Paleolimnological Investigation of South Bay and Gilmour Bay, Chandos Lake, Ontario

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For citizen scientists who donate their time to help protect our natural environment.

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Dr. Katrina Moser, Associate Professor, Western University, provided field and lab equipment, provided mentorship throughout this project, reviewed and revised draft copies of this report, and generally contributed to the production of this report.

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Christine Hollingshead, generously offered her time to be a field assistant on this project and contributed moral support to complete this project.

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EXECUTIVE SUMMARY

Numerous human activities, including anthropogenic climate warming, potentially affect the water quality of lakes. This study used the "top-bottom" paleolimnology approach to determine whether the water quality of South Bay and Gilmour Bay of Chandos Lake located in Ontario has changed from pre-industrial times to present day. A comparison of diatom assemblages (single-celled algae) from pre-industrial and present-day, together with water chemistry data and limnological variables, helped determine if there have been detectable changes in the lake water quality of South Bay and Gilmour Bay with increasing numbers of cottagers on the lake.

Diatom community composition changed from the pre-industrial period to present day indicating longer or stronger thermal stratification and reduced mixing, most likely related to warming temperatures and a longer ice-free season. The diatom changes also indicate a move towards greater eutrophication, but without further analysis down the core, it is difficult to separate out the past anthropogenic influences from the recent global warming effects.

Modern limnology revealed that the hypolimnion of Gilmour Bay is more anoxic than South Bay and as a result had elevated levels of nutrients (N and P). Although the late summer anoxia may be a chronic condition, it is likely acerbated by the recently elevated levels of ions related to road salt use (NaCl; a de-icing agent on Canadian highways). This anthropogenic salt addition would increase the density of bottom waters and increase stratification, thereby reducing mixing and oxygen in the deep waters. This results in an increase in nutrient concentration in the hypolimnion, leading to a greater pulse of nutrients released from the hypolimnion to the epilimnion during fall overturn. This can lead to greater algal production at overturn.

In the future, sedimentary samples between the top and bottom samples could be analyzed to provide a continuous record of past environmental conditions, which would provide further understanding of the changes identified in this report. For example, the reconstructed environmental conditions from the whole core analysis could be compared to the ice-out data available for Chandos Lake to test our assertion that warming temperatures are causing the changes in diatom community composition.

INTRODUCTION

The purpose of this study is to determine if there have been detectable changes in the lake water quality of South Bay and Gilmour Bay of Chandos Lake with increasing numbers of cottagers on the lake. The majority of freshwater studies only extend as far back as instrumental monitoring data. In North America, long-term monitoring of lake ecosystems rarely extends more than several decades (Smol, 2008), which limits our ability to determine whether recent changes in water quality are unusual. Furthermore, many environmental studies are done after a problem has already been identified (such as fish kills due to deepwater anoxia). It is often difficult to effectively assess and treat these problems without some historical knowledge of how and when the problems originally developed. In such instances, paleolimnological techniques that use proxy data archived in lake sediments are critical to extend our records back in time. The ability of paleolimnology to provide records of limnological variables prior to anthropogenic stressors makes it a powerful tool for determining pre-disturbance conditions (Smol, 2008).

Paleolimnology is the study of aquatic systems that uses the physical, chemical, and biological information preserved in sedimentary profiles to reconstruct past environmental conditions (Smol, 2008). Sedimentary material can originate from outside the lake (i.e., allochthonous) and in the water body (i.e., autochthonous). Overall, a sedimentary profile can provide a continuous, complete and reliable record of past environmental conditions (Smol, 2008).

There are many different proxies of past environmental conditions that paleolimnologists can use to determine how lakes have changed overtime, but one of the most frequently used is diatoms. Diatoms are single-celled algae that are characterized by a cell wall composed of opaline silica, which is called a frustule. Diatom frustules are well preserved in sediment records and can be identified to species or sub-species level. Each diatom species has specific ecological requirements, so by analyzing diatom fossil assemblages much can be learned about past water quality.

Detailed assessments of anthropogenic impacts on lake water quality can use continuous, temporal records of diatom assemblages to determine pre- and post-disturbance conditions. However, in a large lake with multiple bays, it is time consuming to analyze the multiple complete sediment records needed to properly assess water quality in these systems. In order to provide a relatively quick assessment of whether there has been a change in water quality, the most time-efficient and effective approach is to analyze microfossils from a present-day sediment core sample to compare to analysis of a pre-disturbance sample (Charles and Smol, 1990). This is referred to as the “top-bottom” paleolimnological approach (Charles and Smol, 1990). Differences between pre-industrial and present-day samples allow us to determine lake water changes caused by anthropogenic activity and provide information on background or reference conditions. Changes in diatom assemblages between top and bottom intervals, together with water chemistry data and limnological variables, will help determine whether water quality has changed from pre-industrial times to present day in South Bay and Gilmour Bay of Chandos Lake.

STUDY AREA

Chandos Lake is located just east of the town of Apsley and north of Peterborough in the township of North Kawartha, Ontario, Canada (Figure 1), and its location and general morphology are listed in Table 1. Along with the main part of the lake, it has three main bays: West Bay, South Bay, and Gilmour Bay.

The primary focus of this study is on South Bay and Gilmour Bay. Chandos Lake is in the Atlantic watershed and the largest lake in the Crowe River watershed. Most of the nearby smaller lakes and ponds (~20) drain into Chandos Lake (Shaw, 1962). Chandos Lake is fed by springs, draining north into the Crowe River (C.L.P.O.A., 2016; Shaw, 1962). The lake was created by glacial scour from the retreat of the Pleistocene glaciation (Shaw, 1962), and the surrounding terrain is mainly low rounded hills with swampy areas and poor drainage.

Table 1: Lake and watershed properties of Chandos Lake.

Properties	**Chandos Lake**
Latitude, Longitude	44°49′30″N, 77°58′30″W
Maximum Depth (m)	48
Surface Water Area (ha)	1400
Water Catchment Area (km^2)	1387
Altitude (m above sea level)	310

Chandos Township forms part of the Laurentian peneplain of the Precambrian Shield. South Bay and Gilmour Bay are underlain by granites and syenites (Shaw, 1962). Deposits of iron, copper, and uranium have been found in the township (Shaw, 1962). Chandos Lake was originally in the Mississauga Anishinaabe Territory and named Mongosogan (C.L.P.O.A., 2016). It was ceded in the early-mid nineteenth century (C.L.P.O.A., 2016; Shaw, 1962). Farmers settled in the northern, eastern, and southern parts of Chandos Township, but much of the cleared land was too poor for agriculture so many of the farms were abandoned and the land reverted to bush. Lumbering was also an important industry in the township, including pine, spruce, balsam, cedar, hemlock, poplar, maple, and birch. Much of the land was reforested with pine and cut for the Christmas tree industry. Sand and gravel pits operated in the township (Shaw, 1962). Cottaging is now a major source of income in the region; 1200 cottages, three marinas, and a public beach are located around Chandos Lake (C.L.P.O.A., 2016).

County Roads 504 and 620 encircle Chandos Lake; County Road 504 around the southern portion and County Road 620 around the north portion (Figure 1). County Road 504 is in closest proximity to the lake body, hugging the southeastern shoreline of Gilmour Bay (Figure 1). County Road 504 was originally maintained by the Ministry of Transportation (MTO) as Highway 504 from 1956 (Wikipedia, 2016) until 1998 when it was transferred to Peterborough County and has since been known as County Road 504 (Kendra Reid, County of Peterborough, September 19, 2016). Preceding 1956, it was likely a development road (Wikipedia, 2016). In 1992, Highway 504 was realigned and reconstructed by the MTO. Prior to this realignment, Highway 504 appeared to follow a path of least resistance (Kendra Reid, County of Peterborough, September 19, 2016). In 2002, County Road 504 underwent maintenance to resurface the section near Gilmour Bay (Kendra Reid, County of Peterborough, September 19, 2016) and in the winter months, a mixture of salt and sand is distributed on County Road 504 as a de-icing mechanism (Kendra Reid, County of Peterborough, September 19, 2016).

