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Environmental Sciences Ltd.

Trout Lake Watershed Study and Management Plan – Background Report

Prepared for: The Corporation of the City of North Bay
Job #: J210014

September 20, 2021

Draft Report

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September 20, 2021 HESL Job #: J210014

Beverley Hillier
City of North Bay
Manager, Planning and Building Services

Dear Ms. Hillier:

Re: Trout Lake Watershed Study and Management Plan – Background Report

Our approach to the development of a management plan for Trout Lake included several phases, the first of which was designed to review the existing relevant lake water quality and land use planning information for the study area.

In this Background Report, we have gathered water quality data from multiple sources and where sufficient data were available, assessed both the spatial and temporal variability in Trout Lake. Our goal was to characterize water quality conditions in relation to municipal (total phosphorus = 7 μg/L, Mean Volume Weighted Hypolimnetic Dissolved Oxygen = 8 mg/L) and provincial water quality objectives, and assess the impact of historical development on water quality in Trout Lake. Data and monitoring efforts have also been reviewed to provide recommendations related to future monitoring based on our findings and to provide a metric with which to track the effectiveness of management recommendations.

In general, we found no significant change over time in nutrient concentrations in Trout Lake, however we did note different water quality in Four Mile Bay compared to the main basin of Trout Lake. In Delaney Bay we noted a decrease in water clarity over time, however supplementary data to support the cause of this change was limited.

We have drafted several recommendations on future monitoring in Trout Lake but expect these to continue to evolve as the project proceeds. Please do not hesitate to contact me if you have any questions or concerns.

Sincerely,
Per. Hutchinson Environmental Sciences Ltd.

Brent Parsons, M.Sc.
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Signatures

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Executive Summary

J.L. Richards and Associates Limited (JLR) and Hutchinson Environmental Sciences Limited (HESL) were retained by the City of North Bay (City), Municipality of East Ferris (East Ferris) and the North Bay-Mattawa Conservation Authority (NBMCA) to complete the Trout Lake Watershed Study and Management Plan (Trout Lake Study). This Background Report is the first deliverable of the project and includes a review of existing and relevant lake water quality information to determine the general health of the lake and how water quality may have changed over time.

A wide variety of background reports and datasets were gathered to characterize water quality conditions in Trout Lake and compare water quality conditions spatially and temporally. General limnology conditions were characterized based on data extracted from reports and provided by NBMCA, but more intense statistical analyses and reporting focused on total phosphorus, mean volume weighted hypolimnetic dissolved oxygen, Secchi disk depth and phytoplankton assemblages.

Historical and more recent data indicate that water quality in Trout Lake is excellent and nutrient concentrations are low. Significant monitoring effort has been invested in the management of water quality of Trout Lake and there is little evidence of a marked impact of development on the lake. Long-term phosphorus data collected from 2000 to 2019 has not shown any significant change in concentrations at the eight long-term monitoring locations on the lake, suggesting that any potential phosphorus loading form recent (i.e., 20 years) development has not occurred or has not been captured by the current monitoring program. Historical data analysis (1975 – 2002) from previous reporting (1977 – 1986 [CRA 1988], 1975 – 2002 [GLL 2002]) have not recorded an increase in phosphorus in the lake over time.

Ice free average total phosphorus concentrations have however exceeded the municipal Minimum Water Quality Objective of 7 μg/L at individual sites and in specific years when sites are combined. Total phosphorus concentrations are variable year-to-year but it is clear that TP concentrations are higher in Four Mile Bay, with annual MWQO exceedances in 2008 (8.32 μg/L), 2009 (7.69 μg/L) and 2011 (8.98 μg/L; Table 2). Mean Volume Weighted Hypolimnetic Dissolved Oxygen Concentrations were also different between Four Mile Bay and the Main Basin resulting in multiple concentrations lower than the municipal regulations (8 mg/L) in Four Mile Bay (1993, 1994, 2015, 2018) and only a single concentration lower than municipal regulations in the Main Basin (1994). Note however that the data which MECP used to complete these calculations were heavily interpolated.

A significant decrease in water clarity measured through Secchi Disk Depth in the most developed basin of Trout Lake (i.e., Delaney Bay) may suggest a localized impact of runoff from urban development, roads and railroads on water quality within the Bay. Exploration of policies and practices to control sediment, erosion and runoff into the lake from urban areas may help to mitigate further reductions in water clarity within Delaney Bay.

Future project phases will include a more quantitative assessment of the impact of development on water quality through evaluation of the Lakecap Model of nutrient status, of water quality data in relation to development data at a broad scale as well as evaluation of more site-specific monitoring data associated with individual development applications (i.e., lot level or subdivision level). Subsequent stages will be focused on consultation and development of management recommendations and related reporting.

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1. Introduction

J.L. Richards and Associates Limited (JLR) and Hutchinson Environmental Sciences Limited (HESL) were retained by the City of North Bay (City), Municipality of East Ferris (East Ferris) and the North Bay-Mattawa Conservation Authority (NBMCA) to complete the Trout Lake Watershed Study and Management Plan (Trout Lake Study). The Trout Lake Study is being completed in partnership with the City, Municipality of East Ferris, North Bay-Mattawa Conservation Authority (NBMCA) and in consultation with a variety of residents and stakeholders. The Trout Lake Study is being completed to review lake water quality data to understand the health of the lake, determine the effectiveness of management actions to date, and adjust the management approach to reflect this new understanding and evolving best practices in this field.

The project will be completed using a three-phase process as described in Table 1. This Background Report is the first deliverable of the project and includes a review of existing and relevant lake water quality information to determine the general health of the lake and whether water quality has changed over time. The general description of lake health and trends over time are important building blocks for the Trout Lake Study and will be expanded in future project phases and deliverables to try and determine if development has impacted water quality in the lake. Updated management recommendations will be developed based on data presented in this report, future Lakeshore Capacity Modelling and review of municipal best practices for planning and consultation.

Table 1. Project Phases and a Summary of the Related Scope and Deliverables from each Phase.

