Hutchinson

Environmental Sciences Ltd.

Nepahwin Lake Causation Study

Prepared for: City of Greater Sudbury
Job #: J190070

July 10, 2020

Final

July 10, 2020 HESL Job #: J190070

Stephen Monet
Manager - Environmental Planning Initiatives
City of Greater Sudbury
200 Brady Street
Sudbury, ON P3A 5P3

Dear Mr. Monet:

Re: Nepahwin Lake Causation Study

Elevated total phosphorus (TP) concentrations measured in Nepahwin Lake in 2017 (20.4 µg/L) and 2018 (19.7 µg/L) triggered the need for the Nepahwin Lake Causation Study. Hutchinson Environmental Sciences Ltd. (HESL) was retained by the City to complete the Causation Study and used a phased approach to examine the potential cause(s) of elevated phosphorus concentrations that included background review, field investigation and investigation of potential causal factors.

Total phosphorus concentrations have been increasing in Nepahwin Lake since 1978 and reached 20 µg/L in recent years. Phosphorus concentrations in lakes are controlled by a multitude of biotic and abiotic conditions and Nepahwin Lake and its watershed are changing as a result of recovery from smelting activities and ongoing climate change. Nepahwin Lake also undergoes hypolimnetic anoxia and resultant internal loading but their role in the lake enrichment cannot be assessed with existing information. Although there are many interacting influences and TP has increased in tandem with DOC, it is not clear what has driven increased DOC or TP concentrations. The most likely reason for enriched phosphorus, as determined by review of the City of Greater Sudbury Water Quality Model (HESL 2014a) and the history and characteristics of the watershed (Hall 1996), is urban runoff. Runoff from urban areas is reflected in the observations of increased chloride concentrations - phosphorus enrichment would come from the same pathway.

Sincerely,
Per. Hutchinson Environmental Sciences Ltd.

Brent Parsons, M.Sc.
Senior Aquatic Scientist

Signatures

Report Prepared by:

Brent Parsons, M.Sc.
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Neil Hutchinson, PhD.
President

Executive Summary

Total phosphorus (TP) concentrations of 20.4 µg/L and 19.7 µg/L were measured in Nepahwin Lake in 2017 and 2018, respectively. These represent a substantial increase from the average value of 12.3 µg/L measured from 2001-2012 (HESL 2014a). The City of Greater Sudbury Official Plan (OP) policies (City of Greater Sudbury, 2019) therefore categorized the lake as "Enhanced Management 1" because the "Lake has a measured total phosphorus (TP) value in at least one (1) of the five (5) most recent sampling years that exceeds 20 micrograms per litre" and a statistically significant increasing trend in total phosphorus, which triggered the need for the Nepahwin Lake Causation Study. The Causation Study was completed to determine the source of TP enrichment in accordance with the City of Greater Sudbury Official Plan policies.

Hutchinson Environmental Sciences Ltd. (HESL) was retained by the City to complete the Causation Study and used a phased approach to determine the cause of elevated phosphorus concentrations that focused on completion of 3 key tasks:

1) Review of existing water quality data,
2) Completion of a site investigation and water quality sampling, and
3) Investigation of potential causal factors.

Data were assembled through background review and field investigation and interpreted with regard to TP. The following existing conditions are noteworthy regarding the causation study:

- Spring overturn phosphorus concentrations in Nepahwin Lake have been rising on a statistically significant trend since 1978. During this period there has been substantial changes in the watershed from urban growth, recovery from smelting activities, a changing climate and invasive species introductions.
- Deep water dissolved oxygen concentrations near zero are prevalent in Nepahwin Lake and concentrations below ~7m of water depth have declined between 1986 and recent years.
- Dissolved Organic Carbon concentrations showed a statistically significant increasing trend between 1990 and 2012.
- Dissolved Organic Carbon and mean ice-free TP concentrations both showed statistically significant increasing trends from 2006 - 2012.
- The elevated TP concentration of 20.4 µg/L in 2017 was based on duplicate samples collected from only one site. Samples were, however, collected from 3 sites in 2018 and the average concentration remained elevated at 19.7 µg/L. The lower value of 14.7 measured by HESL in September 2019 is not representative of the trend in the lake as TP concentrations decline over the summer from high values at spring overturn.

- TP concentrations were substantially higher in May than at other monitoring periods indicating that spring overturn concentrations overestimate average concentrations for the ice-free period.

- TP concentrations were much higher in the bottom waters than near surface, and bottom water anoxia is evident at multiple sites, so internal loading from sediments in Nepahwin Lake is a source of nutrients.

- Orthophosphate concentrations were below the detection limit indicating that a small proportion of the TP is available for biological uptake.

- Secchi disk depths were lowest in May and October, likely as a result of spring freshet or fall algal production. Low Secchi disk depths could indicate elevated total suspended solid concentrations and be driving elevated TP concentrations in May.

- Chloride concentrations are elevated to concentrations that could be impacting zooplankton assemblages.

- Cyanobacteria (blue-green algae) assemblages were low on September 12, 2019.

- *E. coli* concentrations (2014 - 2019) indicate that recreational water quality is acceptable in Nepahwin Lake and unrelated to elevated TP concentrations in 2017 and 2018.

Phosphorus concentrations in lakes are controlled by a multitude of biotic and abiotic conditions and Nepahwin Lake and its watershed are changing as a result of recovery from smelting activities and ongoing climate change. Nepahwin Lake also undergoes hypolimnetic anoxia and resultant internal loading but their role in the lake enrichment cannot be assessed with existing information. Although there are many interacting influences and TP has increased in tandem with DOC, it is not clear what has driven increased DOC or TP concentrations. The most likely reason for enriched phosphorus, as determined by review of the City of Sudbury Water Quality Model (HESL 2014a) and the history and characteristics of the watershed (Hall 1996), is urban runoff. Runoff from urban areas is reflected in the observations of increased chloride concentrations - phosphorus enrichment would come from the same pathway.

Concentrations of TP and chloride are elevated in Nepahwin Lake despite the development and implementation of the Lawn Fertilizer By-Law and the Salt Management Plan. It appears that the likely cause of increased TP and chloride concentrations is urban runoff so additional management options should be developed and implemented based on input from City staff, Nepahwin Lake Stewardship Group, and local scientists with local experience and knowledge of Nepahwin Lake and it's watershed (e.g. Dr. John Gunn). We have identified the following preliminary management recommendations for consideration by such a working group:

1. Identify major stormwater inputs into Nepahwin Lake and associated treatment infrastructure. Explore the potential to retrofit or improve stormwater management infrastructure to reduce nutrient loading to Nepahwin Lake. Calculate TP reductions associated with infrastructure improvements using a Phosphorus Budget Tool such as that developed by HESL for application in the Lake Simcoe Watershed (HESL, 2012) or for use in phosphorus-sensitive watersheds (HESL, 2014b).

Reductions could then be input into the City of Greater Sudbury Water Quality Model (HESL 2014a) to model the impact of TP load reductions on TP concentrations in Nepahwin Lake.

2. Review the age and functionality of sanitary sewers in the Nepahwin Lake watershed which could be leaking and contributing nutrients to the Lake.

3. Review existing shoreline development and associated Best Management Practices (e.g. shoreline buffers). Encourage stewardship through education and potentially enforcement in relation to relevant Official Plan Policies (e.g. Vegetative Buffers - 8.4.7).

4. Complete a phosphorus budget to quantity loadings from major sources

In order to best monitor the situation moving forward we recommend the following:

1. Collect annual spring-overturn samples for TP and DOC and record Secchi disk depths to continue to allow for an assessment of long-term trends.

2. Collect monthly TP samples and Secchi disk depths during the ice-free period to better understand dynamics in the lake over time.

3. Collect dissolved oxygen data throughout the water column during late summer (August 15 to September 15) to track changes in deep water anoxia over time and collect samples at one metre off bottom for TP and iron to assess internal load.

4. Calculate lake contour volumes so that late summer mean volume weighted hypolimnetic dissolved oxygen (MVWHDO) can be calculated and used as a simple metric of lake oxygen status moving forward.

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1. Introduction

Nepahwin Lake has a surface area of 126 ha, shoreline perimeter of 9.9 km, a maximum depth of 22 m and a mean depth of 8.3 m (Figure 1; Hallman, 1996; MNRF, 2020). It is located in the south end area of Sudbury and has a 744 ha watershed which encompasses residential, commercial and industrial areas, two upstream lakes (Still and Bennett), the Idylwylde Golf and Country Club and trails at Laurentian University (Figure 2). Nepahwin Lake receives stormwater inputs from urban areas of Sudbury at a variety of locations as described by Hallman (1996; Figure 3).

Measurements of Total Phosphorus (TP) made during spring overturn in Nepahwin Lake averaged 12.3 +/- 2.8 µg/L from 2001-2012 (HESL 2014a). Total phosphorus (TP) concentrations of 20.4 µg/L and 19.7 µg/L, however, were measured in 2017 and 2018, respectively. The City of Greater Sudbury Official Plan (OP) policies (City of Greater Sudbury, 2019)[1] therefore categorized the lake as “Enhanced Management 1” because the “Lake has a measured total phosphorus (TP) value in at least one (1) of the five (5) most recent sampling years that exceeds 20 micrograms per litre” and a statistically significant increase in total phosphorus, which triggered the Nepahwin Lake Causation Study[2]. The Causation Study was completed to determine the source of TP enrichment in accordance with the City of Greater Sudbury Official Plan policies: “the City will undertake a causal study on individual lakes to determine the source of the phosphorus enrichment unless the source is already established” (City of Greater Sudbury, 2019).

Hutchinson Environmental Sciences Ltd. (HESL) was retained by the City to complete the Causation Study and used a phased approach to determine the cause of elevated phosphorus concentrations that focused on completion of 3 key tasks:

1) Review of existing water quality data,

2) Completion of a site investigation and water quality sampling, and

3) Investigation of potential causal factors.

The following sections summarize our approach and findings based on completion of the 3 tasks.

[1] *Lakes that have been categorized as Enhanced Management 1 must satisfy at least one of the following conditions: a. Lake exceeds the Interim Provincial Water Quality Objective for total phosphorus concentration by meeting both the following criteria: i. Lake has a measured, 10-year mean for total phosphorus (TP) that exceeds 20 micrograms per litre or if less than 10 years of data are available then mean TP exceeds 20 micrograms per litre for at least the five (5) most recent sampling years; and ii. Lake has a measured total phosphorus (TP) value in at least one (1) of the five (5) most recent sampling years that exceeds 20 micrograms per litre. b. Lake has a statistically significant increasing trend in total phosphorus concentrations based on a method established by the City of Greater Sudbury.*

[2] *The analysis completed in this report shows that that the lake is also considered as “Enhanced Management” because of the “statistically significant increasing trend in total phosphorus concentrations”*

Figure 1. Contour Depths of Nepahwin Lake (in meters) (Hallman, 1996).

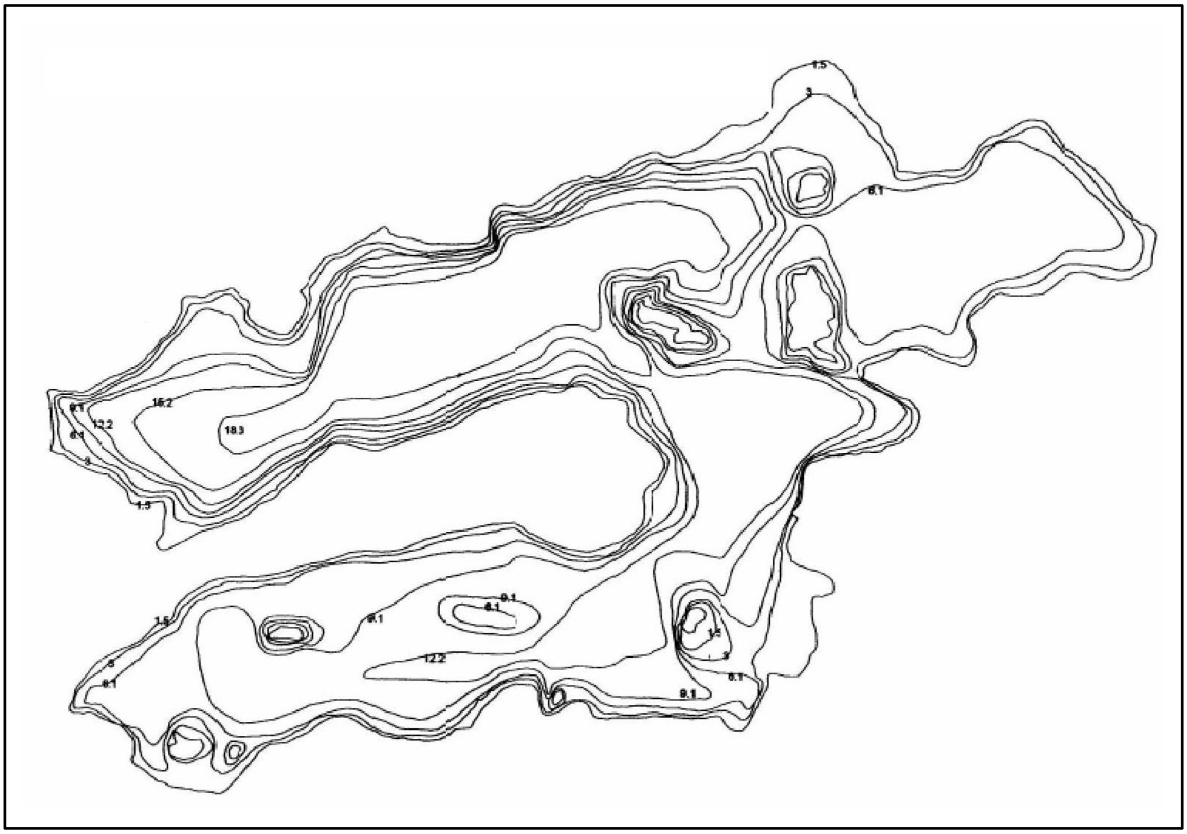


Figure 2. The Nepahwin Lake Watershed (from Hallman, 1996) and locations of the Idwylde Golf Course, Laurentian University, Still and Bennett Lakes.

