Reconstructing past deepwater oxygen conditions using chironomid assemblages in Peninsula Lake (ON)

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ABSTRACT

Human developments can increase nutrient inputs to lakes, increasing algal growth – a phenomenon known as “cultural eutrophication”. Upon death, the decomposition of algal matter consumes oxygen in the hypolimnion of a lake. Peninsula Lake (45° 20′N, 79° 06′W) is located in the district of Muskoka near the town of Hunstville. Since the arrival of European settlers in 1868, Peninsula Lake has been subject to excess nutrients loading starting with the initial forest clearance for farming, then the development of cottages and resorts, and improper sewage treatment. A previous analysis of historical hypolimnetic oxygen conditions between 1870 -1995 found that, despite remediation efforts, deep-water oxygen had not recovered; however, it is uncertain how the deep-water oxygen levels have changed over the past two decades. This study uses paleolimnological analyses to reconstruct deepwater oxygen conditions within Peninsula Lake relative to pre-disturbance conditions, with a focus on changes since 1995. The pre-disturbance assemblages from the late-1800’s were found to be a dominated by taxa indicating Peninsula Lake’s natural hypolimnion was rich in oxygen. Peninsula Lake was very sensitive to cultural disturbances from the initial settlers, as the chironomid assemblages are indicative of increased occurrences of deepwater anoxia from ~1927 through to ~1970, potentially due to the additions of excess nutrients from improper sewage removal and land clearance. Since 1995, the chironomid–inferred volume-weighted hypolimnetic oxygen (VWHO) values have returned to pre-disturbance values, yet the modern chironomid assemblage composition differs in the taxa present from the pre-disturbance assemblage. This study contributes to our knowledge of the lake recovery process and provides historical data on eutrophication trajectories.

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LIST OF COMMON ABBREVIATIONS

1. Volume weight hypolimnetic oxygen- VWHO
2. Anoxia Factor- AF
3. Total Phosphorus- TP
4. Constrained Incremental Sum of Squares- CONISS
5. Dissolved oxygen concentration- DOC

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INTRODUCTION

Human development and other activities have a variety of impacts on aquatic ecosystems (Smith *et al.,* 1999), including increased nutrient and organic matter inputs to surface waters that can often induce “cultural eutrophication” (Reavie *et al.,* 2000). Elevated nutrients, particularly phosphorus and nitrogen, can increase a lake’s primary production in terms of plant and algal biomass. The amount of production in a lake is often used to classify its trophic state as either oligotrophic (low production), mesotrophic (moderate production) or eutrophic (high production). Excess nutrient loading can promote algal growth (often resulting in nuisance algal blooms). Upon death, the decomposition of this algal matter consumes oxygen in the deepest layer of a stratified lake called the hypolimnion (Reavie *et al.,* 2006). Deep-water oxygen concentrations are essential to the respiratory metabolism of deep-water biota, and low levels can disruption food webs (Smith and Schindler, 2009). Long term-data are needed to assess the magnitude of anthropogenic effects on a lake’s deep-water oxygen concentrations.

Thermal Stratification

Within the past century, climate warming has increased global surface temperatures, resulting in changes to lake water temperatures and other limnological characteristics (Livingstone, 2003; IPCC, 2007). Climate warming increases the lake surface temperature affecting density, and in turn lake thermal stratification. Water has a maximum density at ~4°C, with lower densities at temperatures both above and below that temperature (Vallentyne, 1957). Due to the relationship between temperature and density, as temperate lakes warm following ice-off they can stratify into 3 thermal zones:

the epilimnion, metalimnion, and hypolimnion. The epilimnion is the low-density, surface layer, exposed to mixing by the wind. The metalimnion or thermocline is where a steep temperature gradient occurs; its depth depends on the amount of mixing by the wind and the temperature of inflowing water (Vallentyne, 1957). The hypolimnion is the coldest and deepest layer of the lake, and is isolated from the atmosphere for much of the year due to its higher density. These thermal layers act as barrier to complete mixing of the lake, impeding the distribution of nutrients and oxygen throughout the water column (MacIntyre, 1999). Most temperate lakes are dimictic, mixing twice each year, in the spring and fall (Hutchinson and Lofler, 1956). The increasing temperatures associated with climate change strengthen these thermal barriers and lengthen the period of thermal stratification, due to earlier ice-off and onset of stratification. Consequently, the longer a lake is thermally stratified increases the amount of time that the hypolimnion is isolated from the atmosphere, and the replenishment of dissolved oxygen (DO) concentrations (Foley *et al.,* 2012). A variety of lake-specific factors affect a lake's hypolimnetic DO concentration, and without long-term data, it is difficult to measure the influence of climate change on deep-water oxygen concentrations.

Paleolimnology

Paleolimnology is the study of information contained in lake sediments to reconstruct past environmental changes (Smol, 2009). Lake sediments act as a 'natural archive' with more recent sediments deposited on top of older sediments. The analysis of stratigraphic changes in certain paleolimnological indicators can allow paleolimnologists to determine the timing of changes in hypolimnetic oxygen concentrations, and in turn allowing an assessment of local and regional impacts on a given lake. Useful paleolimnological indicators for tracking historical lake water DO concentrations must be widely distributed, well-preserved in sediment, have defined oxygen optima and be taxonomically diagnostic. Past primary production of a lake can be quantified by measuring the concentration of chlorophyll-*a*, a photosynthetic pigment present in all algae and plants (Brown *et al.,* 1977). This indirect technique can aid our understanding of long-term anthropogenic impacts on lakes that lack direct historical monitoring data. Paleolimnology can help develop effective lake management plans to help lakes recover to their pre-impact states.