Figure 1: Aerial view of Chandos Lake (Google Earth, 2016), including County Roads 504 and 620 encircling the lake.

Figure 2: The bathymetry of South Bay including the east and west coring locations (red stars). Contour lines represent 10 ft intervals beginning at 0 ft along the shoreline. Revised from The Angler's Atlas (2007).

Figure 3: The bathymetry of Gilmour Bay including the coring location (red star). Contour lines represent 10 ft intervals beginning at 0 ft along the shoreline. Revised from The Angler's Atlas (2007).

METHODS

Field Methods

Limnological Variables

A YSI 600QS sonde (Quick SampleTM) was used to measure dissolved oxygen (DO, mg/L and %), temperature (TEMP, °C), specific conductivity (SPCOND, mS/cm), pH (pH), ORP (mV), and depth (m) at the three locations used for this study. The YSI 600QS was slowly lowered into the water column where measurements were recorded at continuous 0.5 m intervals. The data was stored on a YSI 650 MDS display-datalogger and transferred onto a Microsoft Excel spreadsheet for further analysis. Secchi measurements were also taken as an indicator of water transparency. A Secchi disk (size: 20 cm) was lowered into the water column until it disappeared; this depth was recorded. The disk was then raised until it reappeared, and the depth recorded. The average of the two depths was the Secchi depth measurement.

Water Sample Collection

Epilimnetic (surface) and hypolimnetic (bottom) water samples were collected in 1 L polyethylene bottles in each of the three sampling locations on August 23-24, 2014. Each 1 L bottle was pre-rinsed three time with E-pure water (pre-treated with distillation followed by reverse osmosis) to minimize contamination. Prior to obtaining a sample, the bottles were rinsed three times with Chandos surface water and samples were collected at a depth of ~ 1 m below the water surface at approximately the deepest part of each of the basins. Bottles were filled and capped underwater. A hypolimnetic water sample was collected using a Van Dorn water sampler (pre-rinsed three times with Chandos lake water) (Van Dorn, 1957). The sampler was lowered to 0.5 m above the maximum depth for measurements (25 m). The sampler was closed for collection of water at depth. The sampler was pulled to the surface and the water in the sampler was poured into a sanitized 1 L polyethylene bottle. All samples were stored at 4°C immediately after sampling, transported to the University of Western Ontario and kept refrigerated until analysis.

Sediment Core Collection and Extrusion

A KB gravity corer (Glew *et al*., 2001) (6.5 cm internal tube diameter) (Figure 4) was used to collect three sediment cores: South Bay east (sediment record collected extended from 0-36.8 cm depth), Gilmour Bay (sediment record collected extended from 0-50.8 cm depth), and South Bay west (sediment record collected extended from 0-44.5 cm depth) (Figure 5) from Chandos Lake on August 23-24 2014. Each core was retrieved from the deepest part of three different sections of the lake (Figure 2; Figure 3), which is the most appropriate coring site to ensure the most continuous, undisturbed, representative sediment record of the entire lake (Smol, 2008). To minimize stratigraphic disturbance, sediment cores were sectioned at continuous 0.5 cm intervals immediately after collection using a vertical extruder in the field (Figure 6). Subsamples were placed into Whirl-Pak® bags and stored at 4°C until further processing. The scraper was cleaned with Chandos surface water between each interval. The top half cm and the bottom half cm of each core were analyzed in this study (Table 2).

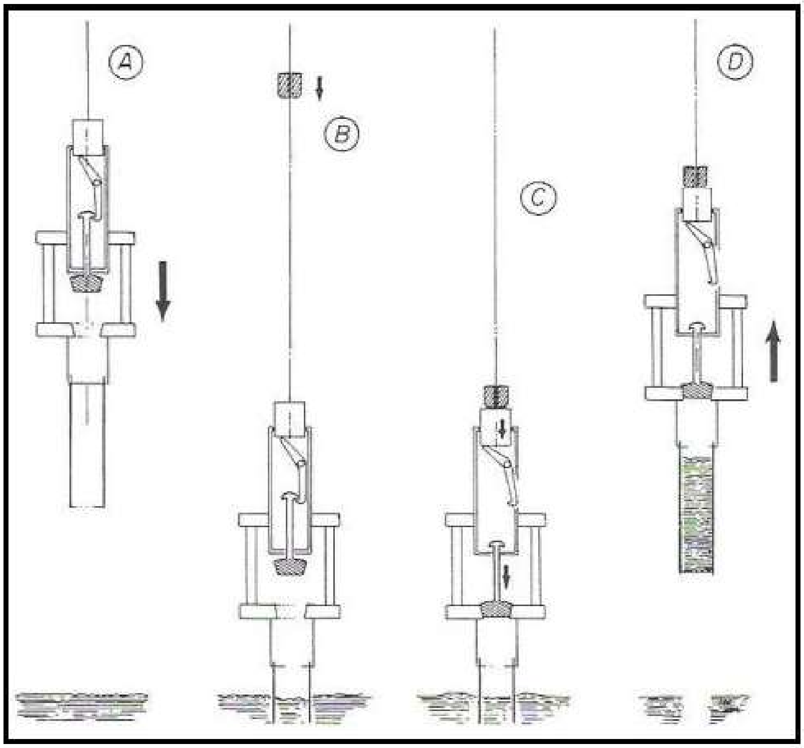


Figure 4: General operation of a messenger-triggered gravity corer. (A) Corer lowered through water column: (B) corer enters the sediment and trigger is released from the surface: (C) trigger hits the corer and forms a seal: (D) corer is vertically removed to obtain sample (Glew *et al*., 2001; Smol, 2008).

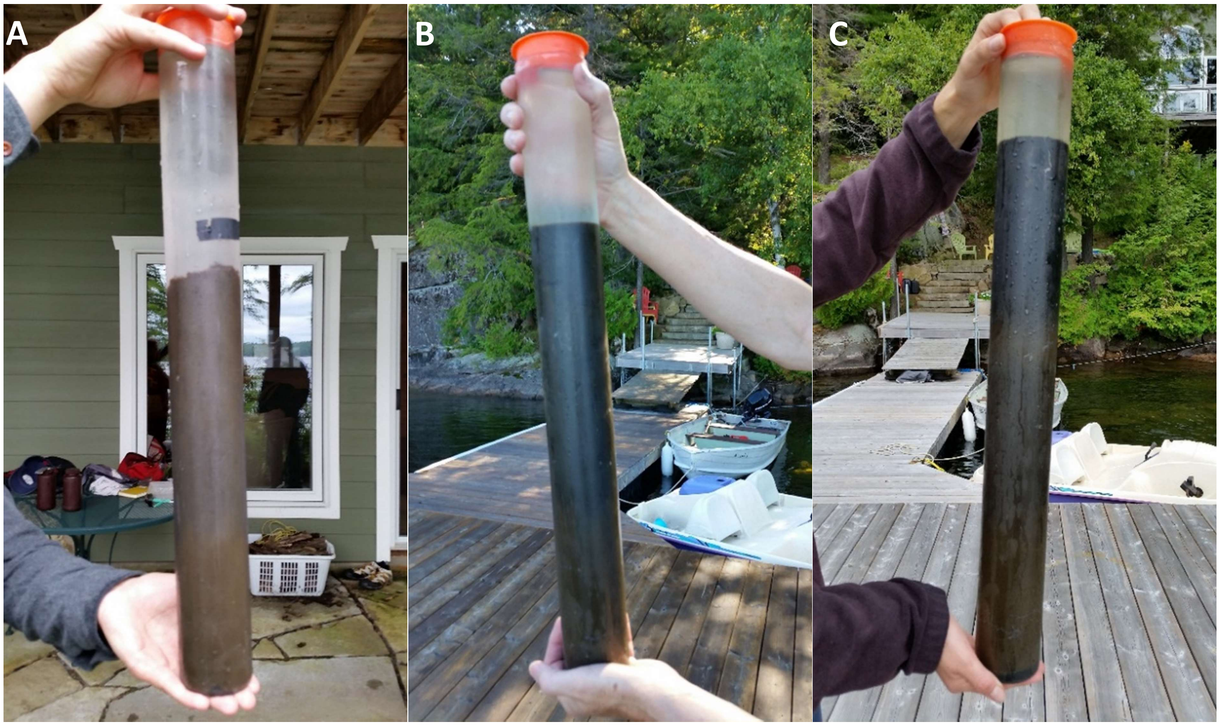


Figure 5: Photographs of Chandos Lake cores: A) South Bay east, B) South Bay west, and C) Gilmour Bay, respectively.