Phase	Scope	Deliverables
Understanding	Review existing and relevant lake water quality and land use planning information	Background Reports
	Complete Lakeshore Capacity Modelling	Updated Lakeshore Capacity Model
	Review municipal best practices and synthesize information from the Background Report and Lakeshore Capacity Model	Issues, Opportunities and Constraints Report
Directions	Consultations with residents and stakeholders to receive feedback	Directions Report
Planning	Consultation with public and stakeholders on Directions Report	Final Report

2. Methodology

Trout Lake is a deep, clear, oligotrophic lake with excellent water quality (Miller Environmental Services Ltd. 2000). It has an area of 1,887 ha and is comprised of two basins: Four Mile Bay and Trout Lake (MECP undated). Four Mile Creek is the main inflow to the lake and the main outflow is the Mattawa River which flows to Turtle Lake. Maximum depth of Four Mile Bay is 27 metres, while the deepest basin of Trout Lake is 63 metres deep, with an average depth of 16.9 m across Trout Lake.

A wide variety of background reports and datasets were gathered to characterize water quality conditions in Trout Lake and to compare water quality conditions spatially and temporally.

2.1 Background Material

2.1.1 Reports

The following reports were reviewed as part of the background review:

- Trout Lake Watershed Management Study (CRA 1988)
- Inventory Information for the Trout Lake Watershed (NBMCA 1985)
- Phosphorus Control Site Plan – Lot 6 – Eastview Development (HESL 2011)
- An Integrated Approach to Watershed Management Planning for Trout Lake, Ontario (McBean et al. 1990)
- Hydrodynamic and Water Quality Numerical Modelling in Trout Lake (MECP 2019)
- Preliminary Evaluation of the Water Quality of Trout Lake (MOE 1973)
- Review of the Vulnerability Scoring and Adjustment to IPZ Delineation for the North Bay Intake (HESL, 2016)
- Return of the Ouananiche to Trout Lake (Fitchko et al. 1996)
- Trout Lake Reservoir – A Water Balance Study (Rees 1974)
- TLCA News – Summer 2021 (Trout Lake Conservation Association, 2021)
- Lake Capacity Assessment: Trout Lake (MECP, Undated)
- Trout Lake Parasite Study (Miller Environmental Services Ltd. 2000)
- Trout Lake Pollution Control Plan Sewage Disposal Systems Inventory and Analysis (Northland Engineering Limited and Beak Consultants 1992)
- Trout Lake Pollution Control Plan – Limnology and Hydrology (Northland Engineering Limited and Beak Consultants Limited 1992)
- Trout Lake Rainwater Water Quality Analysis for Phosphorus (1987)
- Water Quality Modelling and Assessment: Trout Lake (Gartner Lee Limited 2002)

2.1.2 Datasets

Data were extracted from some of the reports listed in Section 2.11 to characterize water quality conditions in Trout Lake. Data from different datasets or reports were not, however, combined to characterize long-term trends, as differences in sampling and laboratory methodologies, minimum detection limits and sampling locations would impose too many uncertainties in the analysis. Pertinent findings from individual reports were however referenced to help describe limnological conditions or inform findings.

General limnology conditions were characterized based on data extracted from reports and provided as electronic files by NBMCA. Statistical analyses and reporting were focused, however, on key indicators of water quality that are routinely linked to development impacts: total phosphorus (TP), mean volume weighted hypolimnetic dissolved oxygen, Secchi disk depth and phytoplankton assemblages based on the availability and quality of data provided.

A variety of independent datasets were provided by Ministry of Northern Development, Mines, Natural Resources and Forestry (MNDMNRF) and North Bay-Mattawa Conservation Authority (NBMCA). Long-term water quality datasets provided by the NBMCA included data for 47 parameters, however the frequency and period of record of these samples varied significantly. The vast majority of parameters were only sampled in a few sampling events and have not been sampled in over a decade. Total phosphorus and Secchi disk depth provided the most complete long-term records in the data provided: from 2000 to 2019 for TP and 2005 - 2019 for Secchi disk depth. A TP dataset from 1986 - 1993 was also reviewed but analysis of TP was focused on data from 2002 onwards (2002 – 2019) because of improvements in collection and low-level analytical methodologies such as field filtering and sampling directly into glass tubes that are later used during laboratory analysis (Clark et al. 2010).

2.1.2.1 Total Phosphorus

Phosphorus is often the primary limiting nutrient in freshwaters in support of macrophyte and algal growth. Phosphorus enters lakes via external loading from the watershed, precipitation and, in certain conditions, through internal loading from sediments at the lake bottom. Effluent from sewage treatment systems and stormwater runoff may have particularly high loadings and as a result phosphorus concentrations are commonly used to assess the impacts of development on water quality. Excessive growth of plants and algae and subsequent decomposition can result in lowering of dissolved oxygen concentrations in deep hypolimnetic waters due to the oxygen requirements of bacteria and this may degrade fish habitat and in extreme cases result in “fish kills”, a phenomenon where water temperature near the surface of the lake is too warm and oxygen concentrations of the water near the bottom are too low to support fish resulting in a mass die-off.

The City of North Bay has established a more stringent minimum water quality objective (MWQO) through its Official Plan of a measured ice-free seasonal average phosphorous concentration of 7 µg/L. Provincial water management policies and guidelines provide the following interim water quality objective for total phosphorus:

- To avoid nuisance concentrations of algae in lakes, average total phosphorus concentrations for the ice-free period should not exceed 20 µg/L;
- A high level of protection against aesthetic deterioration will be provided by a total phosphorus concentration for the ice-free period of 10 µg/L or less. This should apply to all lakes naturally below this value.

Preliminary data screening noted a significant number of non-detects in the total phosphorus data in 2010. Two-thirds of all sampling collected and analyzed in 2010 were below the analytical detection limit of 2 μg/L (n = 87), which was highly unusual compared to data collected in other years and to our knowledge analyzed at the same laboratory. It is not apparent from the metadata provided if there was a laboratory or sampling methodological issue during 2010 sampling and therefore data was retained in the analysis. We did, however, run site-by-site temporal analysis on data with and without 2010 to ensure it did not significantly impact our results or interpretations of the data.

2.1.2.2 Mean Volume Weighted Hypolimnetic Dissolved Oxygen

Mean Volume Weighted Hypolimnetic Dissolved Oxygen (MVWHDO) at the end of summer is often analyzed in relation to Lake Trout habitat guidelines of 7 mg/L (MOE 2010). The Municipalities of East Ferris and North Bay have identified a more conservative MVWHDO target of 8 mg/L. As mentioned in section 2.1.2.1, development can lead to phosphorus loading which in turn, can lower MVWHDO through decomposition of increased growth of plants and algae.

The volume of the hypolimnion must be determined to calculate MVWHDO from profiles of dissolved oxygen concentration measured between the lake surface and the bottom. The hypolimnion is the bottom section of a stratified lake and the upper boundary of the hypolimnion is determined based on a temperature gradient between two depth strata that is <1°C/m. MOE (2010) policy dictates that sampling is completed between August 15 and September 15 to capture the time of year when oxygen stress in the hypolimnion is the greatest.