Chironomidae as Paleolimnological indicators

The Chironomidae are a widely dispersed family of non-biting midges that have been used extensively in paleolimnological analyses to reconstruct past deepwater lake conditions (Broderson, 2006). Non-biting midges are insects that spend the majority of their life in an aquatic larval stage, until their emergence as an adult insect (Walker *et al.,* 2001). Chironomids are a diverse group, containing taxa adapted to a variety of ecological conditions. During their early development, chironomid larvae inhabit the deeper waters of freshwater lakes, and grow through a series of molts shedding their chitinous head capsules each time. The head capsules preserve well in lake sediments and are taxonomically diagnostic, allowing their use in paleolimnological investigations of environmental change, often with a focus on deepwater oxygen levels (Broderson, 2006). The adaptations of some chironomid taxa to low oxygen conditions include higher hemoglobin concentrations in the hemolymph, resulting in an increased ability to bind oxygen under low oxygen conditions (Czegua, 1960; Weber, 1980). Many chironomid species have well-defined oxygen optima and tolerances (Broderson, 2006). Numerous mathematical models have been developed by analyzing the chironomid assemblages of lakes to quantitatively infer their relationship with deepwater oxygen conditions (Quinlan *et al.,* 1998; Quinlan, 2001; Quinlan and Smol, 2010). For example, Little et al. (2000) tracked the deep-water oxygen levels of Gravenhurst Bay (ON) by analyzing chironomid assemblages through time using a chironomid-inferred volume weighted hypolimnetic oxygen (VWHO) model (Quinlan *et al.,* 1998). The use of chironomids to infer past deep-water oxygen concentrations has proven an effective tool to help create effective lake remediation plans for lakes experiencing eutrophication (Smol, 2009).

Peninsula Lake

This study investigates the deepwater oxygen history of Peninsula Lake (45° 20′N, 79° 06′W), located in the Muskoka region of Ontario. In 1868, Peninsula Lake began experiencing excess nutrient loading initially due to forest clearing and farming, then through resort and cottage development, and improper sewage treatment (Peninsula Lake Plan, 2001). A paleolimnological analysis of a sediment core collected from Peninsula Lake in 1995 used an anoxic factor (AF) to identify three distinct periods of hypolimnetic oxygen conditions (Clerk *et al.,* 2000). The AF describes the number of summer days that the hypolimnion would have an absence of oxygen (Nürnberg, 1995). A 'pre-disturbance' period (prior to ~1870) was characterized by chironomid assemblages that indicate the lake was rich in deepwater oxygen levels with an AF below 3 $\text{days}\cdot\text{summer}^{-1}$ (Clerk et al 2000). From ~1870 to ~1960, Peninsula Lake experienced a variety of environmental impacts related to European colonization, including forest clearing for farming, the development of the Deerhurst Resort and cottages, and the subsequent periods of eutrophication from improper sewage disposal that led to a deterioration in oxygen conditions with the AF reaching a high in ~1940 of 16 days·summer^{-1} (Clerk *et al.,* 2000). Clerk et al. (2000) found that the chironomid assemblages ~1995 indicated that the hypolimnetic oxygen levels of Peninsula Lake did not recover, but the diatoms assemblages indicated that total phosphorus [TP] recovered to pre-disturbance levels. From ~1970 to ~1995, Peninsula Lakes' resorts and cottages initiated proper sewage removal protocols, perhaps leading to the observed improvements in [TP] (Clerk *et al.*, 2000). However, it remains unclear how deepwater oxygen conditions have changed since 1995. Have deepwater oxygen concentrations and chironomid assemblages continued to recover or has increased stratification from climate warming and other environmental stressors halted the recovery of deepwater oxygen conditions?

The Scope of Investigation

The objective of this study is to quantify deepwater oxygen conditions within Peninsula Lake relative to pre-disturbance conditions, with a focus on changes since 1995. This study has three specific aims:

1. Quantify chironomid assemblages and chlorophyll-*a* from Peninsula Lake from a dated sediment core, that spans the lake history from pre-disturbance (i.e. prior to 1870) through to 2014.

2. Use the sedimentary chironomid assemblages to infer trends in volume-weighted hypolimnetic oxygen (VWHO) conditions of Peninsula Lake through time.

3. Determine whether deepwater oxygen levels of the lake returned to values similar to the pre-disturbance period.

I test the hypothesis that the deepwater oxygen concentrations of Peninsula Lake have recovered to levels approximating their pre-disturbance state. If my hypothesis is not supported, the recent chironomid assemblages will not resemble those of the pre-disturbance sediment intervals, indicating that hypolimnetic oxygen conditions have not recovered, and this may be due to other factors such as climate change.

SITE DESCRIPTION

Peninsula Lake (45° 20′N, 79° 06′W) is located in the district of Muskoka, near the town of Huntsville in south-central Ontario (Figure 1). The lake has two basins (east and west) and a surface area of 853 hectares and a perimeter of 29.8 km. The drainage area is 5453 hectares and the lake is situated on nutrient-poor soils on Precambrian granite bedrock.

In 1868, the first wave of European settlers arrived to the Muskoka region, and each was given 100 acres of land for clearing and farming (Peninsula Lake Plan, 2001). However, the soils could not sustain agriculture and forestry operations, and therefore the region instead became a popular cottage and holiday destination starting in the 1870's. A canal was constructed in 1889 to increase access to Peninsula Lake by steamship for the public, allowing increased development along the shorelines of Peninsula Lake, and the opening of the Deerhurst Resort in 1896. Simply due to the lack of technological design and development of sewage systems at this time, it was difficult for cottages and resorts to properly remove their sewage without adding excess nutrients to Peninsula Lake. Today Peninsula Lake experiences extensive recreational use and is the site of over 300 cottages, 7 commercial resorts, a commercial ski hill, and a residential condominium (Peninsula Lake Plans, 2001). The Deerhurst Resort is now a year-round vacation resort with a capacity of 1000 visitors and occupies 760 waterfront acres.

Clerk et al. (2000) used paleolimnological approaches to determine that Peninsula Lake's hypolimnion was well oxygenated (AF 3 days·summer^{-1}) in the early-1800's, prior to the onset of major European settlement. After land clearance by the initial settlers, chironomid assemblages indicated a longer duration of hypolimnetic anoxia, coinciding with increases in diatom-inferred [TP] associated with cultural eutrophication (Clerk *et al.,* 2000). From ~1870 to ~1960, large declines in ultra-oligotrophic chironomid taxa infers increased in deepwater anoxia (Clerk *et al.,* 2000). By 1995, Peninsula Lake was considered oligo-mesotrophic and hypolimnetic oxygen availability was gradually increasing (Clerk *et al.,* 2000). Diatom-inferred [TP] indicates a recovery to pre-disturbance values of Peninsula Lake but the chironomid assemblage's inference AF did not yet recover and experience the same pace of recovery as [TP] (Clerk *et al.,* 2000). The District of Muskoka (2014) long-term monitoring data classified the physical and chemical characteristics of Peninsula Lake's west basin having a Secchi disk depth of ~3.5 m and a spring phosphorus of ~9.9 μg/L (Table 1). Today, the fish community of Peninsula Lake consists of cold-water species; lake trout, lake whitefish and cisco (Ministry of Natural Resources, 2010). Artificial stocking is needed to maintain lake trout populations. The deep-water oxygen status of Peninsula lake since 1995 is unclear, therefore a paleolimnological analysis is needed to reconstruct the past hypolimnetic oxygen conditions.

