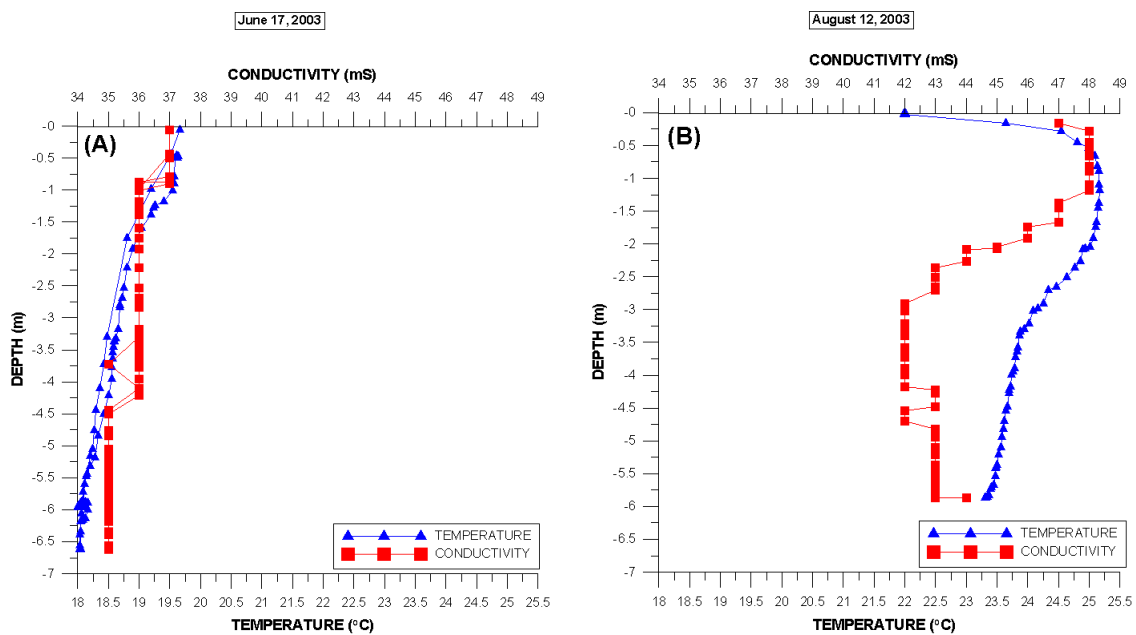


Figure 23: Temperature and conductivity water-column profile (A) from June 17, before the algal bloom; and (B) from August 12, during the algal bloom.

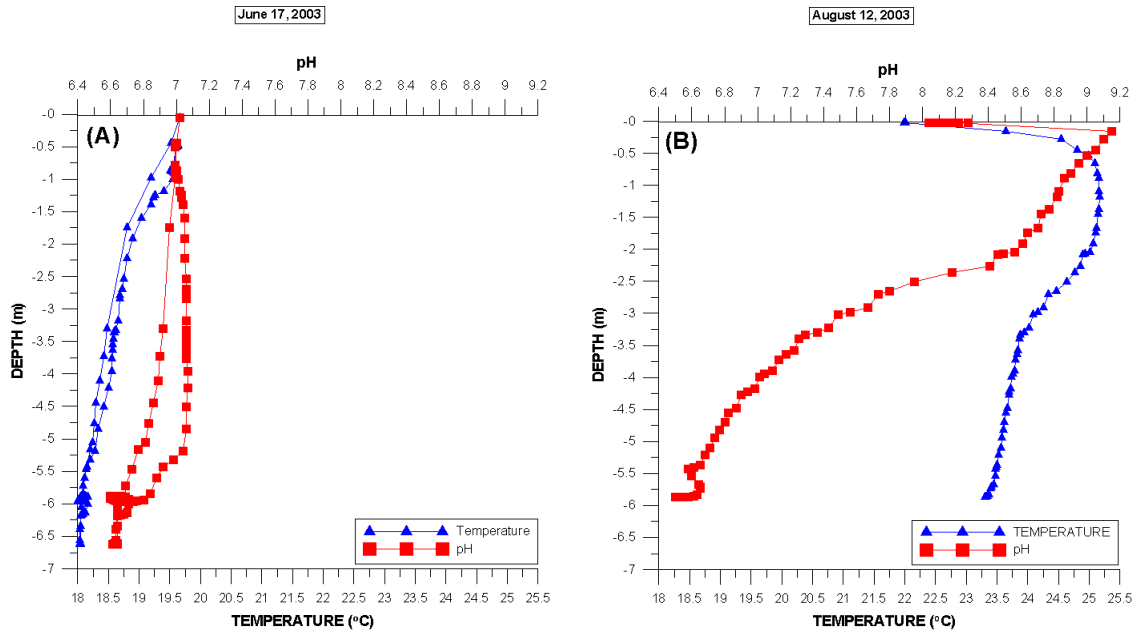


Figure 24: Temperature and pH water-column profile (A) from June 17, before the algal bloom; and (B) from August 12, during the algal bloom.

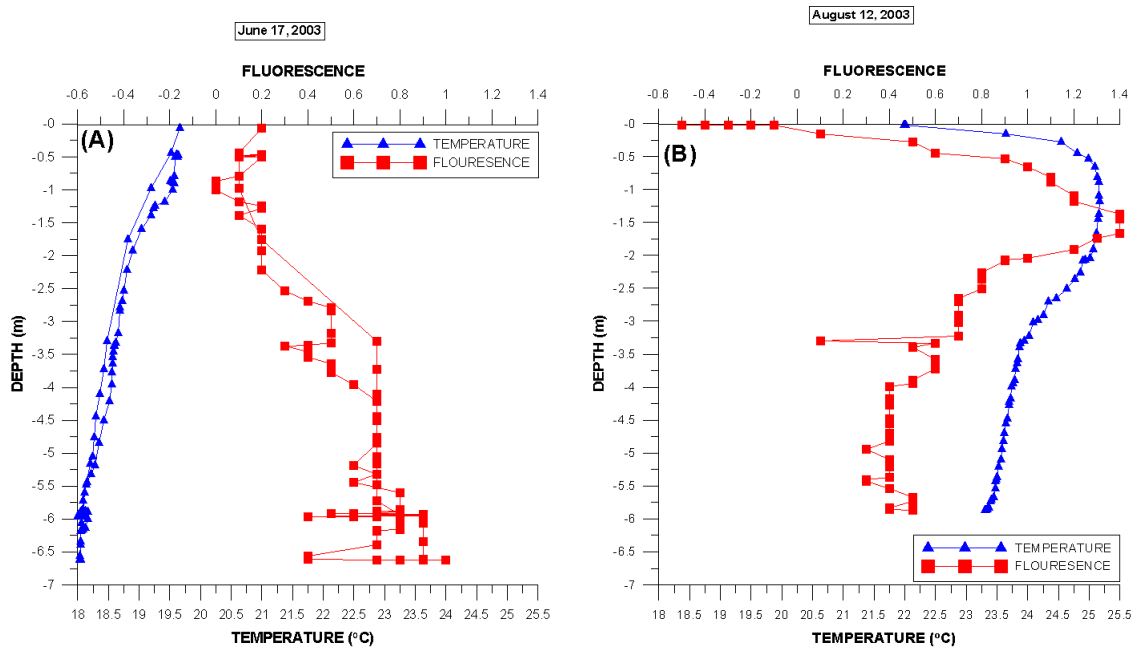


Figure 25: Temperature and fluorescence water-column profile (A) from June 17, before the algal bloom; and (B) from August 12, during the algal bloom.

Table 4: Summary of the summer's ORP and pH data.

<u>Date</u>	Eh (ORP) (v)			pH		
	Mean	Minimum	Maximum	Mean	Minimum	Maximum
11-Jun	0.27	0.22	0.36	7.04	6.8	9.1
17-Jun	0.25	0.04	0.32	6.95	6.4	7.3
11-Aug	0.24	0.16	0.31	7.92	6.1	9.7
12-Aug	0.25	0.18	0.34	7.85	5.9	9.5
15-Aug	0.26	0.17	0.29	7.06	5.3	8.7
20-Aug	0.29	0.24	0.32	7.15	5.9	8.5

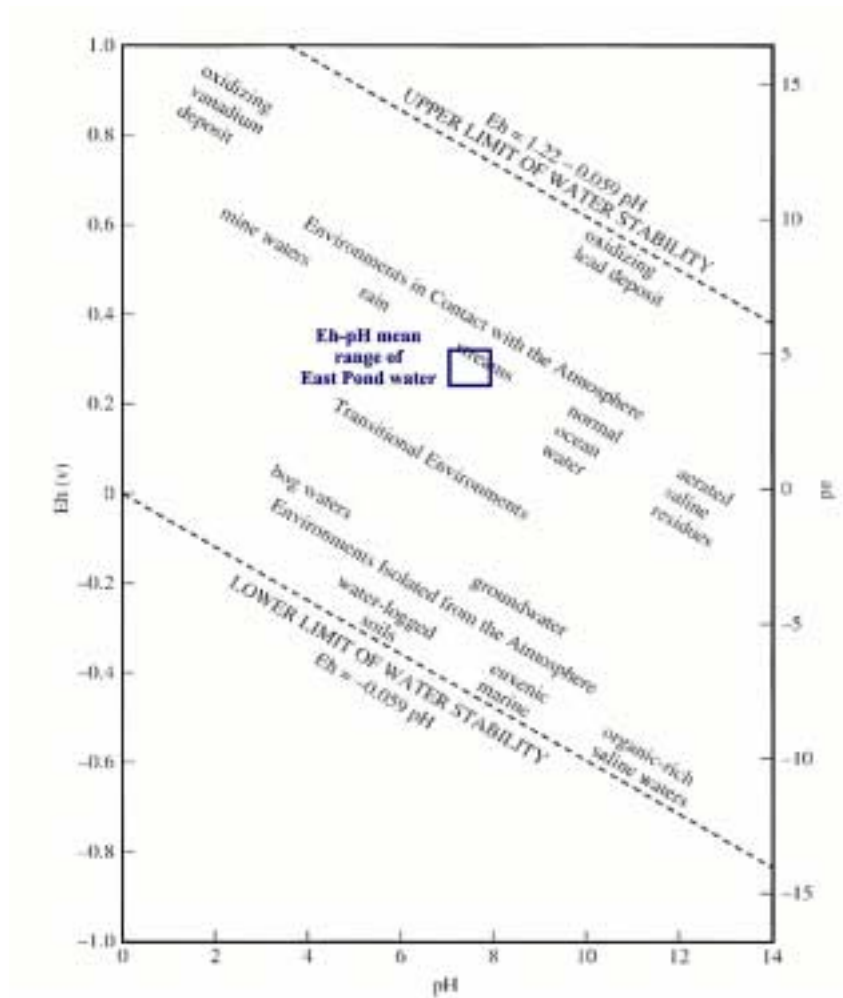


Figure 26: The range of mean ORP and pH values of East Pond water, plotted on an Eh-pH diagram (Garrels & Christ, 1965).

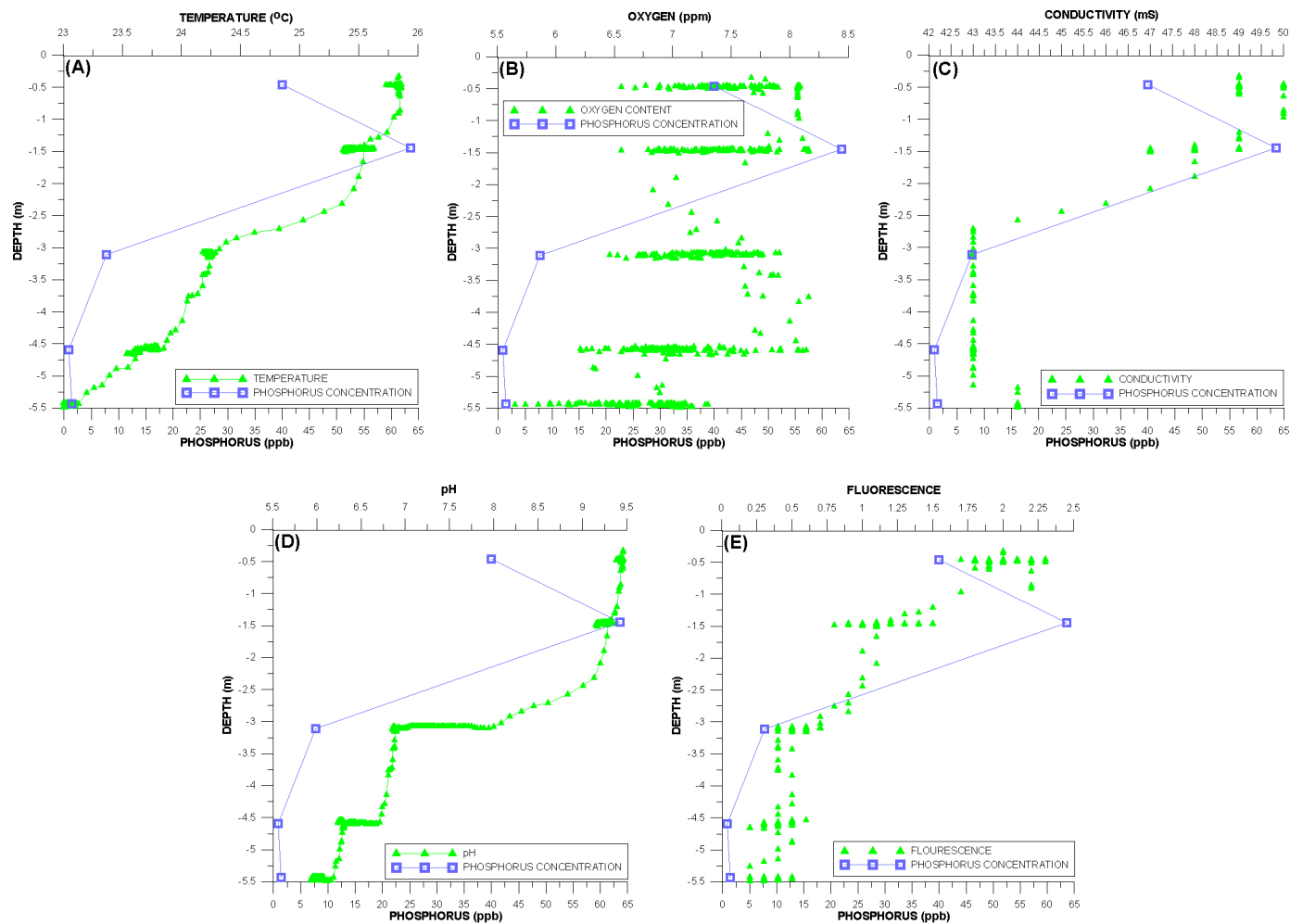


Figure 27: August 12, 2003, phosphorus concentration (blue) throughout the water column compared to other chemical parameters (green): (A) temperature, (B) oxygen concentration, (C) conductivity, (D) pH, and (E) fluorescence.

m depth (Fig. 23B). Pre-bloom pH was also nearly uniform from top-to-bottom; however, like oxygen content, it was lower at the very bottom of the lake (Fig. 24A). pH during the bloom was much higher at the surface than it was before the bloom and decreased steadily with depth (Fig. 24B). Fluorescence showed the greatest change before and during the bloom. On June 17, fluorescence increased fairly constantly with depth (Fig. 25A). On August 12, fluorescence was much higher in the top 0.5 m of water, peaked at 1.5 m, and decreased sharply below 2 m (Fig. 25B).

ORP fluctuated largely and inconsistently both before and during the bloom. However, a general trend in Eh can be described. While ORP ranged from 39.0 to 393.5 throughout the summer and with depth, the water always measured a positive ORP. The mean ORP for the summer was 258.03. Summary of ORP data is provided in Table 4; the position of East Pond water on an Eh-pH diagram is presented in Figure 26.

On August 12, during the algal bloom, phosphorus in the water column ranged from 0.91 ppb ($9.10 \times 10^{-7} \%$) at 4.59 m depth to a maximum of 63.5 ppb ($6.35 \times 10^{-6} \%$) at 1.45 m. The phosphorus-depth profile roughly followed the vertical distribution of the other chemical parameters (Fig. 27).

Seasonal water quality

As can be seen in the two transects indicated in Figure 8B, there is negligible geographic variation in temperature and oxygen across East Pond (Figs. 28 through 31). However, there is a difference with respect to these variables between the shallow (<5 m deep) and deeper (>5 m) waters. Because there appears to be no pattern of lateral variation independent of depth; only changes with respect to depth and time will be discussed. According to the Maine DEP, East Pond officially was experiencing an algal

bloom starting August 6, 2003; the results from the summer-long lake quality monitoring will be discussed before and during the algal bloom.

Before the algal bloom, the lake temperature ranged from 19.5 to 26.0 °C and oxygen content ranged from 1.2 to 10.4 ppm. There was a thin lens of colder, oxygen poor water below 5 m depth. Waters above -5 m were fairly homogenous with respect to both temperature and oxygen (Figs. 28, 29). By mid-August, this lake stratification disappeared. Overall, the lake water had cooled and became more enriched with oxygen. Temperature ranged from 22.5 to 26.0 °C and oxygen content ranged from 1.1 to 9.9 ppm (Figs. 30, 31). Throughout the summer there were several small intervals where stratification occurred at depth; these short stratification events are more pronounced with respect to dissolved oxygen than with respect to temperature (Fig. 32).