2.1.2.3 Secchi Disk Depth

Secchi Disk Depth provides a measure of water clarity which is one indication of the productivity of the lake. For Precambrian Shield lakes, Secchi depth is primarily determined by the amount of Dissolved Organic Carbon (DOC) in the water (Dillon et al. 1986), and this is a function of the amount of wetland in the watershed (Dillon and Molot 1997). High algae growth, however, reduces the penetration of light through the water column and reduces the measured Secchi Depth beyond that related to DOC. Decreases in Secchi Depth over time may therefore be indicative of increased productivity by, for example shoreline disturbance and development activities that increase total suspended solids or phosphorus loading from the watershed.

2.1.2.4 Phytoplankton

As part of recent monitoring programs, data collection has included fluoroprobe measurement of photosynthetic pigments in the water column to estimate algae composition and concentration with depth. Algae is a diverse group of photosynthetic eukaryotic micro-organisms which is comprised of hundreds of thousands of individual species with variable environmental optima and tolerances. As a result, the species present in a lake or stream may be indicative of the environmental conditions including the water quality. Changes in algae, as a result of changes in water quality, may serve as an early warning indicator of risk to other aquatic organisms. Algae data from fluoroprobe measurements in Trout Lake were limited to 2016-2019 and the period of record varied between years. Our analysis focussed on late-August/early-September data at one sampling location (TL4) as data was consistently available in all four monitoring years. We assessed concentrations of pigments from four algal phyla recorded by the fluoroprobe with depth through the water column. Results were compared between years as a measure of interannual variability and to determine if marked differences in algal community or abundance could be linked to activity on the lake as part of future analyses.

2.1.3 Outliers

In relatively small datasets like the Trout Lake dataset, the calculation of average total phosphorus concentration is sensitive to outliers, that is, extreme values that may represent analytical errors or rare events, but which are not representative of the average site condition. Rosner's ESD Many-Outlier Procedure (Rosner's Test; Rosner, 1983) was performed in the R statistical Software Environment, using the "rosnerTest" function of the "EnvStats" package (Millard, 2013), to identify outliers in total phosphorus concentrations collected since 2000 for each Trout Lake monitoring site. This procedure detects high and low extreme values and is not limited for multiple outliers. Statistically significant outliers (at $p<0.05$) were reviewed and removed from the dataset for further analyses.

2.1.4 Censored Data

Censored data are measurements which fall below the detection limit of the laboratory analysis. There is no universally accepted method of treating censored data. For this review, we substituted the value of the detection limit for any data below detection. When a substantial portion of the data is below detection, however, concentrations are overestimated, and statistical analyses may be biased (ANZECC 2000). Parameter records which contained >30% non-detects were therefore not considered for any analyses of statistical inference, e.g., spatial comparisons.

2.1.5 Temporal Trends

We used the Shapiro-Wilk test to assess the normality of the data and determine the most appropriate statistical techniques for its analysis (R Core Team 2013). Non-parametric techniques were shown to be the most appropriate and therefore Mann Kendall Trend analysis was performed using the "mk.test" and "sens.slope" functions of the "Trend" package in R (Pohlert 2017) to assess any long-term changes in total phosphorus concentrations over time (2000-2019) for each site.

The significance of water quality differences between sites was tested using the non-parametric Kruskal Wallis test. Where statistically significant ($p < 0.05$) differences were identified, we performed pairwise post-hoc Dunn's tests to identify which sites differed significantly. Kruskal Wallis and Dunn's tests were performed in R using the core "kruskal.test" function and the "dunntest" function of the Simple Fisheries Stock Assessment Methods (FSA v0.8.11; Ogle, 2021) package. Results were corrected following the Benjamini–Hochberg procedure (Benjamini and Hochberg 1995) to adjust p-values to account for Type I error of multiple comparisons.

2.2 Sampling Locations

Sampling on Trout Lake has taken place over multiple water quality monitoring programs and several watershed management studies. Eight core sampling stations have been consistently sampled across multiple monitoring programs and special studies (Figure 1). Several other stations have been sampled, however the consistency of sampling at these stations limits their usefulness in assessing potential long-term change in water quality.

3. Results

3.1 Background Review Findings

The Trout Lake Watershed Management Study (CRA 1988) was a comprehensive assessment of the Trout Lake watershed that aimed to provide an assessment of watershed conditions, evaluate the relationship between the watershed activities and water quality issues and present management strategies for implementation on Trout Lake. The study found excellent water quality in 1986, with no exceedances of Provincial Water Quality Objectives except for colour and organic nitrogen which exceeded drinking water objectives. An increase in TP was noted between 1986 and 1987 sampling years, however a decrease in chlorophyll a during the same period suggests that the increase in TP did not have a measurable biological impact on the lake. Both lake and stream water quality differed spatially and temporally between the 1986 and 1987 sampling years. Water quality trend assessment compared 1977 and 1986 water quality and found no discernible decline in water quality over the period of record, beyond increased chloride concentrations.

Nearshore measurements did not substantially differ from deep water measurements with the exception of higher nearshore bacteria concentrations (i.e., total coliforms and fecal coliforms) as would be expected due to runoff from urban and developed areas and from natural fecal sources such as waterfowl (CRA 1988). Findings on nearshore and deep-water comparisons were consistent between both the "Preliminary Evaluation of the Water Quality of Trout Lake" (MOE, 1973) and the Trout Lake Watershed Management Study (CRA, 1988).

More recent water quality assessment on the lake was performed in 2002 by Gartner Lee Limited (GLL, 2002) and focused on nutrient concentrations dating back to 1975. Over the 27-year period of record considered, no increase in phosphorus concentrations was noted and the data showed evidence of decreasing concentrations.

Three noteworthy more uncommon stressors to water quality were also noted in the background review: a spill of zinc and lead concentrate, a spill of formaldehyde and introduction of Polyfluoroalkyl Substances (PFAS) in waterways upstream of Trout Lake. The scope of the report and project at large is to define general lake conditions, but these are briefly described for informative purposes and to acknowledge that various anthropogenic stressors associated with various types of development can occur that are often not predicted.