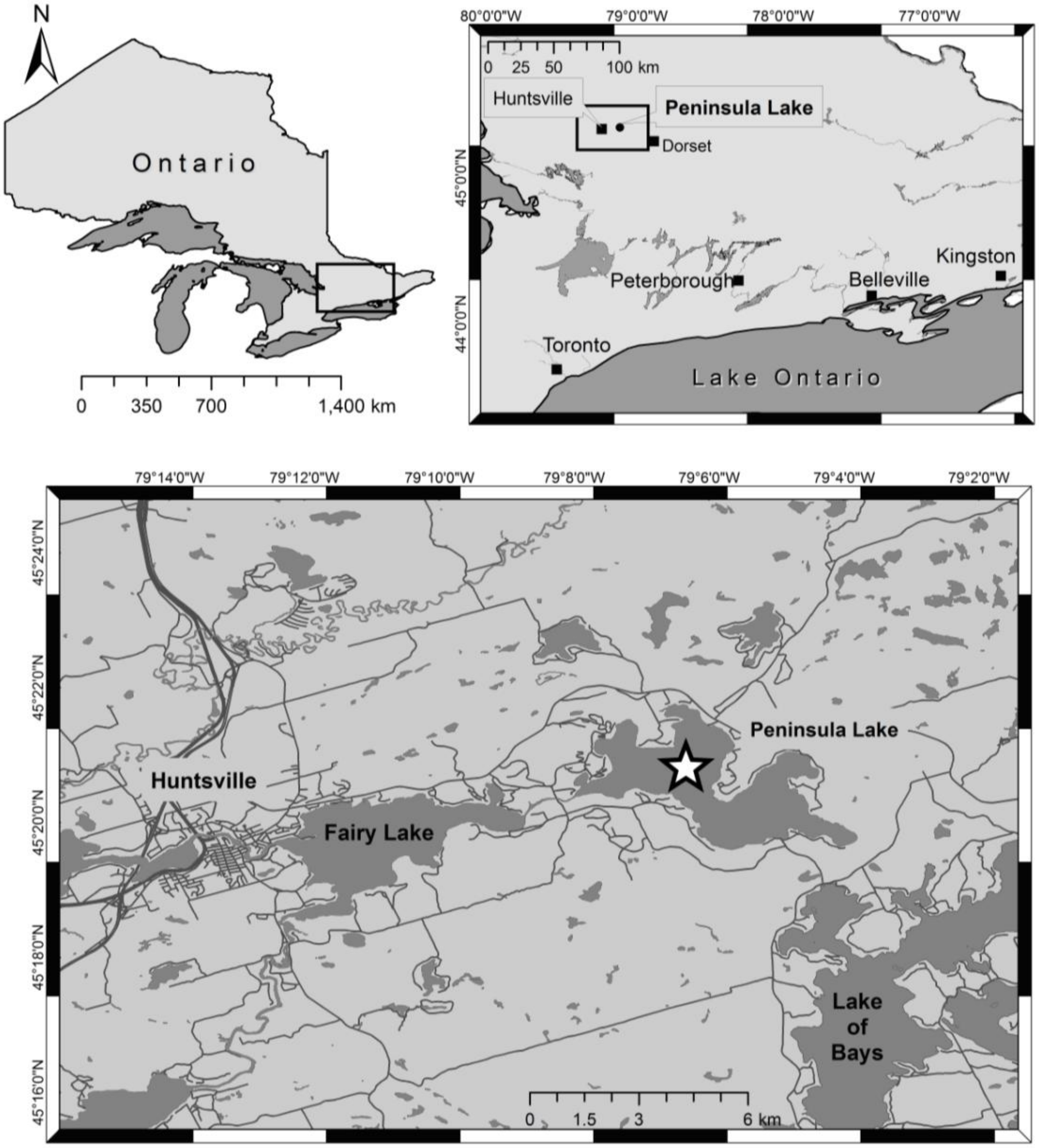

Figure 1. The location of Peninsula Lake in south-central Ontario and a map of Peninsula Lake in relation to Hunstville, including roads. A star indicates the location of the coring side in the west basin of Lake Peninsula.

Table 1. General physical and chemical characteristics of Peninsula Lake's west basin (District of Muskoka, 2014; Ministry of Natural Resources, 2010).

Location	45° 20′N, 79° 06′W
Total Volume (10^4 m^3)	8380
Perimeter (km)	29.8
Surface Area (ha)	840
Drainage Area (ha)	5453
Wetland Area	5%
Max Depth (m)	37
Phosphorus (10-year average) (μg/L)	9.9
Secchi Depth (10-year average) (m)	3.5
Lake Trout Lake?	Yes
Shoreline Development	High

MATERIALS AND METHODS

Field Methods

A sediment core was collected from the west basin of Peninsula Lake (45° 20′N, 79° 06′W) in the summer of 2014 using a Glew (1989) gravity core and extruded on shore using a Glew (1988) extruder. The core was extruded at 0.25 cm intervals from 0 to 10 cm, then at 0.5 cm intervals from 10 to 15 cm, and finally at 1 cm intervals from 15 to 27 cm. Prior to analysis, the sediments were stored in a cold room at the Paleoecological Environmental Assessment and Research Laboratory (PEARL) at Queen's University.

^{210}Pb Dating

To date the sediment, an ORTEC Gamma Counting System was used at the Paleoecological Environmental Assessment Research Laboratory (PEARL) at Queen's University. ^{210}Pb, ^{214}Bi and ^{137}Cs activities were measured using gamma spectrometry following the methods outlined in Schelske et al. (1994). Sediment samples from select intervals of the core were placed in counting tubes in a germanium counting chamber in the gamma counter. The chronology for the core was determined using the Constant Rate of Supply (CRS) model (Appleby, 2001). Additionally, ^{137}Cs activities were measured to provide an independent age marker of indicating the peak of above ground nuclear weapon testing in 1962-1963.