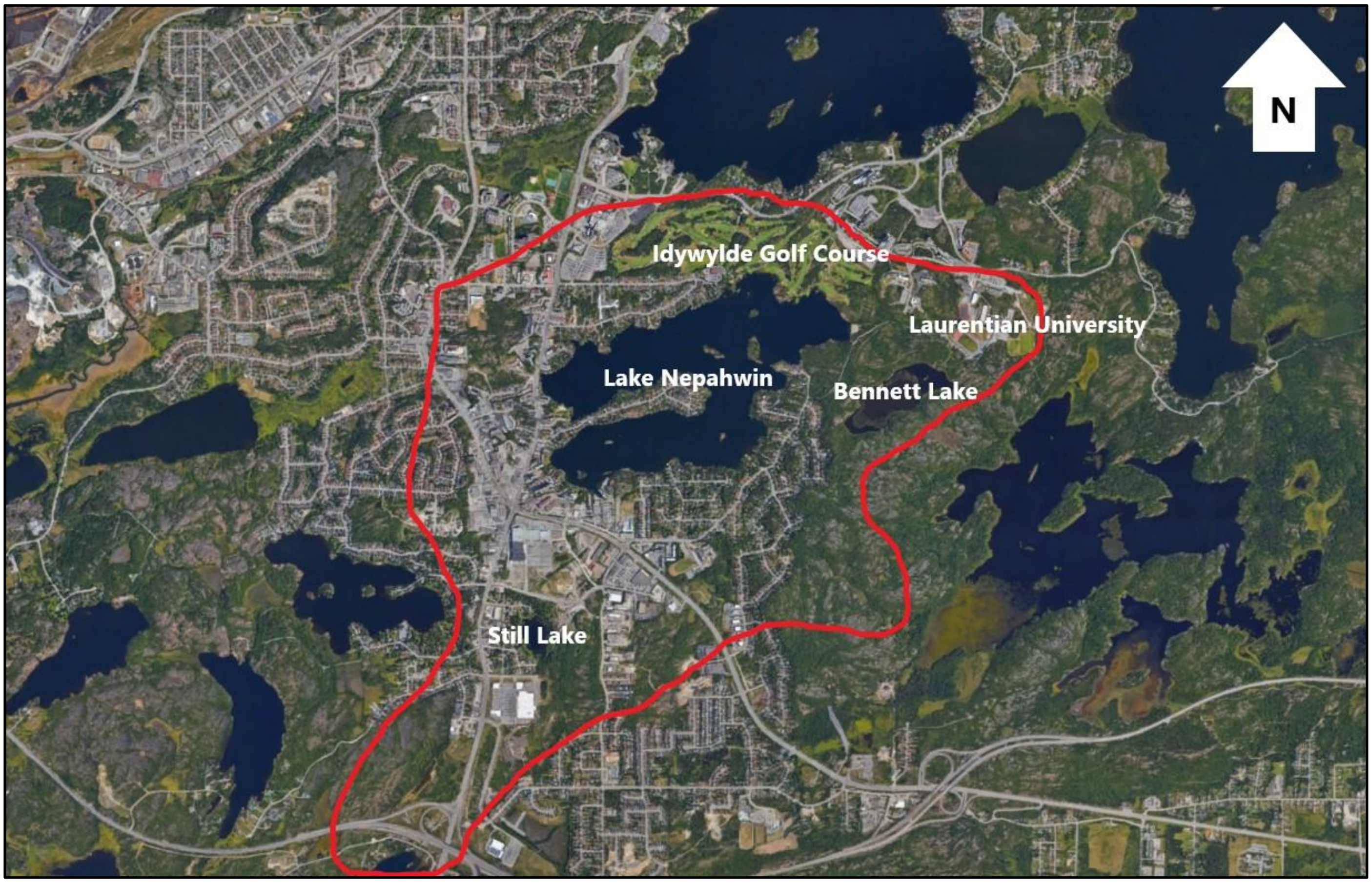
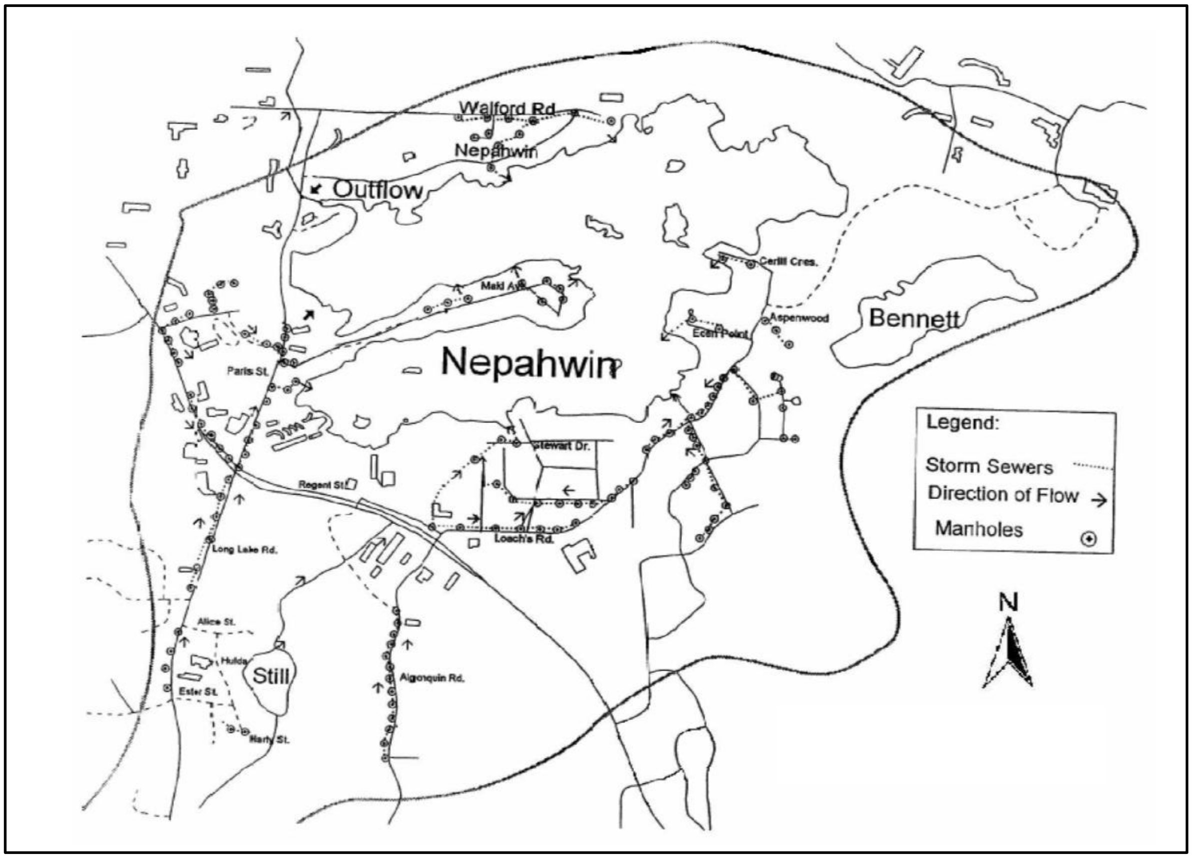


Figure 3. Flow of Water and Location of Storm Sewers (Hallman, 1996).



2. Data Collection

2.1 Background Review

We collected a wide variety of information during completion of the background review. Data described in Table 1 were collected and analyzed as part of the assessment.

Table 1. Background Data Utilized in Study.

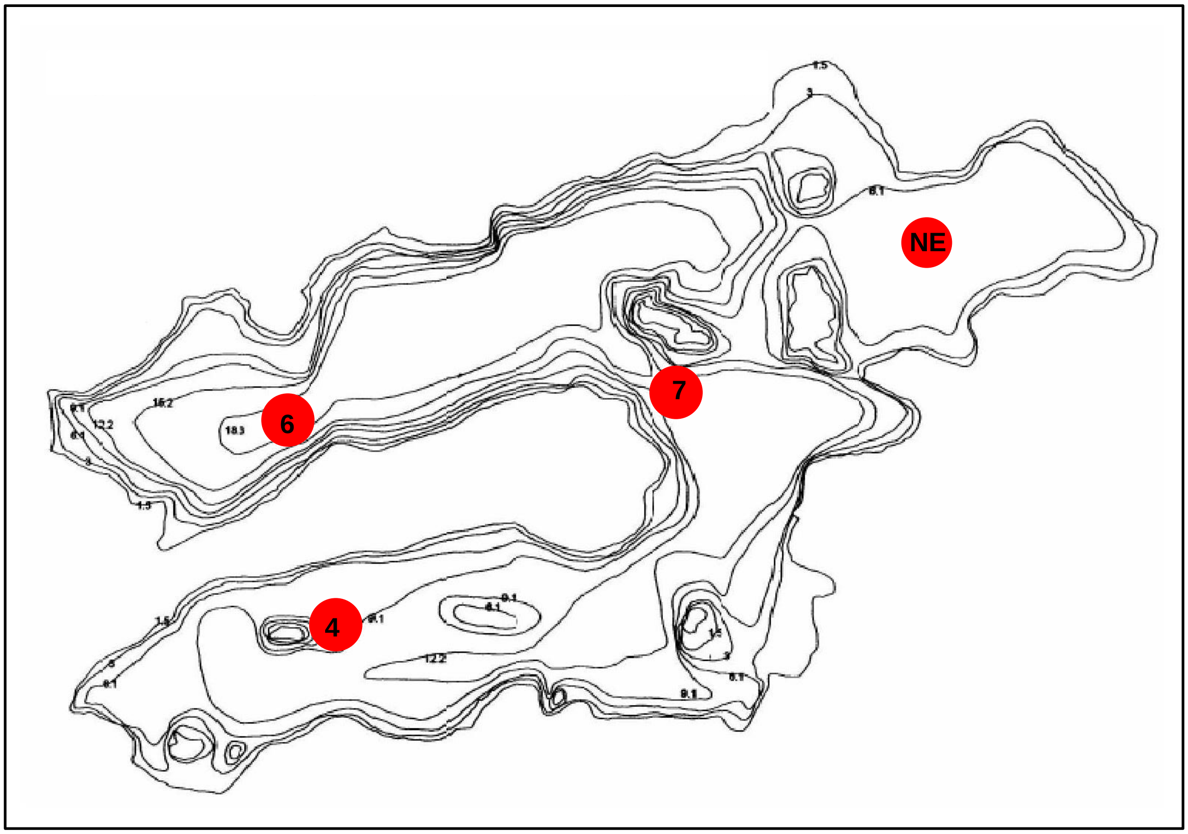
Data Source	Data	Year
City of Greater Sudbury	Total Phosphorus	2001 - 2019
	Water Temperature and Dissolved Oxygen	2018 - 2019
	Secchi Disk Depth	1999 - 2018

	Chloride	2018 – 2019
Ministry of Environment, Conservation and Parks (MECP) – Lake Partner Program	Total Phosphorus	2001 - 2019
	Secchi Disk Depth	2001 - 2019
MECP, Laurentian University, Living with Lakes Centre	Total Phosphorus	2006 - 2012
	Dissolved Organic Carbon	2006 - 2012
	Chlorophyll a	2006 - 2012
MECP Northern Region	Dissolved Oxygen	1986
Public Health Sudbury and Districts	E. coli	2014 - 2019
	Phytoplankton	2006 - 2019

2.2 Field Investigation

HESL completed a water quality sampling event on September 12, 2019 that included collection of water samples from near surface and 1 m off bottom, Secchi disk depth measurements and dissolved oxygen, temperature and pH measurements at 1-m depth intervals using a YSI multiparameter handheld water quality meter at 4 sampling locations (Figure 4). Water samples were kept on ice and shipped to ALS Laboratories and analyzed for TP (both surface and 1 mob), orthophosphate, Dissolved Organic Carbon (DOC), Total Suspended Solids (TSS), Chlorophyll *a* and phytoplankton taxonomy. Sampling locations were selected to overlap with the City's sampling locations (i.e. Site 4, 6 and 7) or characterize an area where few samples have been collected (i.e. Site NE).

Figure 4. Sampling Locations.



3. Results

3.1 Phosphorus

Phosphorus can enter lakes via external loading from the watershed, precipitation or through internal loading. Effluent from sewage treatment systems and stormwater runoff can have particularly high loadings. Phosphorus is the primary limiting nutrient in freshwaters in support of macrophyte and algal growth.

3.1.1 Spring Overturn

Spring overturn water quality grab samples have been collected by the City as part of MECP's Lake Partner Program and used to describe long-term trends as recommended by Clark et al. (2010). The MECP also collected spring overturn samples from 1978 - 1992. Samples collected in May of 2006 - 2012 by the Living Lakes Centre (Sect. 3.1.2) were also added to the spring TP data set. Sampling dates are provided in years where both datasets are available (2006 - 2012). The complete data set is provided in Figure 5 and Table 2.