The impact and recovery from an environmental disaster in 1967 was described in "Return of the Ouananiche to Trout Lake" (Fitchko et al. 1996). Trout Lake was one of the few successful stocking efforts of Atlantic salmon ("Ouananiche ") in Ontario and resulted in a documented self-propagating population. On March 7th, 1967, a train derailment near Four Mile Creek resulted in the spill of zinc and lead concentrate which increased concentrations of zinc to 0.39 mg/L in Four Mile Creek downstream of the spill site in September 1979 (Bowman 1979). These concentrations were well above the Provincial Water Quality Objective (PWQO) of 0.03 mg/L (Ministry of the Environment 1984) and the background levels of Trout

Lake (<0.01 mg/L). The spilled resulted in the extirpation of the Atlantic salmon spawning in Four Mile Creek. Following a period of remediation, zinc concentrations declined to below PWQO (i.e., 0.03 mg/L) by 1994/1995 and evidence suggests that the self-sustaining population of Atlantic salmon has been re-established.

In 2012, an overturned tanker truck north of Silver Lady Lane in North Bay leaked Formaldehyde into Trout Lake resulting in a health advisory notice being issued to residents that draw drinking water from the lake, however North Bay's municipal water supply was not affected by the spill (NBPSDHU 2012).

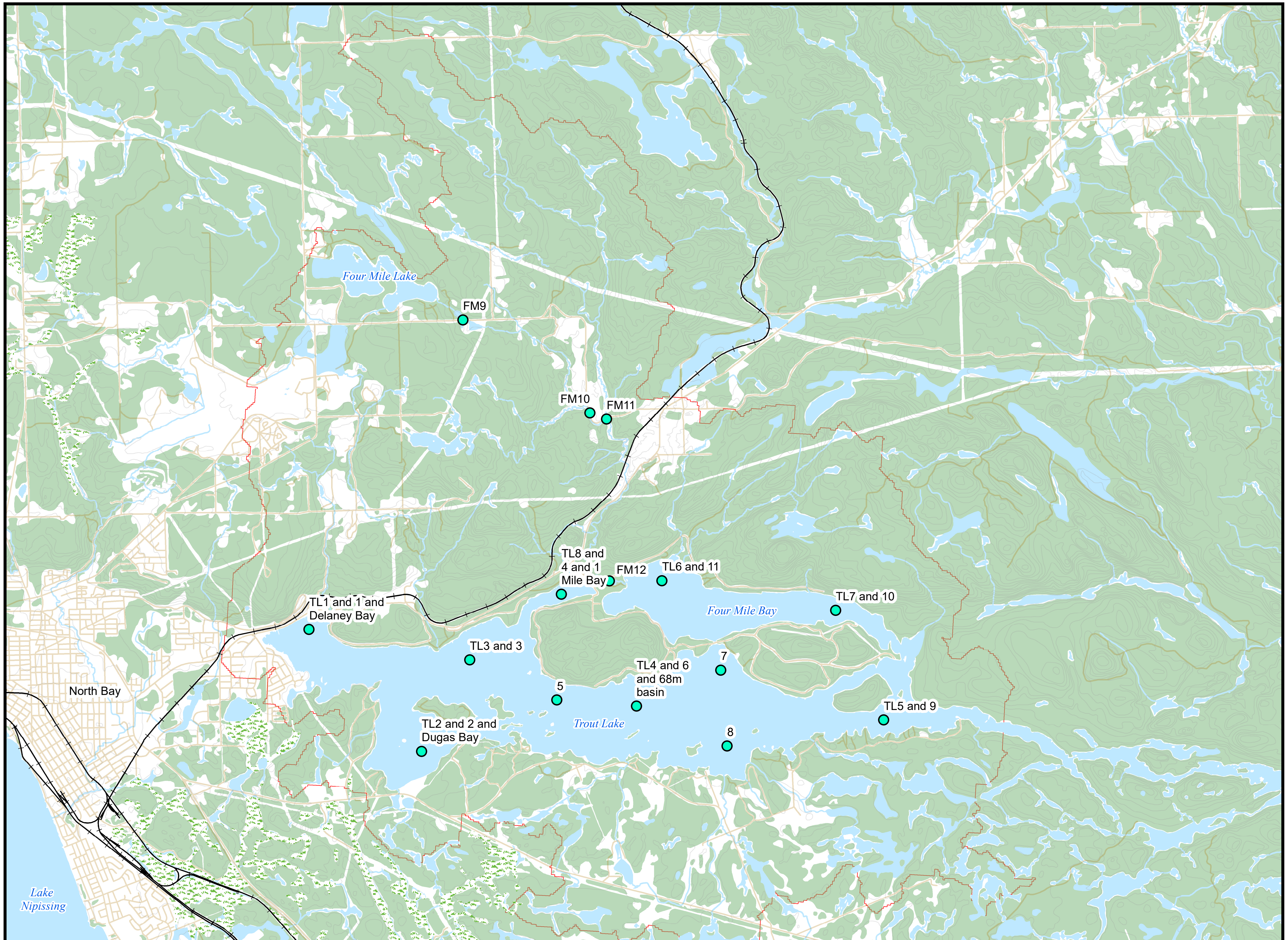
The Trout Lake Conservation Association 2021 newsletter reviewed as part of the background research on Trout Lake included an ongoing discussion of the impacts and risks associated with Polyfluoroalkyl Substance (PFAS). PFAS's are man-made chemicals with a wide range of applications whose original source into Trout Lake is thought to be via Aqueous Fire Fighting Foam. The provincial government has developed a PFAS working standard for eleven different PFAS chemicals of 70 ng/L which are now being applied to Trout Lake. The issues are being investigated by the Department of National Defence (DND) and a remediation agreement between the DND and the City of North Bay has been approved.

3.2 General Lake Characteristics

Total alkalinity is low in Four Mile Bay (7 – 8 mg/L) and Trout Lake (13.4 – 13.8 mg/L), while pH indicates neutral acidity (Four Mile Bay = 6.83 – 7.20; Trout Lake = 7.24 – 7.52; MECP undated). Dissolved Organic Carbon is relatively low as well (3.3 – 5.3 mg/L), indicating that Trout Lake doesn't likely have naturally high TP concentrations.

Total ammonia concentrations in Four Mile Bay (0.005 – 0.011 mg/L) and Trout Lake (0.005 – 0.009), nitrate concentrations in Four Mile Bay (0.031 mg/L – 0.202 mg/L) and Trout Lake (0.033 – 0.194 mg/L) and nitrite concentrations in Trout Lake (0.001 mg/L) were also very low and lower than relevant Canadian Water Quality Guidelines (MECP, undated).