Chironomidae Preparation and Identification

Sediments were deflocculated by adding ~2 g of wet sediment from each interval to a 5% KOH solution and gently warmed for 20 minutes. Due to low chironomid counts in the top intervals of the core, additional dry sediment was processed and chironomid head capsules were collected and identified for samples 0-25, 0.25-0.5, 1-1.25, 2-2.25, 3-3.25 cm. Samples were then sieved through a 100-μm mesh, and ~100 head capsules were picked under a dissecting microscope and transferred to a microscope slide. Slides were mounted for species identification using Entellan, and chironomid species were identified under 400x magnification (Walker, 2001; Brooks *et al.,* 2007). Chironomid specimens were identified to the lowest taxonomic level possible (Brooks *et al.*, 2007).

Statistical Analysis

General trends among chironomid taxa were examined using a cluster analyses (constrained sum of squares (CONISS; Grimm, 1987)) to determine stratigraphic zones using the broken stick model (Bennett, 1996). The CONISS was performed using the "vegan" package within the R software environment (Oksanen et al., 2010; R Development Core Team, 2016). A volume-weighted hypolimnetic oxygen (VWHO) model was used to infer historical VWHO from the sedimentary *Chaoborus* and chironomid assemblages (Quinlan and Smol, 2010). The VWHO model was constructed using the "WA" function in the "rioja" package for the R software environment (R Development Core Team, 2016).

Chlorophyll-a

Chlorophyll-*a* concentrations were spectrally-inferred from the lake sediments to examine past production levels in Peninsula Lake. Freeze-dried sediment from each interval was sieved through a 125 µm mesh onto weight paper. Sediment was transferred to a glass vial, covering the bottom with ~2 mm of sediment. A Visible Near-Infrared Spectroscometer (NIRS) analyzed the sediment reflectance spectra of each interval to determine chlorophyll-*a* concentrations (Michelutti *et al.,* 2010). The correlation between the absorption of the NIRS output and chlorophyll-*a* concentrations is linear; therefore the area under the 650-700 nm peak of a wavelength-absorbance plot indicates the chlorophyll-*a* concentration (Michelutti *et al.,* 2010).

RESULTS

^{210}Pb Dating

The unsupported ^{210}Pb activity and respective constant rate of supply (CRS) sediment depths for the collected core of Peninsula Lake, with an initial date of sedimentation of 1927 at the depth of 16.75 cm (Figure 2; Table 2).

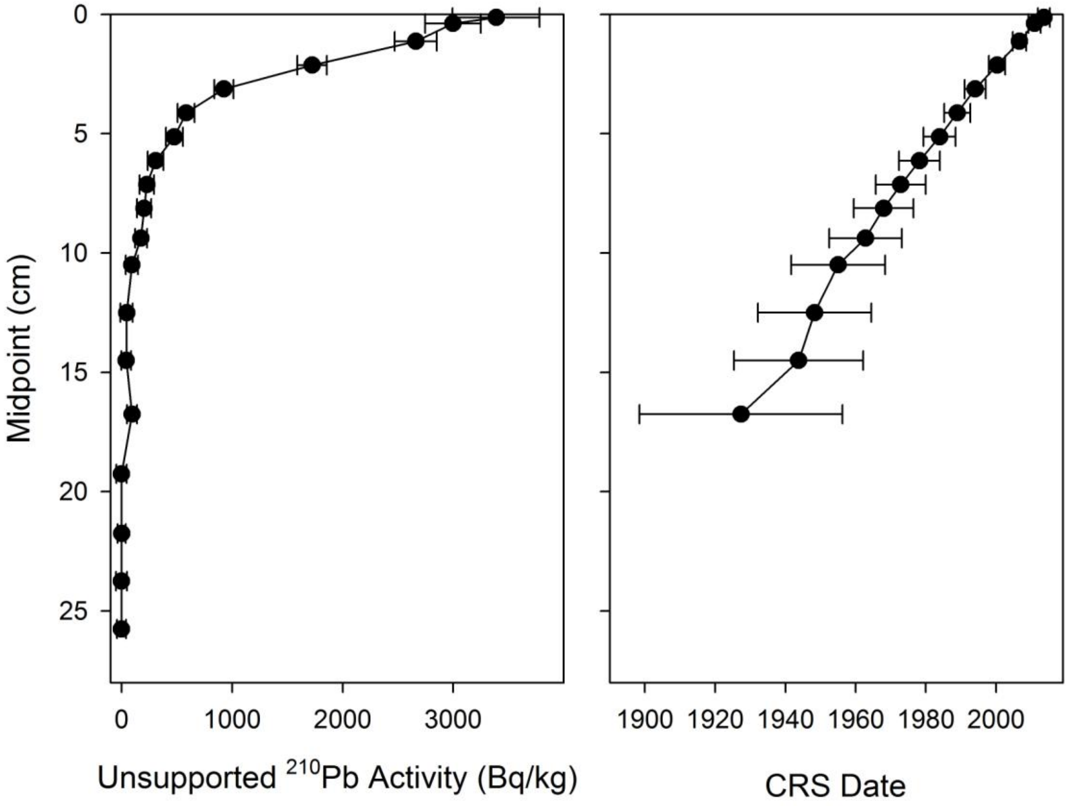

Figure 2. The unsupported ^{210}Pb Activity in relation to the midpoint depths in Peninsula Lake on the left. The Constant Rate of Supply (CRS) date with error bars of sedimentation in Peninsula Lake on the right.

Table 2. Midpoint depths of sediment core intervals and corresponding age according to ^{210}Pb dating.

Midpoint Depth (cm)	**YEAR**
0.125	~2013
0.375	~2010
1.125	~2006
2.125	~2000
3.125	~1994
4.125	~1988
5.125	~1983
6.125	~1978
7.125	~1972
8.125	~1967
9.375	~1962
10.5	~1955
12.5	~1948
14.5	~1944
16.75	~1927

Chlorophyll-a

Sedimentary-inferred chlorophyll-*a* (VRS Chl-*a*) remained constant at ~0.015 mg/g dry mass from prior to ~1927 through to ~1970 (Figure 4). From ~1970 to ~2014, there is a marked increase in lake primary production reaching a maximum ~0.07 mg/g dry mass.