The average pre-bloom secchi depth was -4.3 m across the entire lake (Fig. 33). After July 24, secchi depth started to decrease, starting at the northern margin of the lake. On the day that the Maine DEP officially identified an algal bloom (August 6), the mean secchi measurement for the entire lake was -2.68 m. Our data show that secchi continued to decrease, reaching a minimum of -1.4 m in late August; the bloom continued from early August into November (Fig. 33).

Overall, the NOAA meteorological records indicate that summer 2003 was cooler and wetter than previous years. However, there were no correlations between changing air temperature nor total weekly precipitation and decreased water quality (Figs. 34, 35). Also, there was no relationship between the lake's water temperature at 3 m depth and secchi depth until the algal bloom (Fig. 36). Wind direction fluctuated throughout the summer (Fig. 37). Most winds came from 193° (south-west) at an average of 17.9 mph

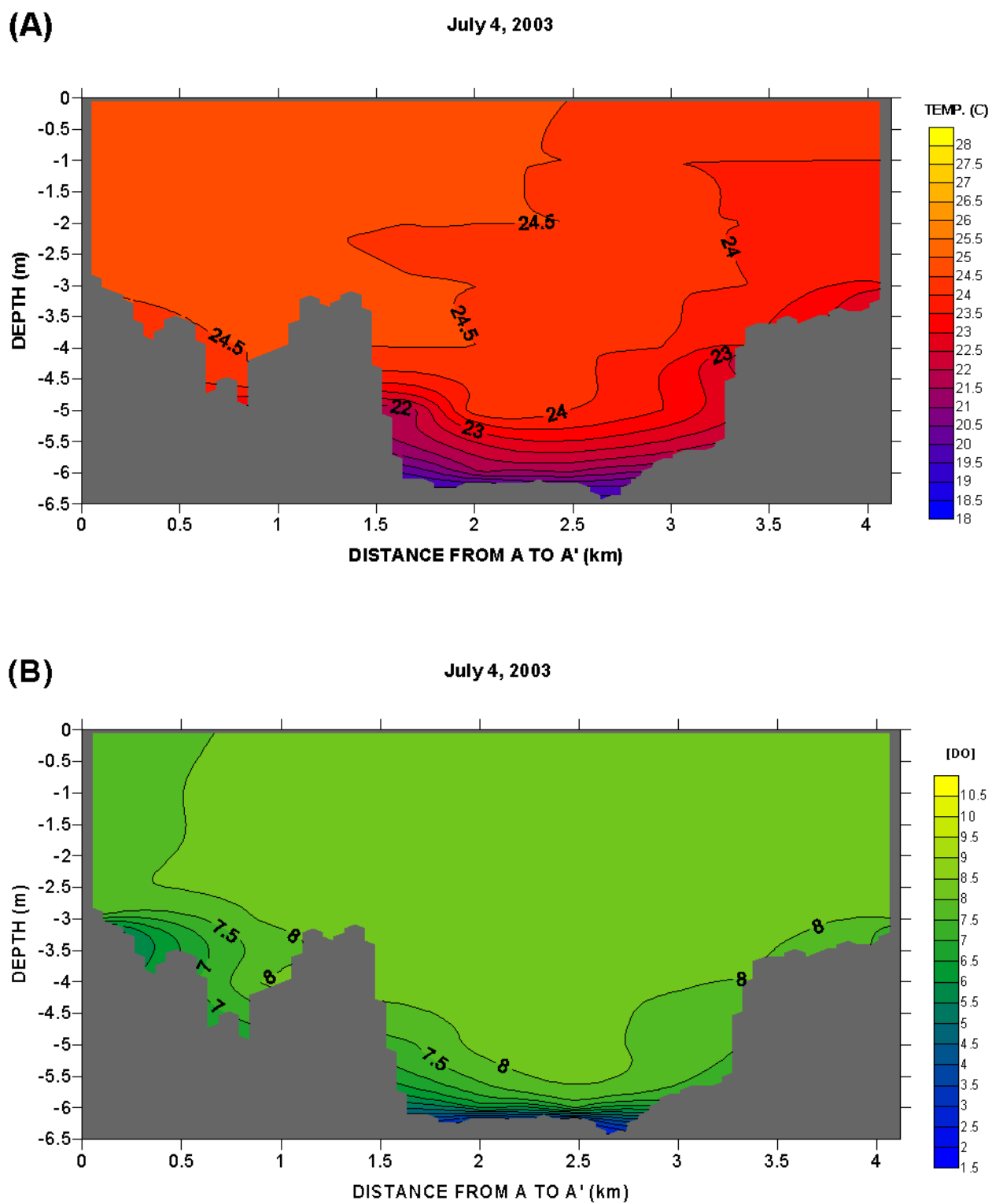


Figure 28: The distribution of (A) temperature and (B) oxygen content along a north-to-south transect before the algal bloom.

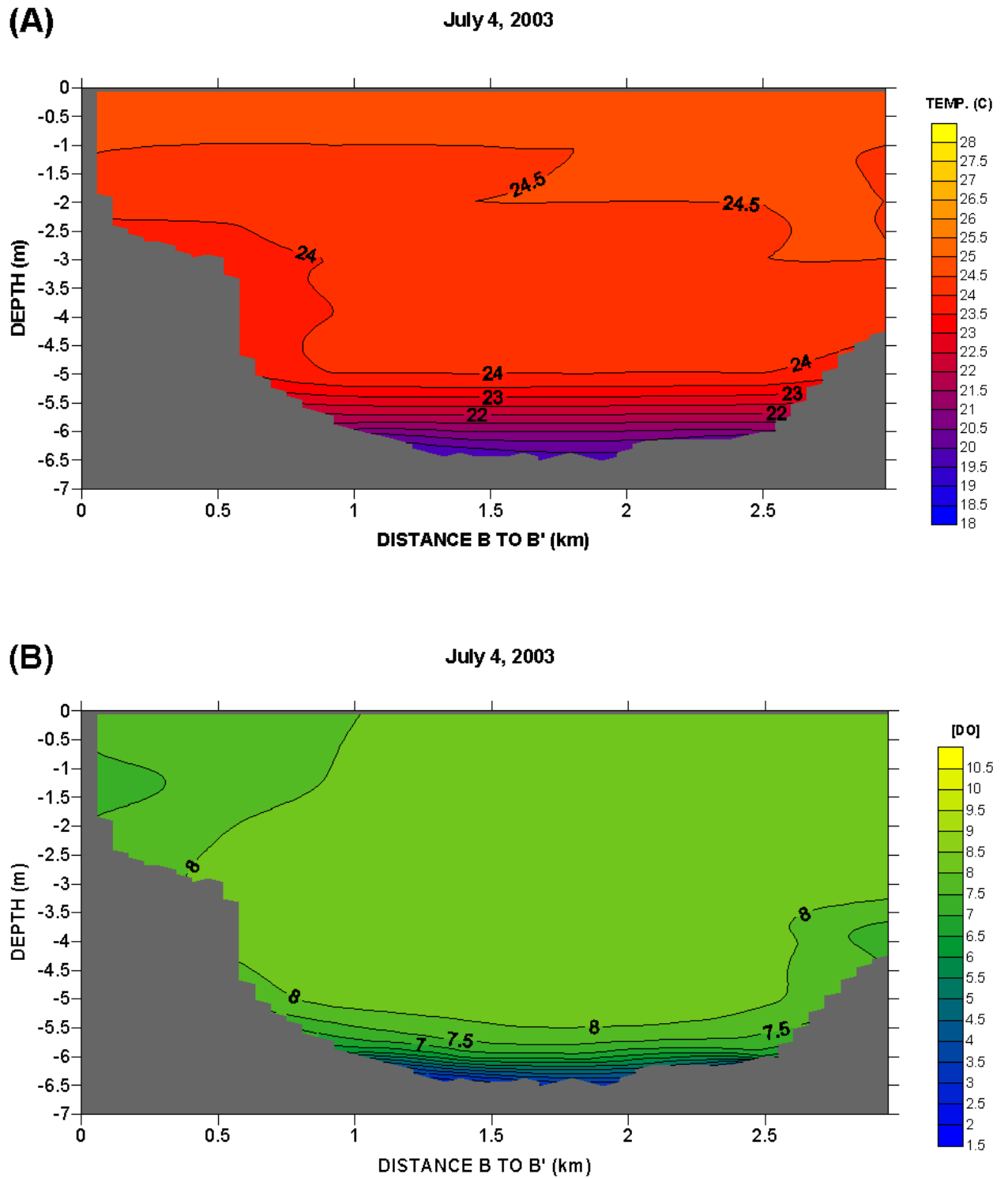


Figure 29: The distribution of (A) temperature and (B) oxygen content along a west-to-east transect before the algal bloom.

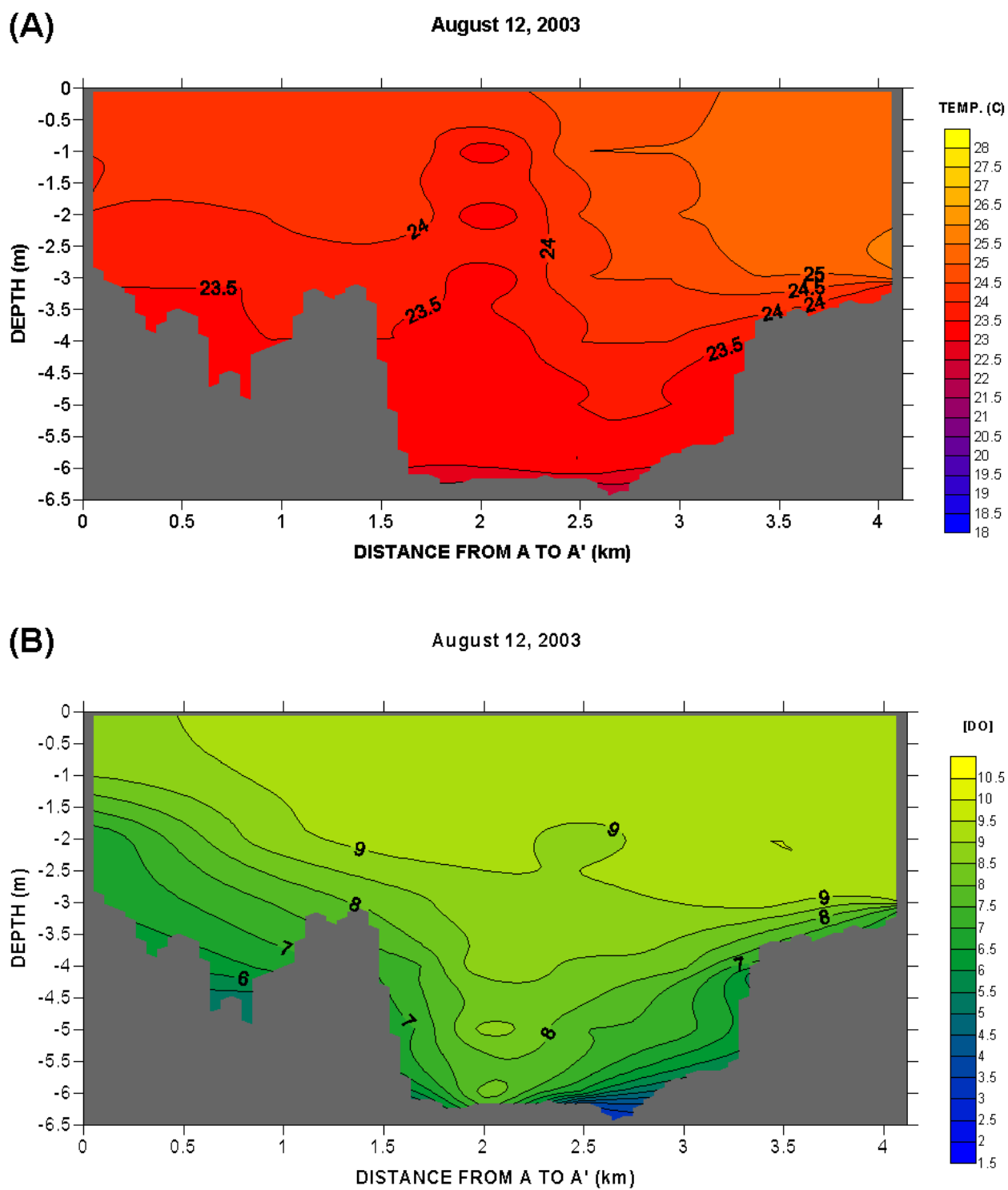


Figure 30: The distribution of (A) temperature and (B) oxygen content along a north-to-south transect during the algal bloom.

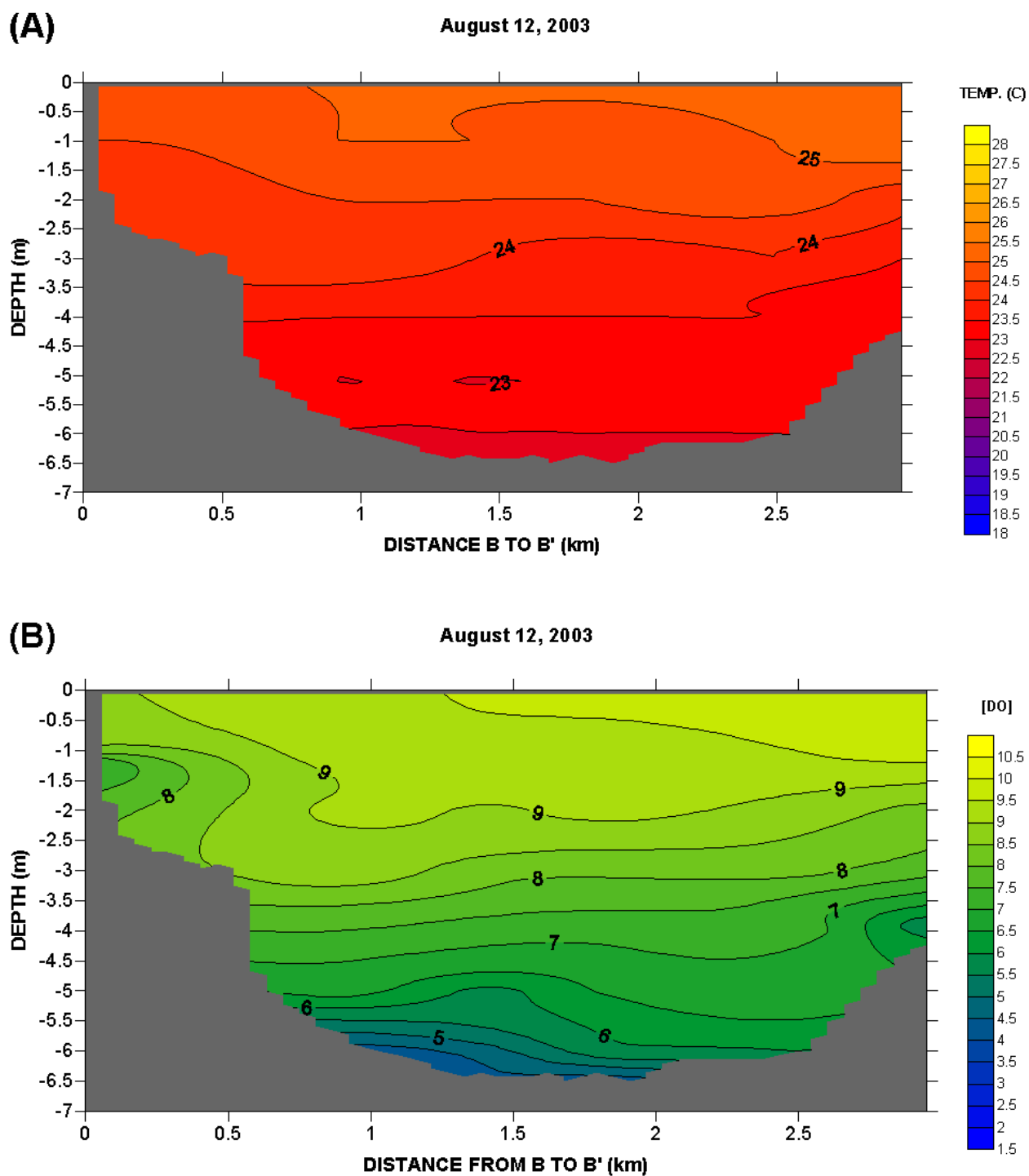


Figure 31: The distribution of (A) temperature and (B) oxygen content along a west-to-east transect during the algal bloom.