Temperature and oxygen profiles are presented for selected basins of the lake using NBMCA data for 2019 and followed typical seasonal stratification found in dimictic lakes. Note that a full open water season of dissolved oxygen profiles were not available for 2021 at the time of reporting but will be added at a later date. Stratification, the separation of the lake into distinctive thermal layers which do not mix, was established at the 6-7m depth in May/June in Trout Lake and Four Mile Bay and persisted throughout the summer until fall overturn in late September to mid-October (Figure 2). The establishment of thermal stratification in lakes prevents mixing of water between the warm surface waters (epilimnion) and the relatively cool deeper water (hypolimnion) and as a result prevents oxygen rich surface water from mixing with oxygen depleted bottom waters. As oxygen is consumed in the deep water over time by bacterial decomposition and other processes, anoxia may develop and result in internal phosphorus loading to the lake. Development of anoxia in the main basin of Trout Lake does not occur (Figure 3) as there is little loss of dissolved oxygen during the early summer or under ice in February. In Four Mile Bay, dissolved oxygen did not typically fall below 2 mg/L in the hypolimnion, however one occurrence of low oxygen concentration (0.8 mg/L) was documented on June 18, 2007. Long-term data from One Mile Bay (TL8) showed the onset of anoxia by September early such that it is likely susceptible to anoxic conditions on an annual basis (Figure 4).



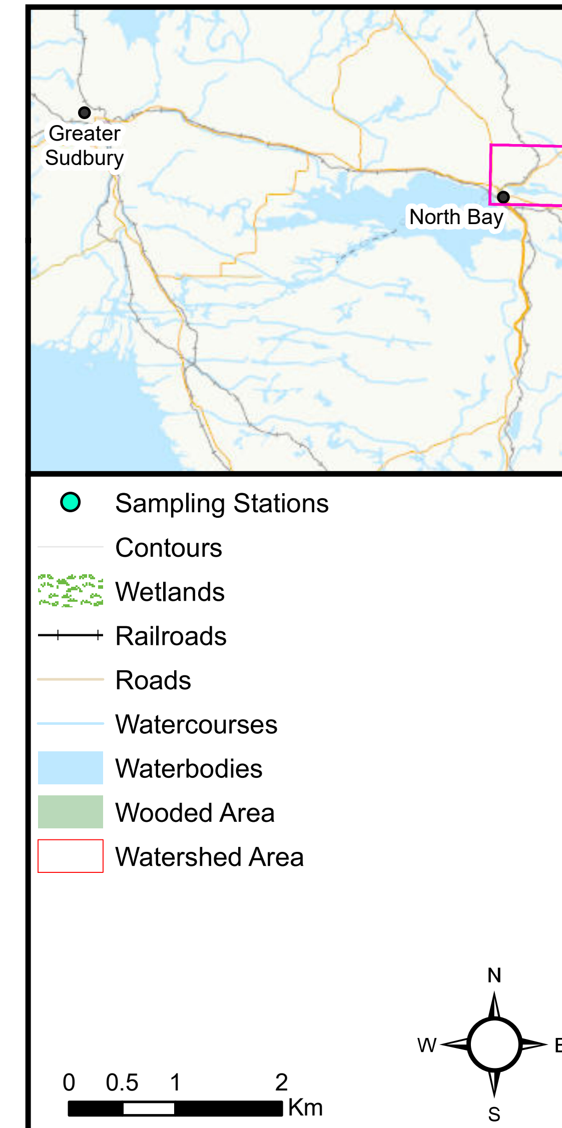


Figure 1:
Sampling Stations

Project Lead: Brent Parsons
Prepared by: Kris Hadley
Data Source: HESL,ESRI Imagery
Coordinate System: NAD 1983 UTM Zone 17N

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Figure 2. 2019 Temperature Profiles from the Central Basin of Trout Lake (TL4) and Four Mile Bay (TL6).