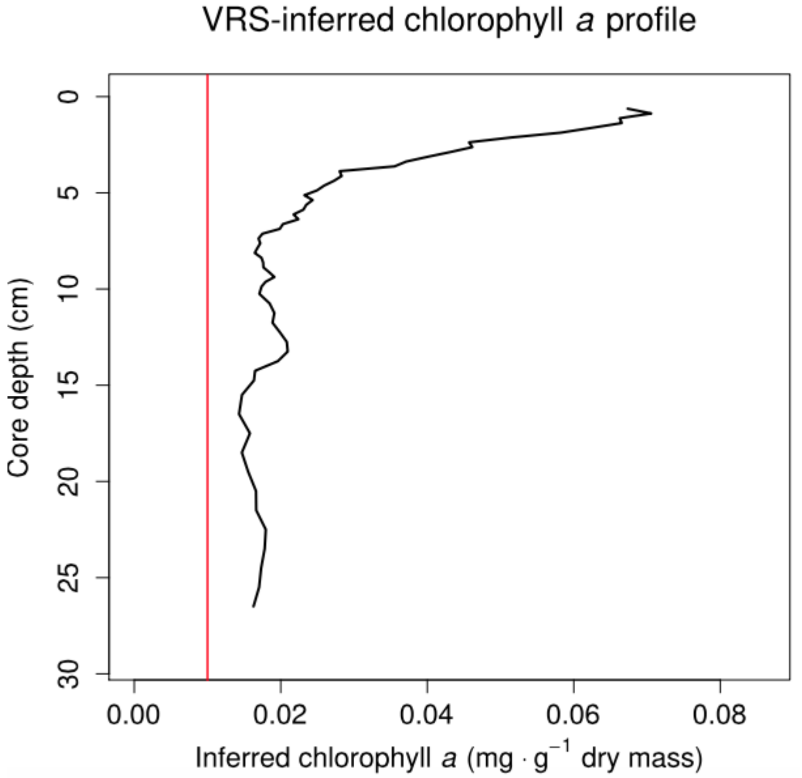

Figure 3. Measured chlorophyll-*a* (mg/g dry mass) over the length of the analyzed sediment core in Peninsula Lake. The red line indicated the detection limit of 0.01 for VRS.

Chironomid Assemblage Analysis

A total of 38 chironomid taxa were identified in the 21 analyzed intervals from the Peninsula Lake core. For clarity of display, the stratigraphy only displays the 18 taxa with relative abundances greater than 3% in 2 sediment intervals (Figure 3). Due to low chironomid counts, intervals 0-0.25 and 0.25-0.5, were combined. Chironomid taxa present in high relative abundances ranging from 10 to 40% throughout the core included *Heterotrissocladius* and *Microspectra insignilobus*-type *and Tanytarsus* spp. The high AF littoral taxa *Tanytarsus* spp. was overall the taxa with the greatest relative abundance throughout the core ranging from 10 to 40% (Quinlan and Smol, 2001b). The large relative abundance of *Tanytarsus* spp. throughout the core could be due to the recovered chironomid head capsules were damaged and lost their mandibles, precluding further classification.

The cluster analysis (CONISS) identified a zonation at a sediment depth of ~7.5 cm corresponding with the year ~1970 (Figure 3). Prior to ~1920, the assemblages were composed primarily of *Heterotrissocladius* and *Microspectra insignilobus*-type*,* *Tanytarsus* spp. and *Parakeifferiella nigra*-type with relative abundances ranging from 5 to 35% relative abundance. From ~1927 to ~1945, an increase in the variety of taxa was observed and a decrease of ~5-10% in the relative abundance of the species *Heterotrissocladius* and *Microspectra insignilobus*-type *and Tanytarsus* spp. These taxa present from ~1927 to ~1945 include; *Chironomini, Dicrotendipes, Endochironomous, Microtendipes, Polypedilum, Corynoneura, Cricotopus, Heterotrissocladius, Procladius, Microspectra and Tanytarsus.* From ~1970 to ~2014 (above the zonation line), there was a 20% increase in the relative abundance of *Procladius*. Additionally, there is an increase in ~25% relative abundance in *Sergentia* in ~1994.