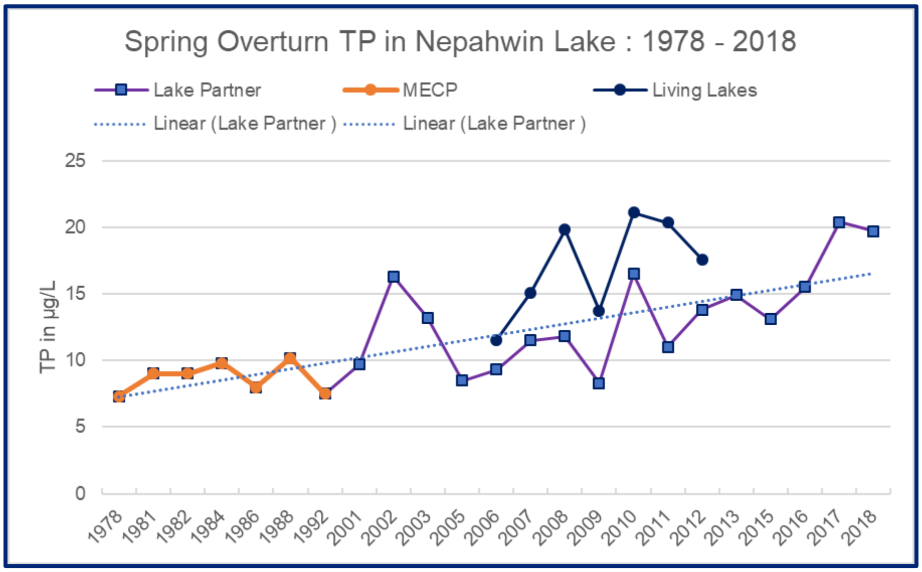
TP concentrations in 2017 (20.4 µg/L) and 2018 (19.7 µg/L) were elevated when compared to historical concentrations but declined to 14.7 µg/L in the autumn of 2019. The 10-yr (2009-2018) ($R^2 = 0.57$, $p < 0.02$),18-yr (2001-2018) ($R^2 = 0.36$, $p < 0.03$) and 41 year ($R^2 = 0.49$, $p < 0.0001$) trends all exhibited statistically significant increases as measured through linear regression, indicating a gradual increase in TP concentrations over, at least, 41 years.

Duplicate water samples were collected by City staff on November 7, 2019 from three sampling locations on Nepahwin Lake and TP concentrations ranged from 10 µg/L - 19 µg/L with an overall average of 14.7 µg/L.

Table 2. Spring Overturn TP Concentrations.

Year	TP (µg/L)	
	MECP Lake Partner	Living Lakes
1978	7.3	
1981	9	
1982	9	
1984	9.8	
1986	8	
1988	10.2	
1992	7.5	
2001	9.7	
2002	16.3	
2003	13.2	
2005	8.5	
2006	9.3 (May 15)	11.6 (May 11)
2007	11.5 (May 17)	15.1 (May 8)
2008	11.8 (May 22)	19.8 (May 12)
2009	8.3 (May 26)	13.8 (May 11)
2010	16.5 (April 14)	21.1 (May 18)
2011	11.0 (May 27)	20.4 (May 10)
2012	13.8 (May 11)	17.6 (May 7)
2013	14.9	
2015	13.1	
2016	15.5	
2017	20.4	
2018	19.7	

Figure 5. Average 1978 - 2018 Spring Overturn TP Concentrations in Nepahwin Lake.



3.1.2 Ice-Free

Water samples were collected monthly between May and October and analyzed for TP by the Living with Lakes Centre from 2006 - 2012 (Figure 6, Figure 7). Average annual ice-free TP concentrations ranged from 9.1 µg/L to 15.6 µg/L at Site 4 and 10.2 µg/L to 14.9 µg/L at Site 6 and increasing trends were apparent between 2006 and 2012. The average ice-free concentration at each site was 12.5 µg/L (Table 3). Average monthly TP concentrations were highest in May at both sites and declined over the course of the summer.

Table 3. 2006 - 2012 TP Data Collected by Living Lakes Centre.

Site	Month	2006	2007	2008	2009	2010	2011	2012	Average
4	May	12.8	14.6	15.3	13.5	20.9	19.8		16.2
	June	10.2	15.0	14.2	9.4	17.6	14.5		13.5
	July	9.9	8.7	12.9	9.5	13.6	15.6		11.7
	August	13.8	16.2	9.2	-	15.2	14.5		11.5
	September	7.7	9.7	8.6	11.3	11.6	17.2		11.0
	October	8.6	11.5	9.2	10.7	14.4	11.4		11.0
	Average	10.5	12.6	11.6	9.1	15.6	15.5		12.5
6	May	10.3	15.6	24.3	14.0	21.3	20.9	17.6	17.7
	June	9.4	10.4	14.0	9.9	15.6	14.5	16.7	12.9
	July	10.4	9.8	12.2	17.4	16.8	10.6	13.2	12.9
	August	10.5	13.2	9.0	-	14.4	11.8	11.6	10.1
	September	7.7	10.5	9.7	9.5	11.4	10.6	12.7	10.3
	October	12.7	12.5	10.3	10.4	10.0	11.0	9.3	10.9
	Average	10.2	12.0	13.3	10.2	14.9	13.2	13.5	12.5

Figure 6. Average 2006 - 2012 Ice-Free TP Concentrations in Nepahwin Lake.

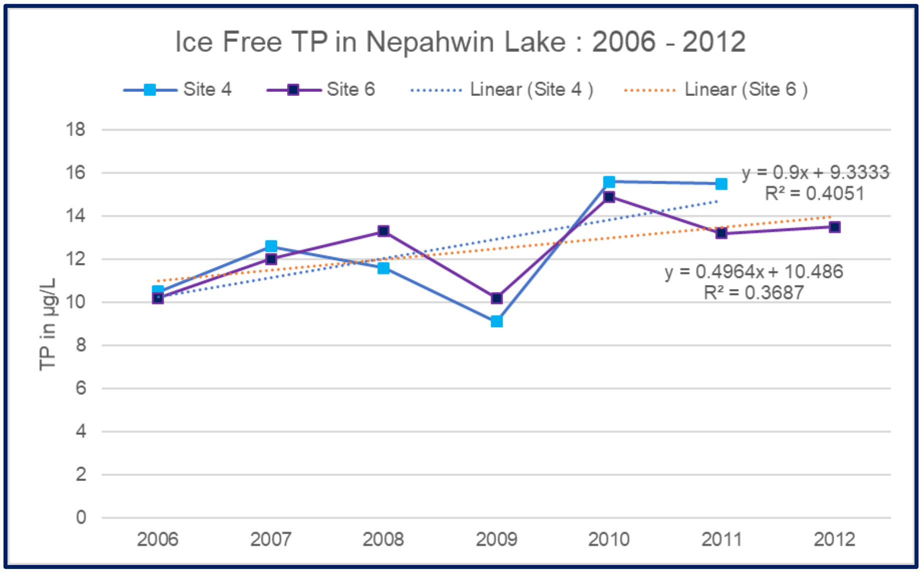
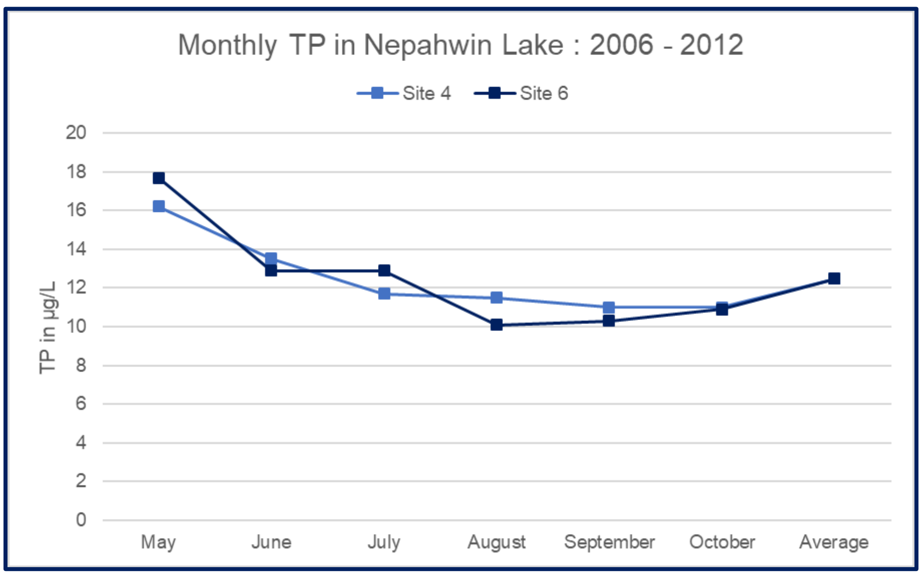
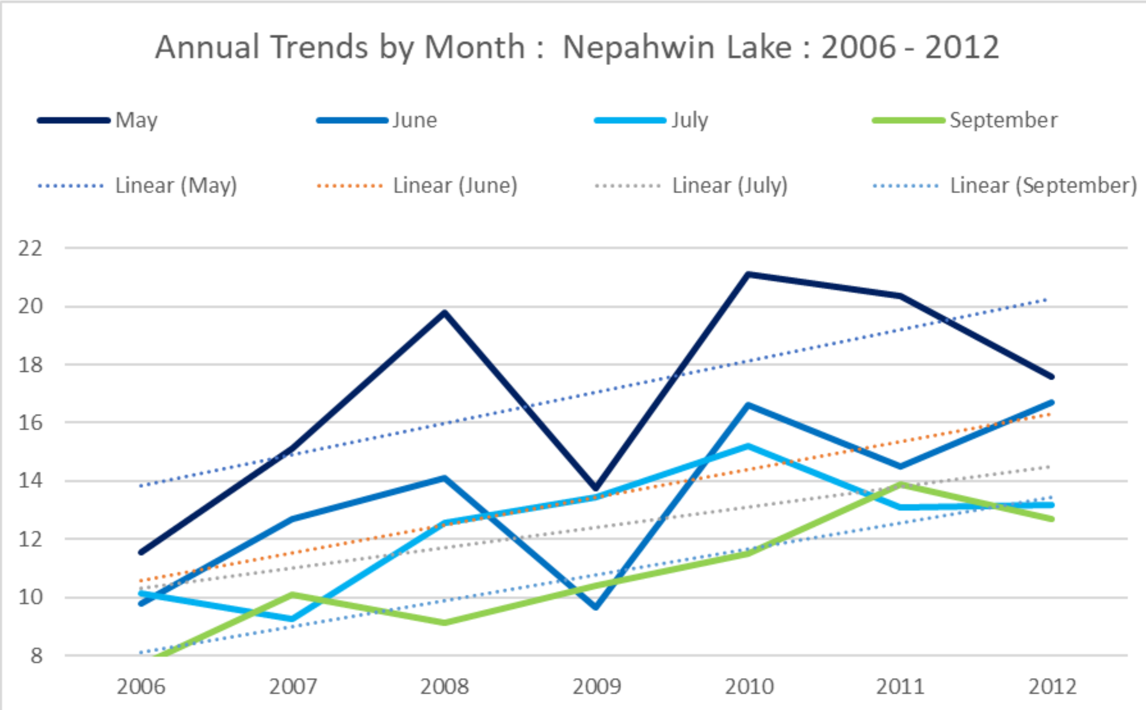


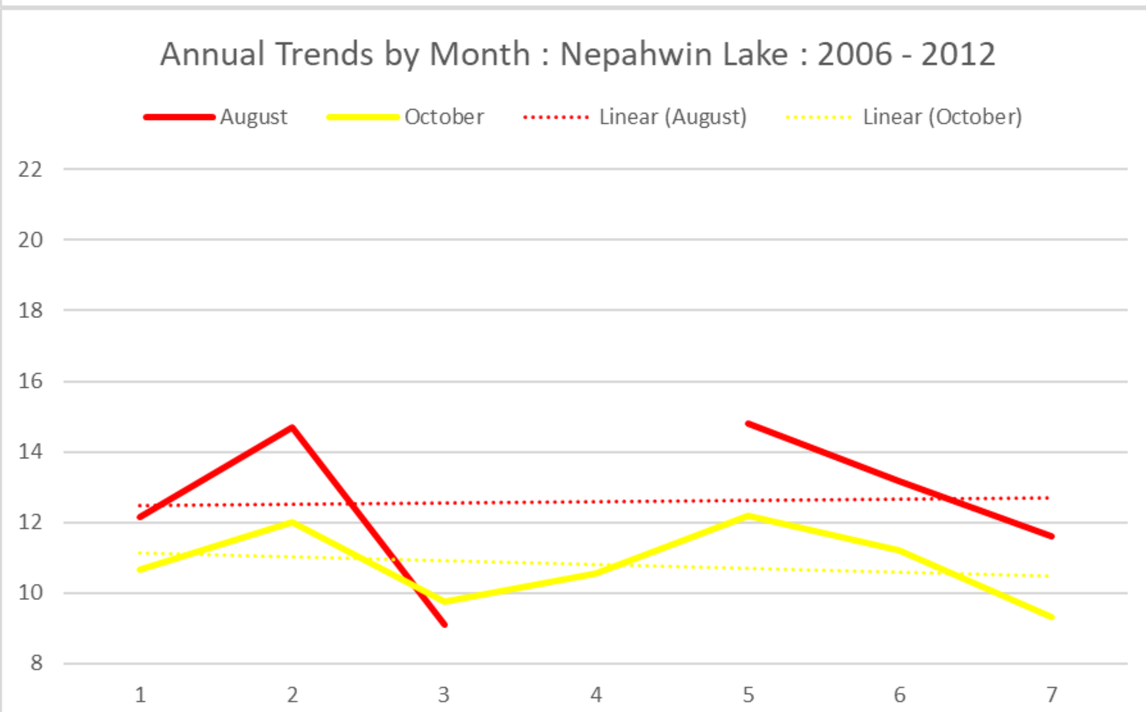
Figure 7. Average Monthly TP in Nepahwin Lake: 2006 - 2012.