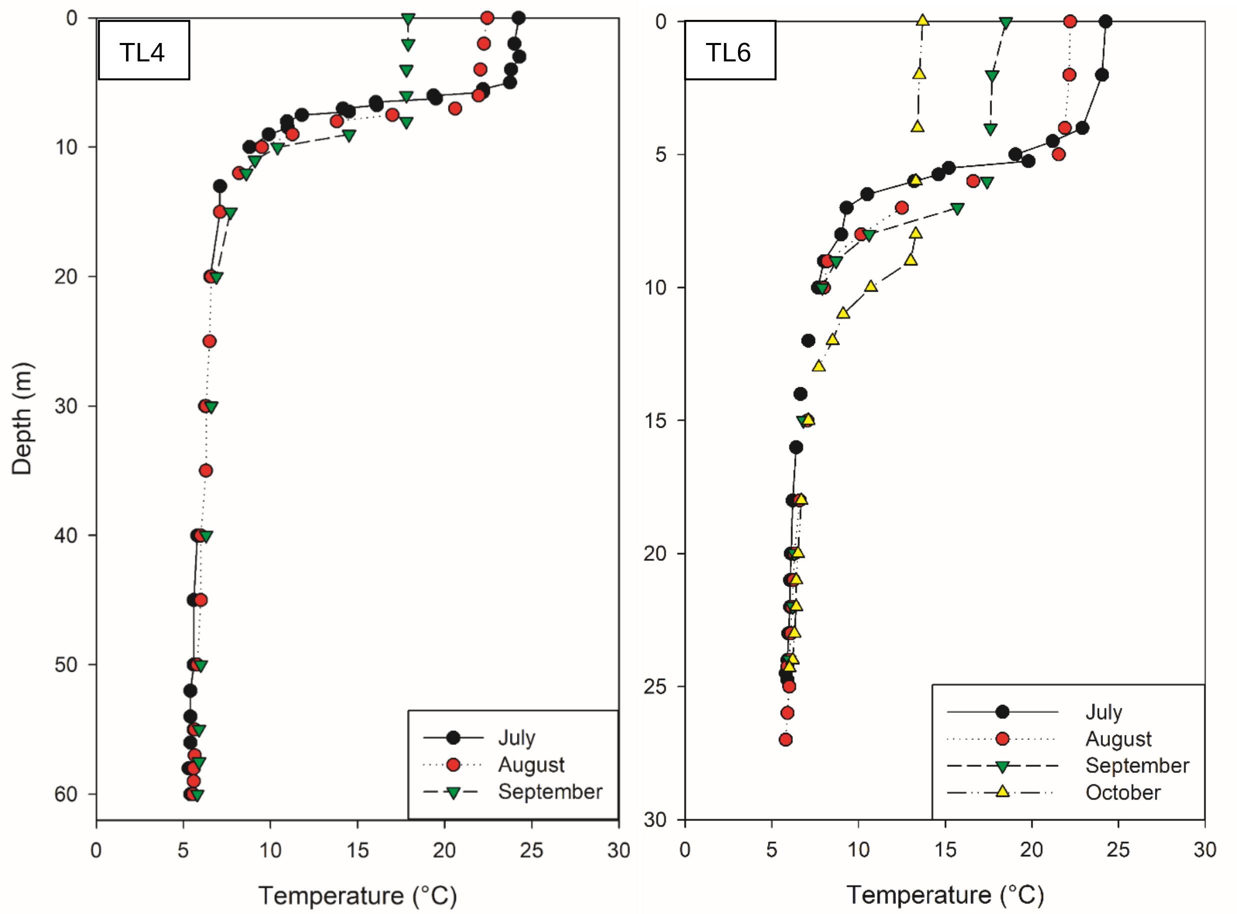


Figure 3. 2019 Dissolved Oxygen Profiles from the Central Basin of Trout Lake (TL4) and Four Mile Bay (TL6).

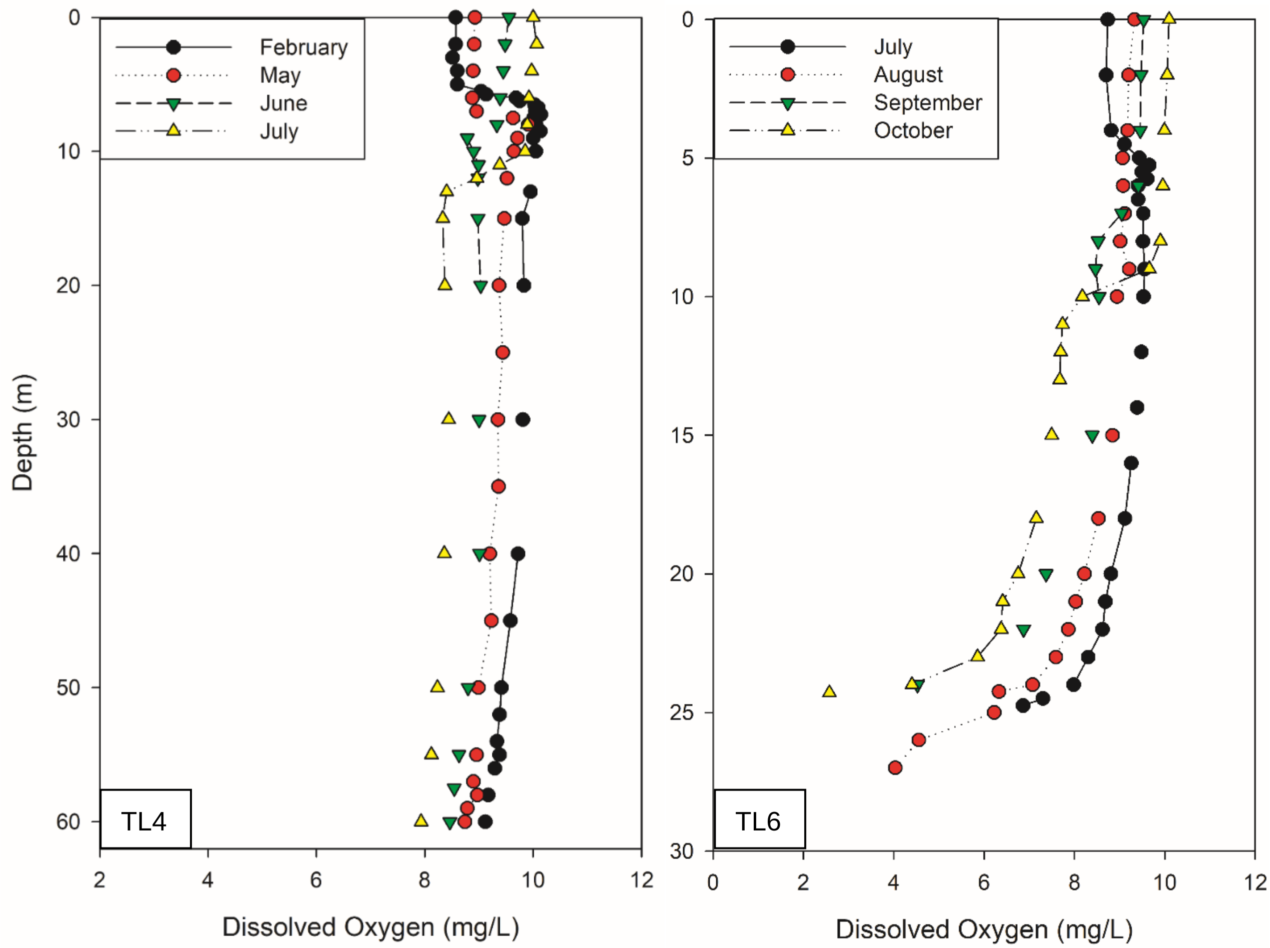
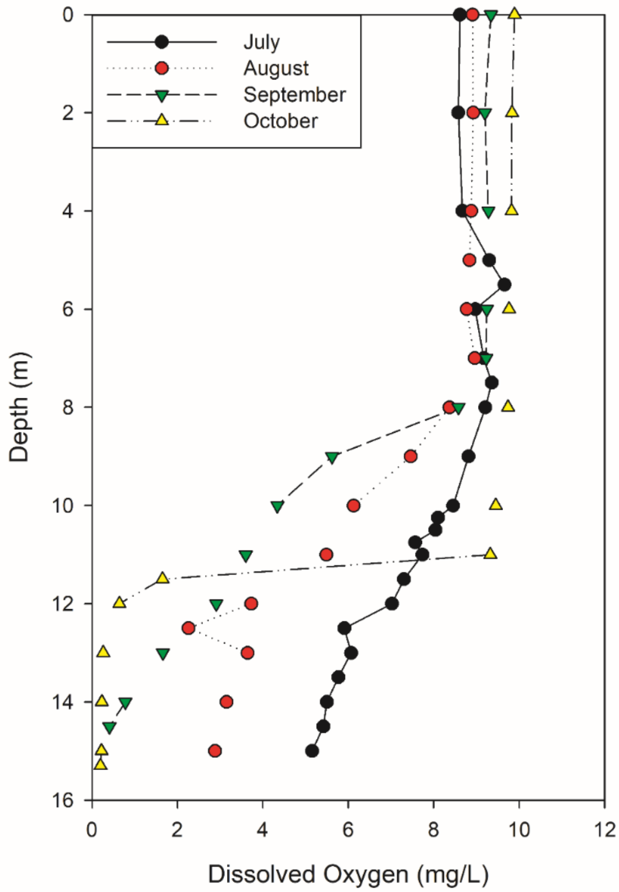


Figure 4. 2019 Dissolved Oxygen Profiles from the One Mile Bay of Trout Lake (TL8).