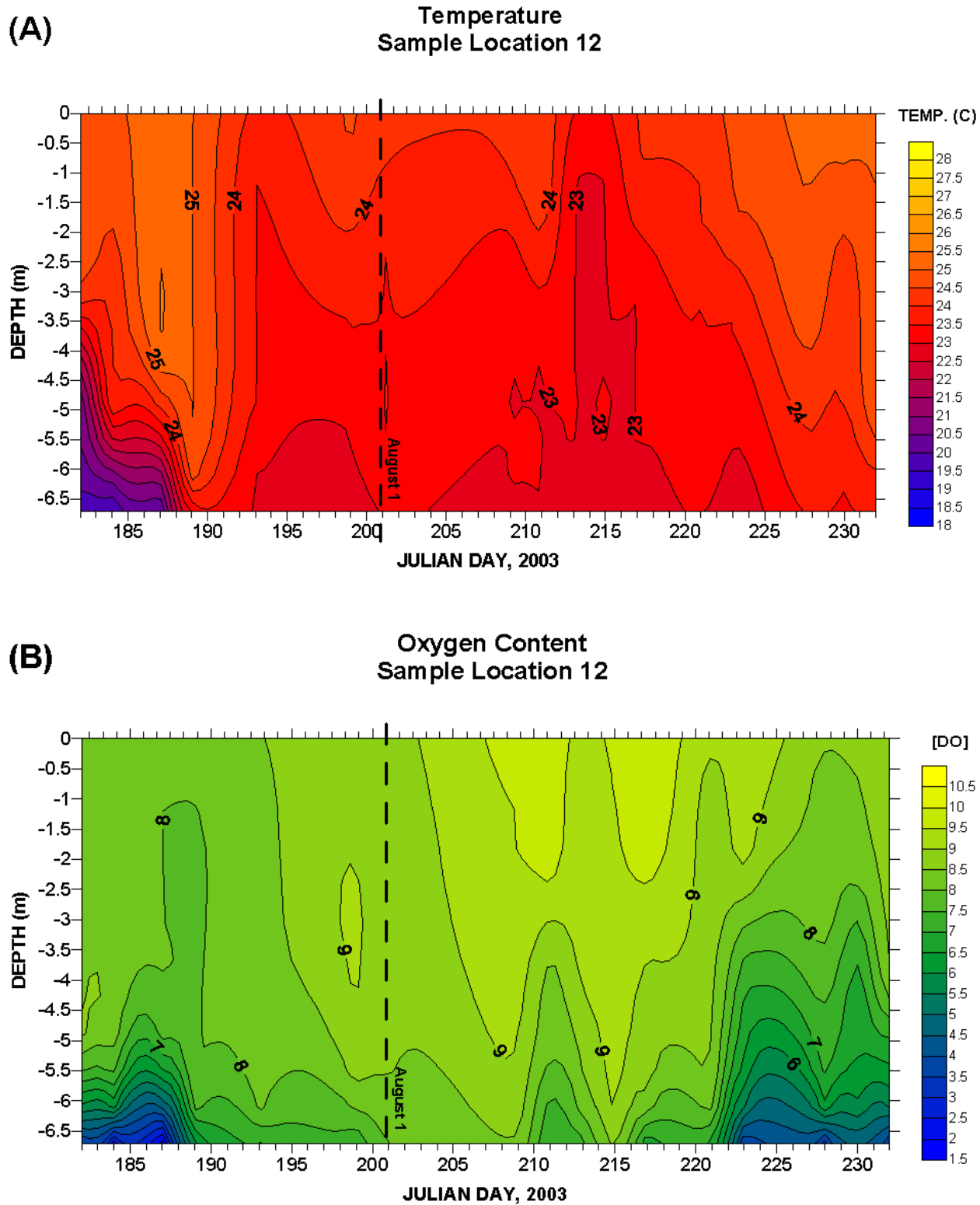


Figure 32: The vertical distribution of (A) temperature and (B) oxygen throughout the summer of 2003, at sample site 12 ($N 44.60539^\circ$, $W 69.79177^\circ$), located at the center of the lake.

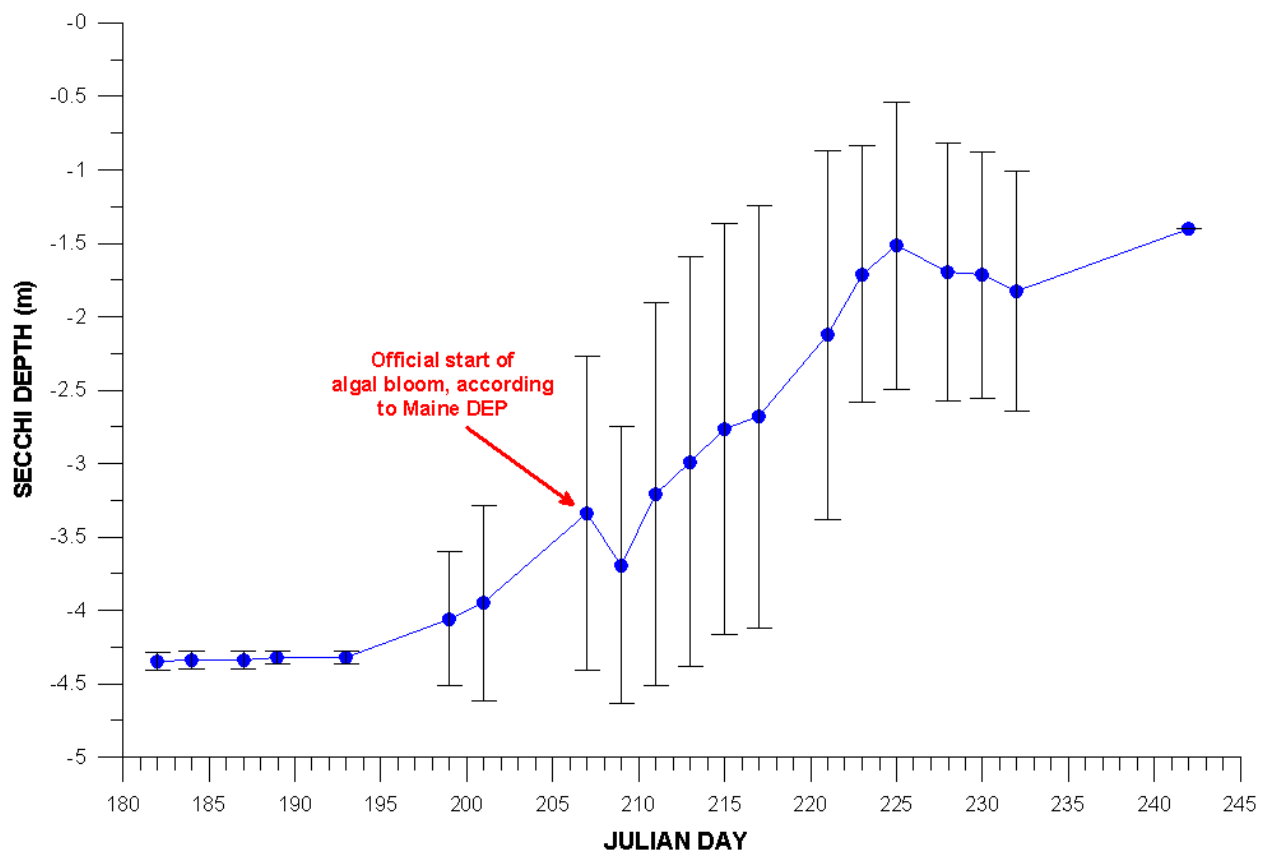


Figure 33: The mean of all secchi measurements for each date, with 95% confidence interval.

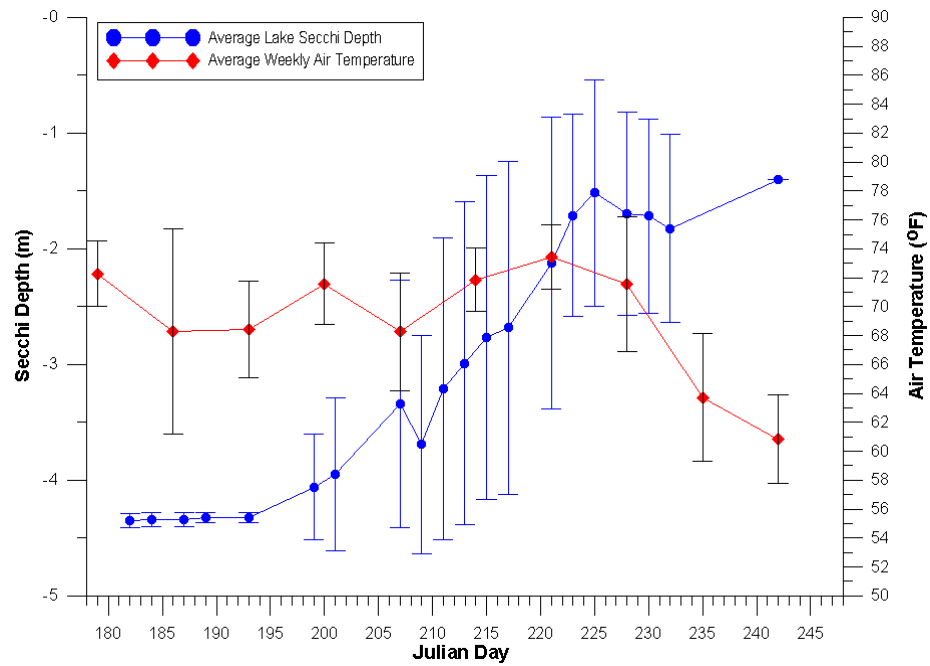


Figure 34: The mean secchi depth (blue) and mean weekly air temperature (red) with 95% confidence interval plotted throughout the summer 2003.

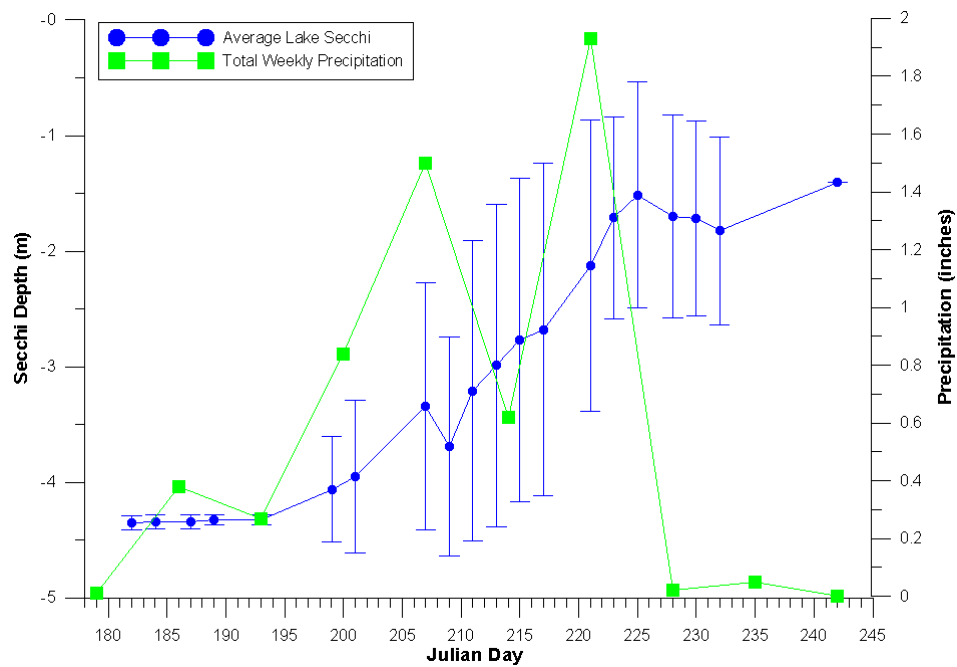
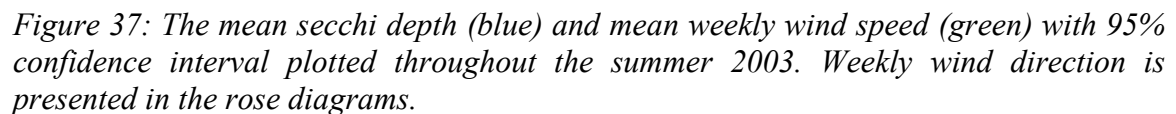
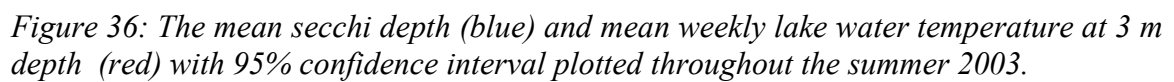


Figure 35: The mean secchi depth with standard deviation (blue) and total weekly precipitation (green) plotted throughout the summer 2003.



(12.0 to 26.0 mph); however, the strongest winds came from 300° (north-west) at 29.0 mph. There was no correlation between wind velocity and secchi depth, and a only tenuous relationship between wind velocity and wind direction (Fig. 38). There is a change in dominant wind direction the week before the algal bloom (Fig. 38).

Discussion

The bathymetry and geometry of East Pond play a key role in the processes occurring within the lake. As Figure 5 illustrates, the lake is roughly oval-shaped and the long axis lying in a southeast-to-northwest orientation. Overall, the lake is shallow, with a mean depth of -4.5 m and a maximum depth of -7.3 m. The bathymetry data collected by the Colby College research group during the summer of 2002 are high resolution and based on more than 20,000 data points; therefore, the calculations from these data (area, volume, etc.) are more accurate than previously reported statistics (e.g., BI493, 1993; PEARL, 2003). Several studies report that both depth and lake morphology play a key role in lake nutrient cycling (e.g., Davis *et al.*, 1978; Nürnberg, 1984; Levine & Schindler, 1992; Nieratko, 1992; Petterson, 1998). Nieratko (1992) found a positive inverse statistical correlation between lake depth and trophic state, as well as between lake area/volume and trophic state in Maine lakes. In generally, shallower basins exhibit decreased water quality.

East Pond's asymmetrical bottom bathymetry is roughly bowl-shaped, with broad shallow lake margins extending from the north and south; the southern margin has a gentler slope than the north, west, and east margins. There is a nearly circular-shaped deep area in the lake center – the depth abruptly declines from ~-4 m to ~-7 m. On the northwest margin of the deep lake center are a cluster of islands (including Miller Island)

and an aerially exposed boulder field. The Serpentine bog and outlet are located in the northwestern corner of the lake, in the lee of the islands. The entire northern end of East Pond is surrounded by bog, which is to be the focus of a future study by Colby College.

The present study found that the physical and chemical processes acting within East Pond functionally divide the lake into two sections: areas with depths greater than -5 m versus less than -5 m. All shallow (<-5 m) areas are fairly homogenous, the only differences within the lake exist between the shallow and deep (>-5 m) waters. This observed distinction defines the hypolimnion (deeper) and epilimnion (shallower) of East Pond. The total volume of water contained below -5 m (hypolimnion) was calculated to be $2.3 \times 10^6 \text{ m}^3$, the total volume of water above -5 m (epilimnion) was calculated to be 2.4×10^7 . Other than this depth distinction, there is little lateral variation in water temperature and dissolved oxygen (Figs. 28-31).

Sediment Characterization

East Pond bottom sediments can be characterized as an organic rich, moderately well-sorted silt. This is consistent with the lake's glacial formation and subsequent Holocene history. Both the grain sizes present and their distribution are to be expected in a hydrodynamically low energy system. Also, the results of the grain-size analysis correlate well to similar studies conducted on Messalonskee Lake, the terminal lake in the Belgrade Lakes chain (Allen *et al.*, 2003; & unpublished data, Colby College Geology Department). Here, Allen *et al.* (2003) found bottom sediments with grain-sizes ranging from ~ 4 to $< 6 \Phi$, TOC ranging from 0.24 to 13.25%, and TOC:TON ratios ranging from 10 to 15. The absence of clay-sized clasts in both the bottom sediments and suspended load of East Pond is unexpected, while also consistent with Messalonskee Lake. It is

suspected that a miniscule clay fraction may exist in East Pond sediments; this clay fraction is too small to be represented in the small sample size analyzed by the LPC. Also, given that East Pond is the first lake in the chain, it is possible that clay-sized particles were flushed through and deposited further down-stream of the Belgrade Lakes. Sediment in the water column is likely re-suspended/entrained bottom sediments; the low concentration of suspended load in the water also reflects the low-energy within the lake.

The geographic distribution of sediment grain-size roughly follows a fining inward pattern, typical of lake settings, and is independent of depth (Fig. 10). Notably, the finest sediments are located immediately adjacent to the island/rock barriers to the northwest of the deep lake center; coarser sediments are in the lee of the islands. The observed pattern can best be understood when correlated with the meteorological data. NOAA weather data for June 1 through August 31, 2003, revealed that the majority of wind originated from the south (Fig. 38). Southerly winds moved the water towards the island barriers to the northwest of the lake center. Water reaching the islands abruptly decreased in velocity resulting in a reduced sediment-transport capacity. Thus, the islands/boulders act as baffles, resulting in the sedimentation of fine particulate in front of the islands. The finer sediments residing in the deeper lake center is coincidental to the relative locations of the deep center to the islands. The fining-inward pattern may also be in part the result of human activity – several of the extremely coarse sediments samples at the lake's margin (e.g., sample 022) may be the result of imported sand for beaches and construction on the lake's shore.