The trends in increasing TP between 2006 and 2012 were driven by increasing trends for May, June, July and September (Figure 8, top) but no trends for August and October (Figure 8, bottom) were evident over that time period.

Figure 8. Annual Average TP by Month: 2006 – 2012.





The City collected ~bi-weekly samples in the late summer of 2018 and 2019 from Sites 4, 6 and 7 from the near surface and 1 metre off bottom to determine the presence or absence of internal loading of nutrients from sediments. TP concentrations near surface were relatively consistent at all sites except for July 24, 2019 at Site 6 (26 µg/L). TP concentrations were much higher 1 metre off bottom at the deeper sites (Site 6 and 7), indicating internal loading of nutrients from sediments. Internal loading was most pronounced (i.e. Bottom TP > Top TP) on September 26, 2018, July 24, 2019 and September 12, 2019.

Table 4. 2018/19 TP Data Collected by the City.

Date	Site 4 (10m water depth)		Site 6 (19m water depth)		Site 7 (15m water depth)	
	Top	Bottom	Top	Bottom	Top	Bottom
12-Sep-18	6	13	6.5	51	7	37.5
18-Sep-18	8.5		8.5	40.5	8	73.5
26-Sep-18	10		11	52	12.5	108.5
02-Oct-18	11		10	21	10.5	56
24-Jul-19			26	152		
06-Aug-19			8	101	10	
13-Aug-19			10	116	10	41
12-Sep-19[1]	7.3	10.7	10.2	139	7.5	48
Average	8.6	11.9	11.3	84.1	9.4	60.8

Note: [1]Data collected by HESL

Samples collected on September 12, 2019 by HESL were analyzed for orthophosphate which is a reactive portion of TP that is biologically available for uptake by plants and algae. Orthophosphate was less than the minimum detection limit (0.003 mg/L) at all sites, indicating that the proportion of reactive phosphorus was low.

3.2 Water Temperature and Dissolved Oxygen

Dissolved oxygen measurements were collected ~monthly by MECP- Northern Region in 1986 and ~bi-weekly by the City in 2018 and 2019 (Figure 9 - Figure 12).

Site 4 - Dissolved oxygen concentrations ranged from 2.4 mg/L to 11.4 mg/L at Site 4 in 1986 (Figure 12). Near surface concentrations declined throughout the monitoring period in 1986 and concentrations were similar throughout the water column before declining below 11 m in late August and October. Dissolved oxygen concentrations at Site 4 ranged from 1.14 mg/L to 11.28 mg/L in 2018, and 1.12 mg/L to 9.52 mg/L in 2019 (Figure 9). Concentrations were generally ~8 mg/L - 9 mg/L up to 6 m below surface before declining at greater depths to ~1 - 2 mg/L near bottom. A seasonal pattern of more sharply declining dissolved oxygen concentrations at greater depths was observed throughout the monitoring period in 2018 but a clear pattern was not observed in 2019. A positive heterograde oxygen profile was also observed in July 2018 as a result of oxygen production by phytoplankton in water depths from 5 - 9 m below surface.

Site 6 - Dissolved oxygen concentrations ranged from 0.2 mg/L to 11.6 mg/L in 1986 (Figure 12) and from 0.21 mg/L to 11.2 mg/L at Site 6 in 2018 and 2019 (Figure 10). Concentrations were typically ~8 mg/L - 9 mg/L up to 5 m below surface before sharply declining between 5 and 10 m below surface, and then gradually declining between 10 m below surface and the bottom. Dissolved oxygen concentrations declined throughout the season in the hypolimnion and anoxic or hypoxic conditions were prevalent near bottom near the end of July to the end of the monitoring season. A positive heterograde oxygen profile was also observed in July and August 2018 as a result of oxygen production by phytoplankton in water depths from 6m - 8m below surface. Dissolved oxygen concentrations also generally increased between ~9m - 12m below surface, this could be a result of blue-green algae that have scavenged nutrients from the bottom waters and moved up in the water column to photosynthesize. In 1986, dissolved oxygen patterns differed slightly as deep water oxygen concentrations remained high in bottom water in May and July and oxygen concentrations did not increase throughout the ~6m - 8m and ~9 - 12 m depths.

Dissolved oxygen patterns at Site 7 were similar to the patterns observed at Site 6 (Figure 11).

Figure 9. 2018 and 2019 Site 4 Dissolved Oxygen Profiles.

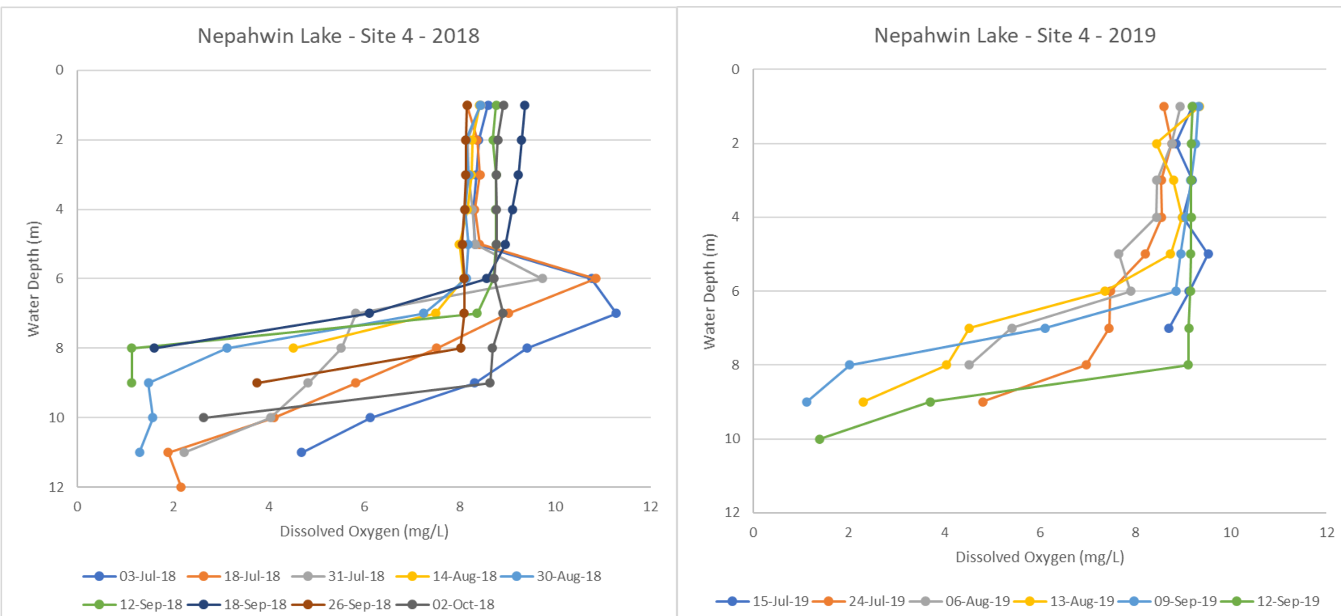


Figure 10. 2018 and 2019 Site 6 Dissolved Oxygen Profiles.

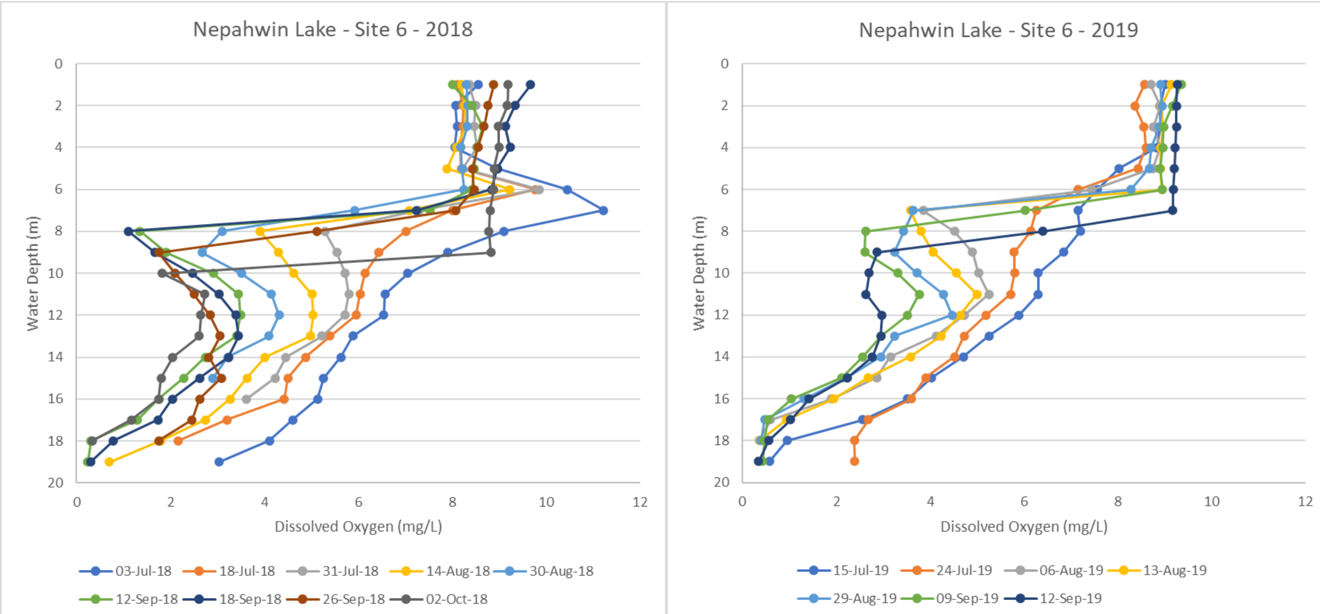


Figure 11. 2018 and 2019 Site 7 Dissolved Oxygen Profiles.