Figure 6: South Bay west sediment core in extruder ready for sectioning in the field.

Table 2: Core depths for each analysis.

Lake	Top Sample (cm)	Bottom Sample (cm)
South Bay east	0 – 0.5	27.5 – 28.0
South Bay west	0 – 0.5	34.5 – 35.0
Gilmour Bay	0 – 0.5	41.0 – 41.5

Laboratory Methods

Water Chemistry Preparation and Analysis

Within four hours after water collection, lakewater samples were divided and prepared for various chemical analyses following procedures by Environment Canada (1994) as outlined in Appendix A. Water samples were sent to Environment Canada in Edmonton, Alberta for analysis of major ions, trace metals, nutrients, and chlorophyll *a* (Chl-*a*).

Paleolimnological Data

Diatom Sample Preparation & Analysis

Sediment samples from Chandos Lake were prepared for diatom analysis in the Lake and Reservoir Systems (LARS) Research Facility at the University of Western Ontario following standard procedures reported in Battarbee *et al.* (2001). At least 600 diatom valves (Pappas and Stoermer, 1996) were identified and enumerated to species level along a minimum of one half of one horizontal transect across each slide (Table 2) under oil immersion (1000x magnification) using a Leica® E-600 light microscope equipped with Nomarski DIC optics. To ensure a representative and reproducible sample, each count ended at precisely halfway or at the end of the transect. Diatom identification to the lowest taxonomic level possible (species or variety) was based primarily on Krammer and Lange-Bertalot (1986, 1988, 1991a,b). *Fragilaria cf. tenera* and *Fragilaria crotenensis* were grouped into one category during enumeration due to the difficulty identifying these species when they were observed in long chains. Chrysophecean cysts were also counted, but not identified, on each slide enumerated for diatoms. The ratio of Chrysophycean cysts to fossilized diatom frustules (C:D) can be useful for inferring trophic status in temperate lakes (Smol, 1985) using the following equation:

$$C{:}D\ ratio = \left[\frac{(Chrysophecean\ cysts)}{\left(\frac{Chrysophecean\ cysts + Diatom\ valves}{2}\right)}\right] \times 100$$

Digital photographs of all dominant taxa were taken using a Retiqua® black and white digital camera (Appendix C).

Data Analysis and Presentation

In order to better understand changes in diatom assemblages through time, the diatom assemblages identified in the top sample were compared to the bottom sample from South Bay east, South Bay west, and Gilmour Bay using plots created in C2, a program for the analysis and visualization of ecological and palaeoenvironmental data. Only dominant diatom taxa (i.e., those taxa that exceeded 1% relative abundance in at least three samples (Wilson *et al.*, 1994)) were included in the graph. The percentage of each diatom taxon was calculated using the total number of individuals of each taxon divided by the total number of all diatoms in the sample. Diatom species were grouped as planktonic (free floating) or benthic (living on and in the sediments) and a plot was created of the C:D values presented in figure 10. The planktonic *Fragilaria* species were in long chains or broken and the *Cyclotella* complex species were small creating difficulty distinguishing between species without a Scanning Electron Microscope; therefore, on the diatom stratigraphy, the *Fragilaria* complex represents *Fragilara cf. tenera* and *Fragilaria cf. crotonensis* and the *Cyclotella* complex represents *Cyclotella stelligera*, *Cyclotella pseudostelligera*, and *Cyclotella michiganiana*.

RESULTS

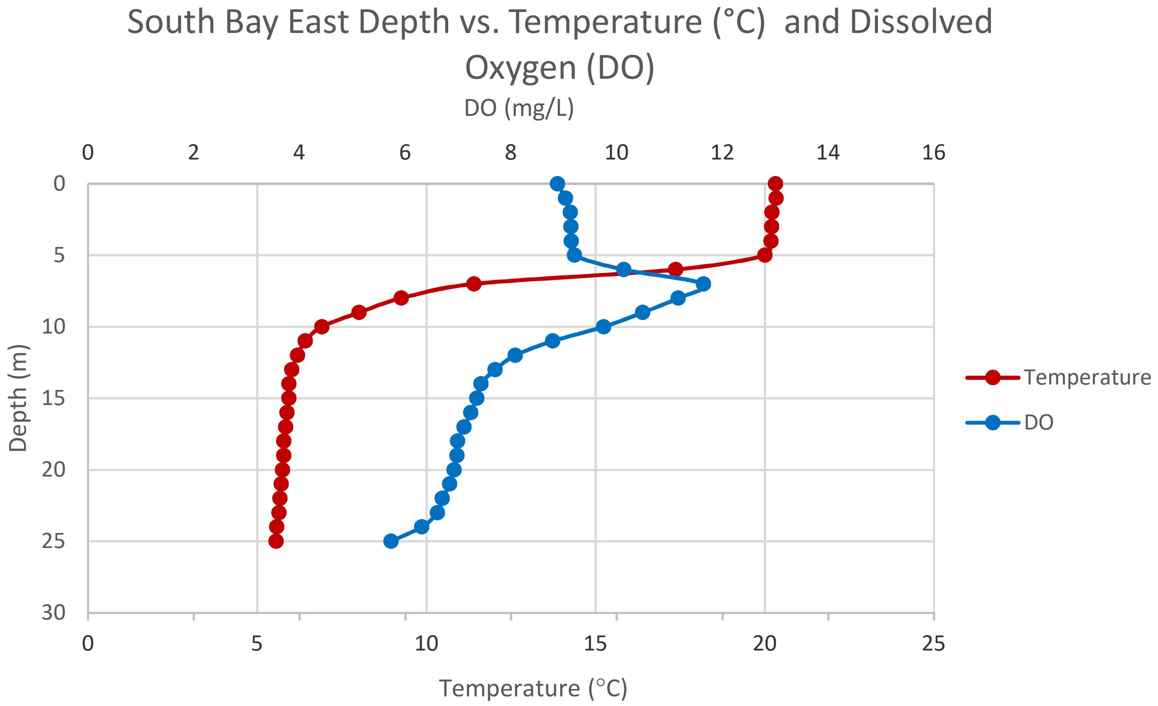
Limnological Characteristics and Water Chemistry

Temperature (TEMP) and dissolved oxygen (DO) measurements at the two locations in South Bay were almost identical (Table 3). The epilimnetic temperature values were 20.3°C and 20.5°C compared to hypolimnetic temperatures of 5.6°C and 5.4°C. DO values were 9.03 mg/L and 9.22 mg/L at the surface to 6.31 and 6.06 mg/L in the hypolimnion. In Gilmour Bay temperatures and epilimnetic oxygen were similar to South Bay, but oxygen was nearly depleted in the hypolimnion (Table 3). The temperature at the surface was 20.9°C compared to a hypolimnetic temperature of 4.5°C. The surface DO value was 9.1 mg/L, and the hypolimnion was anoxic (DO = 0.54 mg/L). The thermocline occurs at 7 m in both South Bay east and Gilmour Bay and is at 9 m in South Bay west (Figure 7). Peak DO, which occurs in all three lakes at similar depths, likely occurs as a result of chlorophyll maxima (a common feature in temperate lakes occurring slightly above the thermocline where algae take advantage of nutrients diffusing up from the nutrient-rich hypolimnion) (Figure 7). Measurements also show that Chandos Lake is slightly alkaline, has low specific conductivity and low transparency (Table 3).

Table 3: Limnological characteristics from South Bay east, South Bay west, and Gilmour Bay. Epilimnetic measurements are recorded at 1 m below the surface of the water; hypolimnetic measurements are recorded at 0.5 m above the maximum depth for measurements. (E) represents epilimnion and (H) represents hypolimnion.