3.3 Total Phosphorus

3.3.1 Combined Sites

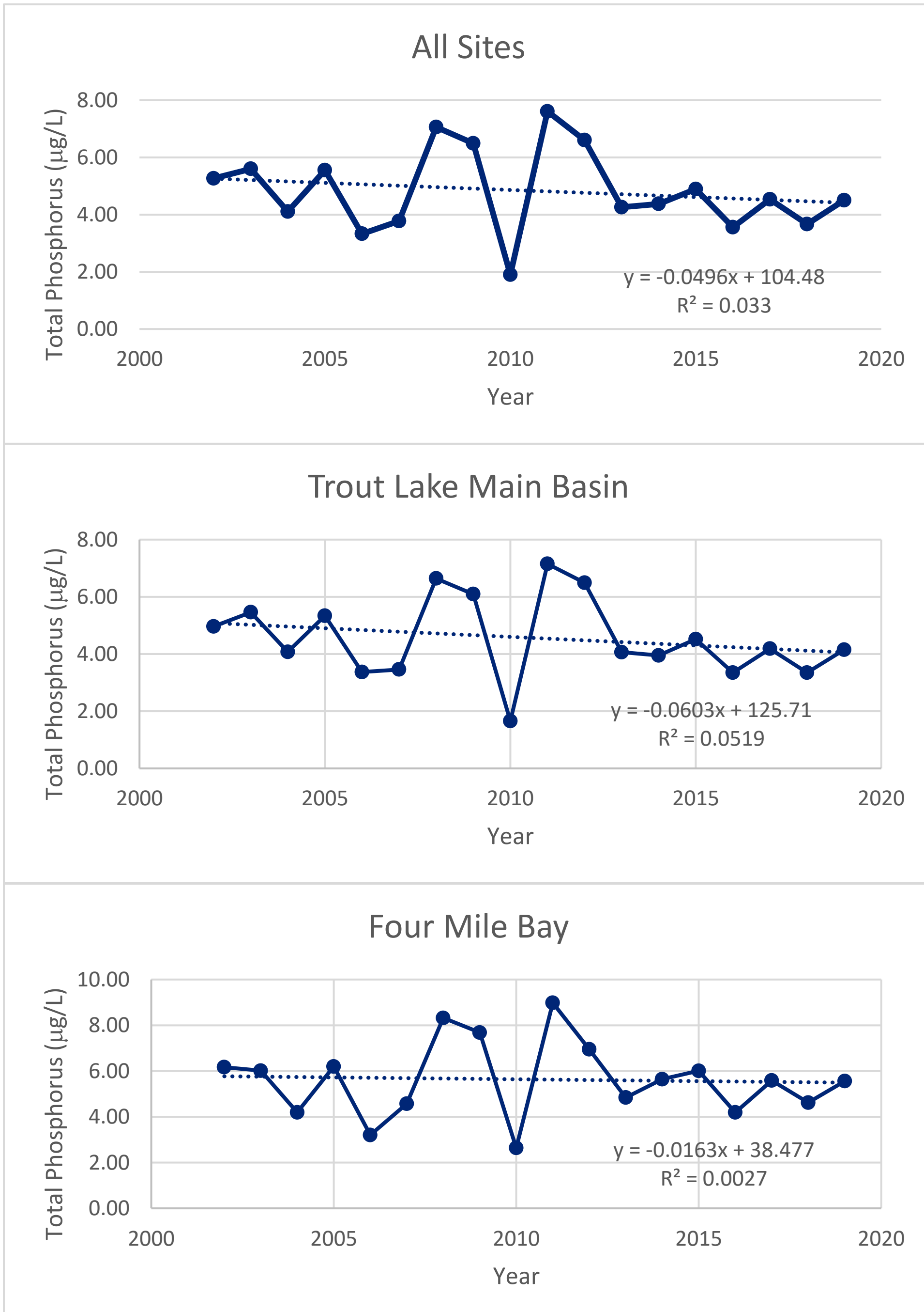
Annual average TP concentrations in Trout Lake, when all sites were combined, were highly variable and ranged from 1.90 to 7.61 µg/L with average concentrations exceeding the City's Minimum Water Quality Objective ([MWQO] 7 µg/L) in 2008 (7.1 µg/L) and 2011 (7.6 µg/L; Table 2). Average annual TP concentrations in the main basin (Sites TL1-5 and TL8) ranged from 1.7 to 6.1 µg/L and exhibited no exceedances of the City of North Bay's Minimum Water Quality Objective ([MWQO] ice-free average of 7 µg/L), while Four Mile Bay (Sites TL6 and TL7) ranged from 3.2 to 9.0 µg/L with annual MWQO exceedances in 2008 (8.32 µg/L), 2009 (7.69 µg/L) and 2011 (8.98 µg/L; Table 2).

When average annual TP concentrations were calculated for all sites, Trout Lake Main Basin and Four Mile Bay, a declining pattern was noted (Figure 5) but low R^2 values (0.003 – 0.05) indicate that the pattern is highly variable. Concentrations were generally elevated in 2008, 2009, 2011 and 2012, and extremely low in 2010.

Table 2. Average Annual Ice-Free Total Phosphorus Concentrations in Trout Lake.