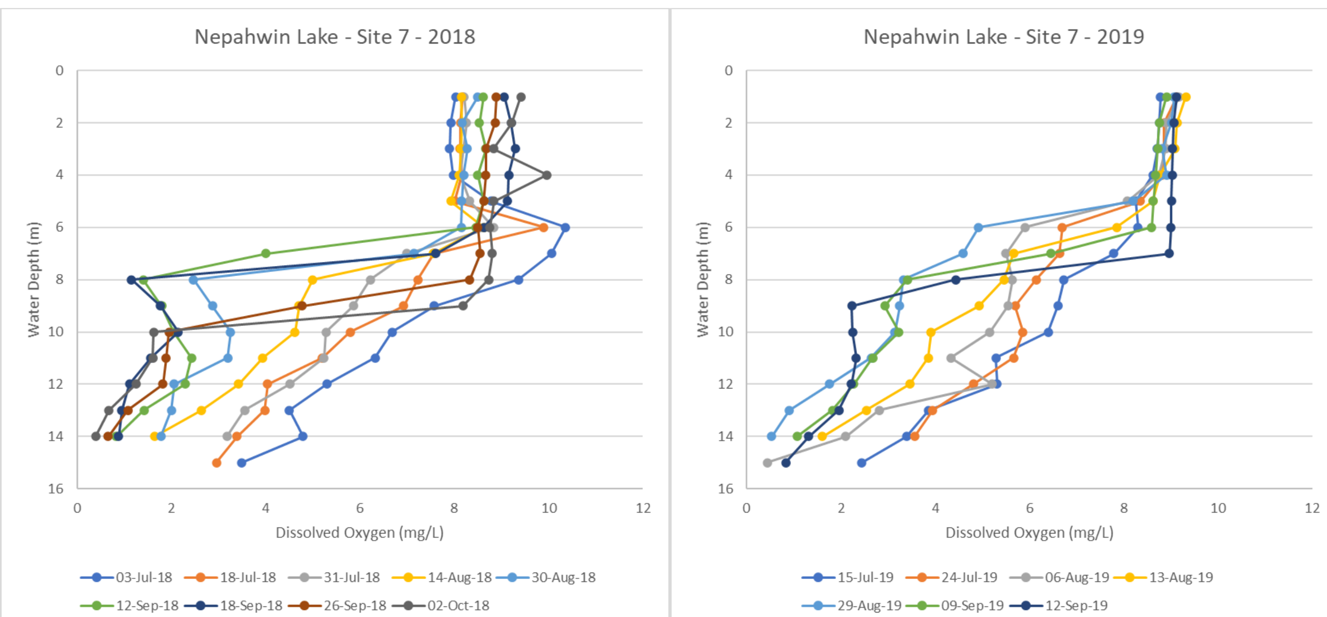
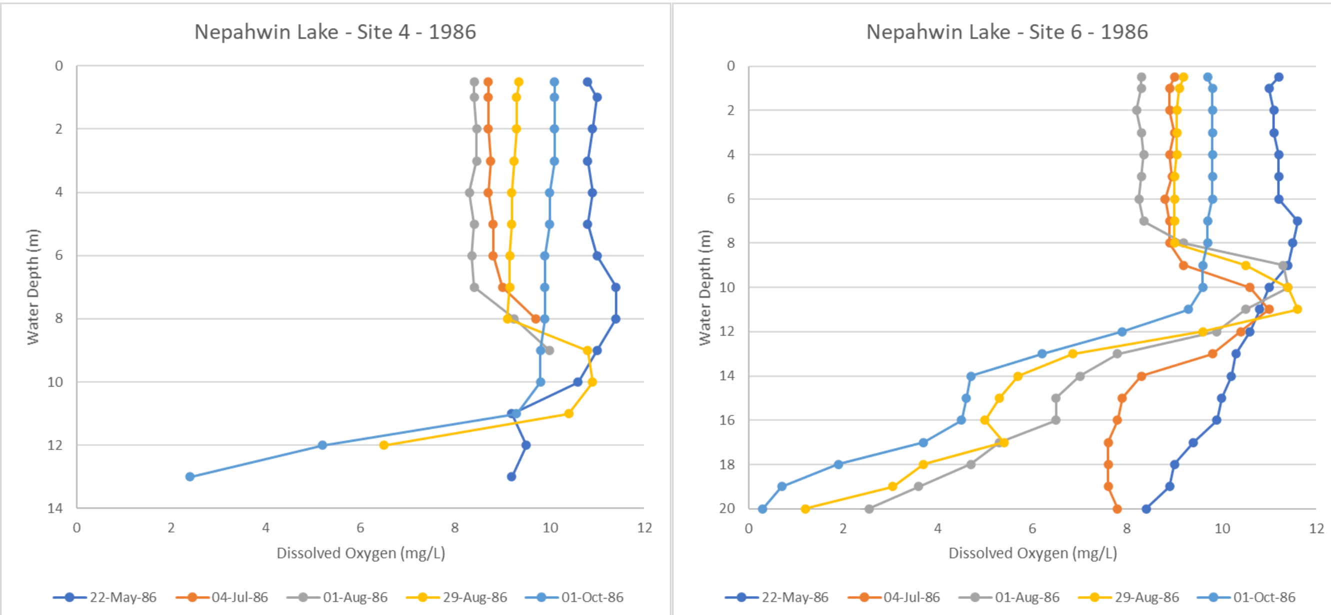
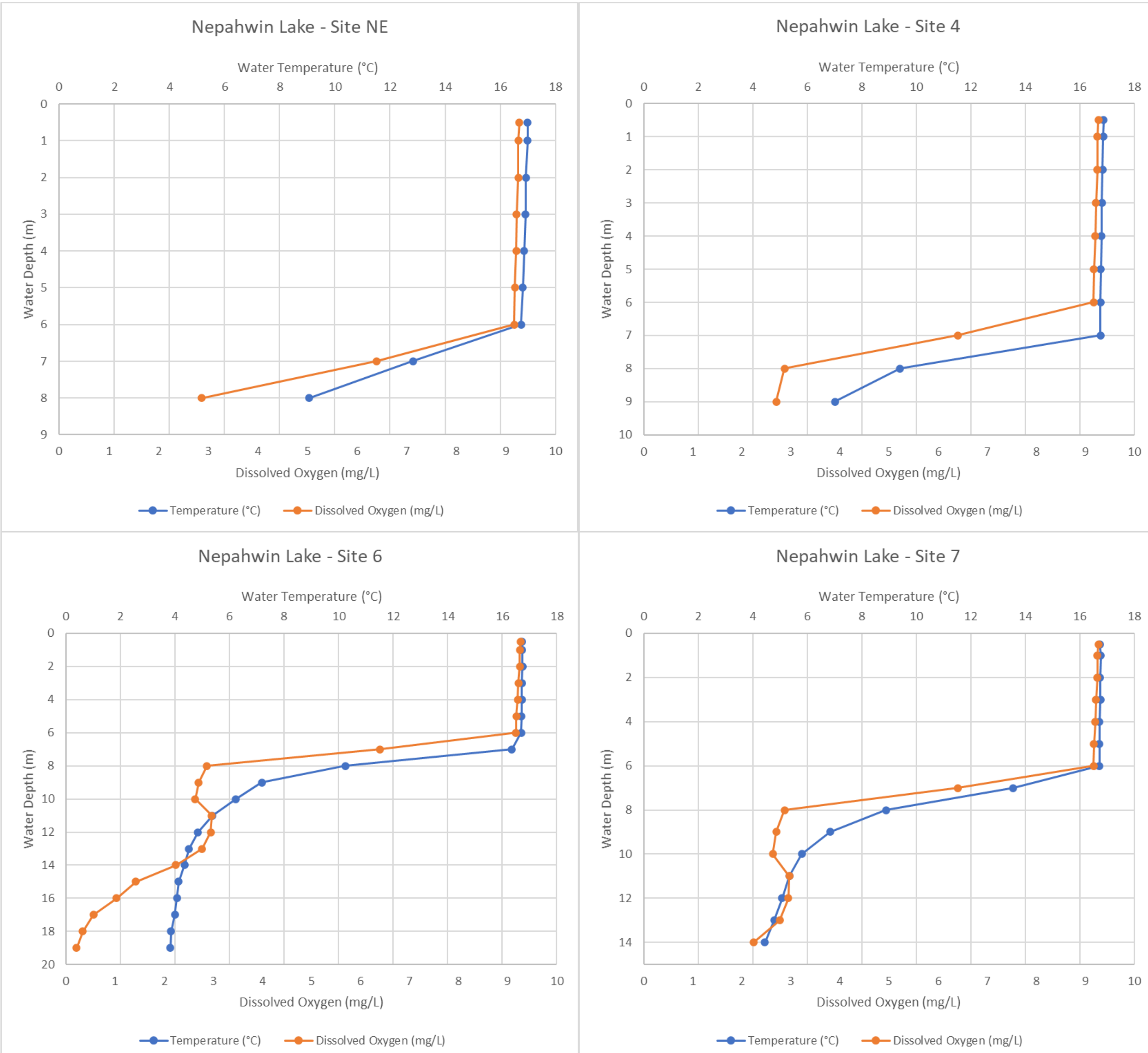


Figure 12. 1986 Site 4 and 6 Dissolved Oxygen Profiles.



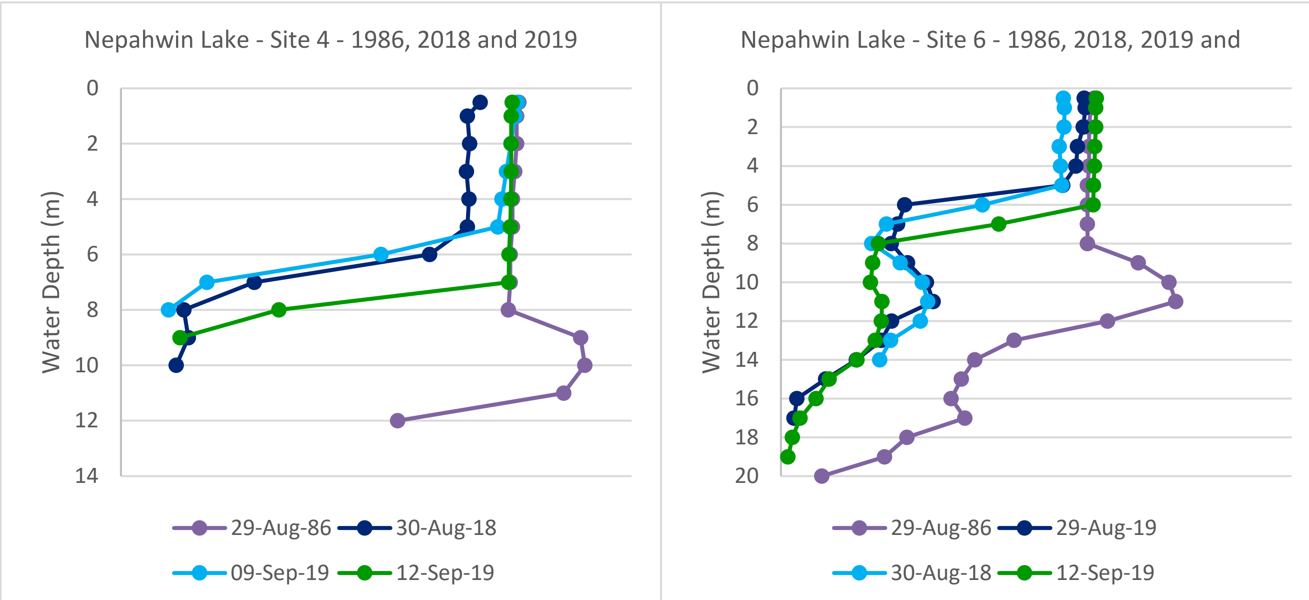
HESL staff recorded additional profiles on September 12, 2019 (Figure 13). Water temperatures of ~17°C were measured from surface to 6m of depth before declining sharply through the thermocline at Sites 4, NE, 6 and 7. Dissolved oxygen followed a similar pattern and anoxic conditions were noted near bottom at Site 6. Slightly higher dissolved oxygen was measured at 11 – 13 m water depths at Sites 6 and 7 when compared to concentrations at surrounding depths.

Figure 13. HESL Water Temperature and Dissolved Oxygen Profiles – September 12, 2019.



Dissolved oxygen profiles that were collected in the late summer at Sites 4 and 6 in 1986, 2018 and 2019 were compared to assess changing conditions over time (**Figure 14**). Historical and more recent sampling locations are located in the same areas but not the exact same sampling locations (as can be seen in the different depths measured) but it is clear that dissolved oxygen concentrations at depths beyond ~7 m were consistently and considerably higher in 1986 than in recent years.

Figure 14. A Comparison of Dissolved Oxygen Profiles at Site 4 and 6 Over Time.



3.3 Secchi Disk Depth

Secchi disk depth is a measurement of water clarity. Secchi disk depths were gathered from a variety of sources and monthly averages were collected to evaluate the presence or absence of seasonal trends (Table 5). A long-term evaluation of Secchi disk depths (and Chlorophyll *a*) was not completed because the data were not collected at specific time intervals or frequencies to allow for an accurate determination of long-term trends.

Secchi disk depths between 1999 and 2018 ranged from 2.3 m to 7 m and averaged 4.8 m. Secchi disk depths were lowest in May (2.4 m) and October (2.6 m) and higher from June - September (5.0 m - 5.7 m; Table 5).

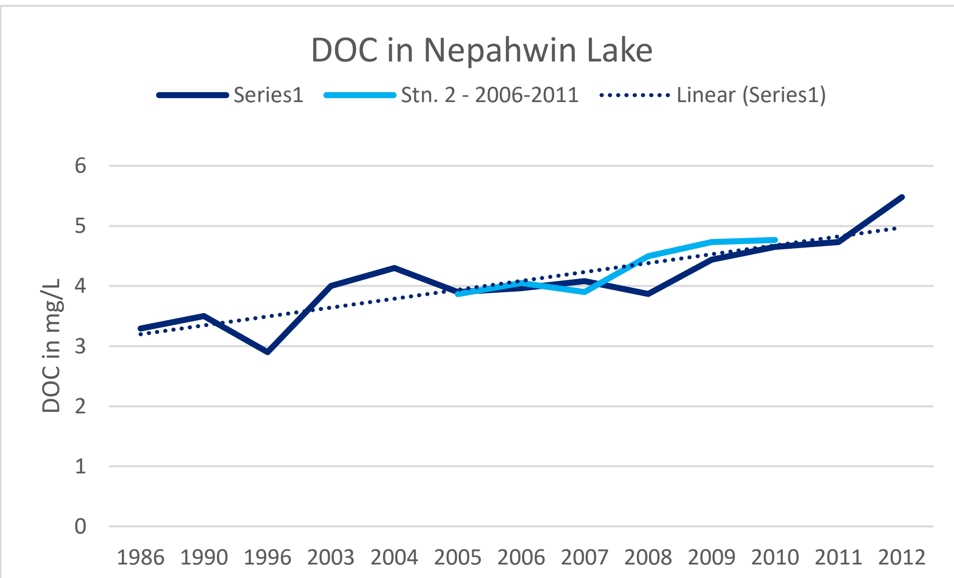
Table 5. Monthly Average Secchi Disk Depth Measurements.

Month	Secchi Disk Depth (m)
May	2.4
June	5.7
July	5.1
August	5.0
September	5.0
October	2.6

3.4 Dissolved Organic Carbon

Dissolved Organic Carbon (DOC) is often elevated in lakes that receive substantial wetland drainage and it is frequently correlated with naturally elevated TP concentrations (Dillon and Molot, 2005). Although DOC concentrations have been rising in south-central areas of the PreCambrian Shield, TP concentrations have been stable or are falling in the same areas (Palmer et al. 2011). Dillon and Molot (2005) reported a very strong correlation between DOC export from lake catchments and depth of runoff, that runoff was the primary determinant of DOC load to lakes and that export decreased in dry years. MECP sampling documented increasing DOC in Nepahwin Lake in ~bi-monthly water samples collected from 2006 to 2012 and occasional samples between 1986 and 2005 (Figure 15). The trends were statistically significant ($p<0.02$) for 1986 - 2012 (Stn. 1), 2006 - 2012 (Stn.1) and 2006 – 2011 (Stn. 2) and were accompanied by statistically significant increases in spring TP (Figure 6). More recent data are not available, however, to inform the recent TP increases (Figure 5).

Figure 15. DOC in Nepahwin Lake: 1990 – 2012.



Monthly average concentrations were consistent and ranged from 4.17 mg/L in June to 4.71 mg/L in August (Table 6) although TP concentrations declined from May to August (Figure 7).

Table 6. Monthly Average DOC Measurements: 2006-2012.