Environmental Variable	**South Bay East**		**South Bay West**		**Gilmour Bay**	
	E	H	E	H	E	H
Max Depth (m)	25		32		20	
TEMP (°C)	20.33	5.58	20.48	5.42	20.94	4.52
SPCond (µS/cm)	143	144	143	143	149	186
DO Conc (mg/L)	9.03	6.31	9.22	6.06	9.09	0.54
pH	8.33	7.81	8.26	7.62	8.3	7.41
Secchi Depth (m)	11.4		10.7		10.8	

A



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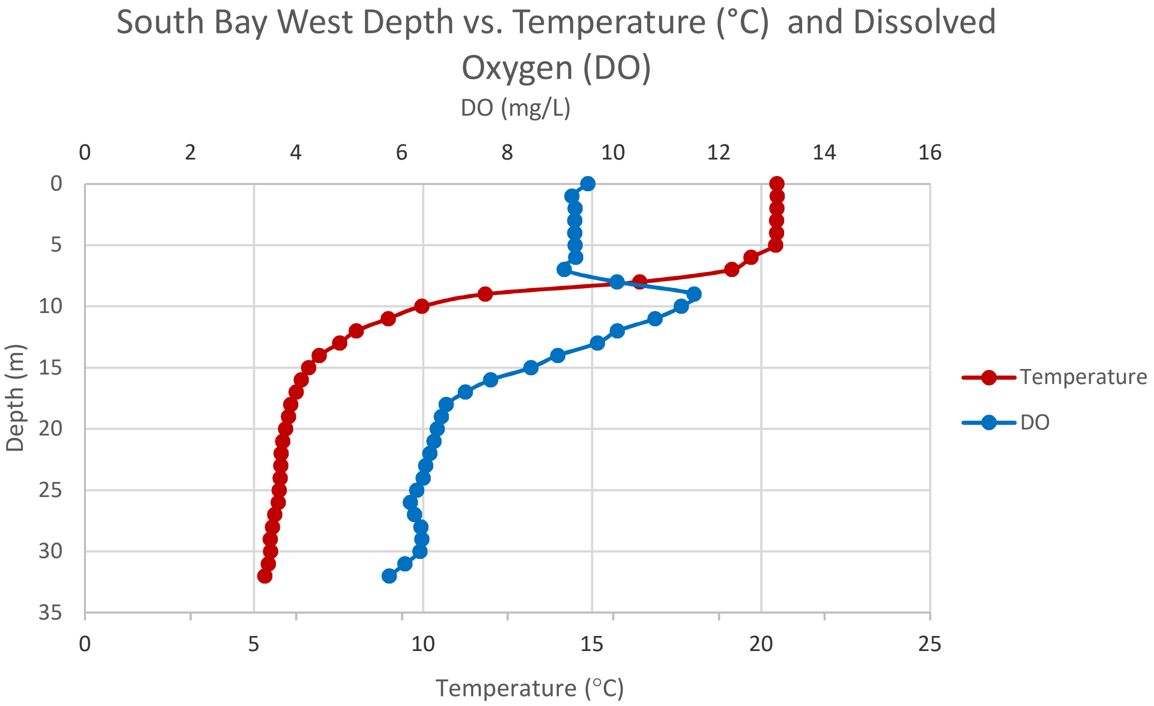

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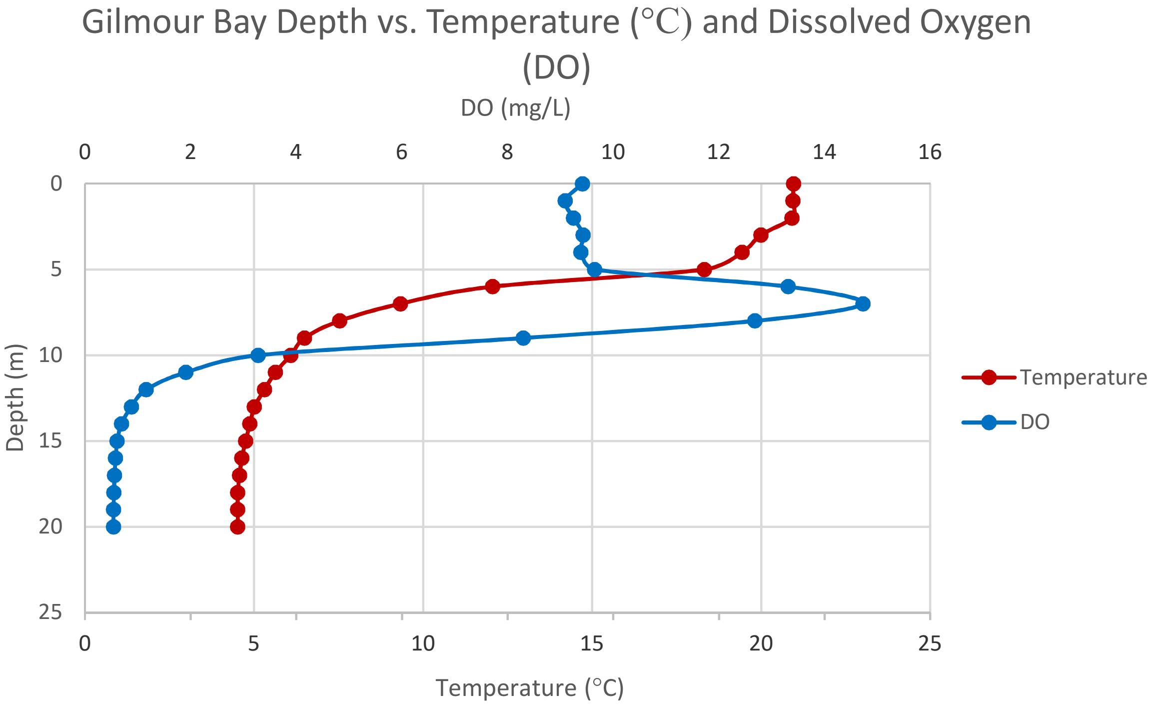


Figure 7: Dissolved oxygen (mg/L) and Temperature (°C) plots scaled against depth (m) from A) South Bay east B) South Bay west, and C) Gilmour Bay.

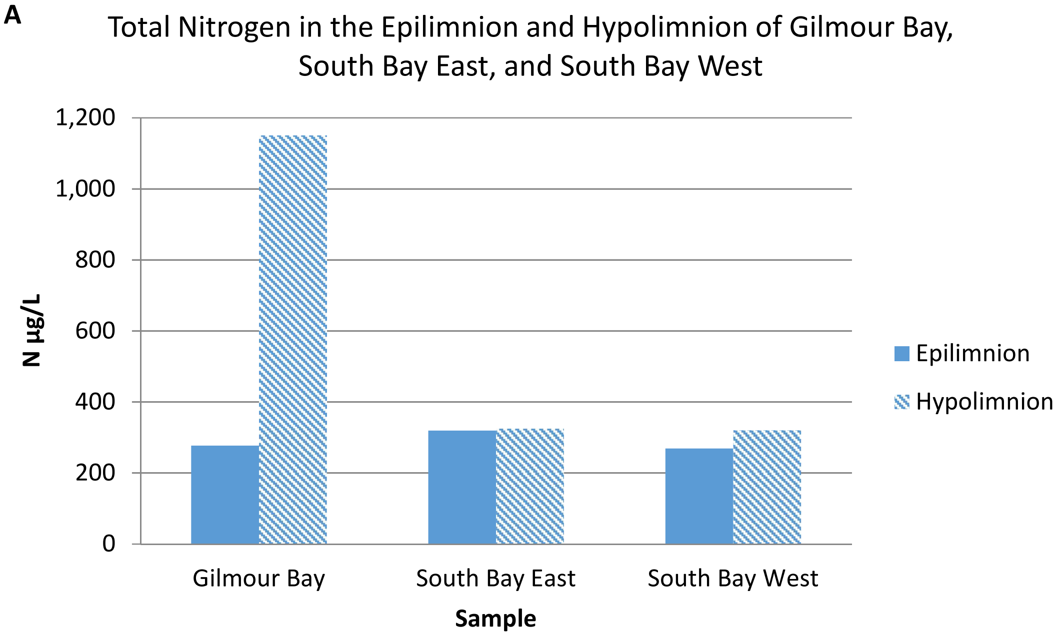
Water chemistry results for South Bay east, South Bay west, and Gilmour Bay are summarized in Table 4. Based on McCauley and Downing (1992), which indicates a lake is phosphorus limited (P-limited) if the nitrogen to phosphorus (TN:TP) ratio is greater than 17, P is the limiting factor for phytoplankton growth in the epilimnion of South Bay east, South Bay west and Gilmour Bay with ratios of 35.4, 53.8, and 39.6, respectively (Table 5). The total nitrogen (TN) concentrations were similar in the epilimnions and hypolimnions of South Bay east and South Bay west. The epilimnetic TN concentration was 319 µg/L and 269 µg/L and the hypolimnetic TN concentration was 325 µg/L and 320 µg/L in South Bay east and South Bay west, respectively. The total phosphorus (TP) was 9 µg/L and 5 µg/L in the epilimnion to slightly higher concentrations of 10 µg/L and 13 µg/L in the hypolimnion, respectively. In Gilmour Bay, the epilimnetic concentrations of TN (mostly ammonia) and TP were similar to South Bay, but the hypolimnetic concentrations were greater. The TN and TP concentrations were 277 µg/L and 7 µg/L, respectively, in the epilimnion compared to higher concentrations of 1150 µg/L and 140 µg/L, respectively, in the hypolimnion (Figure 8).