The TOC content of the bottom sediments is elevated (lake mean = 5.42%) across the lake, indicating loading of organic matter. Sediments from and around the Serpentine

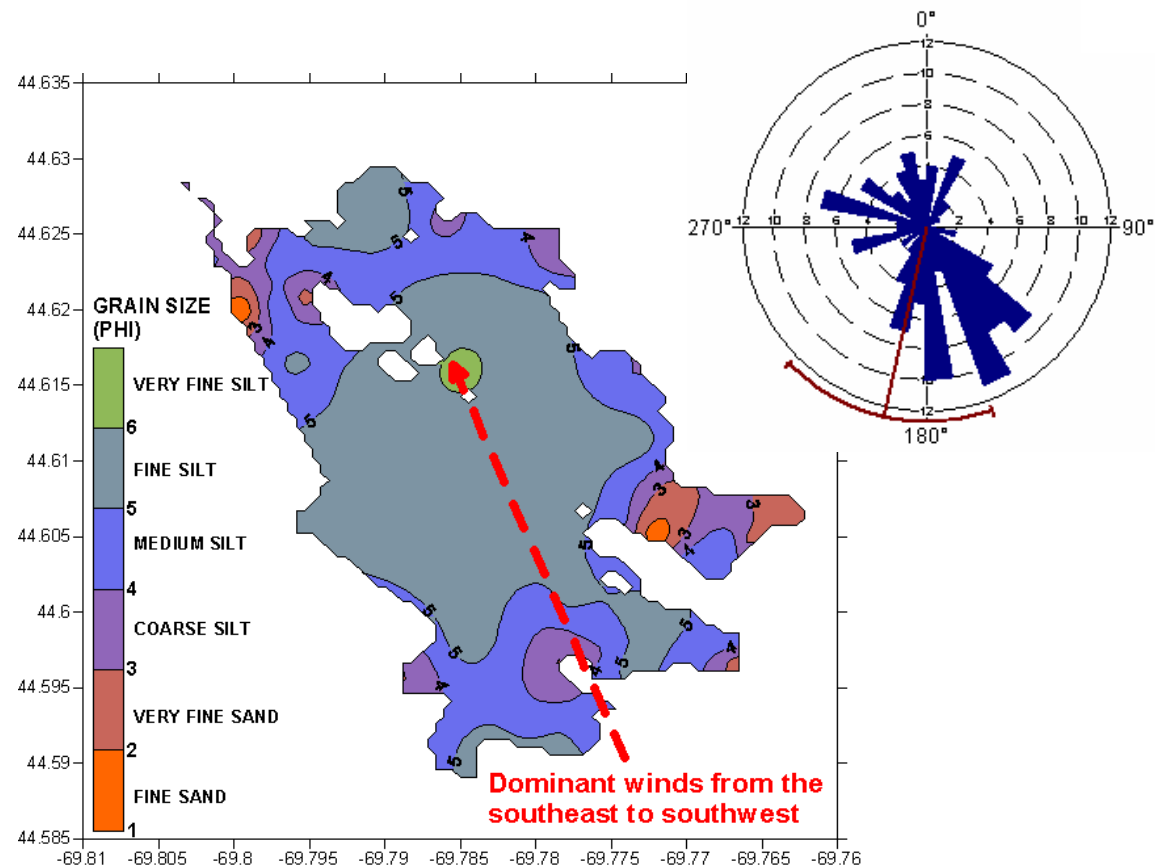


Figure 38: Distribution of the median sediment-grain diameter (Φ) with the dominant wind direction indicated by the red arrow. In the top right corner is a rose diagram of the wind direction from June 1 to August 31, 2003. The statistical mean direction and 95% C.I. are indicated by the maroon line. Note that the majority of the winds are from the southeast; however, the statistical mean is shifted to the southwest by several episodes of northwesterly winds over the summer months.

outlet had the highest TOC values due to the presence of the bog itself (Fig. 12A). Overall, East Pond sediments have a slightly higher TOC content than those of Messalonskee Lake (Allen *et al.*, 2003; unpublished data, Colby College Geology Department). The TOC:TON ratios (lake mean = 10.92, Fig. 12B) indicate that most of the organic matter is of algal origin with some terrestrial contribution (Brown *et al.*, 1998); consequently, both intrinsic and extrinsic processes contribute biomass to East Pond. The only sample with a TOC:TON ratio >20 (sample 018), indicating purely terrestrial organic matter, occurs adjacent to the bog and is derived from aquatic and subaerial plants in that setting (Fig. 12B).

The sediment mineralogy is consistent with glacial till and the local country rock (Bloom, 1960; Ockay & Hubert, 1996) with the notable absence of phosphate precipitates and clay minerals. This reflects the speciation of P in the lake-bottom sediments – solid/mineral P is not among the forms present in East Pond. The absence of clay minerals indicates that phosphorus is not incorporated into the sediments of East Pond at the molecular level. Phosphorus molecules may reside within the lake-bottom sediments, but are not likely chemically incorporated within the sediment grains. Pearce (1997) and Amirbahman *et al.* (2003) affirm that the dominant form of P in Maine lake sediments occurs as iron-hydroxide complexes residing within the lake-bottom sediments. Furthermore, both studies have correlated Fe(III) reduction in lake bottoms to P release from sediments. Lotse (1973) measured the concentration of Fe and Al-bound phosphorus in four Maine lakes to range from 0.0008 to 0.0038 %; however, given differences in P-extraction methodologies, fractionation comparisons are difficult.

The organic-P fraction is, on average, larger than the inorganic fraction (Fig. 15),

and it is suspected that the majority of nutrients in East Pond sediments are derived from organic matter. Considering the TOC:TON ratio, it is likely that most of the organic phosphorus is the result of decaying algae (or biota that feeds on algae) from previous blooms (Figs. 1, 2). The algal origin of nutrients is also consistent with the fairly uniform TOC and organic P distributions across the lake (Figs. 12A, 17B) – algae die and rain-down, and are buried-in/incorporated into the bottom sediments. However, both TOC and organic P show a very slight correlation to sediment grain-size (Figs. 14A, 14B, 19A), indicating that the organics are bound to or associated with the finer clasts. Nieratko (1992) noted that organic matter is associated more commonly with sediments containing a high clay fraction. In this situation, phosphorus either is adsorbed to the clasts or in organic complexes. The inorganic P fraction is likely residing in the lake bottom sediments, given both the slight positive correlation with grain-size (Fig. 19B) and sediment distribution throughout the lake (Fig. 17A). Inorganic phosphorus in Fe-PO₄ complexes resides within the sediments and, therefore, is subject to the same distribution as the sediments themselves. Behavioral differences between organic and inorganic phosphorus, such as those observed in East Pond, also have been noted by Williams *et al.* (1971).

The high sediment concentration of phosphorus in the sediments of East Pond is sufficient to support algal blooms indefinitely. The highest concentrations are located in the deep lake center, in areas >5 m deep (Fig. 16). The distribution of sediment phosphorus concentrations can be better explained by evaluating the C:N:P ratio in East Pond compared to the predicted Redfield Ratio for algae. Because this study measured C, N, and P concentration in mass percent, the stoichiometric Redfield Ratio of 106:16:1

must be converted to mass ratios. By mass, Redfield predicts a C:N ratio of 5.7, a C:P ratio of 40, and a N:P ratio of 7 for algal material. Comparison of East Pond's sediment C, N, P concentrations to these predicted ratios indicates that most East Pond sediments are proportionally higher in carbon than Redfield's algae (Fig. 39). Note, the two bog-dominated samples deviated most from Redfield (Figs. 39A, 39B) and were the most diluted in carbon. There is also one sample that is enriched with respect to phosphorus (Figs. 39B, 39C) likely as the result of analytical error. As can be seen in Figure 39, N:P (TON:Total Phosphorus) values in East Pond show the closest relation to the predicted Redfield algae values. This suggests that there is an algal contribution of organic matter that obeys Redfield's predicted ratio. The sediments are then diluted with respect to carbon by input of terrestrial organic matter. Therefore, phosphorus is not enriched in the lake center, it is instead extremely diluted at the lake margins with increased terrestrial input. Notably, the samples that most closely obey Redfield ratios (samples 029, 041, 045, 048, 049, 051, 052) are confined between the -5 and -5.5 m contours. Below -5 m, P is released from the sediments into the overlying dysoxic water of the hypolimnion. This process results in the departure from Redfield in the deep lake center. Dilution by C-rich terrestrial organic matter explains the deviation at shallower depths/along the lake margins. Furthermore, the lower phosphorus concentrations along the lake margins may be the result of increased P export to terrestrial plants in the near-shore areas.

Hecky *et al.* (1993) are among the few researchers to discuss Redfield ratios in lacustrine sediments. They comment that an influx of terrestrial organic matter frequently causes inflated C:N, C:P, and N:P ratios in lakes because compared to algae, boreal forest soils and vegetation are relatively depleted in phosphorus. Furthermore, they

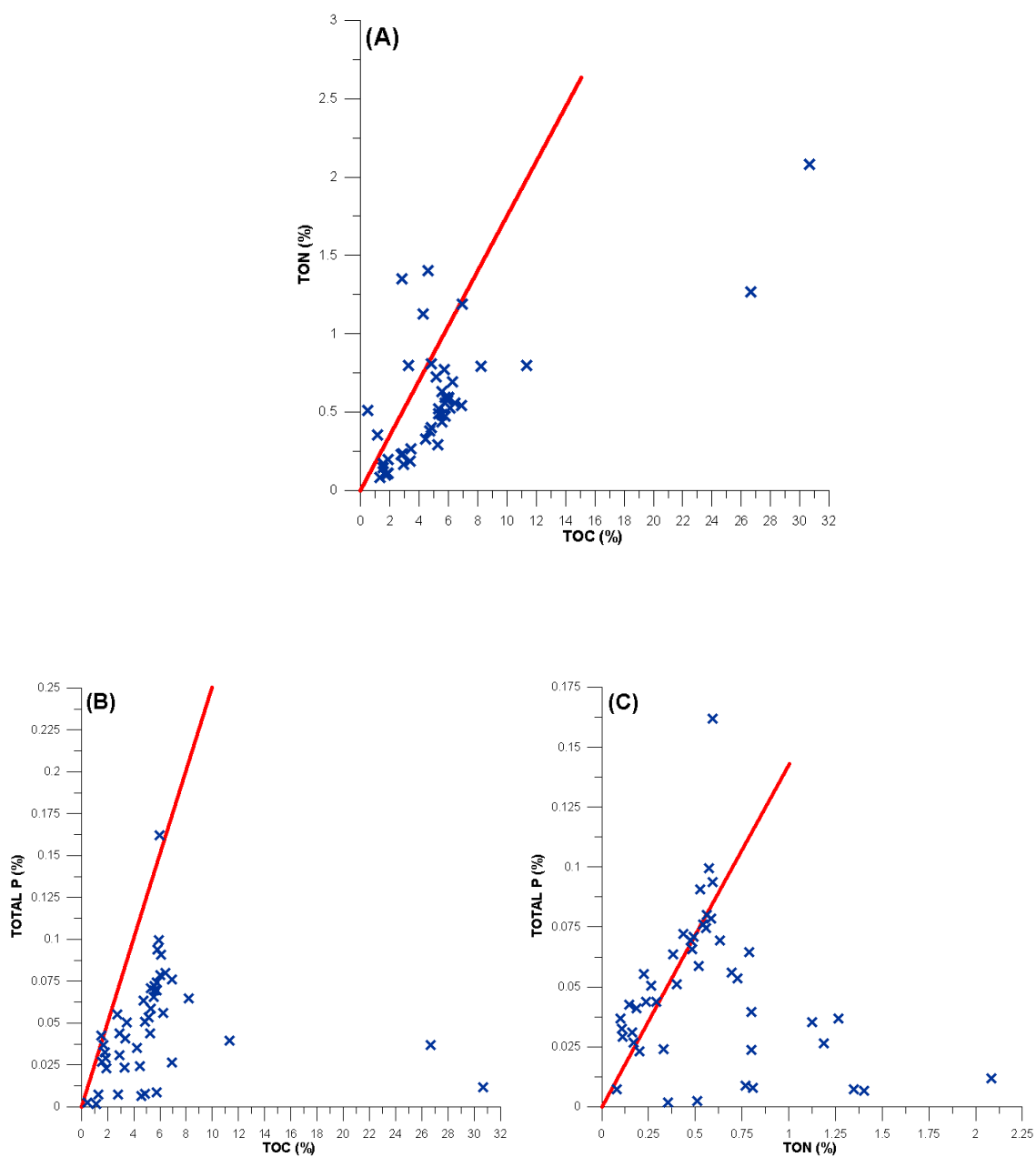


Figure 39: Comparison of nutrients in East Pond sediments (blue) to predicted Redfield mass ratios for algae (red line). (A) TOC:TON, predicted Redfield mass ratio for algae = 5.7; (B) TOC:Total phosphorus, predicted Redfield mass ratio for algae = 40; and (C) TON:Total phosphorus, predicted Redfield mass ratio for algae = 7.

indicate that a wider range of C:P and N:P ratios in lakes can still be considered to obey Redfield (converted to mass ratios, C:P = 28 to 56 and N:P = 4 to 9). Even by this extended range, East Pond sediments are extremely diluted with carbon and less so with nitrogen (TOC:Total Phosphorus = 36 to 2579, TON:Total Phosphorus = 3 to 216 with an average = 10.5 if bog samples are excluded).

In both of the hand-driven cores, up-column changes in sediment chemistry correlate well to the different sediment units (Figs. 20, 21). In the Heron Cove core, there is a large incursion of terrestrial organic matter (C:N > 20) and a marked increase of phosphorus concentration between 4 and 6 cm (Figs. 20C, 20D); this corresponds to the boundary of the sandy interval (Figs. 20A, 20B). The organic rich silt unit above 9 cm is typical of the sediment grab samples extracted from the lake margin. Throughout this unit the C:N ratio decreases up-column, indicating organic matter of mixed algal-terrestrial source, and the phosphorus concentration increases up-column to the sediment-water interface (Figs. 20C, 20D). Evaluating the C:P and N:P ratios throughout the core, and comparison to the predicted Redfield algal values indicates that the sand interval is depleted in carbon; and that sediments above 9 cm are diluted with terrestrial carbon (Fig. 40A). Nitrogen was depleted compared to Redfield except in the top 1 cm of the core (Fig. 40A).

Based on the different sediment units and corresponding chemical analysis, the Heron Cove core is interpreted to provide the record of the formation of the lake. The basal peat unit below 4 cm could be a shallow, well vegetated wetland that was flooded when the dam was installed, forming East Pond. This was followed by a depositional pulse of terrestrial sand, possibly imported beach material. The silt overlying the sand,

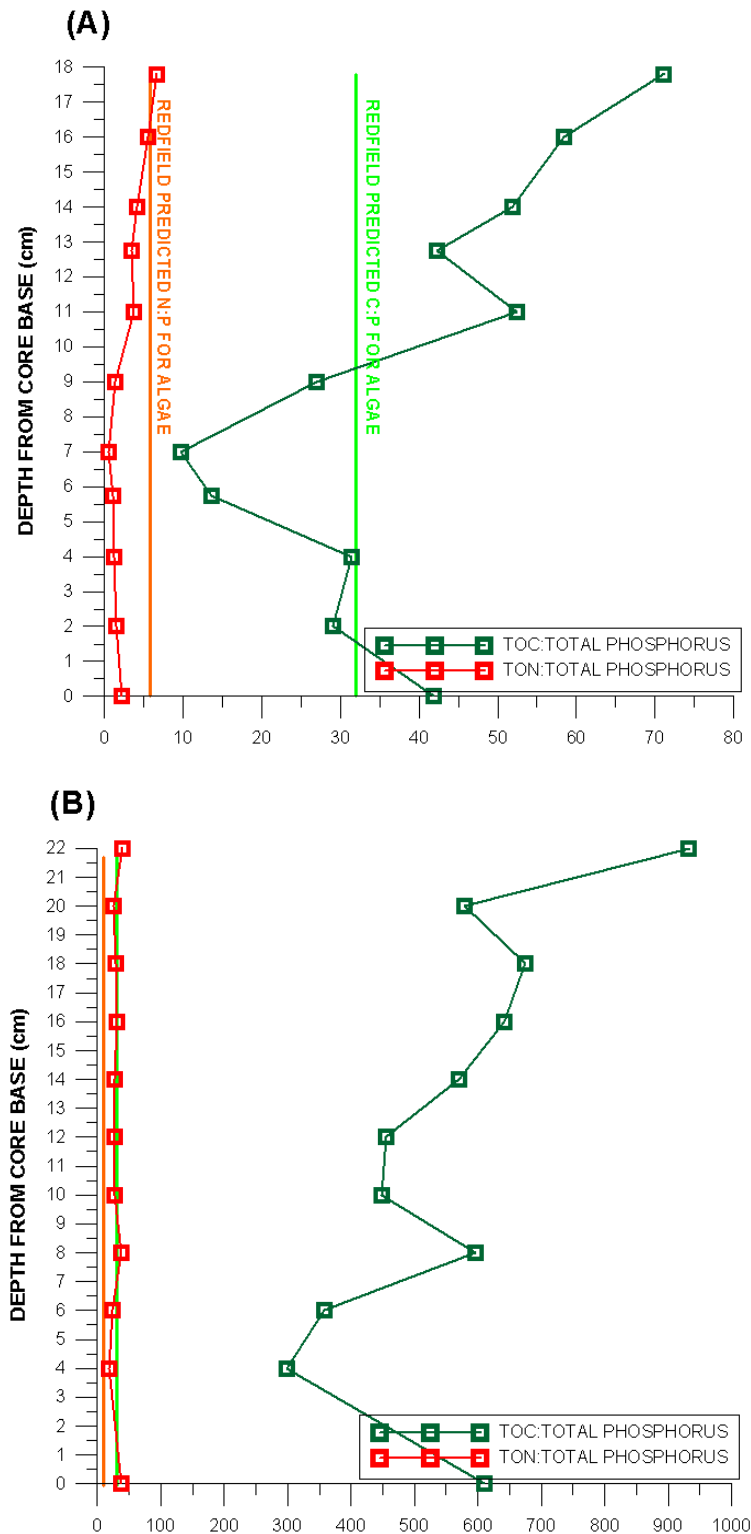


Figure 40: Comparison of nutrients in the hand driven cores to predicted Redfield mass ratios for algae. (A) The Heron Cove core, from the southeast margin of the lake; and (B) the Serpentine outlet core, extracted from the bog-outlet (note the difference in scale).

above 6 cm, is indicative of modern sedimentation. The up-column increasing phosphorus concentration is not consistent with the East Pond Lake Association's phosphorus diversion efforts. It is hypothesized that, due to changing redox conditions throughout the sediment column, Fe(III) at the sediment-water interface is sequestering phosphorus up-core. The observed up-core increase in phosphorus is the result on increased stability of phosphorus secondary to the Fe species. Upward mobility of phosphorus through the sediment column in other lakes has been reported by Carignan & Flett (1981). Thus, the accumulation of sediment at the lake bottom has created a redox-dependent Fe-gradient that results in the movement of historical phosphorus upward through the sediment column to the sediment-water interface.