Month	DOC (mg/L)
May	4.29
June	4.17
July	4.45
August	4.71
September	4.53

October	4.25

DOC concentrations measured by HESL on September 12, 2019 were slightly higher: Site NE (5.26 mg/L), Site 4 (5.97 mg/L), Site 6 (5.26 mg/L) and Site 7 (5.85 mg/L) with an average value of 5.6 mg/L.

3.5 Chlorophyll a

Chlorophyll *a* is a photosynthetic pigment which is often used as a proxy to determine the abundance of algae in lakes and rivers. MECP – Living with Lakes collected ~bi-monthly water samples that were analyzed for chlorophyll *a* from 2006 to 2012. Concentrations ranged from less than the laboratory minimum detection limit of 0.001 mg/L to 0.0038 mg/L, averaged 0.0017 mg/L and showed no monthly patterns (Table 7).

Table 7. Monthly Average Chlorophyll *a* Measurements

Month	Chlorophyll *a* (mg/L)
May	0.0018
June	0.0014
July	0.0017
August	0.0017
September	0.0018
October	0.0017

3.6 Chloride

Chloride concentrations are increasing in many lakes throughout Ontario as a result of road salt application. The Canadian Water Quality Guideline (CWQG) for the Protection of Aquatic Life is 120 mg/L (Canadian Council of Ministers of the Environment, 2011) but recent research has indicated that zooplankton in Precambrian Shield Lakes are impacted at much lower concentrations (5 mg/L - 40 mg/L; McClymont, 2020).

Average chloride concentrations from the City of Greater Sudbury program in 2018-19 ranged from 150 mg/L to 159 mg/L and averaged 156 mg/L in Nepahwin Lake. All results were greater than the CWQG.

Table 8. Chloride concentrations.

Date	Chloride (mg/L)
03-Jul-18	150
30-Aug-18	159
12-Sep-18	152

18-Sep-18	157
26-Sep-18	157
02-Oct-18	158
06-Jun-19	157
15-Jul-19	158
min	150
max	159
mean	156

3.7 Algae Assemblages

Cyanobacteria (blue-green algae) blooms in Nepahwin Lake were confirmed by Public Health Sudbury and Districts in September 2015, November 2016, September 2017 and August 2018 (Public Health Sudbury and Districts, 2020).

Chrysophacea (golden algae) was the most dominant class of algae collected on September 12, 2019, followed by Chlorophyceae (green algae) and Cryptophycaea (Table 9). Assemblages were relatively consistent between sites. Chrysophyceae are often dominant in late summer as a result of high-water temperatures and water column stability. Cyanophyceae concentrations were low (25,000 cells/L - 54,000 cells/L) which is much lower than the World Health Organization guidelines for low probability of adverse health effects (20,000,000 cells/L).

Table 9. Phytoplankton Results from September 12, 2019.

Class	Sites Combined		NE		4		6		7	
	Cells/L	%	Cells/L	%	Cells/L	%	Cells/L	%	Cells/L	%
Bacillariophyceae	85000	1	19000	1	16000	1	32000	2	18000	1
Chlorophyceae	2431000	27	633000	27	517000	22	488000	25	793000	36
Chrysophyceae	4127000	47	1114000	47	1510000	65	612000	31	891000	41
Cryptophyceae	1987000	22	551000	23	235000	10	786000	40	415000	19
Cyanophyceae	178000	2	54000	2	37000	2	25000	1	62000	3
Dinophyceae	39000	0	1000	0	13000	1	6000	0	19000	1
Euglenophyceae	1000	0	1000	0	0	0	0	0	0	0

3.8 Bacteria

Public Health Sudbury and Districts collected weekly water samples from 5 locations adjacent to Nepahwin and Laurentian Beaches, analyzed samples for *E. coli* and compared results to Recreational Water Quality Guidelines for *E. coli* of a geometric mean concentration of a minimum of five samples of 200 *E. colil*/100 mL or a single-sample maximum concentration of 400 *E. coli*/100 mL (Health Canada, 2012). Concentrations only exceeded the water quality guidelines on August 4 (3 of 5 sites) and 6 (6 of 10 sites), 2015 at Nepahwin Beach.

Mean *E. coli* concentrations were calculated (Table 10). Mean values at Nepahwin Beach ranged from 28 CFU/mL in 2014 to 133 CFU/mL in 2017, and from 11 CFU/mL in 2014 to 34 CFU/mL in 2016 at Laurentian University Beach. *E. coli* concentrations were highest at Nepahwin Beach in 2017 but concentrations were below the mean value at Laurentian University Beach that year, and concentrations were not elevated in 2018 at either beach.

Table 10. E. Coli monitoring results (Public Health Sudbury and Districts, 2020).

Beach	2014	2015	2016	2017	2018	2019	Mean
Nepahwin	28	83	51	133	65	47	68
Laurentian University	11	15	34	19	19		20
Mean	19	49	43	76	42	47	

3.9 Summary

The following existing conditions are noteworthy regarding the causation study:

- Spring overturn phosphorus concentrations in Nepahwin Lake have been rising on a statistically significant trend since 1978. During this period there has been substantial changes in the watershed from urban growth, recovery from smelting activities, a changing climate and invasive species introductions.

- Deep water dissolved oxygen concentrations near zero are prevalent in Nepahwin Lake and concentrations below ~7m of water depth have declined between 1986 and recent years.

- Dissolved Organic Carbon concentrations showed a statistically significant increasing trend between 1990 and 2012,

- Dissolved Organic Carbon and mean ice-free TP concentrations both showed statistically significant increasing trends from 2006 - 2012

- The elevated TP concentration of 20.4 µg/L in 2017 was based on duplicate samples collected from only one site. Samples were, however, collected from 3 sites in 2018 and the average concentration remained elevated at 19.7 µg/L. The lower value of 14.7 measured by HESL in September 2019 is not representative of the trend in the lake as TP concentrations decline over the summer from high values at spring overturn.

- TP concentrations were substantially higher in May than at other monitoring periods indicating that spring overturn concentrations overestimate average concentrations for the ice-free period.

- TP concentrations were much higher in the bottom waters than near surface, and bottom water anoxia is evident at multiple sites, so internal loading from sediments in Nepahwin Lake is a source of nutrients.

- Orthophosphate concentrations were below the detection limit indicating that a small proportion of the TP is available for biological uptake.

- Secchi disk depths were lowest in May and October, likely as a result of spring freshet or fall algal production. Low Secchi disk depths could indicate elevated total suspended solid concentrations and be driving elevated TP concentrations in May.

- Chloride concentrations are elevated to concentrations that could be impacting zooplankton assemblages.

- Cyanobacteria (blue-green algae) assemblages were low on September 12, 2019 but blue-green algal blooms have been common in recent years.

- *E. coli* concentrations (2014 - 2019) indicate that recreational water quality is acceptable in Nepahwin Lake and unrelated to elevated TP concentrations in 2017 and 2018.

4. Analysis of Potential Causal Factors

Total phosphorus concentrations could become elevated due to a multitude of different chemical, biological or physical factors. Our investigation has included analysis of data from the City of Greater Sudbury, MECP, Living Lakes Centre, Public Health Sudbury and Districts and HESL.

There are a variety of potential direct and indirect causal factors that are considered in this section. Nephawin Lake is fully serviced for municipal water and wastewater such that, aside from the potential that several lots were not connected, phosphorus loading from septic systems on the shoreline of Nepahwin Lake are not a contributing factor to the change in phosphorus concentration.

4.1 Role of Development

The City of Greater Sudbury seeks to manage shoreline development to protect water quality for lakes within its jurisdiction, largely through Official Plan policies that limit development, or which specify development conditions for lakes that are considered nutrient-sensitive. Lake sensitivity was established in a modelling exercise and recommendations (HESL 2014a), and Nepahwin Lake was classified as "Enhanced Management" based on its sensitivity to nutrient enrichment. Residences on Lake Nephawin are serviced by the municipal sewage and water systems and so phosphorus enrichment from septic systems is not considered to be a factor in the increasing phosphorus levels[3]. Review of the Sudbury water quality model, with connection for full municipal sewage service on Nepahwin Lake showed that:

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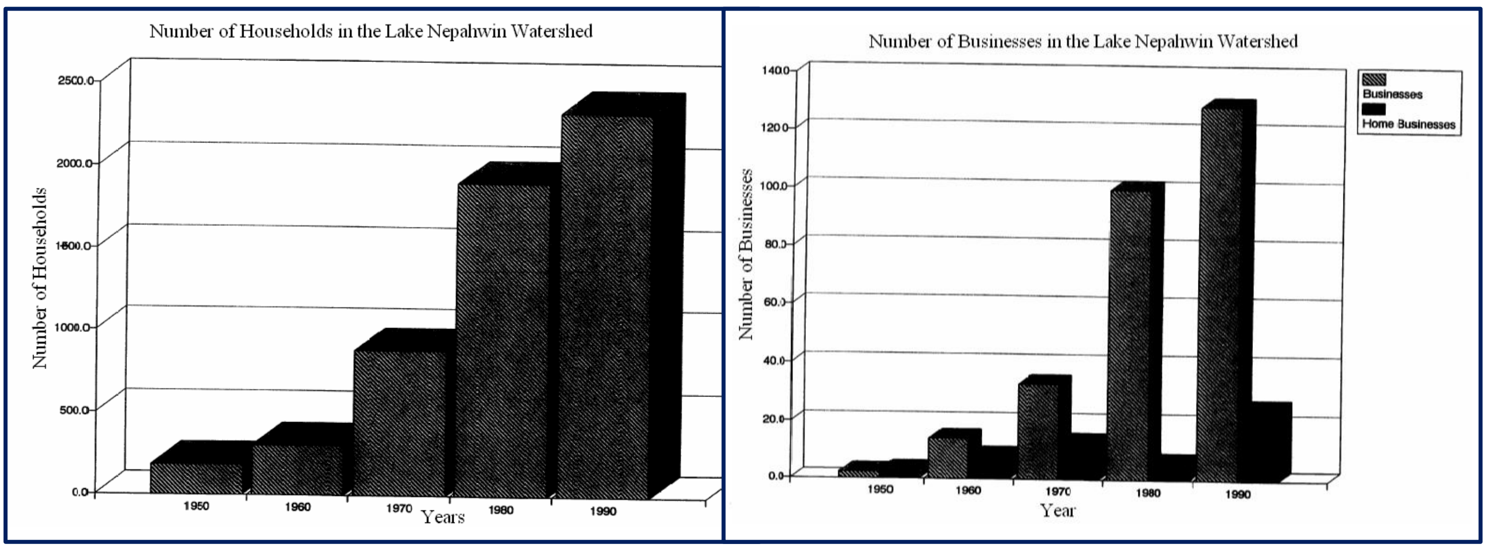
[3] *During the original modelling exercise, the lake was modelled as having no municipal service, with septic systems servicing all residences and all septic system phosphorus migrating to the lake. The model predicted a spring overturn total phosphorus concentration of 36 µg/L compared to the measured value of 12.3 µg/L at the time, with substantial loadings from a) septic systems on the lake and b) urban runoff from the City of Sudbury. The model was clearly overestimating TP in the lake. HESL has confirmed that Nepahwin Lake residences had municipal service at the outset of this causation study.*

- The pre-development (no human sources) spring overturn TP concentration in Nepahwin Lake was estimated as 3.4 µg/L with an annual loading of 51.3 kg (21 from atmospheric loading and 30.2 from the watershed),
- The current spring overturn TP concentration in the lake was predicted as 20.7 µg/L, nearly identical to the current measured values,
- ~303 kg/yr of phosphorus was added to the lake from urban and overland runoff, calculated as 132 mg/m^2/yr from 2.4 ha of high intensity development in the catchment,
- 18 kg of phosphorus is required to raise TP concentrations in the lake by 1 µg/L.

Phosphorus concentrations in Nepahwin Lake rose from 7-9 µg/L to ~20 µg/L in the past 40 years as the population of Sudbury has grown from ~92,000 in 1981 to ~165,000 in 2016[4]. The rate of growth in the City is matched by the rate of growth in the number of residences and businesses located in the Nepahwin Lake watershed (Figure 16, from Hall (1996)), all of which contribute runoff and storm water to Nepahwin Lake from numerous storm sewers (Figure 3, Hall 1996). There have been no major developments or alterations to stormwater management in the Nepahwin Lake watershed in the recent past, indicating that the storm water discharges described in Hall (1996) are still representative of current conditions (P. Javor, City of Greater Sudbury, personal communication, March 2020).

Figure 16. Urban Growth in Nepahwin Lake Watershed (Hall, 1996).



Urban growth and associated runoff are therefore likely to represent a substantial contribution to enriching the nutrient status of Nepahwin Lake.

[4] *https://thecanadianencyclopedia.ca/en/article/sudbury-greater*

4.2 Recovery of Lakes in the Sudbury Area Affected by Smelter Deposition

Lakes in the Sudbury area have been affected by the deposition of acid and metal particulates due to over 100 years of metal smelting (Keller et al. 2004). Water quality (pH and metals) has improved as pollution controls have been implemented and substantial recovery (“greening”) of the watershed has been documented. Lake response is complicated, however, by a variety of chemical interactions associated with lake acidity, metal and dissolved organic carbon concentrations, and improvements in the health of aquatic biota at various trophic levels, including increased species richness in phytoplankton and zooplankton and proliferation of less acid tolerant species (Keller et al. 2004, 2018). Nepahwin Lake is also impacted by climate change and a variety of stressors associated with urban development, both along the lakeshore and within the watershed. These multiple stressors further challenge the ability to confidently expose specific mechanisms for the heightened phosphorus concentrations observed in 2017 and 2018, for example, Keller et al. (2018) noted that TP was increasing in 4 study lakes (Bob, Klock, Tillie and Crooked) in the Sudbury area without any obvious explanation after examination of lake and watershed characteristics. The 40-year trend of increasing phosphorus concentrations and 20 year trend of increasing DOC, urban growth and associated phosphorus export do however suggest that watershed-level changes are important.