Table 4: Water chemistry results taken from the epilimnion and hypolimnion of South Bay east and Gilmour Bay on August 23, 2014 and from South Bay west on August 24, 2014. Epilimnetic samples were taken 1 m below the surface of the water and the hypolimnetic water sample was taken at approximately 18 m depth. (E) represents epilimnion; (H) represents hypolimnion; <LOD represents less than limit of detection.

Chemical Symbol	**Name**	**Gilmour Bay**		**South Bay East**		**South Bay West**	
		E	H	E	H	E	H
TN (N µg/L)	Total Nitrogen	277	1,150	319	325	269	320
TP (P µg/L)	Total Phosphorus	7	140	9	10	5	13
NH_3 (N µg/L)	Ammonia Nitrogen	3	543	4	<LOD	<LOD	7
NO_2+NO_3 (N µg/L)	Nitrate and Nitrite	<LOD	<LOD	<LOD	93	<LOD	86
NO_2 (N µg/L)	Nitrite Nitrogen	<LOD	<LOD	<LOD	<LOD	<LOD	<LOD
SRP (P µg/L)	Soluble Reactive Phosphate-Phosphorus	<LOD	41	1	5	<LOD	5
DOC(C mg/L)	Dissolved Organic Carbon	5.0	5.0	5.0	4.5	4.9	4.3
DIC(C mg/L)	Dissolved Inorganic Carbon	10.9	12.1	11.4	11.4	11.3	11.7
Cl (mg/L)	Chloride	10.77	14.78	7.37	7.07	7.39	7.29
SO_4 (mg/L)	Sulphate	4.21	3.03	4.20	4.32	4.18	4.37
Na (mg/L)	Sodium	6.26	9.03	4.25	4.10	4.11	3.97
K (mg/L)	Potassium	0.81	1.03	0.92	0.93	0.88	0.92
Ca (mg/L)	Calcium	20.37	21.25	22.02	22.03	21.51	22.19
Mg (mg/L)	Magnesium	1.41	1.59	1.32	1.30	1.27	1.33
SiO2 (Si mg/L)	Dissolved Silica	0.70	2.77	0.93	2.20	0.94	2.41
Chl-*a* (µg/L)	Chlorophyll-*a*	2.37	3.13	2.60	1.31	2.97	1.61

Table 5: Total nitrogen (TN) and total phosphorus (TP) in the epilimnion and hypolimnion of South Bay east, South Bay west, and Gilmour Bay (P-limited = TN:TP >17; N-limited = TN:TP <14 (McCauley and Downing (1992)).

Chemical Symbol	South Bay East		South Bay West		Gilmour Bay	
	E	H	E	H	E	H
TN (N µg/L)	319	325	269	320	277	1150
TP (P µg/L)	9	10	5	13	7	140
TN:TP	35.4	32.5	53.8	24.6	39.6	8.2



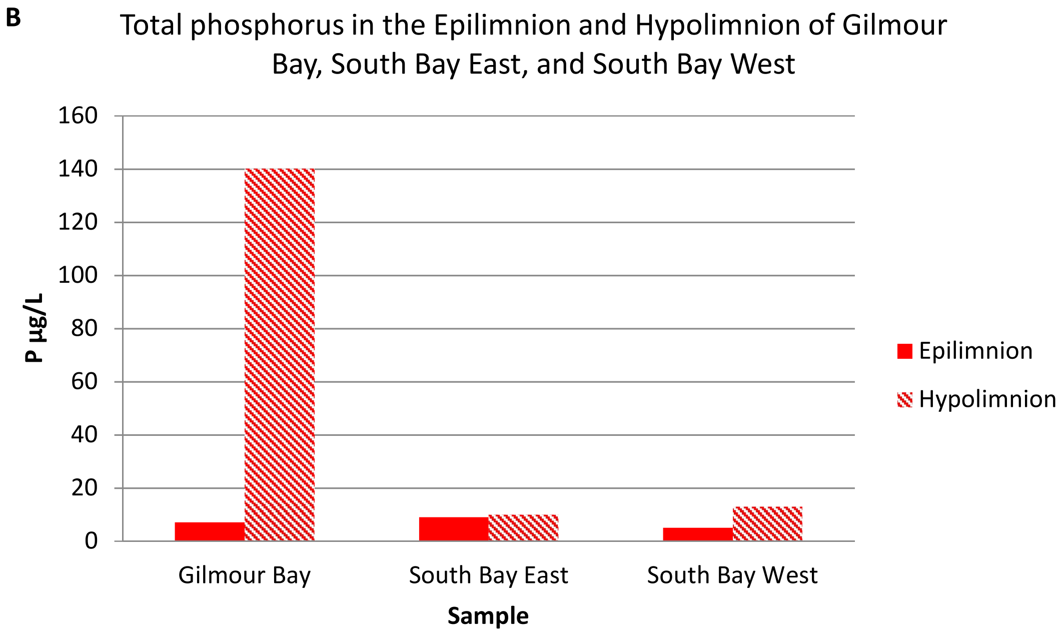


Figure 8: (A) Total Nitrogen and (B) Total Phosphorus plots in the Epilimnion and Hypolimnion of Gilmour Bay, South Bay east, and South Bay west.

Variables related to salinity are summarized in Table 3 (specific conductivity (SPCond)) and Table 4 (ionic concentrations of Dissolved Inorganic Carbon (DIC), Cl, SO_4, Na, K, Ca, Mg). In all three bays, most salinity-related variables show little difference between sites, with the exception of Gilmour Bay where Na and Cl are elevated (Table 4; Figure 9). As well, there is little difference (<15%) between epilimnetic and hypolimnetic values of salinity-related variables, with the exception of Na, Cl and K in Gilmour Bay, which are 25% greater in the hypolimnion than the epilimnion (Table 4; Figure 9).