Interpretation of the Serpentine-outlet core is more straight forward. The C:N ratios and phosphorus concentration indicate increasingly terrestrial organic matter up-column (Figs. 21C, 21D). Decreased phosphorus concentrations at the sediment-water interface could be due to phosphorus export to terrestrial plants within the bog. Comparison to Redfield ratios indicate carbon and nitrogen enrichment well above algal sources (Fig. 40B).

Lake dynamics

Taking both the lake's bathymetry and the distribution of sediment phosphorus into account aids in understanding the bloom dynamic within East Pond. The highest phosphorus concentrations exist in the deep lake center (Fig. 16); subsequently, it takes the release of this phosphorus pool into the water column before algal populations can multiply, resulting in an algal bloom. During the summer 2003, East Pond experienced the earliest and longest algal bloom in the lake's history (Maine DEP, 2001; Maine DEP,

2003; J. Tipper, pers. comm.; PEARL, 2003). According to Maine DEP, East Pond officially bloomed on August 6, 2003. However, data collected and observations made by Liz Andrews indicate that the lake experienced decreasing water quality starting July 24 (day 194).

There are two key factors controlling East Pond's bloom dynamic (Fig. 41). First, there is a precondition of water-column stratification that allows for phosphorus release from the sediments into the bottom water. Second, there is a trigger to vertically mix the water column and transport the P-rich bottom water to the lake surface. Both of these factors are needed for a bloom to occur – without the precondition, the phosphorus would be trapped in the Sediments. And, without the trigger there would be no vertical mixing trapping the lens of phosphorus-rich water at depth.

Precondition

A thin lens of colder, oxygen depleted water (shown in blue) occurred below -5 m early in the summer/before the 2003 bloom (Figs. 28, 29). A similar vertical distribution was seen in the water-chemistry data collected – the pre-bloom oxygen and pH profiles show an abrupt decrease below -5 m (Figs. 22A, 24A). These water profiles indicate that the water-conditions were vertically consistent throughout the lake, to 5 m depth. Stratification below -5 m provides the dysoxic conditions needed for phosphorus release from the sediments. The diffusion moves phosphorus out of the sediments into the bottom water (mechanism 1, Fig. 3), the P-rich lens itself is trapped at depth and, therefore, the phosphorus remained unavailable to photosynthesizing biota at the lake's surface. Thus, there was a oxygen depleted, cooler, P-rich pool of water trapped below -5 m before the algal bloom.

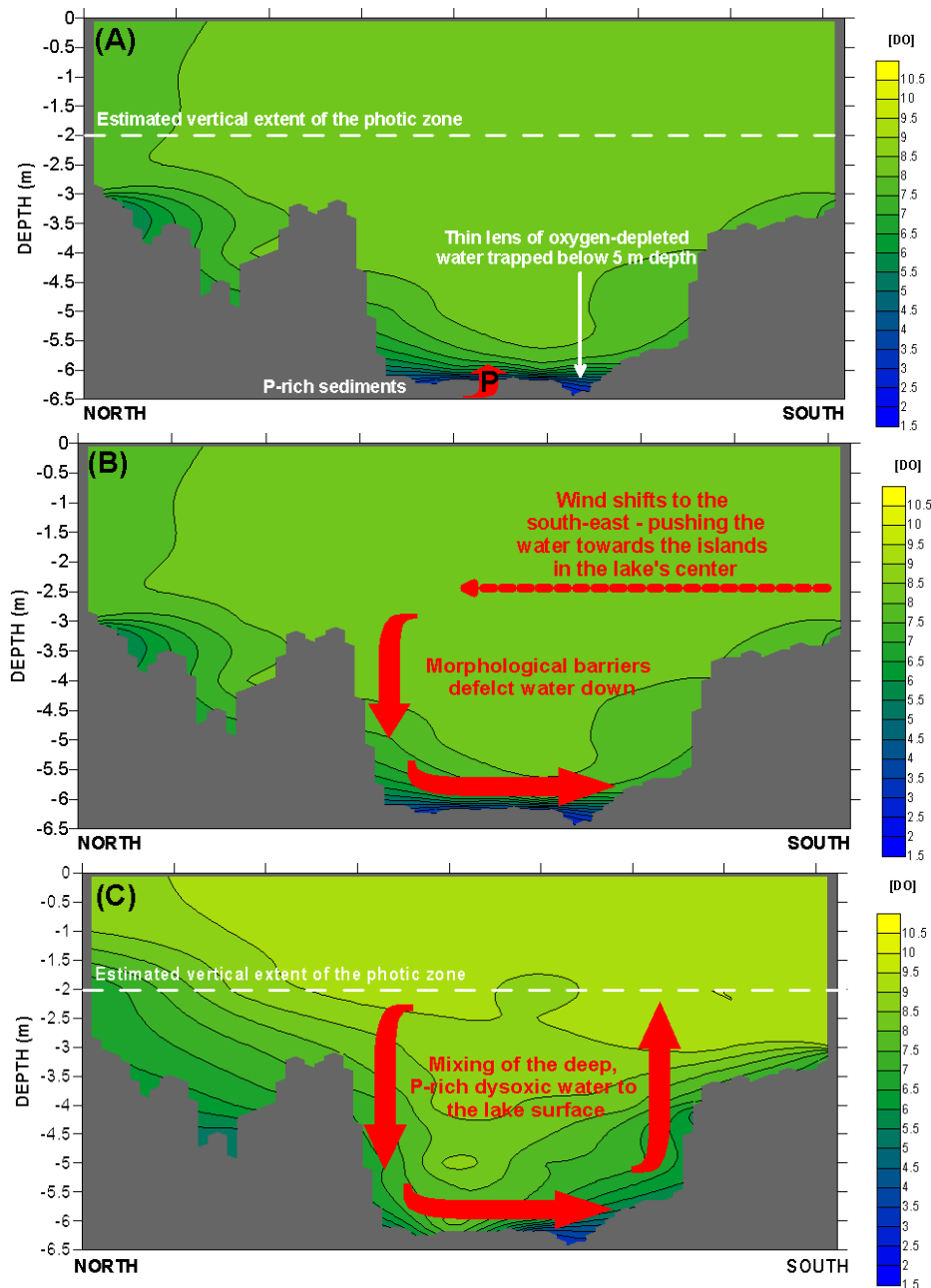


Figure 41: A two-stepped dynamic is proposed to account for algal blooms in East Pond. (A) The early summer pre-condition – temperature-oxygen stratification below –5 m creates a thin, dysoxic lens in the deep center of the lake, into which sediment phosphorus can be released. This phosphorus-rich lens is trapped at depth. Thus, P is released into the water-column yet unavailable to algae restricted to the photic zone. (B) The wind shifts from the south-east, moving the water towards the islands to the north-west of the deep lake center. These barriers force the surface water to depth. (C) The P-rich, dysoxic water from below –5 m is mixed to the lake surface by a vertical gyre-type dynamic. Increased P concentrations within the photic zone cause increased photosynthesis/algal populations, resulting in the observed algal blooms.

The early-summer stratification disappeared by day 188 (Fig. 32), a few days prior to the algal bloom. Because vertical homogenization of the deep lake center was followed within days by decreased water quality, it is suspected that over-turn of the P-rich bottom water resulted in increased algal productivity and the bloom. Furthermore, the stratification only occurred in water deeper than –5 m and was restricted to the center of the lake, consequently where the sediment phosphorus concentration was highest (Fig. 16). Above –5 m, the water column was homogenized both vertically and laterally (Figs. 28-31). Given that stratification/mixing dynamics did not exist elsewhere in the lake nor above 5 m depth, they ultimately neither prohibit nor promote blooms in East Pond. Only the dynamics of the deep center seem to matter.

Mixing Trigger

The second part of the bloom dynamic is the mixing event that homogenizes the water column, releasing the pool of P-rich water from depth. Comparison of the NOAA weather data and secchi depth trend revealed that there was a shift in the dominant wind direction during the week before the observed change in water quality (Fig. 37). Further analysis of the summer 2003 wind directions exposed a distinct relationship that could explain the vertical mixing of the water column.

Prior to July 13 (day 182), the statistical mean wind direction was from the southwest, with the 95% confidence interval ranging from southeast to northwest (Fig. 42A). Starting July 14 (day 183), the dominant wind direction shifted to the southeast (Fig. 42B). Southeasterly winds moved surface water directly towards the islands to the northwest of the deep lake center. This current direction coupled with the lake bathymetry resulted in the surface water deflected downward by the island barriers. This

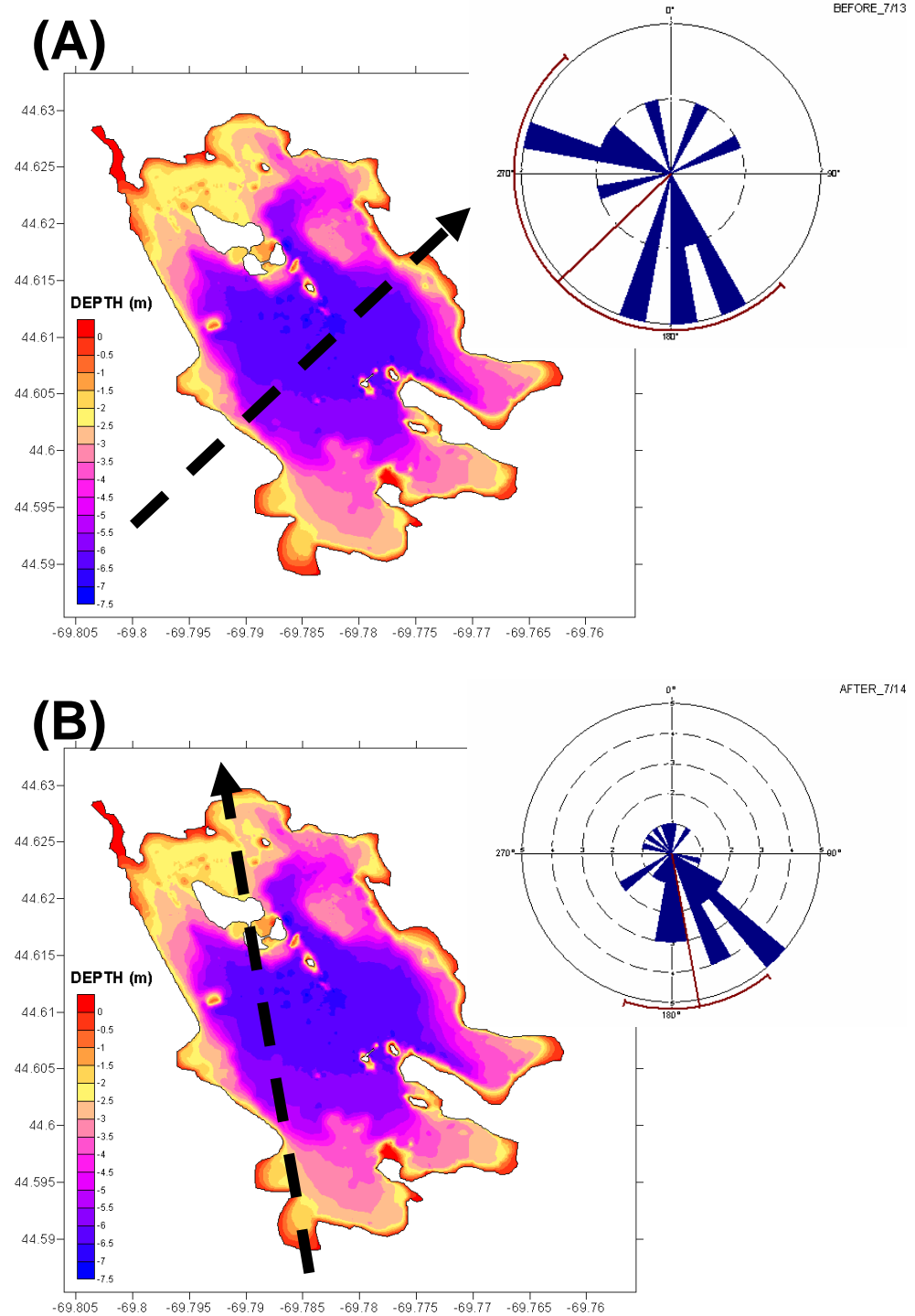


Figure 42: Shifting wind direction is the proposed trigger for vertical mixing in East Pond. A rose diagram of the wind direction is presented to the right, the maroon line represents the mean direction and 95% C.I.. The mean wind direction is superimposed onto a map of East Pond (black arrow). (A) The wind direction from June 1 through July 13. (B) The wind direction from July 14 through August 31.

created a vertical gyre which resulted in vertical homogenization and transport of the P-rich hypolimnion from the deep lake center to the lake's surface (Fig. 41), ultimately leading to the algal bloom.

Vertical mixing of the entire water column triggered by a shift in wind direction fits the observed 2003 temperature and oxygen data, homogenization, decreased water quality measurements, and NOAA data. Shifting wind-direction acting as the mixing trigger is further supported by the sediment grain-size distribution (Fig. 10) – southeasterly winds move water towards the islands, which act as baffles resulting in the finest sediments dropping out of suspension (Fig. 38). Also, Figures 30 and 31 both show continued temperature-oxygen stratification existing in the northern and western ends of the transects (in the lee of the islands) than at the southern and eastern ends. If the southeasterly winds and island barriers are forcing the vertical mixing of the deep lake center, they would have little effect on the extent of stratification to the lee of the islands, as observed.

Summary of lake dynamics

Towards the end of August, at day 221, the deeper water was again stratified with respect to oxygen (Fig. 32B); however, water quality did not improve (Fig. 33). As can be seen in Figure 37, there was a lull in southeasterly winds in the week prior to this re-stratification event and this lull persisted for several weeks. The exact opposite occurred earlier in the lake earlier in the summer. Winds out of the southeast cause the destruction of the water stratification, and subsequently the absence of southeasterly winds coincides with re-stratification. However, water quality did not improve despite the re-stratification quite likely because there was already sufficient phosphorus within the water column to

support algal growth. Had the stratification lasted longer, perhaps the algae would have consumed all the available phosphorus and the bloom would have ended. Hence, there is apparently a lag between release of phosphorus from the lake bottom and improvement of water quality.

A timeline of the events leading up to the bloom of 2003 can be summarized. Before July 13, the lake was partially stratified with respect to oxygen below -5 m, such that there was a thin lens of dysoxic water into which P was diffusing in the deep lake center (Figs. 28, 29). This P-rich pool was trapped at depth and unavailable to photosynthesizing organisms at the lake's surface. On July 13 the dominant wind direction shifted to the southeast, moving water towards the islands to the northwest of the deep hole (Figs. 37, 41, 42). The southeasterly winds combined with the lake bottom morphology forcing the development of a vertical-gyre that mixed the deep lake water with the overlying water. Thus, the P-rich water was released to the surface (Fig. 41). Destratification occurred several days after the shift of wind direction, and the lake was vertically homogenized by July 16 (day 187; Fig. 32). Once phosphorus was transported to the lake's photic zone, it took several more days for algal biomass to increase to observable quantities. Liz Andrews observed the first signs of decreasing water quality on July 24 (day 194), the algal population continued to grow until the lake officially was declared to be experiencing an algal bloom on August 6 (day 207) (Fig. 33). A summary of the P-forms and transport mechanisms within East Pond is provided in Table 5.

Water chemistry

During the bloom, there was a dramatic change in water chemistry from the observed pre-bloom conditions. Based on the vertical distribution of fluorescence data,

Table 5: A summary of the major reservoirs of phosphorus, the forms present in each reservoir, the two mechanisms that account for P-mobility, and the major factors contributing to each mechanism in East Pond.