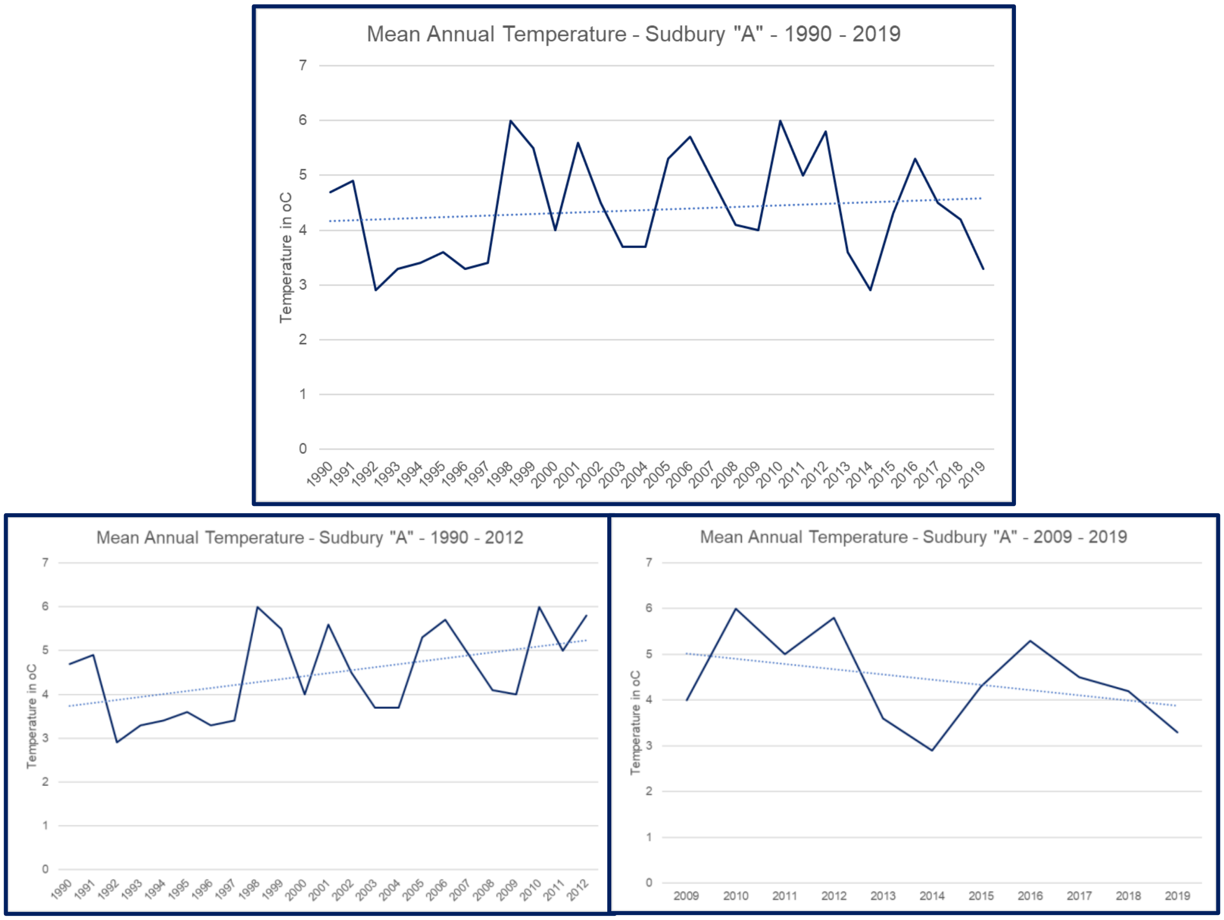
4.3 Climate

Climate is a major determinant of TP in lakes as a result of a myriad of direct and indirect causal factors such as direct precipitation inputs, stormwater induced runoff, thermal stratification periods/internal loading rates and air/water temperatures.

4.3.1 Air Temperature

Increasing summer temperatures over the period of record could result in earlier lake stratification and greater potential for internal load. This is a potentially feasible mechanism but was not assessed in detail because although Nepahwin Lake does experience periods of anoxia and internal load was documented (Section 3.2), the absence of consistent long term data on oxygen status and deep water TP concentrations makes it difficult to document changes that would support this mechanism. In addition, although mean annual temperature in Sudbury increased between 1990 and 2019, the trend was inconsistent and broken into two segments: an increase from 1990 to 2012 but a decrease between 2012 and 2019 (Figure 17).

Figure 17. Sudbury Temperature Records.



The temperature record does not show a consistent temperature increase over the period of TP increase and so it may not play a strong role in the observed responses. The role of internal load is feasible but can only be speculative in the absence of more detailed assessment.

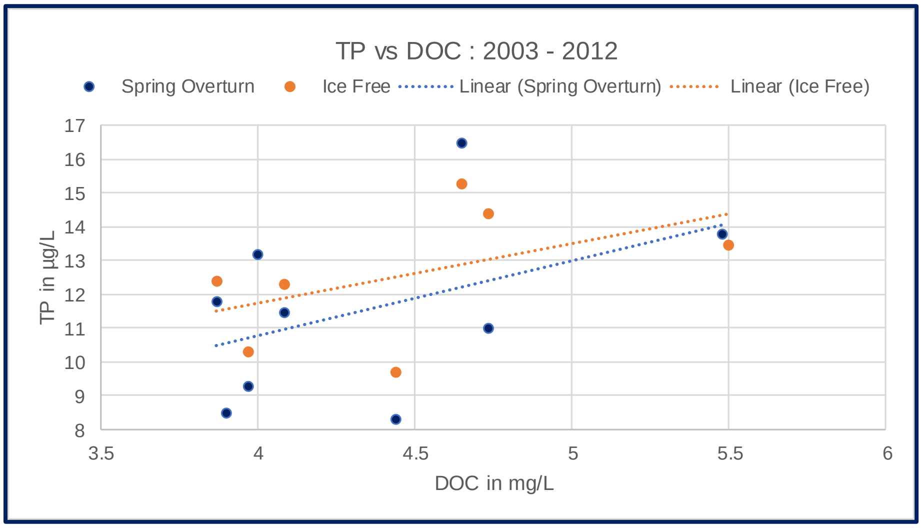
4.3.2 Precipitation, Winter Snowpack and DOC

Changes in precipitation could alter the export of DOC and associated phosphorus into the lake. Section 3 showed that annual measurements of spring overturn and ice-free TP were increasing in statistically significant trends along with increases in DOC. TP concentrations were highest in May and decreased between May and late summer. Detailed temporal data series showed that DOC increased from 2006 – 2012 and that phosphorus concentrations measured in May, June, July and September increased over the same time frame while August and October concentrations were stable. Although there were no seasonal differences in DOC concentrations, the seasonality of TP measurements and observations of reduced Secchi depth in spring suggested that loadings were highest in the spring when snowmelt and spring precipitation could influence export to the lake.

Although DOC concentrations have been rising in south-central areas (Muskoka-Haliburton) of the PreCambrian Shield, TP concentrations have been stable or are falling in the same areas (Palmer et al

2011). The Nepahwin Lake watershed is largely urban, however, and the non-urban portions of it have been altered by, and are currently recovering from, decades of smelter deposition. The DOC-TP dynamics may therefore differ from those of south-central Ontario. Although there was a positive relationship between DOC and TP for data collected from 2003 – 2012 in Nepahwin Lake, the relationship was not statistically significant (Figure 18).

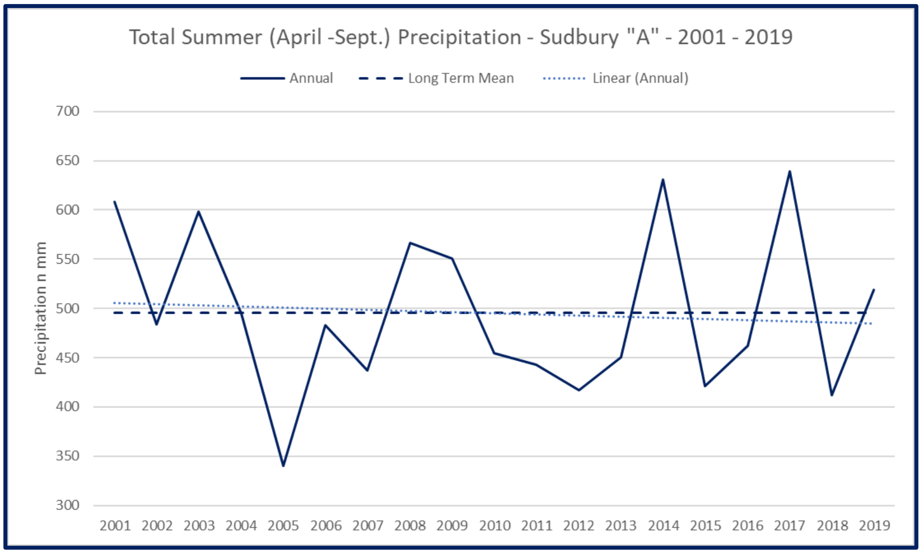
Figure 18. TP vs DOC in Nepahwin Lake.



Dillon and Molot (2005) reported a very strong correlation between DOC export from lake catchments and depth of runoff, that runoff was the primary determinant of DOC load to lakes and that export to lakes decreased in drier and warmer years. The amount of runoff is directly related to precipitation and so the role of precipitation in the DOC/TP increases in Nepahwin Lake were investigated – under a hypothesis that increasing DOC and TP were related to higher precipitation.

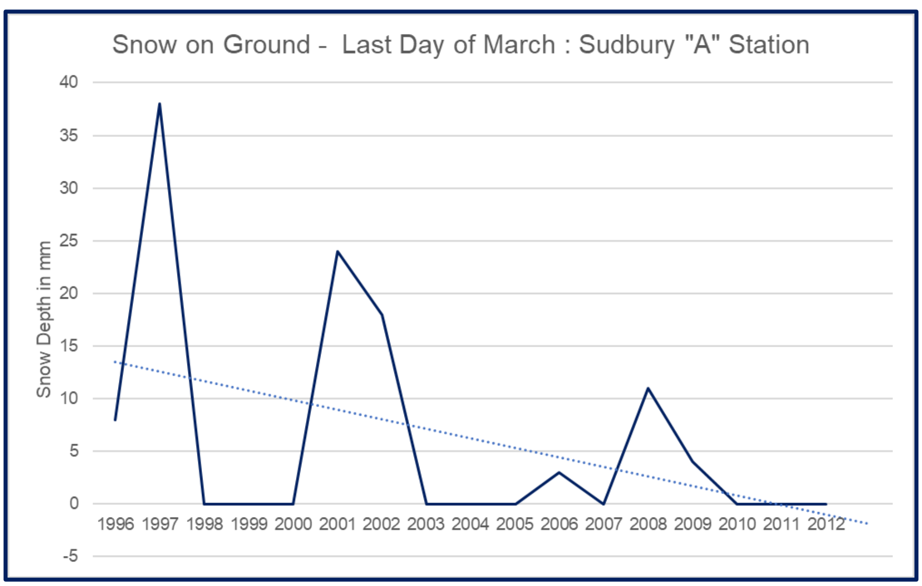
Total precipitation, whether annual, spring-summer (April – September) or May declined between 2001 and 2019 (Figure 19) although there were alternating years of below and average precipitation, such that drier conditions could be present and cycling between drought and flood conditions could alter DOC and TP export.

Figure 19. Summer Precipitation Record: 2001 - 2019.



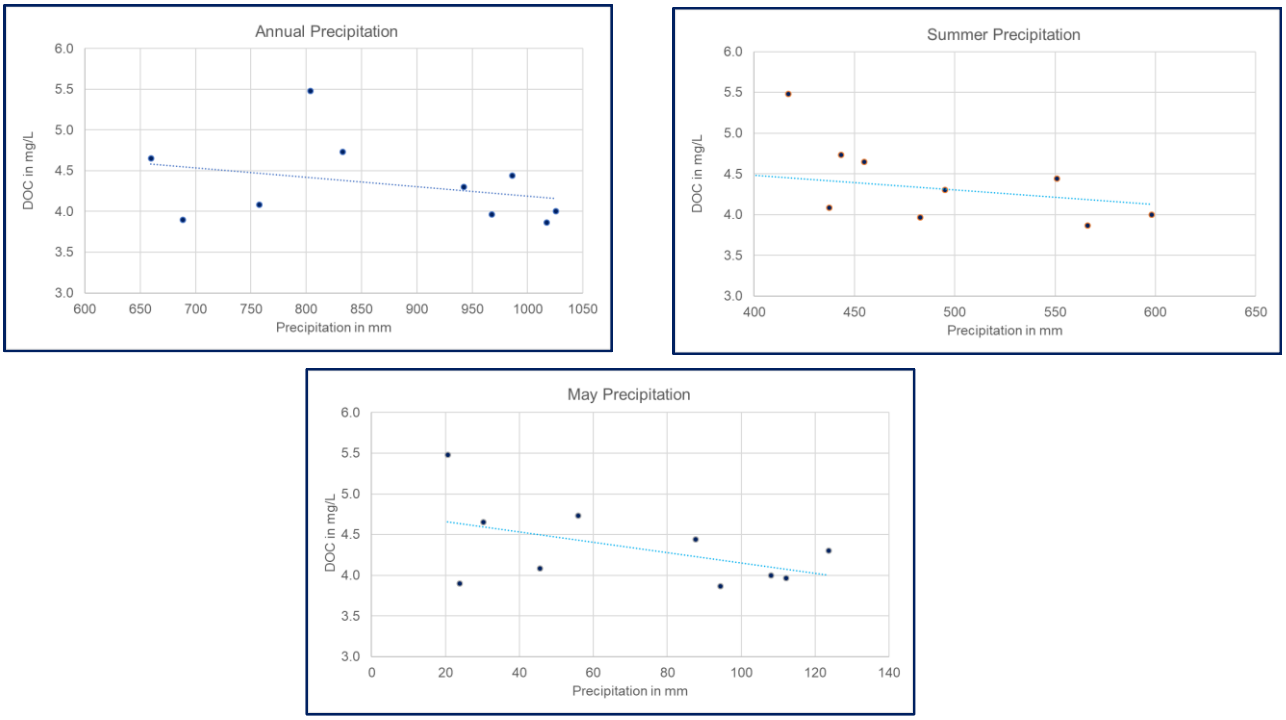
The amount of winter snowpack in Sudbury declined over the 6 year period on which DOC and TP increased in Nepahwin Lake (Figure 20) resulting in drier spring conditions in the Nepahwin Lake watershed which would reduce the depth of runoff during the spring, in contrast to the increases in DOC documented over that period.