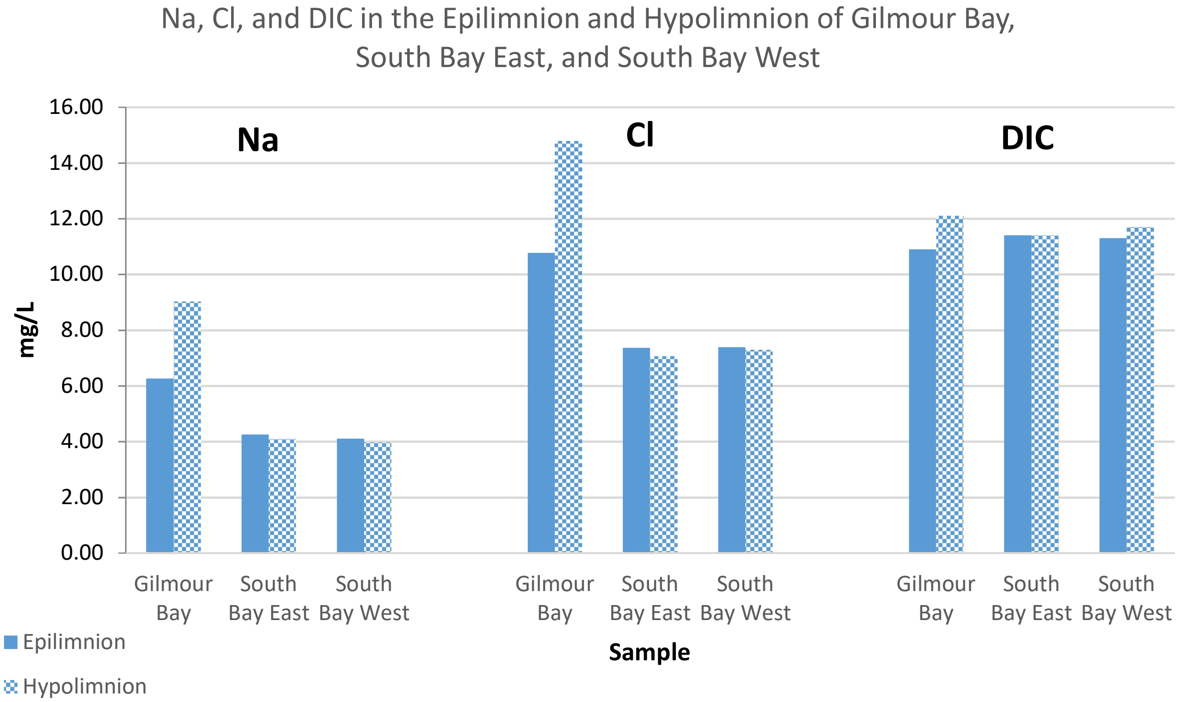


Figure 9: Sodium (Na), chlorine (Cl), and dissolved inorganic carbon (DIC) plots in the epilimnion and hypolimnion of Gilmour Bay, South Bay east, and South Bay west.

Sediment Description

Several sedimentological changes were observed in the cores retrieved from South Bay east, South Bay west, and Gilmour Bay (Figure 5). In South Bay east, the top 0-24 cm consisted of dark brown organics and from 24-37 cm the sediments changed to light brown organics. In South Bay west, the top 0-27 cm consisted of medium brown organics and from 29-44.5 cm the sediments changed to light brown organics. In Gilmour Bay, the top 0-15 cm consisted of dark brown organics; from 18-36 cm the sediments changed to medium brown organics; and from 38-52 cm the sediments changed to light brown organics.

Chronological Control

Present-day (0-0.5 cm interval) and pre-industrial (>20 cm core depth) (Table 2) sediment samples from all three cores were analyzed. Confidence that the core bottom samples represented pre-industrial (i.e., pre-1850) conditions is based on previous nearby research. ^{210}Pb sediment dating from large numbers of other Precambrian, south-central Ontario lakes indicates that a sediment depth of 15 to 20 cm represents the pre-1850 period (Evans and Dillon 1982; Uutala *et al*. 1994).

Diatoms

Seventy four diatom taxa were identified and enumerated in the six samples investigated from South Bay east, South Bay west, and Gilmour Bay. Twenty diatom taxa occurred with a relative abundance of ≥1% in at least three samples (Figure 10). Appendix B lists these 20 diatom species and their corresponding authorities. Because diatom authorities are included in Appendix B they are not provided in the text. Diatom photomicrographs of common diatom taxa identified in South Bay east, South Bay west, and Gilmour Bay are presented in Appendix C. All three sediment cores show similar trends in diatom species assemblage change from the pre-industrial period to present day (Figure 10).

The pre-industrial sample of Gilmour Bay is comprised mainly of *Aulacoseira ambigua*, *Cyclotella stelligera*, and *Tabellaria flocculosa*. *Aulacoseira ambigua* is a heavily silicified, meso-eutrophic diatom species (Battarbee *et al*., 2001). Compared to the pre-industrial sample, the present day sample is characterized by a decrease in *Aulacoseira ambigua*, *Cyclotella stelligera*, and *Tabellaria flocculosa* and an increase in planktonic diatom taxa *Fragilaria* complex, *Cyclotella* complex, and *Asterionella formosa*. *Asterionella formosa.* These planktonic diatoms generally favour eutrophic conditions (Reavie & Smol, 2001).

Similar to Gilmour Bay, the pre-industrial sample of South Bay east is dominated by *Aulacoseira ambigua*, *Tabellaria flocculosa*, and *Cyclotella stelligera,* which are replaced in the present day sample by planktonic assemblages similar to that in the present day sample of Gilmour Bay.

Similar to Gilmour Bay and South Bay east, the pre-industrial sample of South Bay west is dominated by heavily silicified *Aulacoseira ambigua*, *Tabellaria flocculosa*, and *Cyclotella stelligera*. These diatom taxa decrease in the present day sample of South Bay west and are replaced by eutrophic *Fragilaria* complex, planktonic, meso-oligotrophic *Cyclotella michiganiana*, and the *Cyclotella* complex.