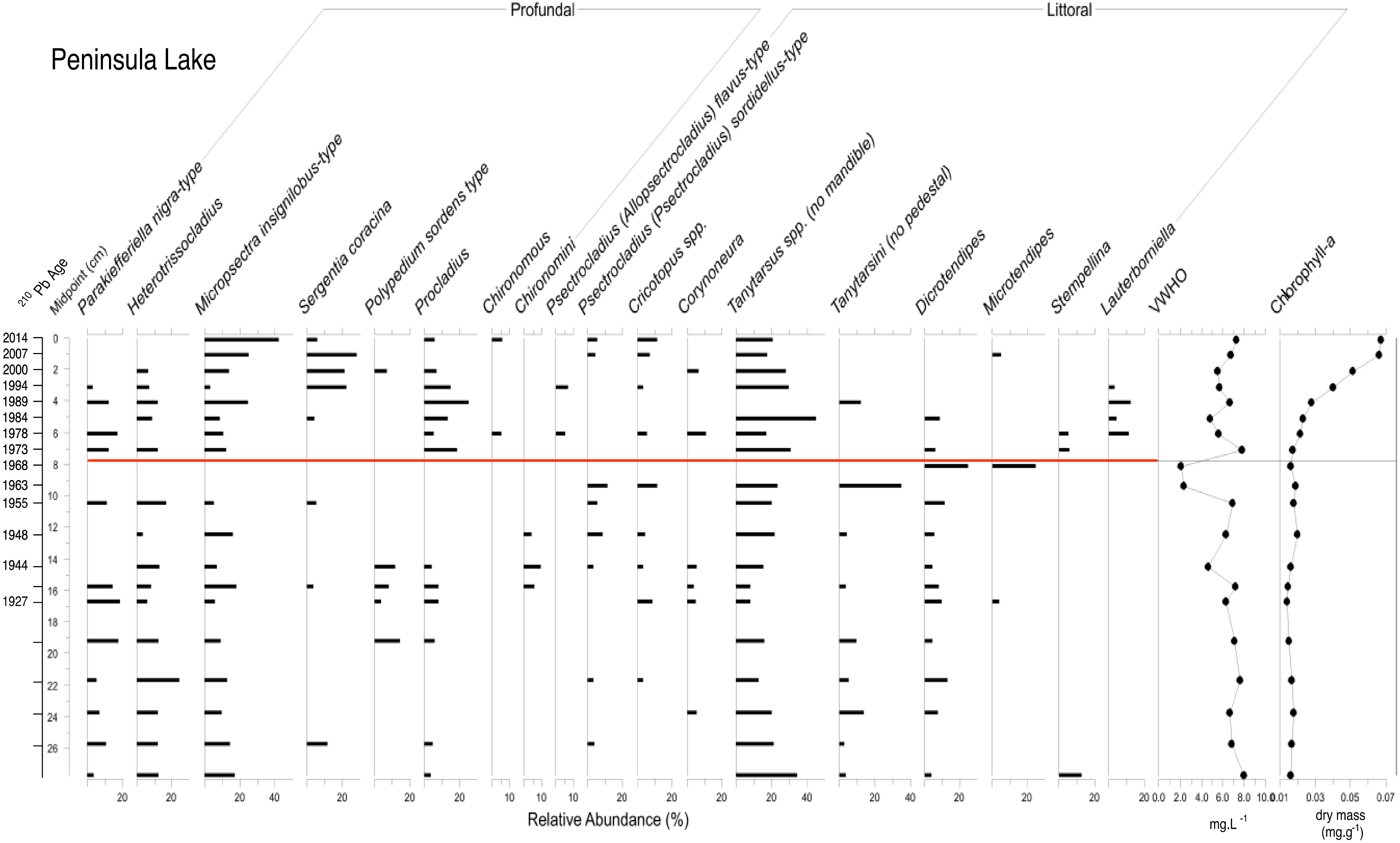

Figure 4. A stratigraphy of the relative abundances of profundal and littoral major chironomid taxa and VWHO recorded in Peninsula Lake. Measured chlorophyll-*a* is on the left of the profile and ^{210}Pb dates are on the right of the profile with corresponding intervals. The red line denotes the most significant clustering in chironomid assemblages by a cluster analysis (CONISS).

DISCUSSION

The chironomid-inferred VWHO from the Peninsula Lake sediment core provided an assessment of the trends in deepwater oxygen conditions within Peninsula Lake relative to pre-disturbance conditions, with a focus on changes since 1995 (Figure 4). Two main zones in the sedimentary chironomid assemblages of Peninsula Lake were identified, from the late-1800's through to ~1970 and from ~1970 through to the present. The most recent assemblages (from ~1995 to 2014) suggest a third zone of recovery in VWHO to pre-disturbance levels.

The pre-disturbance assemblages from the late-1800's through to 1970 are dominated by taxa that suggest Peninsula Lake's natural hypolimnion was rich in oxygen. The relative abundances of the chironomid assemblages found prior to 1927 should be interpreted with caution due low chironomid count (44 headcount) in the 26-27 interval (Appendix 2). Increased sample size is needed to increase the power of the statistical analysis and to reach the minimum 50 head capsule abundances for chironomid inference model (Quinlan and Smol, 2001a). In the late-1800's, when European settlement and development began, Peninsula Lake still had a well-oxygenated hypolimnion indicated by species with low AF optima (e.g. *Micropsectra insignilobus*-type, *Heterotrissocladius*, *Parakeifferiella nigra*-type, *Stempellina*). The VWHO model indicates that the pre-disturbance hypolimnion was rich in oxygen (8 mg/L). However, it is unclear whether the 2014 Peninsula Lake sediment core extends back to 1870, when European settlement first took place in the vicinity of the lake, as only two zones were identified in contrast with the pre-disturbance period, impacted period and recovery period identified by Clerk et al.

(2000). The pre-disturbance state was dominated by low AF profundal taxa that are indicative of well-oxygenated waters (e.g. *Heterotrissocladius*, *Parakeifferiella nigra-type*, and *Micropsectra insignilobus*-type; Clerk *et al*., 2000).

Peninsula Lake was very sensitive to the effects of land clearance for farming, logging and resort and cottage development, from the initial settlers. The chironomid assemblages are indicative of increased occurrence and longer duration of deepwater anoxia occurred from prior to ~1927 through to ~1970, which may be due to the elevated nutrients added to the lake from improper sewage removal and land clearance. The profundal and littoral chironomid assemblages prior to ~1970 showed changes in their relative abundances indicative of increased periods of anoxia. Chironomid assemblages from ~1927 to ~1970 in the profundal zone showed increase in relative abundance of high AF taxa (e.g. *Procladius*, *Sergentia coracina*), which is indicative of increased periods of anoxia. Additionally, the chironomid assemblages in the littoral zone showed a shift to greater relative abundances of littoral taxa with high AF (e.g. *Dicrotendipes*, *Cricotopus*, *Psectrocladius sordidellus*-type). Littoral taxa do not directly infer hypolimnetic oxygen levels but increased relative abundances of littoral taxa can suggest increased periods of anoxia as littoral zones are still rich in oxygen even with eutrophication (Walker *et al.,* 1993; Clerk *et al.*, 2000). In addition, increased macrophyte growth from increased primary production may provide littoral species with more areas of shelter and refuge. The VWHO model also shows similar decreasing trends, with the lowest VWHO value was 2 mg/L, corresponding with the year ~1968, coinciding with the 25% increase in relative of high AF littoral taxa (e.g. *Dicrotendipes* and

Microtendipes) and decrease in low AF profundal taxa (*Heterotrissocladius* and *Microspectra-insignilobus*-type). Similar to the findings of Clerk et al. (2000), from ~1945 to ~1970 there was a decrease in the number of profundal taxa and increased relative abundances of littoral taxa, which may suggest increased productivity in the lake.

In the mid-1960's Peninsula Lake began implementing proper sewage removal treatments to reduce excess nutrient loading. From ~1960 to ~1970, a large increase in VWHO to 8 mg/L occurred, due to increases of low AF taxa (*Parakiefferialla nigra*-type, *Heterotrissocladius* and *Micropsectra insignilobus*-type). The VWHO then indicates a decrease in deepwater oxygen to 4.5 mg/L from 8 mg/L - this may be due to a large increase in littoral taxa and the emergence of high AF profundal taxa (e.g. *Procladius*) that may be indicative of increased primary production in Peninsula lake that is corroborated by the chlorophyll-*a* increase after ~1970 (Figure 4). Clerk et al. (2000) reported that chironomid assemblages from ~1960 to ~1995 infer increased trend in deepwater oxygen availability. Clerk et al. (2000) postulated that these findings might indicate that chironomid assemblage composition may lag behind oxygen improvements due to factors such as climate change and food-web composition changes (Carpenter, 1988).