Location within Lake	Forms of Phosphorus	Mechanism of P-Transfer	Factors Effecting P-Transfer
The water column above –5 m (homogenized and oxygenated, including the photic zone)	Incorporated into biota, concentrated between -1 and -2 m	<u>MECHANISM 2:</u> P-rich water from the hypolimnion below –5 m vertically mixed with the rest of the water column, ultimately transported to the photic zone	Mixing event – shallow depth, lake morphology and orientation such that SE winds cause vertical mixing of P-rich deep lake center.
Water below –5 m in the deep lake center (dysoxic bottom water/hypolimnion at equilibrium with sediment pore waters)	Released from sediments by reduction of Fe(III)		
Incorporated in sediments	Fe(III) complexes, incorporated into decaying autochthonous and allochthonous organic matter	<u>MECHANISM 1:</u> Phosphorus from the sediments to the pore water/anoxic bottom waters	Chemical factors occurring in dysoxic conditions, likely dominated by diffusion and redox – dependant on stratification of the deep lake center

the algae were concentrated at ~1 to 1.75 m depth (Fig. 25B) during the bloom. All other chemical attributes showed rapid departure at these depths, indicating that biochemical processes including photosynthesis played a role in the observed changes. The temperature increase above -2.5 m was likely the result of the exothermic algal activity (Fig. 22B), and conductivity closely followed the temperature profile both before and during the bloom (Figs. 23A, 23B). Oxygen content and pH both roughly mirrored the fluorescence profile (Figs. 22B, 24B) due to photosynthetic activity – photosynthesis releases oxygen and uses CO₂ increasing the pH of the water. While there was a large range in Eh-pH conditions throughout the summer of 2003, all measured values were within the expected region for a terrestrial, freshwater lake (Garrels & Christ, 1965; Fig. 26); the lake water was near-neutral and always oxidizing. Several of the ORP values were less than 200 mV, which de Montigny & Prairie (1993) indicate is the condition under which Fe(III) is reduced, releasing Fe-bound phosphorus into the water column.

The water-column phosphorus concentration during the algal bloom (64 ppb, Fig. 27) was 10x higher than 6 ppb, the concentration at which lakes are at risk for bloom, and 4x higher than 15 ppb, the targeted concentration for minimizing algal blooms in East Pond according to the Maine DEP (2001). Furthermore, water-column P-concentrations were higher than recorded measurements of 12 to 29 ppb in previous years (Appendix A; PEARL, 2000). Coinciding peaks of phosphorus and fluorescence at ~1.5 m depth indicate that the majority of phosphorus in the water column is incorporated into the algae, which are concentrated at this depth. While the P-concentration decreased with depth, it increased slightly at -5.5 m, indicating the presence of a phosphorus-rich hypolimnion at the lake-bottom. Amirbahman *et al.* (2003) described two categories of

lakes: low-P lakes with phosphorus concentrations ranging from 6-19 ppb, and high-P lakes with hypolimnetic phosphorus concentrations ranging from 185-460 ppb and epilimnetic concentrations of 15-54 ppb. In East Pond, the water-column phosphorus ranged from 0.9 to 63.6 ppb, placing it between the categories of Amirbahman *et al* (2003). According to Davis *et al.* (1978), East Pond is classified as “mesoeutrophic” (phosphorus concentration = 10-30 ppb) to “hypereutrophic” (phosphorus concentration = 30-5000 ppb) based on phosphorus concentration within the water column.

Comparison to other Maine lakes

Based on the studies published by Davis *et al.* (1978) and information available at the Public Educational Access to Environmental Information in Maine (PEARL) website (2003) East Pond is typical of Maine lakes. The concentration of phosphorus in the sediments is elevated, but roughly consistent with other eutrophic Maine lakes (e.g., Lotse, 1973; Pearce, 2000). The PEARL on-line database contains a 20 year record (starting in 1971) of water-column phosphorus concentration, pH, secchi depth, temperature, and oxygen concentration from over one thousand lakes state-wide. Measurements were taken from/during a variety of locations, depths, and seasons. According to these data, there is a wide range of water-column phosphorus concentrations (0.1 to 1500 ppb) in lakes throughout the state. At its peak, East Pond's maximum P-concentration (63.5 ppb) is at the lower end of this range. However, phosphorus concentrations of samples taken at -7.5 m and shallower provided a range of 0.1 to 68.0 ppb, nearly identical to those measured in East Pond (0.9 – 63.5 ppb; Fig. 27). Furthermore, there is a similar trend in vertical distribution of P throughout shallow Maine lakes – phosphorus is highest at -1 m and below -5 m, and lower at the lake

surface (0 to -1 m) and between -2 m and -5 m. There is also a wide pH range in Maine lakes – 4.3 to 9.9, with a mean of 6.8. While the pH of East Pond was elevated at the surface (9.7; Fig. 24B), the overall conditions were at the higher end of this range. East Pond has a neutral to basic pH and has not experienced acidification like other Maine lakes (Table 4). Comparison to both water temperature and dissolved oxygen concentration reveals that East Pond is well within the wide range of other Maine lakes (mean temperature = 15.1° C, mean oxygen content = 6.84 ppm). There have been conflicting reports on the effect of flushing rate/residence time on lake trophic state (e.g., Davis *et al.*, 1978; Nieratko, 1992; Hecky *et al.*, 1993). However, it should be noted that East Pond's flushing rate of 0.25 per year is relatively slow compared to other Maine lakes (Appendix A; Davis *et al.*, 1978; PEARL, 2000). In effect, there is no way East Pond can flush phosphorus out of the lake due to its long residence time.

Lake stratification affects internal phosphorus loading and lake nutrient cycling, which are key factors in eutrophication (e.g., Nürnberg, 1984; Forsberg, 1989; Levine & Schindler, 1992; Petterson, 1998). In Maine, increased hypolimnic phosphorus concentrations have been directly attributed to lake stratification (Davis *et al.*, 1978). However, East Pond has previously been categorized as an un-stratified, wind-driven lake, despite the development of a thin hypolimnion during the early summer months (Appendix A; BI493, 1993; PEARL, 2000; Maine DEP, 2001). The relationship between lake depth/morphology, and the extent and temporal stability of stratification has been previously emphasized (e.g., Davis *et al.*, 1978; Levine & Schindler, 1992; Petterson, 1998). Davis *et al.* (1978, p. 16) commented on the “morphometries and orientations (re:wind)” ultimately effecting nutrient cycling and eutrophication in Maine lakes by

destruction of the thermocline. Nieratko (1992, p. 67) described a dynamic nearly identical to the that modeled for East Pond: “Temporary deoxygenation of a thin layer of water above the sediments can develop during the summer months in both shallow and deep lakes. Subsequent sediment release of phosphorus and wind induced mixing of this anoxic layer into the main body of the lake is more likely to occur in shallower lakes than in deeper lakes.” Furthermore, a Water Quality Summary for East Pond (2000), published on the PEARL website and in Appendix A states “The potential for TP [total phosphorus] to leave the bottom sediments and become available to algae in the water column (internal recycling) is high, due to the effects of wind disturbance.” Thus, wind-driven mixing mechanisms have been implicated before, and highly suspected on East Pond. The data from the summer 2003 further refine this relationship – such that the dynamics leading up to the bloom can be confined to a series of events. Therefore, blooms can be predicted based on the climate variables operating over the course of the summer.

Summary

The three proposed hypotheses for this study were that (a) recent organic loading of the lake-bottom sediments serve as the nutrient source for the algal blooms; (b) changing conditions throughout the summer may prohibit or promote phosphorus release from the sediments and produce an algal bloom; and (c) the net movement of phosphorus from the bottom sediments to the lake’s surface is accomplished through early-summer lake stratification, which allows phosphorus release from the sediments, and later vertical homogenization of the water-column. The results of this study support these hypotheses and allow for the refinement of these relationships during the summer of 2003.

The basin morphology and coincidental orientation to local winds underlie many

of the observed processes in East Pond, including the sediment distribution, vertical mixing of the water column, and subsequent algal blooms. This set of factors may explain why East Pond is the only lake in the Belgrade Lakes watershed that suffers from algal blooms, despite the similar Holocene histories of the lakes. East Pond's shallow depth may be the feature that distinguishes it from the other Belgrade Lakes.

The release of nutrients from the sediment and subsequent algal blooms can be described through a positive feedback loop. It starts with the formation of the basin and subsequent deposition of bottom sediments. Increased anthropogenic input of organic matter into the lake ultimately loads the lake-bottom sediments with phosphorus. Organic matter is decomposed at the sediment-water interface by respiring bacteria. The decay of organic matter escalates the oxygen demand of the sediments, resulting in the development of a thin, dysoxic hypolimnion below -5 m. This stratification allows for the release of phosphorus from the lake-bottom sediments. Basin morphology and orientation are such that southeasterly winds force the vertical mixing of the water column, transporting the P-rich bottom waters to the lake surface and thus, creating conditions to support an algal bloom. Dead algae rain-down to the lake bottom, re-depositing nutrients in proportions close to those predicted by Redfield (1958) although terrestrial input continues. Notably, there is a no net loss of nutrients. Furthermore, because algae are preferentially consumed by the respiring bacteria responsible for organic decay at the lake bottom, the increased algal biomass results in increasing dysoxia in the hypolimnion which, in turn, allows for more phosphorus release early in the season.

Remediation

The understanding of the nutrient conditions and cycling within East Pond

provided by this study implicates several specifics concerning remediation of the algal blooms. Anthropogenic nutrient loading and internal cycling are the dominant processes contributing East Pond's eutrophication. Continued diversion of non-point pollution is recommended; however, given the high sediment P concentration, diversion alone will not improve water quality in the near future. Understanding the processes involved will hopefully aid residents in understanding and possibly predicting the bloom. Ultimately, the source of the phosphorus is the sediments – removal or containment of the lake bottom sediments should prevent further eutrophication. This could be accomplished through either physically removing (dredging) the sediments, or capping them with clay or alum. Given that it takes the turnover of the deep lake center to cause a bloom, dredging or capping would only need to occurring in the area that is deeper than –5 m. Bioremediation – removing some of the top tier fish to increase the zooplankton population that would consume more algae – is currently being evaluated by the DEP, and may provide a cost-effective solution (East Pond Association, 2004).

Recommended future studies

(1) Continued water-quality monitoring of East Pond throughout the summer, as was conducting in 2003, should be continued to confirm that the relationship between stratification, homogenization, and the algal bloom was not coincidental in 2003. Future monitoring only needs to focus on the deep lake center. Also, continued collection of chemical data, specifically before and after the bloom, is recommended.

(2) Historical secchi and weather data (available through the PEARL online database, NOAA, and the East Pond Lake Association) should be evaluated to see if the correlation between shifting wind and decreased water quality holds for previous blooms.

Furthermore, other weather-lake relationships (such as the effect of temperature and precipitation) may exist. Based on the observations of summer 2003, I hypothesize that historical secchi and NOAA data can be correlated such that a mid-to-late summer shift in wind direction to the southeast will immediately presage the algal bloom, provided early-summer stratification of the water column.

(3) Further research should be conducted into the history and development of East Pond to address questions such as: what was the lake morphology before the dam was built? Why did the blooms start ten years ago when the area has been developed for over a century? Is the bog surrounding the Serpentine outlet encroaching on the lake or vice versa?

(4) A study similar to this project should be repeated on North Pond, the next lake in the Belgrade chain. This would allow for comparison between the connected lakes.

(5) More detailed chemical studies of East Pond bottom-sediments should be conducted to determine the oxygen-demand of, the chemical species present, and the rate of P release from the sediments, as well as more in depth mineralogical analysis.

(5) With existing data from this study, the following should be further explored:

- (a) The deviation from the Redfield ratio should be quantified and the distribution plotted across the lake.
- (b) Redfield relationships should be used to determine the relative contribution of intrinsic and extrinsic processes/organic matter.
- (c) Given the existing data set includes phosphorus concentration, as well as lake volume, future studies can evaluate moles of phosphorus present in East Pond and mass-balance conditions.

- (d) The amount/depth of bottom-sediment that is interacting with the overlying water should be determined.

Conclusions

- East Pond is a fairly small, shallow lake, with mean depth of 4.5 m and a maximum depth of 7.3 m. Basin bathymetry and physical/chemical processes functionally divide the lake into two portions: areas shallower than –5 m (the epilimnion) and areas deeper than –5 m (the hypolimnion).

- East Pond bottom sediments are characterized as an organic rich, moderately well-sorted, quartz silt. This reflects the lake's glacial origin, and is consistent with other lakes in the Belgrade Lakes system.

- The sediment distribution is the result of lake bathymetry, orientation, and local wind patterns. Frequent southeasterly winds transport water across the lake, towards islands/boulders located to the northwest of the deep lake center. These barriers act as baffles – as the water slows, finer sediments are deposited in front of the islands, in the deep lake center.

- East Pond sediments contain a very high concentration of phosphorus; enough to support algal blooms indefinitely. The highest concentration occurs in the deep lake center.

- The bottom sediments are loaded with organic matter from an algal source with some addition of terrestrial material. Nitrogen and phosphorus are deposited primarily by algae, sediments are then diluted with terrestrial/extrinsic carbon, especially along the lake margins.

- Most of the phosphorus in East Pond sediments are associated with organic material, likely decaying algal cells. The inorganic fraction is most likely in the form of Fe(III)-complexes.

- There is suspected upward mobility of phosphorus throughout the sediment column resulting from sequestering of historical phosphorus by Fe(III) at the sediment-water interface.

- Factors controlling the net transport of phosphorus from the bottom sediments to the lake surface leading to the algal blooms, consist of two distinct steps. First, a precondition of water-column stratification forms a thin, dysoxic lens at depth, which allows for P release from the sediments. Second, winds shifting from the southeast move water towards the islands/boulders in the lake center, deflecting the water downward and essentially forming a vertical gyre that mixes the P-rich lens from the lake bottom to the surface.

- East Pond's water chemistry is typical of Maine lakes and is effected by increased algal populations during the bloom.

- During the bloom, water-column phosphorus concentrations are elevated well above the bloom threshold, as well as the targeted concentration proposed by Maine DEP (2001), and previously recorded concentrations in East Pond.

- The majority of the algal bloom occurs between –1 and –2 m, this is also where water-column phosphorus concentration was highest. Phosphorus in the water column was primarily incorporated into biota.

- Due to the high P-concentrations in the lake-bottom sediments and complex bloom trigger, capping the sediments with clay or alum is recommended to remediate

East Pond. Bioremediation is also currently being considered by Maine DEP and the East Pond Lake Association.

Acknowledgements

Acknowledgement is made out to: Dr. D.B. Allen of the Colby College Department of Geology and Dr. D.M. Thamatoor of the Colby College Department of Chemistry. Special thanks to Jerry and Betsy Tipper, Charles and Elizabeth Andrews, as well as the East Pond Lake Association; Michael Gastaldo, Brian Foley, Ivan Mihajlov, Nicholas Mwai, Hong Zhang, and Robert Selover for all their help with field work; and Eric Roy and Hengtian Lin for all their help with laboratory analysis. This research was supported, in part, by NSF grant MRI 0115900 and Colby College.

References

Allen, J.P., Lansdale, A.L., Bierwirth, M.S., Dushman, B.E., Kaferle, A.M., Nesbada, R., Ossolinski, J.E., Selover, R.W., and Gastaldo, R.A., 2003, Sediment characteristics of Messalonskee Lake, Belgrade Lakes Region, central Maine: Geologic Society of America, Abstracts with Program, v. 35, no. 3, p. 72.

Amirbahman, A., Pearce, A.R., Bouchard, R.J., Norton, S.A., and Kahl, J.S., 2003, Relationship between hypolimnetic phosphorus and iron release from eleven lakes in Maine, USA: Biogeochemistry, v. 65, p. 369-386.

Bacon, L., 1996, Lake assessment: *in* Maine DEP, 1996, Water quality assessment, Augusta, ME, p. 13-18.
<www.maine.gov/dep/blwq/docmonitoring/pg13_18.pdf>

Ballinger, D.G., and McKee, G.D., 1971, Chemical characterization of bottom sediments: Journal WPCF, v. 43:2, p. 216-227.

Belgrade Lakes Association, 2002, The Belgrade Lakes Association web page:
<<http://www.belgradelakesassociation.com/>>

Bengtsson, L., 1975, Phosphorus release from highly eutrophic lake sediment: Verhandlungen der Internationalen Vereinigung für Theoretische und Angewandte Limnologie, v. 19, p. 1107-1116.

BI493, 2000, Water Quality in East Pond: Factors Contributing to Algal (sic) Blooms and Strategies for Remediation: unpublished class project, Colby College Biology Department, 189p.

BI493, 1991, An analysis of East Pond and the Serpentine watersheds in relation to water quality: unpublished class project, Colby College Biology Department, 178p.

Bloom, A.L., 1960, Late Pleistocene changes of sea level in southwestern Maine: Maine Geological Survey, 143p.

Boström, B., and Pettersson, K., 1982, Different patterns of phosphorus release from lake sediments in laboratory experiments: Hydrobiologia, v. 92, p. 415-429.

Brown, S.L., Hierman, P.R., Mehrrens, C.J., and Lini, A., 1998, Terrigenous layers in lake cores document fluctuations in New England's Holocene climate: GSA Abstracts with Programs, v. 81, p. 2523-2524.

Campbell, P., 1994, Phosphorus budget and stoichiometry during the open-water season in two un-manipulated lakes in the Experimental Lakes Area, northwestern Ontario: Canadian Journal of Fisheries and Aquatic Science, v. 51, p. 2739-2755.

Carignan, R., and Flett, R.J., 1981, Post depositional mobility of phosphorus in lake sediments: *Limnology and Oceanography*, v. 26:2, p. 361-366.