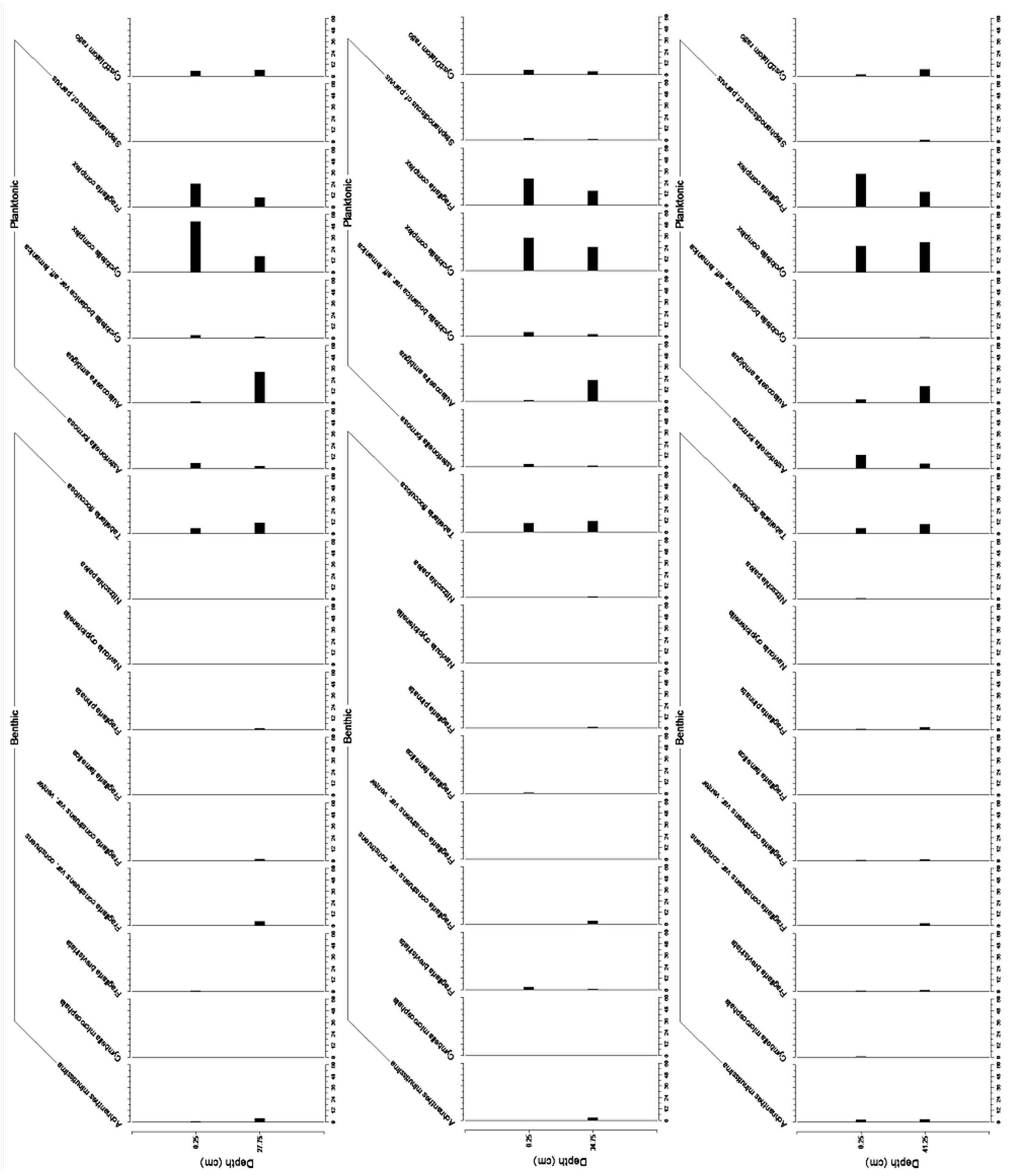


Figure 10: Diatom stratigraphy scaled by depth (cm) showing relative abundance of taxa ≥ 1 % and occurred in a minimum of three samples and C:D ratio for: A) South Bay east for two intervals: 0 – 0.5 cm and 27.5-28.0 cm; B) South Bay west for two intervals: 0 – 0.5 cm and 34.5 – 35.0 cm; C) Gilmour Bay for two intervals: 0 – 0.5 cm and 41.0 – 41.5 cm.

DISCUSSION

Modern Limnology

The thermal properties of South Bay and Gilmour Bay are similar; however, the hypolimnetic dissolved oxygen (DO) is more depleted in Gilmour Bay. One factor that could be playing a role in the anoxic conditions in Gilmour Bay is road salt. Salinity-related variables, Na, Cl and K, are more concentrated in the epilimnion of Gilmour Bay compared to the epilimnion samples of South Bay, possibly indicating different amounts or sources of Na, Cl and K inputs to the two different bays (Table 4; Figure 9). This difference could be related to slight variations in underlying geology, but seems more likely to be related to differences in the proximity of roads and the use of road salt. Road salt (NaCl), is commonly used as a de-icing agent on Canadian roadways (Health Canada, 2011). County Road 504 is de-iced with a mixture of salt (NaCl) (Kendra Reid, County of Peterborough, September 19, 2016). The close proximity of County Road 504 to the east and south lake shores of Gilmour Bay may cause this bay to receive greater ionic inputs in runoff, and therefore have higher concentrations of ions than South Bay (Figure 9). These ions would slowly accumulate in the hypolimnion, as observed in Gilmour Bay, which would increase the density of the bottom waters, which would reduce mixing between top and bottom waters (Smol *et al*., 1983). Stronger stratification in Gilmour Bay could cause prolonged anoxic conditions in the hypolimnion.

The more anoxic conditions in the hypolimnion of Gilmour Bay also result in the greater concentrations of hypolimnetic nutrients (N and P). The epilimnetic concentrations of nutrients are similar in both Gilmour Bay and South Bay, suggesting similar inputs. However, in Gilmour Bay the hypolimnetic concentration of total nitrogen is nearly four times and the concentration of total phosphorus is nearly 13 times the epilimnetic concentrations (Table 4; Figure 8). This suggests that the increased nutrients are being released from the sediments due to the anoxic conditions (Wetzel, 2001). Neither the chlorophyll *a* values nor the Secchi disc values, both indicators of algal production, show a significant difference between the two bays. In autumn, the increased nutrients in the hypolimnion of Gilmour Bay will be released when the lake overturns; this could lead to a diatom bloom, and potentially greater production at that time.

Paleolimnology

Diatom community composition changes from the pre-industrial period to the present day indicate increased nutrients and warming temperatures. Gilmour Bay and both basins of South Bay experienced an increase in *Asterionella formosa* and *Fragilaria* complex, diatoms that favour eutrophic conditions (Reavie & Smol, 2001) and are often indicative of spring blooms (Reynolds, 1983; Reynolds, 1984). The increase in these diatoms, therefore, indicates an increase in nutrients in Gilmour Bay and South Bay from pre-industrial times to present day. A more productive system utilizes oxygen quicker and can create anoxic conditions in the hypolimnion, as observed in Gilmour Bay.

Aulacoseria ambigua is also indicative of spring blooms; however, in well stratified lakes, it is at a competitive disadvantage compared to *Asterionella formosa* and *Fragilaria* complex. *Asterionella formosa,* which forms star-shaped colonies, and the long, needle-shaped *Fragilaria* taxa, float readily, staying in the photic zone, however, *Aulacoseria ambigua* is a heavily silicified species that tends to sink below the photic zone, particularly in thermally stable lakes (Rühland *et al*., 2008). Therefore, the decrease in *Aulacoseria ambigua* may be in response to warming temperatures that result in longer ice-free periods leading to Gilmour Bay and South Bay becoming stratified earlier in the spring and becoming more intensely stratified throughout the summer. Research has shown similar changes from temperate lakes across Canada (Rühland *et al*., 2008) and the northern hemisphere (Rühland *et al.,* 2008; Smol *et al*., 2005). This research has shown that in many lakes *Cyclotella* species are increasing and *Aulacoseira* species and benthic *Fragilaria* species are decreasing in response to warming.

CONCLUSION AND RECOMMENDATIONS

The hypolimnion of Gilmour Bay is more anoxic than South Bay and as a result had elevated levels of nutrients (N and P). This is linked to elevated levels of ions related to road salt. Salinity-related variables increase the density of bottom waters and increase stratification, reducing mixing and oxygen in the deep waters. This results in an increase in nutrient concentration in the hypolimnion, leading to a greater pulse of nutrients released from the hypolimnion to the epilimnion during fall overturn. This can lead to greater algal production at overturn.

Diatom community composition changed from the pre-industrial period to present day due to warming temperatures and a longer ice-free season leading to increased thermal stratification and less mixing.

Next Steps

The “top-bottom” paleolimnology approach can only estimate water chemistry changes that have occurred between present day and pre-industrialization (~1850). This approach cannot infer trends that have occurred during the period between these two points in time. We have shown that Chandos Lake has changed from pre-industrial times to the present, and that the change can be linked to changes in stratification; however, it is unclear whether changes in stratification are linked to differences in the proximity of roads and related inputs of ions and/or warming temperatures, although the changes are related to increased nutrients. Additional research is required to investigate the period between the two points in time investigated in this study to reveal trends through time and the impacts of these activities on the lake water quality of South Bay and Gilmour Bay of Chandos Lake.

Diatom ecology in this study indicates an earlier ice-free lake. The reconstructed environmental conditions from the whole core analysis could be compared to the ice-out data available for Chandos Lake to determine the on-set and magnitude of warming and the effects warming has on stratification of South Bay and Gilmour Bay.

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APPENDICES

APPENDIX A: Laboratory procedures used to prepare lake water samples for chemical analyses (Environment Canada, 1994).

Chemical Analysis	**Laboratory Preparation**
Total Phosphorus (TP) - Unfiltered	Filled 125 ml glass bottle with lakewater. Sealed with polypropylene caps and wrapped in newspaper.
Total Phosphorus (TP) – Filtered	Filtered 125 ml of lakewater with cellulose acetate filter (4.7 cm) pore size 0.45 µm. Filled 125 ml glass bottle with filtered lakewater. Sealed bottle with electrical tape and wrapped in newspaper.
Nutrients	Filtered 125 ml of lakewater with cellulose acetate filter (4.7 cm), pore size 0.45 µm. Filled 125 ml glass bottle with filtered lakewater. Sealed bottle with electrical tape and wrapped in newspaper.
Dissolved Organic Carbon (DOC)/Dissolved Inorganic Carbon (DIC)	Filtered 125 ml of lakewater with cellulose acetate filter (4.7 cm), pore size 0.45 µm. Filled 125 ml glass bottle with filtered lakewater. Sealed bottle with electrical tape and wrapped in newspaper.
Major ions	Filled 500 ml polyethylene bottle with lakewater. Sealed with polypropylene caps and electrical tape.
Chlorophyll a (Chl-a)	Filtered 250 ml of lakewater with GF/C filters (4.7 cm). Using tweezers removed filter and place in petri dish. Sealed with electrical tape and wrapped in aluminum foil.