The deep-water oxygen concentrations in Peninsula Lake have recovered to pre-disturbance values since 1995; however, the present-day assemblage taxa composition differs from the pre-disturbance assemblage (Figure 4). Large VWHO values (~8 mg/L) and chironomid assemblages containing high relative abundances of low AF profundal taxa (e.g. *Micropsectra insignilobus*-type and *Sergentia coracina*), indicate a recent recovery in deep-water oxygen levels. The VWHO results from ~1995 to 2014 should be interpreted with caution due to a low number of recovered chironomid head capsules (Appendix 2). Additionally, the VWHO values may be overestimates, as a consequence of climate change in the south-central Ontario region. Increased air temperatures cause the surface waters to heat up quickly, causing the longevity and strength of the thermal stratification of a lake to increase, resulting in decreased volume in the epilimnion and increased volume in the hypolimnion (Cahill *et al.,* 2005; Palmer *et al.,* 2014). Additionally, the dissolved organic carbon (DOC) in Peninsula Lake may have increased, as seen in lakes in the region of Dorset Ontario (Palmer *et al.,* 2014). As DOC increases the temperature of surface waters increases more quickly, causing the epilimnion to decrease in volume and the hypolimnion to increase volume, potentially causing the increase in recent VWHO values (Cahill *et al.,* 2005; Palmer *et al.,* 2014). From ~1995 to ~2014, chlorophyll-*a* continued to increase to 0.07 mg/g (Figure 4). Increased primary production of lakes may be consequential of climate change and longer ice-free seasons of lakes. This climate change driven trend of increased chlorophyll-*a*, as well, can be found in other lakes in south-central Ontario (Palmer *et al.,* 2014).

Comparison with monitoring records

The Ministry of Natural Resources (MNR) measured the VWHO of the east and west basin of Peninsula Lake from 1990 to 2014 (Appendix 1). The VWHO of the east basin was measured at a depth of 25 m and depth for the west basin was 37 m. Since 1990, the two basins show a large difference in measured VWHO, values in the west basin have increased to pre-disturbance VWHO levels of around ~8 mg/L, while the east basin VWHO still has very poor oxygen levels ranging from 0- 2.5 mg/L. Although different, the VWHO in the west basin could be overestimates, if they were taken too early in the fall season, since more VWHO would be present. Additionally, the monitoring records by MNR could have been taken at depths above the true bottom depth of Peninsula Lake; therefore VWHO readings could have been overestimates. The low measured VWHO in the east basin could be due to the shallower depth being more affected by climate change or increased lake production. This may have severe implications for the deep-water biota of Peninsula Lake that can only survive in high deepwater oxygen concentrations (e.g. lake trout). If the east basin measured VWHO is poor, these deep waters biota only have the west basin for refuge.

Shortcomings/ study limitations

There are many potential limitations of this paleolimnological analysis of Peninsula Lake. Firstly, the number of chironomid head capsules for many intervals throughout the core did not reach the target count of 50 (Appendix 2). In the top intervals of the core, none exceeded the minimal statistically valid number of head capsules, therefore any assessment of the recent recovery of Peninsula Lake is uncertain. A potential problem that may have occurred is associated with the procedure of picking chironomid head capsules. A bias towards easily retrievable and identifiable chironomid species could have arose, therefore not a true representation of the chironomid assemblages could have been found at the time of sedimentation. Lastly, it may be difficult to disentangle anthropogenic impacts from climate and other environmental stressors on deep-water concentrations in Peninsula Lake (Smol, 2010). I suggest a multi-proxy approach to help mitigate this problem and currently there is ongoing research doing so.

Conclusions

Pre-disturbance assemblages are dominated by taxa that suggest Peninsula Lake's hypolimnion was rich in oxygen. Relative to the pre-disturbance assemblages, the assemblages from ~1995 to 2014 indicate a recovery of hypolimnetic oxygen in Peninsula Lake. In addition, chlorophyll-*a* concentrations have increased substantially since 1995; this trend is similar to other lakes found in south-central Ontario that experience longer ice-free seasons. Further investigation is needed to assess how climate change and other environmental factors have affected the recovery of hypolimnetic oxygen concentrations in Peninsula Lake.

Environmental Significance

This study provides information necessary for the evaluation of the effectiveness of lake remediation in regions experiencing multiple environmental stressors as well, information on historical eutrophication incidents on boreal lakes. This study will also allow the District Municipality of Muskoka to update their water quality records of their lake monitoring programs. Since the results indicate a recovery in the deep-water oxygen level of Peninsula Lake after its history of eutrophication, this study provides insight into the nature of the lake's recovery progress. Recognizing the impact of development and nutrient enrichment on deepwater oxygen availability in Ontario lakes is fundamental to the creation of effective lake management and restoration strategies.

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SUMMARY

1. The pre-disturbance assemblages of Peninsula Lake infer that the natural hypolimnion was rich in oxygen, in agreement with the findings from Clerk et al. (2000). Chironomid assemblage's contained species with low AF optima and the VWHO model indicated the pre-disturbance hypolimnion was rich in oxygen (8 mg/L).
2. The chironomid assemblages and VWHO model show that Peninsula Lake was very sensitive to the activities from initial settlers that included clear-cutting surrounding forest for faming, logging and resort and cottage development. The chironomid assemblages are indicative of increased occurrence and longer duration of deepwater anoxia occurred from ~1927 through to ~1970. Chironomid assemblages in the profundal zone showed increase in relative abundance of high AF taxa and littoral taxa shifted to greater relative abundances of littoral taxa with high AF.
3. Since 1995, the chironomid–inferred VWHO values have recovered to pre-disturbance values. Chironomid assemblages infer a recovery of oxygen; however, assemblage taxa composition has not returned to the pre-disturbance assemblage. This period showed a shift to increased relative abundances of low AF profundal taxa and the VWHO from showed an increasing trend to the pre-disturbance value of ~8 mg/L.

APPENDIX 1

This appendix contains the VWHO data from 1990 to 2014 of the west and east basin of Peninsula Lake, collected by the Ministry of Natural Resources.