Carignan, R., and Lean, D.R.S., 1991, Regeneration of dissolved substances in a seasonally anoxic lake: The relative importance of processes occurring in the water column and in the sediments: *Limnology and Oceanography*, v. 36:43, p. 683-707.

Carman, R., Edlund, G., and Damberg, C., 2000, Distribution of organic and inorganic phosphorus compounds in marine and lacustrine sediments: A ^{31}P NMR study: *Chemical geology*, v. 163, p. 101-114.

Davis, R.B., Bailey, J.H., Scott, M., Hunt, G., and Norton, S.A., 1978, Descriptive and comparative studies of Maine lakes: Life Sciences and Agriculture Experiment Station, Orono, ME, 337p.

de Montigny, C. and Prairie, Y.T., 1993, The relative importance of biological and chemical processes in the release of phosphorus from a highly organic sediment: *Hydrobiologia*, v. 253, p. 141-150.

Dushman, B.E. and Shosa, J.D., 2003, A geochemical investigation of bog/lake interactions in the Belgrade Lakes watershed, Maine: GSA Abstracts with Program.

East Pond Lake Association, 2003, East Pond Lake Association web page: <<http://www.eastpond.org>>

EPA, 2003, Mid-Atlantic integrated assessment – Eutrophication: <<http://www.epa.gov/maia/html/eutroph.html>>

Forsberg, C., 1989, Importance of sediments in understanding nutrient cyclings in lakes: *Hydrobiologia*, v. 176/177, p. 263-277.

Furrer, G., and Wehrli, B., 1996, Microbial reaction, chemical speciation, and multi-component diffusion in porewaters of a eutrophic lake: *Geochemica at Cosmochemica Acta*, v. 60:13, p. 2333-2346.

Gächter, R. and Müller, B., 2003, Why the phosphorus retention of lakes does not necessarily depend on the oxygen supply to the sediment surface: *Limnology and Oceanography*, v. 48, p. 929-933.

Garrels, R.M., and Christ, C.L., 1965, Solutions, minerals, and equilibrium: Harper & Row, NY, 450 p.

Golterman, H.L., 1996, Fractionation of sediment phosphate with chelating compounds: a simplification, and comparison with other methods: *Hydrobiologia*, v. 335, p. 87-95.

Goulden, P.D., 1972, The chemical analysis of nutrients: *in* Allen, H.S., and Kramer, J.R., eds., 1972, *Nutrients in Natural Waters*: New York, Wiley, p. 125-146.

Hecky, R.E., Campbell, P., and Hendzel, L.L., 1993, The stoichiometry of Carbon, Nitrogen and Phosphorus in particulate matter of lakes and oceans: *Limnology and Oceanography*, v. 38:4, p. 709-724.

Hessen, D.O., Gjessing, E.T., Knulst, J., and Fjeld, E., 1997, TOC fluctuations in a humic lake as related to catchment acidification, season and climate: *Biogeochemistry Dordrecht*, v. 36:1, p. 139-151.

Holdren, G.R. Jr., 1977, Factors affecting phosphorus release from lake sediments: Thesis Dissertation. Madison, WI: University of Wisconsin, p.

Kassila, J., Hasnaoui, M., and Yahyaoui, A., 2000, Sequential extractions of inorganic and org-Phosphate from fish pond sediments (Deroua station, Beni Mellal, Morocco) by different fractionation methods: *Hydrobiologia*, v. 431, p. 51-58.

Keeney, D.R., 1973, The nitrogen cycle in sediment-water systems: *Journal of Environmental Quality*, v. 2:1, p. 15-29.

Keizer, P., and Sinke, A.J.C., 1992, Phosphorus in the sediments of the Loosdrecht lakes and its implications for lake restoration perspectives: *Hydrobiologia*, v. 233, p. 39-50.

Kerr, P.C., Brockway, D.L., Paris, D.F., and Craven, S.E., 1973, Carbon cycle in sediment-water systems: *Journal of Environmental Quality*, v. 2:1, p. 46-52.

King, D.E., Gastaldo, R.A., and Shosa, J.D., 2003, Design and implementation of an integrated sampling platform for geochemical investigations of Maine lakes: Abstract GEOC86, 25th ACS National Meeting.

Kramer, J.R., Herbes, S.E., and Allen, H.E., 1972, Phosphorus: analysis of water, biomass, and sediment: *in* Allen, H.S., and Kramer, J.R., eds., 1972, *Nutrients in Natural Waters*: New York, Wiley, p. 51-100.

Levine, S.N. and Schnidler, D.W., 1992, Modification of the N:P ratio in lakes by in situ processes: *Limnology and Oceanography*, v. 37:5, p. 917-935.

Lotse, E.G., 1973, Phosphate retention in lake sediments: completion report, University of Maine, Orono, 36p.

Maine Department of Environmental Protection, 2003, Reports of Algal Blooms: Maine DEP, <<http://www.state.me.us/dep/blwq/doclake/repblooms.htm>>.

Maine Department of Environmental Protection, 2001, East Pond Total Maximum Daily (Annual) Load – Final lakes TMDL Report: MDEP, Augusta ME, 47p.

NETSTATE.COM, 2003, Maine Geography:
<http://www.netstate.com/states/geography/me_geography.htm>

Nieratko, D.P., 1992, Factors controlling phosphorus loading to lakes in Maine: A statistical analysis: unpublished M.S. Thesis in Geological Sciences, The University of Maine, Orono, ME, 82p.

NOAA National Climatic Data Center, 2004, Unedited local climatological data (LCD): <<http://www.ncdc.noaa.gov/servlets/ULCD>>

Nürnberg, G.K., 1984, The prediction of internal phosphorus load in lakes with anoxic hypolimnia: *Limnology and Oceanography*, v. 26, p. 111-124.

Ockay, C., and Hubert, J.F., 1996, Mineralogy and provenance of Pleistocene outwash-plain and modern beach sands of outer Cape Cod, Massachusetts, USA: *Marine Geology*, v. 130, p. 121-137.

Ossolinski, J.E., Burrows, A.M., and Shosa, J.D., 2002, An investigation of the seasonal hydrogeochemical dynamics of a forested peatland in central Maine: *GSA Abstracts with Program*, v. 34, no. 6, p. 117.

Ostrofsky, M.L., Osborne, D.A., and Zebulske, T.J., 1989, Relationship between anaerobic sediment phosphorus release rates and sedimentary phosphorus species: *Canadian Journal of Fisheries and Aquatic Science*, v. 46, p. 416-419.

Ostrom, N.E., Long, D.T., Bell, E.M., and Beals, T., 1998, The origin and cycling of particulate and sedimentary organic matter and nitrate in Lake Superior: *Chemical Geology*, v. 152, p. 13-28.

Ostrom, P.H., Ostrom, N.E., Henry, J., Eadie, B.J., Meyers, P.A., and Robbins, J.A., 1998, Changes in the trophic state of Lake Erie: Discordance between molecular $\delta^{13}\text{C}$ and bulk $\delta^{13}\text{C}$ of sedimentary records: *Chemical Geology*, v. 152, p. 163-179.

Pearce, A.R., 2000, Phosphorus cycling in Maine lakes: a geochemical study: Unpublished M.S. thesis in Civil and Environmental Engineering, The University of Maine, Orono, ME, 181p.

PEARL, 2003: <<http://pearl.spatial.maine.edu/>>

PEARL, 2000, Water quality summary, East Pond, Smithfield:
<<http://pearl.spatial.maine.edu/>>

Pettersson, K., 1998, Mechanisms for internal loading of phosphorus in lakes: *Hydrobiologia*, v. 373/374, p. 21-25.

Pettersson, K., and Boström, B., 1984, Phosphorus exchange between sediments and water in Lake Balaton: proceedings of the Third International Symposium on Interactions Between Sediments and Water, p. 39-50.

Pettersson, K., Boström, B., and Jacobsen, O.S., 1988, Phosphorus in sediments – speciation and analysis: *Hydrobiologia*, v. 170, p. 91-101.

Prothero, D.R., and Schwab, F., 1996, *Sedimentary Geology – An Introduction to Sedimentary Rocks and Stratigraphy*, p. 86-88.

Redfield, 1958, The biological control of chemical factors in the environment: *American Scientist*, v. 46, p. 205-222.

Reiners, W.A., 1986, Complementary models for ecosystems: *American Naturalist*, v. 127:1, p. 59-73.

Shosa, J.D., Gastaldo, R.A., and King, D.W., 2002, Integration of research and curriculum: the Belgrade Lakes project: National CUR Meeting, Connecticut College.

Sterner, R.W., and Elser, J.J., 2002, *Ecological stoichiometry: the biology of elements from molecules to the biosphere*: Princeton University Press, 439p.

Syers, J.K., Harris, R.F., and Armstrong, D.E., 1973, Phosphate chemistry in lake sediments: *Journal of Environmental Quality*, v. 2:1, p. 1-14.

Twinch, A.J., and Breen, C.M., 1982, Vertical Stratification in sediments from a young oligotrophic South African impoundment: implications in phosphorus cycling: *Hydrobiologia*, v. 92, p. 295-298.

Twinch, A.J., and Peters, R.H., 1984, Phosphate exchange between littoral sediments and overlying water in an oligotrophic north-temperate lake: *Canadian Journal of Fisheries and Aquatic Sciences*, v. 41:11, p. 1609-1617.

Williams, J.D.H., Syers, J.K., Armstrong, D.E., and Harris, R.F., 1971, Characterization of inorganic phosphate in noncalcareous lake sediments: *Proceedings – Soil Science Society of America*, v. 35:4, p. 556-561.

Williams, J.D.J., Syers, J.K., Shukla, S.S., Harris, R.F., and Armstrong, D.E., 1971, Levels of inorganic and total phosphorus in lake sediments related to other sediment parameters: *Environmental Science and Technology*, v. 5:11, p. 1113-1120.

Wisconsin Dept. of Natural Resources, 2003, Alum treatments to control phosphorus in lakes:
<http://www.dnr.state.wi.us/org/water/fhp/papers/alum_brochure.pdf>

WATER QUALITY SUMMARY

East Pond, Smithfield

Midas: 5349, Basin: Primary

The Maine Department of Environmental Protection (ME-DEP) and the Volunteer Lake Monitoring Program (VLMP) have collaborated in the collection of lake data to evaluate present water quality, track algal blooms, and determine water quality trends. This dataset does not include bacteria, mercury, or nutrients other than phosphorus.

Water quality monitoring data for East Pond has been collected since 1975. During this period, 12 years of basic chemical information was collected, in addition to Secchi Disk Transparencies (SDT). In summary, the water quality of East Pond is considered to be below average to poor, based on measures of SDT, total phosphorus (TP), and Chlorophyll-a (Chla). The potential for nuisance algal blooms in East Pond is moderate to high.

Water Quality Measures: East Pond is a non-colored lake (average color 16 SPU) with an average SDT of 4.4m (15.5ft); some readings hit bottom. The range of water column TP for East Pond is 12-29 parts per billion (ppb) with an average of 20 ppb, while Chla ranges from 1.7-23.0 ppb with an average of 8.3 ppb. Recent dissolved oxygen (DO) profiles show minimal DO depletion in deep areas of the lake, however, East Pond is not a strong thermally stratified lake. The potential for TP to leave the bottom sediments and become available to algae in the water column (internal recycling) is high, due to the effects of wind disturbance.

The flushing rate is the amount of time required for the lake water to be renewed each year. The average flushing rate is about 1-1.5 flushes per year for Maine lakes. The flushing rate for East Pond is 0.25 flushes per year (flushes once every 4 years).

Comments: East Pond is at the top of the Belgrade lakes drainage system and flows directly into North Pond via the Serpentine Stream outlet dam. It is on the DEP list of lakes most at risk from developmental pressures and has been intensively studied by the Colby College biology program in 1991 and 1999. Their study includes recommendations for addressing land use impacts and lake improvements. Belgrade Regional Conservation Alliance (BRCA) with help from DEP conducted a watershed survey in 1999. BRCA through funding from EPA will be developing a watershed management plan for the Great Pond watershed which includes East Pond.

See ME-DEP Explanation of Lake Water Quality Monitoring Report for measured variable explanations. Additional lake information can be found on the World Wide Web at: pearl.spatial.maine.edu and/or state.me.us/dep/blwq/lake.htm, or telephone ME-DEP at 207-287-3901 or VLMP at 207-255-2070.

Filename: 5349east, Revised: 01/2000, By dh

Appendix B: Grain-size analysis data for all 59 sediment samples.

SAMPLE	LAT (N)	LON (W)	DEPTH (m)	MEDIAN Φ	MEAN Φ	STAN'D DEV.	SKEWNESS	KURTOSIS	% SAND (<4 Φ)	% SILT (4-8 Φ)	% CLAY (>8 Φ)	SAND:SILT	SILT:CLAY
016	44.62944	-69.7905	1.4	5.307767	5.32150	0.2407093	6.1216867	1.0894667	0.00	100.00	0.00	0.00	0.00
017	44.62552	-69.7894	2.9	5.808093	5.80944	0.2600983	5.8283133	0.9514660	0.00	100.00	0.00	0.00	0.00
018	44.62512	-69.7947	2.1	5.420810	5.42229	0.3609293	3.6567700	0.9707590	0.00	100.00	0.00	0.00	0.00
021	44.62081	-69.7954	2.7	2.40	2.48	1.23	0.19	1.83	86.89	13.11	0.00	6.63	0.00
022	44.62010	-69.7994	1.3	1.10	1.02	0.89	-0.10	1.29	99.22	0.78	0.00	126.88	0.00
023	44.61645	-69.7960	3.7	5.433603	5.44165	0.2712317	5.3243267	1.0958337	0.00	100.00	0.00	0.00	0.00
024	44.60999	-69.7935	5.4	5.877723	5.85780	0.3394553	4.0964533	0.8955993	0.00	100.00	0.00	0.00	0.00
027	44.60532	-69.7949	2.1	5.306653	5.31804	0.2573580	5.6246100	1.0255960	0.00	100.00	0.00	0.00	0.00
029	44.60505	-69.7884	6.4	5.602057	5.60906	0.2864917	4.9647367	1.0115583	0.00	100.00	0.00	0.00	0.00
031	44.61052	-69.7890	6.9	5.288320	5.29015	0.3426973	3.9456867	1.0089867	0.00	100.00	0.00	0.00	0.00
032	44.61527	-69.7894	4.0	5.701113	5.68644	0.2249403	6.4025400	0.9007317	0.00	100.00	0.00	0.00	0.00
038	44.59717	-69.7877	1.1	3.75	3.82	0.82	0.19	1.15	63.05	36.95	0.00	1.71	0.00
039	44.59169	-69.7841	2.5	5.641350	5.65168	0.3738448	3.7378525	0.9474790	0.00	100.00	0.00	0.00	0.00
040	44.59778	-69.7846	4.1	5.611247	5.64337	0.3391177	4.0799867	0.9303170	0.00	100.00	0.00	0.00	0.00
041	44.60187	-69.7846	6.2	5.595040	5.61290	0.2992477	4.5242900	0.9218763	0.00	100.00	0.00	0.00	0.00
042	44.60552	-69.7836	6.6	5.495807	5.51874	0.2685003	5.3290333	0.9314833	0.00	100.00	0.00	0.00	0.00
043	44.61089	-69.7842	6.9	5.299660	5.29517	0.3584093	3.6994200	1.0270007	0.00	100.00	0.00	0.00	0.00
044	44.61528	-69.7850	4.8	6.147890	6.18299	0.2877707	5.8300267	1.0453077	0.00	100.00	0.00	0.00	0.00
045	44.62083	-69.7857	6.0	5.653280	5.65677	0.2808513	5.1195767	1.0241230	0.00	100.00	0.00	0.00	0.00
046	44.62584	-69.7862	3.9	3.50	3.23	1.54	-0.23	0.70	61.51	38.49	0.00	1.60	0.00
047	44.62546	-69.7792	1.3	3.45	3.70	1.28	0.21	0.78	58.51	41.49	0.00	1.41	0.00
048	44.62040	-69.7795	4.1	5.506737	5.49935	0.2769607	5.3750833	1.0690697	0.00	100.00	0.00	0.00	0.00
049	44.61514	-69.7786	6.2	5.274927	5.28228	0.2378923	6.2623667	1.1567300	0.00	100.00	0.00	0.00	0.00
050	44.61077	-69.7785	6.7	5.352473	5.35077	0.2785157	5.2946167	1.0600237	0.00	100.00	0.00	0.00	0.00
051	44.60561	-69.7782	6.5	5.290723	5.29176	0.2207290	6.7692400	1.1121933	0.00	100.00	0.00	0.00	0.00
052	44.60079	-69.7778	6.0	5.330763	5.36380	0.2693853	5.0957000	1.0168390	0.00	100.00	0.00	0.00	0.00
053	44.59683	-69.7786	4.1	2.85	2.72	1.47	-0.13	0.82	79.30	20.70	0.00	3.83	0.00
054	44.59161	-69.7786	3.3	5.257825	5.26624	0.3295133	4.2431800	1.1085623	0.00	100.00	0.00	0.00	0.00

Appendix B (continued): Grain-size analysis data for all 59 sediment samples.