Figure 20. Depth of Snowpack in Sudbury 1996- 2012.



Finally, DOC concentrations in Nepahwin Lake showed negative relationships with annual, total and May precipitation, declining as precipitation decreased (Figure 21).

Figure 21. Precipitation vs DOC in Nepahwin Lake.



In summary, although both DOC and TP have increased in Nepahwin Lake, the increases are not related to climate, which has become warmer and drier over the period of record, in contrast to the relationships reported by Dillon and Molot (2005). The Nepahwin Lake watershed, in contrast to the watersheds described by Dillon and Molot (2005), is highly urbanized and altered by smelting activities. The increased DOC and TP may be related to alterations between wet and dry years or responding to other factors than climate which would require more detailed study.

4.3.3 2017 and 2018

The impact of climate on elevated TP concentrations in 2017 and 2018 were also assessed in relation to:

- Cumulative total precipitation (mm) that occurred the day of and two days prior to sampling to see if TP concentrations are influenced by precipitation patterns,
- The number of days of freeze/thaw (i.e. negative to positive temperature swings) that occurred the day of and 6 days prior to sampling to see if TP concentrations are influenced by freeze/thaw (i.e. runoff) events,
- Maximum wind gusts measured on the day of sampling to determine if wind mixing was a determining factor.

Total precipitation and max wind gusts were low in 2017 and 2018 compared to other years while the days of freeze/thaw were low in 2018 and within the range (0 – 7 days) noted during other sampling years in 2017 (3 days; Table 11). No obvious cause and effect were noted during the assessment of these 3 potential climate causal factors.

Table 11. TP Concentrations and Potential Climate Causal Factors

Year	Sample Date	TP (µg/L)	Total Precipitation (mm)	Days of Freeze/Thaw	Max Wind Gust (km/h)
2005	16-May	13.9	3.8	2	35
2006	15-May	9.3	17.2	0	<31
2007	17-May	11.5	4.4	0	<31
2008	22-May	11.8	8	1	34
2009	26-May	8.3	5.6	0	<31
2010	14-Apr	16.5	0	7	<31
2011	27-May	11	8.1	0	37
2012	11-May	13.8	3.1	2	37
2013	23-May	14.9	34.6	0	59
2015	20-May	13.1	6.7	2	44
2016	12-May	15.5	19.6	3	35
2017	11-May	20.4	0.3	3	33
2018	18-May	19.7	0	0	<31

Average monthly air temperatures from May - October were calculated from 2005 to 2018 to determine if monthly temperatures have influenced stratification patterns in the lake (Table 12). Average monthly air temperatures in 2017 and 2018 were well within the range of temperatures observed in other years.

Table 12. Average Monthly Air Temperatures (2005 - 2018)

Year	May	June	July	August	September	October
2005	11.1	19.6	20.6	19.3	15.8	8.5
2006	13.1	17.3	20.4	17.5	12.1	5.1
2007	12.4	17.7	18.4	18.4	14.4	9.2
2008	9.3	17.1	18.7	17.7	13.1	5.7
2009	9.5	16.1	16.7	17.1	14.3	4.5
2010	14.6	16	21	19.4	12.3	6.3
2011	12.1	16.4	21.3	19.1	14.2	8.2
2012	13.7	18.1	21	18.6	12.9	6.6
2013	12.5	15.8	18.9	17.4	12.7	7.3
2014	11.3	17.1	16.9	16.8	12.6	6.2

2015	12.5	15.9	18.8	18.1	16.3	5.3
2016	12.3	16.5	19.6	20.0	15.3	7.4
2017	10.2	15.9	18.1	16.3	15.3	9.7
2018	13.3	16.5	20.9	19.5	14.1	3.8
Mean	12.0	16.9	19.4	18.2	14.0	6.7
Min	9.3	15.8	16.7	16.3	12.1	3.8
Max	14.6	19.6	21.3	20.0	16.3	9.7

4.4 Spiny Water Flea

Spiny Water Flea (*Bythotrephes longimanus*) are an invasive species that can alter zooplankton populations and entire food chains in lakes which could result in distorted nutrient concentrations through altered predator-prey dynamics. Spiny water fleas have been observed in McCharles Lake, Nepahwin Lake, Panache Lake, Lake Wanapitae and Wavy Lake (City of Greater Sudbury, 2020a). A detailed assessment of the impacts on Spiny Water Flea was not however completed because 1) it is unknown when Spiny Water Flea was introduced into each lake, 2) TP data from the other lakes is not sufficient to confidently assess long-term trends, and most importantly 3) zooplankton assemblages are shifting as lakes recover in the Sudbury area so the impacts of Spiny Water Flea would be difficult to parse out without focused study.

4.5 Watershed Influences

There is potential for a wide variety of watershed impacts on TP concentrations in Nepahwin Lake because of the urban watershed and residential, commercial and industrial land uses. The Idywylde Golf Course is located along the northern shore of Nepahwin Lake and golf courses have the potential to elevate TP concentrations in downstream lakes through fertilizer application and stormwater runoff. The Idywylde Golf Course has however been in operation for 98 years were consistent with other years and monitoring results did not indicate any issues with runoff (Arnott, T. (Idywylde Golf Course General Manager and C.O.O.), personal communication, March 2020). The golf course is also part of the Audubon Cooperative Sanctuary Program and a variety of Best Management Practices are implemented to minimize downstream nutrient enrichment:

- The course contains a minimum 3 m plant buffer zone per the National Golf Course Owners Association,
- Fertilizer utilized is foliar as opposed to granular for more efficient uptake by plants, and
- Monitoring is completed in accordance with Audubon's requirements for water quality management and no impacts were identified in 2017 or 2018 (Arnott, T., personal communication, March 2020). Fertilizer application and runoff have in fact declined over the last 10 years as a result of improved application (Arnott, T., personal communication, March 2020).

4.6 Bennett Lake

Bennett Lake is located 200 m east of Nepahwin Lake and drains into it through an intermittent watercourse that is controlled by beaver activity (Hallman, 1996; Photographs 1 and 2). Bennett Lake is 13.6 ha in size and has a maximum depth of 2 m (City of Greater Sudbury, 2020b). We didn’t find water quality information, but the lake is tea-stained (Hallman, 1996) and is likely naturally high in both DOC and TP, both of which are increasing in Nepahwin Lake. Drainage from Bennett Lake could impact TP concentrations in Nepahwin Lake depending on beaver activity and water levels, but no data are available to assess this potential linkage.

Photographs 1 and 2. Bennett Lake Outlet (top) and Beaver Dam (below)

4.7 Lake Characteristics

Several results discussed in Section 3 could directly or indirectly affect TP concentrations in Nepahwin Lake but it is difficult to quantify these impacts based on available data. TP concentrations are much higher in the bottom waters than near surface, and bottom water anoxia is evident at multiple sites, so internal loading from sediments in Nepahwin Lake is a source of nutrients. It is not possible to accurately quantify the amount of internal loading that occurred in 2017 and 2018 based on available data. Lake contour volumes should be calculated so that Mean Volume Weighted Hypolimnetic Dissolved Oxygen (MVWHDO) concentrations can be calculated based on dissolved oxygen profiles collected between August 15 and September 15. MVWHDO can then be used as a single standardized metric to track deep water anoxia over time for comparison with TP concentrations. Oxygen status and TP concentrations (surface and bottom) under ice should be measured at the end of winter to determine if internal loading over winter contributes to the high measurements of TP in spring.

Secchi disk depths were lowest in May and October, likely as a result of spring freshet or turnover and/or stormwater runoff. Low Secchi disk depths could indicate elevated total suspended solid concentrations from runoff which could be driving higher TP concentrations in May. Although DOC concentrations have been increasing in Nepahwin Lake along with TP they were not historically elevated in May or October, so elevated TP concentrations are not being driven by seasonal DOC inputs from the watershed.

5. Conclusions

Total phosphorus concentrations have been increasing in Nepahwin Lake since 1978 and reached 20 µg/L in recent years. Phosphorus concentrations in lakes are controlled by a multitude of biotic and abiotic conditions and Nepahwin Lake and its watershed are changing as a result of recovery from smelting activities and ongoing climate change. Nepahwin Lake also undergoes hypolimnetic anoxia and resultant internal loading but their role in the lake enrichment cannot be assessed with existing information. Although there are many interacting influences and TP has increased in tandem with DOC, it is not clear what has driven increased DOC or TP concentrations. The most likely reason for enriched phosphorus, as determined by review of the City of Greater Sudbury Water Quality Model (HESL 2014a) and the history and characteristics of the watershed (Hall 1996), is urban runoff. Runoff from urban areas is reflected in the observations of increased chloride concentrations - phosphorus enrichment would come from the same pathway.

5.1 Management Recommendations

The City of Greater Sudbury has developed and implemented management recommendations designed to improve water quality in lakes in the area, including Nepahwin Lake. The Lawn Fertilizer By-Law (By-Law 2012-58) was implemented on April 1, 2012 (City of Greater Sudbury, 2020c). The By-Law restricts utilization of lawn fertilizers with phosphorus within the City of Greater Sudbury except when starting a new lawn, when a test shows the soil’s phosphorus level is not sufficient to support a lawn, for agricultural applications, or for sod farms and golf courses.

The City is also focused on balancing the impacts of road salt on lakes while still maintaining safe roads. GHD (2017) completed the 2016 Salt Management Plan which included a description of the winter maintenance program, continuous improvement practices and strategies, monitoring and updating measures and 2016 inspection results. The City continually looks to mitigate impacts associated with road salt application through the following efforts:

- Periodic review of industry best practices
- Continuous education and training of City and Contract personnel
- Periodic updating of the City's Salt Management Plan
- Optimizing response to winter weather events
- Reducing the number of roads that received salt in accordance with the City's winter maintenance policy
- Improving salt application equipment
- Increasing public awareness of how road salt is used in the City (City of Greater Sudbury, 2020d)

Concentrations of TP and chloride are elevated in Nepahwin Lake despite the development and implementation of the Lawn Fertilizer By-Law and the Salt Management Plan. It appears that the likely cause of increased TP and chloride concentrations is urban runoff so additional management options should be developed and implemented based on input from City staff, Nepahwin Lake Stewardship Group, and local scientists with local experience and knowledge of Nepahwin Lake and it's watershed (e.g. Dr. John Gunn). We have identified the following preliminary management recommendations for consideration by such a working group:

1. Identify major stormwater inputs into Nepahwin Lake and associated treatment infrastructure. Explore the potential to retrofit or improve stormwater management infrastructure to reduce nutrient loading to Nepahwin Lake. Calculate TP reductions associated with infrastructure improvements using a Phosphorus Budget Tool such as that developed by HESL for application in the Lake Simcoe Watershed (HESL 2012) or for use in phosphorus-sensitive watersheds (HESL 2014). Reductions could then be input into the City of Greater Sudbury Water Quality Model (HESL 2014a) to model the impact of TP load reductions on TP concentrations in Nepahwin Lake.

2. Review the age and functionality of sanitary sewers in the Nepahwin Lake watershed which could be leaking and contributing nutrients to the Lake.

3. Review existing shoreline development and associated Best Management Practices (e.g. shoreline buffers). Encourage stewardship through education and potentially enforcement in relation to relevant Official Plan Policies (e.g. Vegetative Buffers - 8.4.7).

4. Complete a phosphorus budget to quantity loadings from major sources

5.2 Monitoring Recommendations

In order to best monitor the situation moving forward we recommend the following:

1. Collect annual spring-overturn samples for TP and DOC and record Secchi disk depths to continue to allow for an assessment of long-term trends.

2. Collect monthly TP samples and Secchi disk depths during the ice-free period to better understand dynamics in the lake over time.

3. Collect dissolved oxygen data throughout the water column during late summer (August 15 to September 15) to track changes in deep water anoxia over time and collect samples at one metre off bottom for TP and iron to assess internal load.

4. Calculate lake contour volumes so that late summer mean volume weighted hypolimnetic dissolved oxygen (MVWHDO) can be calculated and used as a simple metric of lake oxygen status moving forward.

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