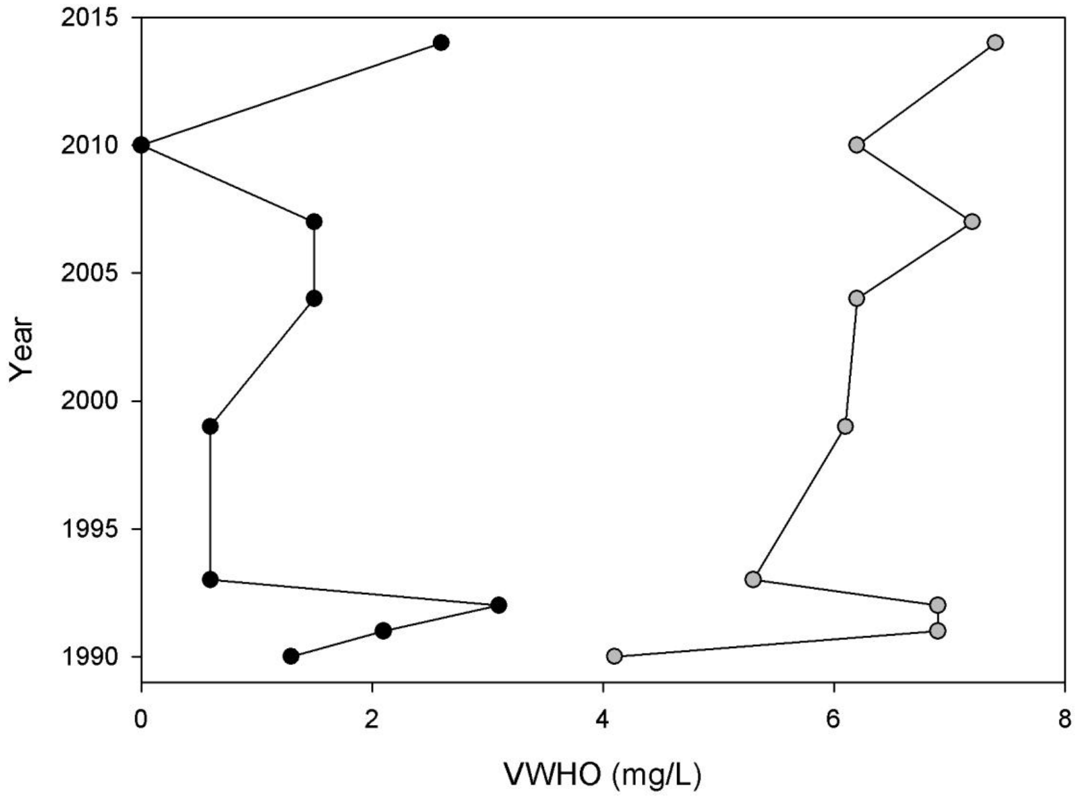

Figure A.1 The measured VWHO data from Ministry of Natural Resources of the East Basin (black) and West Basin (grey) of Peninsula Lake, Ontario.

APPENDIX 2

This appendix includes the raw chironomid taxa counts for of the core collected from Peninsula Lake. It also includes the ^{210}Pb age, the interval and interval midpoint.

Table A.2 Peninsula Lake raw chironomid taxa combined counts and ^{210}Pb dating for select intervals throughout the core.

Interval	0.0-0.5	1.0-1.25	2-2.25	3.0-3.25	4.0-4.25	5.0-5.25	6.0-6.25	7.0-7.25	8.0-8.25	9.25-9.5	10.25-10.75	12.25-12.75	14.25-14.75	15.25-16.25	16.25-17.25	18.25-20.25	21.25-22.25	23.25-24.25	25.25-26.25	27.25-28.25
Midpt	0.125	1.125	2.125	3.125	4.125	5.125	6.125	7.125	8.125	9.375	10.5	12.5	14.5	15.75	16.75	19.25	21.75	23.75	25.75	27.75
Age	2013.58	2006.65	2000.23	1994.02	1988.93	1983.88	1978.14	1972.87	1967.95	1962.8	1955.04	1948.33	1943.78		1927.35					
Chironomini											2	4	8	3	2				2	
Chironomous	2	2					2					2						2		
Dicrotendipes						4		2	2		8	5	4	4	10	3	14	8	2	2
Enchochironomus sp.											2		2	2			2	2		
Microtendipes		4							2						4				2	
Parachironomus varus-type						2														
Polypedium sordens type			2									2	10	4	4	9		2	4	
Sergentia coracina	2	22	6	12		2					4			2			2		18	
Strictochironomus sp.												2								
Corynoneura			2				4				2	2	5	2	5			6	4	
Cricotopus spp.	4	6		2			2			2		4	3		9		4	2	4	
Heterotrissocladius		2	2	4	2	4		4			12	3	11	4	6	8	26	12	18	6
Hydrobaenus conformis-type															2		2			
Orthocladius oliveri-type													2							
Parakiefferiella sp.												4								
Parakiefferiella bathophilia-type																				2
Parakiefferiella nigra-type				2	2		6	4			8	2		7	18	11	6	7	16	2
Psectrocladius flavus-type				4			2													
Psectrocladius calcaratus-type										2										
Psectrocladius sordidellus-type	2	4								2	4	8	3				4	2	6	
Pseudosmittia													2							
Pseudorthocladius												1								
Stilocladius															2		2	4		
Synorthocladius												2			2		2			
Procladius	2	2	2	8	4	6	2	6			2	2	4	4	8	4	2	2	8	2
Cladotanytarsus mancus-type 2									2											
Micropsectra contracta-type												2								
Micropsectra insignilobus-type	14	20	4	2	4	4	4	4			4	14	6	9	6	6	14	10	22	8
Micropsectra pallidula-type																2				
Paratanytarsus spp.									2											
Stempellina							2	2			2	1	2		2		2	2		6
Stempellina-Zavrelia																				
Tanytarsini (no pedestal)					2					6	2	4		2		6	6	14	5	2
Tanytarsus spp. (no mandible)	7	14	8	16		20	6	10		4	14	19	13	4	8	10	14	20	32	16
Protanypus		2																		
Lauterborniella?				2	2	2	4													
Cryptotendipes?													2		2					
Heterotanytarsus?													3							
Tventia-bavarica																	2			
C. sayomia mandible			2	1			1			1	3	2	2	1	6	2	2	2	4	
Total	33	78	28	53	16	44	35	32	8	17	69	85	82	48	96	61	106	97	147	46