SAMPLE	LAT (N)	LON (W)	DEPTH (m)	MEDIAN Φ	MEAN Φ	STAN'D DEV.	SKEWNESS	KURTOSIS	% SAND (<4 Φ)	% SILT (4-8 Φ)	% CLAY (>8 Φ)	SAND:SILT	SILT:CLAY
055	44.59630	-69.7740	3.6	5.428597	5.43498	0.2493903	5.8734733	1.1377600	0.00	100.00	0.00	0.00	0.00
056	44.60078	-69.7731	3.1	5.399013	5.40084	0.4015965	5.1610767	0.9759467	0.00	100.00	0.00	0.00	0.00
057	44.59680	-69.7678	2.8	3.60	3.70	1.26	-0.01	1.01	62.93	37.07	0.00	1.70	0.00
058	44.60468	-69.7663	2.0	2.95	2.83	1.66	-0.10	0.86	73.29	26.71	0.00	2.74	0.00
059	44.61117	-69.7729	4.7	5.579577	5.57960	0.2439773	5.6937233	0.8648433	0.00	100.00	0.00	0.00	0.00
060	44.61569	-69.7736	3.2	4.00	3.77	0.91	-0.24	1.05	50.78	49.22	0.00	1.03	0.00
061	44.61995	-69.7885	3.5	5.303583	5.32322	0.2459780	5.8346667	1.0939500	0.00	100.00	0.00	0.00	0.00
062	44.59247	-69.7847	1.5	4.321873	4.37559	0.3197020	3.9959267	1.4289000	0.00	100.00	0.00	0.00	0.00
063	44.59590	-69.7886	1.3	2.90	2.75	2.00	-0.25	0.97	65.76	34.24	0.00	1.92	0.00
064	44.59310	-69.7803	3.5	4.289280	4.28928	0.2338050	5.6600300	1.2665733	0.00	100.00	0.00	0.00	0.00
065	44.59296	-69.7773	3.8	4.359040	4.41943	0.3350353	3.6338433	1.1187627	0.00	100.00	0.00	0.00	0.00
066	44.59768	-69.7816	4.5	4.535507	4.56546	0.3825000	3.1177500	0.9734113	0.00	100.00	0.00	0.00	0.00
067	44.60026	-69.7796	4.5	4.30	3.80	1.53	-0.48	0.91	35.33	64.67	0.00	0.55	0.00
068	44.59737	-69.7754	3.5	4.00	3.62	1.85	-0.28	0.78	50.94	49.06	0.00	1.04	0.00
069	44.59804	-69.7669	3.0	4.60	4.55	0.40	-0.15	0.93	8.66	91.34	0.00	0.09	0.00
070	44.59672	-69.7668	1.8	2.50	2.50	0.98	0.06	1.36	92.21	7.79	0.00	11.84	0.00
071	44.60632	-69.7742	6.8	4.406917	4.46311	0.3577630	3.3711933	1.0373787	0.00	100.00	0.00	0.00	0.00
072	44.60507	-69.7720	4.8	1.00	1.25	1.61	0.26	1.24	89.11	10.89	0.00	8.18	0.00
073	44.60363	-69.7698	4.8	4.60	4.45	1.00	-0.51	2.23	21.40	78.60	0.00	0.27	0.00
074	44.60466	-69.7670	3.5	4.720763	4.76240	0.3542907	3.4916600	0.9776010	0.00	100.00	0.00	0.00	0.00
075	44.60830	-69.7713	5.3	2.75	3.22	1.10	0.56	0.66	70.31	29.70	0.00	2.37	0.00
076	44.62553	-69.7822	4.8	4.70	4.70	0.66	-0.14	1.13	9.56	90.44	0.00	0.11	0.00
077	44.62442	-69.7818	4.8	4.374807	4.44078	0.3507367	3.4813867	1.1188217	0.00	100.00	0.00	0.00	0.00
078	44.62303	-69.7791	3.0	3.65	3.63	0.82	-0.01	0.79	61.26	38.74	0.00	1.58	0.00
079	44.62399	-69.7890	4.5	4.607423	4.63555	0.3745287	3.2856733	1.0246383	0.00	100.00	0.00	0.00	0.00
080	44.62288	-69.7916	3.0	4.694170	4.68590	0.3604410	3.4010533	1.0673920	0.00	100.00	0.00	0.00	0.00
081	44.62324	-69.7973	3.3	4.629813	4.65462	0.3651907	3.3939067	1.0653380	0.00	100.00	0.00	0.00	0.00
082	44.62490	-69.7991	2.0	2.00	2.12	1.72	0.09	1.08	85.95	14.05	0.00	6.12	0.00

Appendix B (continued): Grain-size analysis data for all 59 sediment samples.

SAMPLE	LAT (N)	LON (W)	DEPTH (m)	MEDIAN Φ	MEAN Φ	STAN'D DEV.	SKEWNESS	KURTOSIS	% SAND (<4 Φ)	% SILT (4-8 Φ)	% CLAY (>8 Φ)	SAND:SILT	SILT:CLAY
083	44.62029	-69.7971	3.8	5.055480	5.07780	0.3369857	3.6933733	0.9344423	0.00	100.00	0.00	0.00	0.00
084	44.62323	-69.8014	0.5	4.308643	4.33366	0.2678447	4.7031133	1.2636967	0.00	100.00	0.00	0.00	0.00
085	44.61484	-69.7953	4.5	4.420017	4.48266	0.3712860	3.2220500	0.9186250	0.00	100.00	0.00	0.00	0.00
Lake x				4.51	4.51	0.62	3.07	1.05	20.78	79.22	0.00		

Appendix C: Sediment chemistry data for all 59 sediment samples. TOC = Total Organic Carbon, TON = Total Organic Nitrogen, Org P and OP = Organic Phosphorus = HCl + NaOH-extractable phosphorus, Inorg P and IP = Inorganic Phosphorus = EDTA-extractable phosphorus, TP = Total Phosphorus = organic + inorganic.

SAMPLE	LAT (N)	LON (W)	DEPTH (m)	% TOC	% TON	TOC:TON	% ORG P	% INORG P	% TOTAL P	TOC:OP	TOC:IP	TON:OP	TON:IP	TOC:TP	TON:TP
016 ⁱ	44.62944	-69.7905	1.4	5.28	0.29	17.99	0.0300	0.0138	0.0438	175.972	382.014	9.782	21.236	120.48	6.70
017 ¹	44.62552	-69.7894	2.9	8.21	0.79	10.39	0.0518	0.0127	0.0645	158.522	644.332	15.254	62.000	127.22	12.24
018 ¹	44.62512	-69.7947	2.1	26.64	1.27	21.03	0.0200	0.0168	0.0368	63.263	1588.507	63.263	75.539	724.00	34.43
021 ¹	44.62081	-69.7954	2.7	1.89	0.20	9.47	0.0186	0.0044	0.0231	101.578	427.854	10.730	45.196	82.09	8.67
022 ¹	44.62010	-69.7994	1.3	1.31	0.08	16.33	0.0049	0.0025	0.0074	268.775	517.155	16.456	31.663	176.86	10.83
023 ¹	44.61645	-69.7960	3.7	6.27	0.69	9.04	0.0382	0.0178	0.0560	18.154	351.526	18.154	38.872	111.91	12.37
024 ¹	44.60999	-69.7935	5.4	1.52	0.15	10.36	0.0225	0.0201	0.0426	67.523	75.731	6.515	7.307	35.70	3.44
027 ¹	44.60532	-69.7949	2.1	1.56	0.17	9.16	0.0169	0.0099	0.0268	91.840	157.672	10.030	17.219	58.04	6.34
029 ¹	44.60505	-69.7884	6.4	5.76	0.56	10.35	0.0300	0.0443	0.0744	18.535	129.969	18.535	12.553	77.49	7.48
031 ¹	44.61052	-69.7890	6.9	5.93	0.57	10.35	0.0515	0.0481	0.0996	115.160	123.320	11.128	11.916	59.55	5.75
032 ¹	44.61527	-69.7894	4.0	2.89	0.24	12.21	0.0260	0.0176	0.0437	110.959	164.004	9.087	13.431	66.18	5.42
038 ¹	44.59717	-69.7877	1.1	4.45	0.33	13.49	0.0105	0.0136	0.0241	31.508	326.298	31.508	24.179	184.62	13.68
039 ¹	44.59169	-69.7841	2.5	11.33	0.80	14.17	0.0159	0.0235	0.0394	711.943	482.577	50.255	34.064	287.62	20.30
040 ¹	44.59778	-69.7846	4.1	5.32	0.52	10.22	0.0384	0.0202	0.0586	138.505	263.325	13.547	25.755	90.76	8.88
041 ¹	44.60187	-69.7846	6.2	6.00	0.59	10.23	0.0434	0.0352	0.0786	13.510	170.427	13.510	16.664	76.31	7.46
042 ⁱⁱ	44.60552	-69.7836	6.6	5.78	0.59	9.74	--	--	0.0938	--	--	--	--	61.63	6.33
043 ²	44.61089	-69.7842	6.9	5.98	0.59	10.08	--	--	0.1620	--	--	--	--	36.91	3.66
044 ¹	44.61528	-69.7850	4.8	2.77	0.23	12.22	0.0260	0.0293	0.0553	8.729	94.483	8.729	7.731	50.10	4.10
045 ¹	44.62083	-69.7857	6.0	6.90	0.54	12.71	0.0392	0.0370	0.0762	176.147	186.610	13.864	14.687	90.61	7.13
046 ¹	44.62584	-69.7862	3.9	3.38	0.19	18.09	0.0292	0.0117	0.0409	115.507	289.451	6.385	16.001	82.56	4.56
047 ¹	44.62546	-69.7792	1.3	1.88	0.11	17.06	0.0190	0.0102	0.0292	5.792	184.578	5.792	10.819	64.36	3.77
048 ¹	44.62040	-69.7795	4.1	5.32	0.49	10.86	0.0487	0.0221	0.0708	109.390	240.925	10.069	22.177	75.23	6.92
049 ¹	44.61514	-69.7786	6.2	6.44	0.56	11.49	0.0380	0.0420	0.0800	169.433	153.073	14.741	13.318	80.42	7.00
050 ¹	44.61077	-69.7785	6.7	6.10	0.53	11.58	0.0469	0.0437	0.0906	11.230	139.399	11.230	12.042	67.27	5.81
051 ¹	44.60561	-69.7782	6.5	5.55	0.48	11.49	0.0365	0.0292	0.0657	152.000	190.350	13.229	16.567	84.51	7.36
052 ¹	44.60079	-69.7778	6.0	5.76	0.48	12.08	0.0363	0.0331	0.0694	158.787	173.887	13.140	14.390	83.00	6.87

Appendix C (continued): Sediment chemistry data for all 59 sediment samples.

SAMPLE	LAT (N)	LON (W)	DEPTH (m)	% TOC	% TON	TOC:TON	% ORG P	% INORG P	% TOTAL P	TOC:OP	TOC:IP	TON:OP	TON:IP	TOC:TP	TON:TP
053 ¹	44.59683	-69.7786	4.1	1.80	0.11	16.84	0.0245	0.0079	0.0324	4.360	226.717	4.360	13.460	55.47	3.29
054 ¹	44.59161	-69.7786	3.3	4.74	0.38	12.46	0.0470	0.0166	0.0636	100.822	285.341	8.088	22.892	74.50	5.98
055 ¹	44.59630	-69.7740	3.6	4.84	0.40	12.10	0.0302	0.0208	0.0510	160.178	232.650	13.238	19.227	94.86	7.84
056 ¹	44.60078	-69.7731	3.1	5.15	0.73	7.08	0.0350	0.0185	0.0535	20.757	278.702	20.757	39.350	96.24	13.59
057 ¹	44.59680	-69.7678	2.8	1.70	0.10	16.97	0.0262	0.0105	0.0367	64.666	162.286	3.811	9.565	46.24	2.73
058 ¹	44.60468	-69.7663	2.0	2.91	0.16	17.82	0.0193	0.0116	0.0310	150.687	249.883	8.458	14.026	94.00	5.28
059 ¹	44.61117	-69.7729	4.7	5.57	0.44	12.76	0.0519	0.0202	0.0720	8.418	276.111	8.418	21.646	77.31	6.06
060 ¹	44.61569	-69.7736	3.2	3.45	0.26	13.11	0.0364	0.0141	0.0504	94.964	245.405	7.241	18.713	68.47	5.22
061 ¹	44.61995	-69.7885	3.5	5.56	0.63	8.83	0.0440	0.0253	0.0693	126.346	219.508	14.316	24.872	80.19	9.09
062 ⁱⁱⁱ	44.59247	-69.7847	1.5	11.19	--	--	--	--	--	--	--	--	--	--	--
063 ²	44.59590	-69.7886	1.3	5.26	--	--	--	--	--	--	--	--	--	--	--
064	44.59310	-69.7803	3.5	2.80	1.35	2.07	0.0212	0.0071	0.0071	131.880	393.242	63.661	189.825	393.24	189.82
065 ²	44.59296	-69.7773	3.8	4.33	--	--	--	--	--	--	--	--	--	--	--
066	44.59768	-69.7816	4.5	4.58	1.40	3.26	0.0272	0.0065	0.0065	168.232	704.718	51.547	215.929	704.72	215.93
067	44.60026	-69.7796	4.5	3.29	0.80	4.11	0.0172	0.0024	0.0236	190.880	1368.570	46.391	332.615	139.41	33.88
068 ^{2iv}	44.59737	-69.7754	3.5	2.85	--	--	--	--	--	--	--	--	--	--	--
069 ²	44.59804	-69.7669	3.0	3.72	--	--	--	--	--	--	--	--	--	--	--
070 ²	44.59672	-69.7668	1.8	0.54	--	--	--	--	--	--	--	--	--	--	--
071 ^{2v}	44.60632	-69.7742	6.8	6.14	--	--	--	--	--	--	--	--	--	--	--
072	44.60507	-69.7720	4.8	0.47	0.51	0.92	0.0124	0.0024	0.0024	37.677	195.836	41.176	214.021	195.84	214.02
073 ²	44.60363	-69.7698	4.8	5.49	--	--	--	--	--	--	--	--	--	--	--
074 ²	44.60466	-69.7670	3.5	5.00	--	--	--	--	--	--	--	--	--	--	--
075 ²	44.60830	-69.7713	5.3	1.58	--	--	--	--	--	--	--	--	--	--	--
076 ²	44.62553	-69.7822	4.8	4.99	--	--	--	--	--	--	--	--	--	--	--
077	44.62442	-69.7818	4.8	4.27	1.13	3.79	0.0235	0.0080	0.0352	181.904	535.932	48.034	141.519	121.26	32.02
078 ²	44.62303	-69.7791	3.0	1.84	--	--	--	--	--	--	--	--	--	--	--
079 ²	44.62399	-69.7890	4.5	7.14	--	--	--	--	--	--	--	--	--	--	--

Appendix C (continued): Sediment chemistry data for all 59 sediment samples.

SAMPLE	LAT (N)	LON (W)	DEPTH (m)	% TOC	% TON	TOC:TON	% ORG P	% INORG P	% TOTAL P	TOC:OP	TOC:IP	TON:OP	TON:IP	TOC:TP	TON:TP
080	44.62288	-69.7916	3.0	6.92	1.19	5.83	0.0339	0.0091	0.0263	204.002	763.176	34.983	130.872	263.00	45.10
081 ²	44.62324	-69.7973	3.3	8.87	--	--	--	--	--	--	--	--	--	--	--
082	44.62490	-69.7991	2.0	1.13	0.35	3.19	0.0061	0.0017	0.0017	184.426	680.503	57.838	213.412	680.50	213.41
083	44.62029	-69.7971	3.8	5.74	0.77	7.46	0.0269	0.0086	0.0086	213.816	664.966	28.666	89.151	664.97	89.15
084	44.62323	-69.8014	0.5	30.64	2.08	14.71	0.0251	0.0119	0.0119	1219.023	2578.721	82.886	175.337	2578.72	175.34
085	44.61484	-69.7953	4.5	4.84	0.81	5.97	0.0179	0.0077	0.0077	270.929	624.480	45.373	104.582	624.48	104.58
Lake x				5.42	0.57	10.92	0.0294	0.0179	0.0476	151.784	421.959	22.888	59.450	224.64	35.55

ⁱ Phosphorus analysis completed in two batches – HCl-extractable and total P measured; later, EDTA-extractable P measured. NaOH-extractable P determined by subtracting HCl and EDTA-extracted concentrations from measured total concentration.

ⁱⁱ Analytical error in measuring the individual phosphorus fractions, only total phosphorus was obtained.

ⁱⁱⁱ Analytical error in measuring TON, phosphorus analysis not completed.

Appendix D: Grain-size analysis data from suspended particulate.

DEPTH (m)	MEDIAN Φ	MEAN Φ	STAN'D DEV.	SKEWNESS	KURTOSIS	% SAND (<4 Φ)	% SILT (4-8 Φ)	% CLAY (>8 Φ)	SAND:SILT	SILT:CLAY
0.5	5.287653333	5.214566667	0.625782	2.006793333	0.892609667	0.00	100.00	0.00	0.00	0.00
3.0	5.69177	5.712276667	0.508578667	3.82521	1.186426333	0.00	100.00	0.00	0.00	0.00
5.5	5.823723333	3.799219	0.568883667	2.935726667	1.099541667	0.00	0.00	0.00	0.00	0.00