APPENDIX B: Diatom species and authorities for all species ≥ 1 % relative abundance and a minimum of three samples from East South Bay, West South Bay, and Gilmour Bay.

Diatom Species	**Authority**
Achnanthes minutissima	Kütz. 1833
Asterionella formosa	Hass. 1850
Aulacoseira ambigua	(Grun. in Van Heurck) Simonsen 1979
Cyclotella bodanica var. aff. lemanica	(O. Müll. ex Schröt.) Bachm. 1903
Cyclotella complex	N/A
Cyclotella michiganiana	Skvort. 1937
Cyclotella pseudostelligera	Hustedt
Cyclotella stelligera	Cleve & Grunow
Cymbella microcephala	Grun. in Van Heurck 1880
Fragilaria brevistriata	Grun. in Van Heurck 1885
Fragilaria construens var. construens	(Ehrenb.) Grun. 1862
Fragilaria construens var. venter	(Ehrenb.) Grun. in Van Heurck 1881
Fragilaria famelica	(Kütz.) Lange-Bertalot 1980
Fragilaria pinnata	Ehrenb. 1843
Fragilaria crotonensis	Kitt. 1869
Fragilaria cf. tenera	(W. Sm.) Lange-Bertalot 1980
Navicula cryptotenella	Lange-Bertalot 1985 fo. 1 PISCES
Nitzschia palea	(Kütz.) W. Sm. 1856
Stephanodiscus cf. parvus	Stoermer & Håkansson 1984
Tabellaria flocculosa	str. IIIp sensu Koppen 1975

APPENDIX C: Light micrographs of common diatoms recovered from the sediment cores of East South Bay, West South Bay, and Gilmour Bay. All micrographs are at 1000X.

1-2: *Achnanthes minutissima*
3: *Asterionella formosa*
4: *Aulacoseira ambigua*
5-6: *Cyclotella bodanica var. aff. lemanica*
7-8: *Cyclotella* complex
9-11: *Cyclotella michiganiana*
12-15: *Cyclotella pseudostelligera*
16: *Cyclotella stelligera*
17: *Cymbella microcephala*
18: *Fragilaria brevistriata*
19: *Fragilaria construens var. construens*
20: *Fragilaria construens var. venter*
21: *Fragilaria famelica*
22: *Fragilaria pinnata*
23: *Fragilaria crotonensis*
24: *Fragilaria cf. tenera*
25: *Navicula cryptotenella*
26: *Nitzschia palea*
27-28: *Stephanodiscus cf. parvus*
29: *Tabellaria flocculosa*

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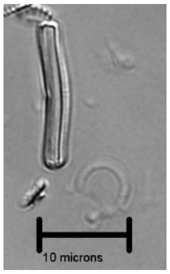

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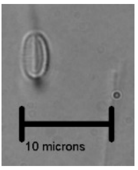

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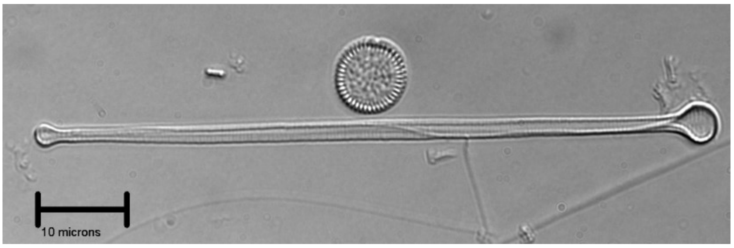

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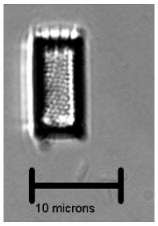

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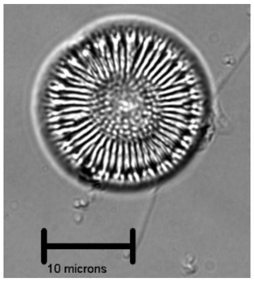

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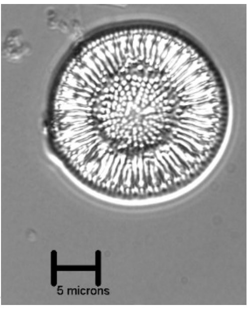

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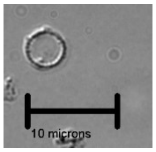

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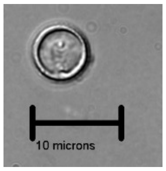

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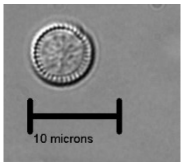

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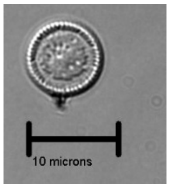

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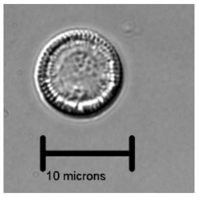

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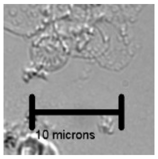

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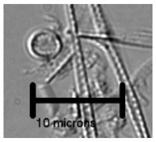

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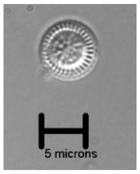

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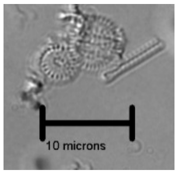

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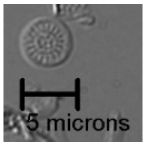

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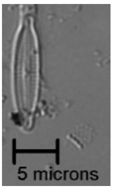

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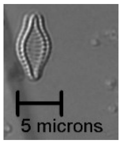

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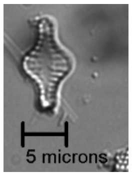

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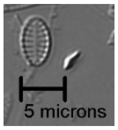

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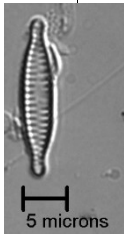

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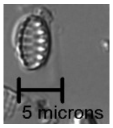

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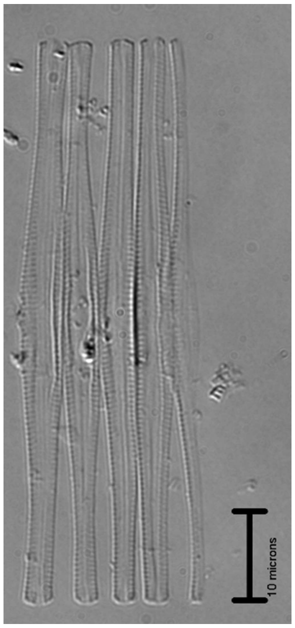

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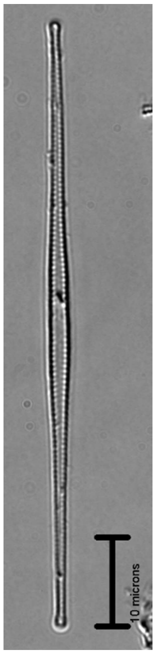

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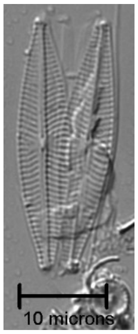

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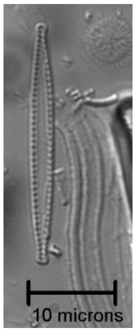

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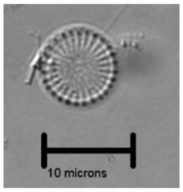

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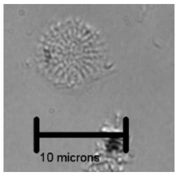

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