Year	TL1	TL2	TL3	TL4	TL5	TL6	TL7	TL8	All Sites	Trout Lake Main Basin	Four Mile Bay
2002	4.56	5.33	4.90	4.88	4.50	6.45	5.89	5.60	5.26	4.96	6.17
2003	6.02	6.15	6.18	4.14	5.20	5.83	6.20	5.06	5.60	5.46	6.02
2004	3.39	4.40	4.74	3.54	4.73	4.52	3.87	3.64	4.10	4.07	4.20
2005	4.85	4.35	5.80	4.60	7.50	6.22	6.18	4.92	5.55	5.34	6.20
2006	3.98	4.54	2.59	3.47	2.60	3.21	3.20	3.03	3.33	3.37	3.21
2007	3.28	3.63	3.48	3.24		4.04	5.10	3.66	3.78	3.46	4.57
2008	7.00	5.67	5.71	6.13	7.50	8.25	8.39	7.83	7.06	6.64	8.32
2009	6.82	5.64	5.64	6.18	6.18	7.82	7.55	6.09	6.49	6.09	7.69
2010	1.27	1.55	1.52	1.67	2.44	2.60	2.68	1.47	1.90	1.65	2.64
2011	7.24	7.88	7.21	6.42	6.66	8.36	9.60	7.49	7.61	7.15	8.98
2012	6.15	4.25	4.98	8.56	7.33	6.15	7.75	7.67	6.61	6.49	6.95
2013	4.48	3.62	3.72	3.86	4.44	4.83	4.85	4.26	4.26	4.06	4.84
2014	4.35	3.55	3.98	3.70	4.20	5.91	5.38	3.91	4.37	3.95	5.65
2015	4.82	4.07	4.46	4.07	4.78	5.84	6.18	4.90	4.89	4.52	6.01
2016	3.97	3.03	2.68	3.50	3.40	4.24	4.14	3.50	3.56	3.35	4.19
2017	4.81	3.84	3.92	4.48	4.12	5.46	5.71	3.93	4.53	4.18	5.59
2018	3.36	3.26	3.12	3.38	3.50	4.62	4.62	3.46	3.67	3.35	4.62
2019	4.12	3.88	3.88	4.19	4.65	5.73	5.39	4.17	4.50	4.15	5.56
								Minimum	1.90	1.65	2.64
								Maximum	7.61	7.15	8.98
								Mean	4.84	4.57	5.63

Figure 5. Annual Average Ice-Free TP for Combined Sites.



3.3.2 Station-by-Station

Assessment of site-by-site spatial trends in TP in Trout Lake showed highly consistent concentrations across all monitoring stations with the exception of TL6 and TL7 in Four Mile Bay (Figure 5). Median ice-free total phosphorus concentrations in Four Mile Bay were 5.0 µg/L (range = 1.0 - 17.0 µg/L) at both monitoring stations, which is significantly higher than the range of 3.7 to 4.0 µg/L (range = 1 – 18 µg/L) at the six long-term monitoring stations in the main basin.

Open water sites (i.e., TL3 and TL4; Figure 1) and large, relatively open water bays (i.e., TL1 and TL2) on Trout Lake have experienced a single exceedance of the City of North Bay's Minimum Water Quality Objective (ice-free average of 7 µg/L) in 2011 (TL1, 2, and 3) or 2012 (TL4), while in isolated bays (TL6, 7 and 8) and near the Mattawa River outflow (TL5) exceedances have occurred in 3 or 4 years. No exceedances of the MWQO have been recorded since 2012 at any monitoring station on Trout Lake.

Concentrations of TP in Four Mile Creek ranged from 2-160 µg/L with the highest concentrations being recorded in July and August during storm events. However, data from other tributaries on Trout Lake are not readily available for comparison to put the Four Mile Creek water quality data into regional perspective.

No historical exceedances of the PWQO for total phosphorus (10 µg/L) occurred at any of the 8 long-term monitoring stations suggesting a high level of protection against aesthetic deterioration across Trout Lake (Figure 6).

Figure 6. Spatial Trends in Total Phosphorus Concentrations on Trout Lake.

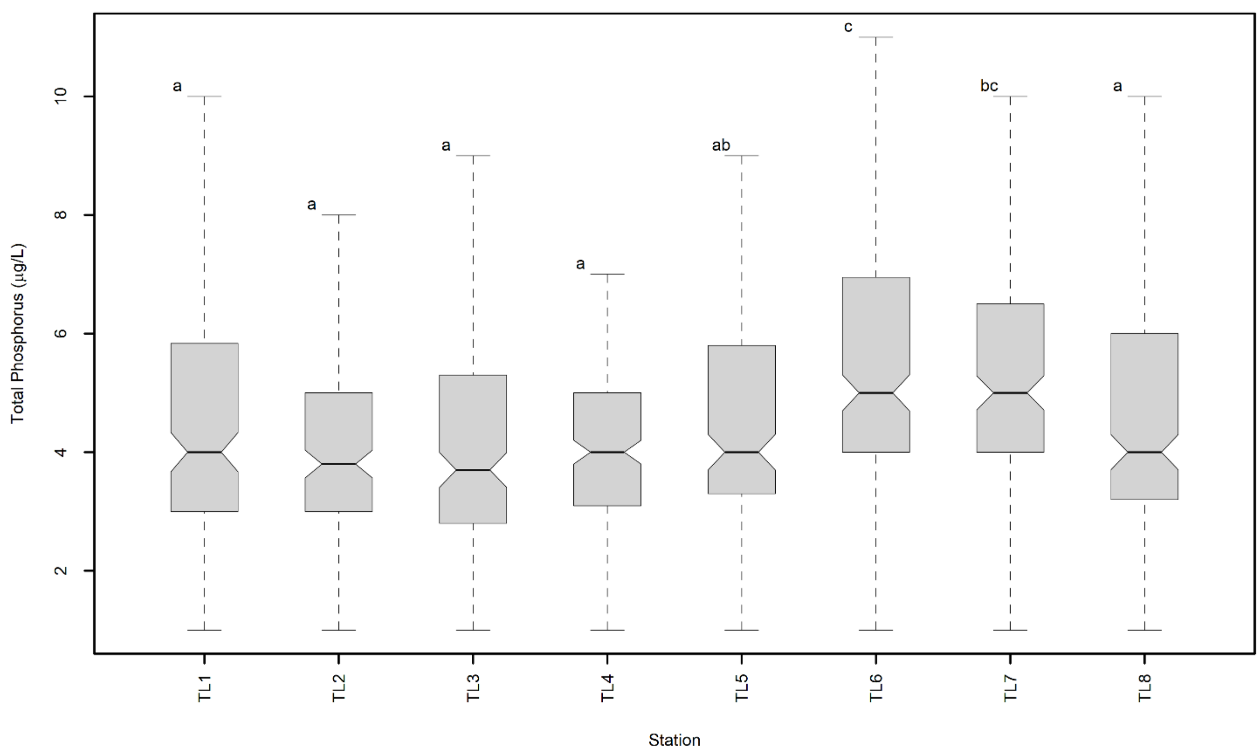
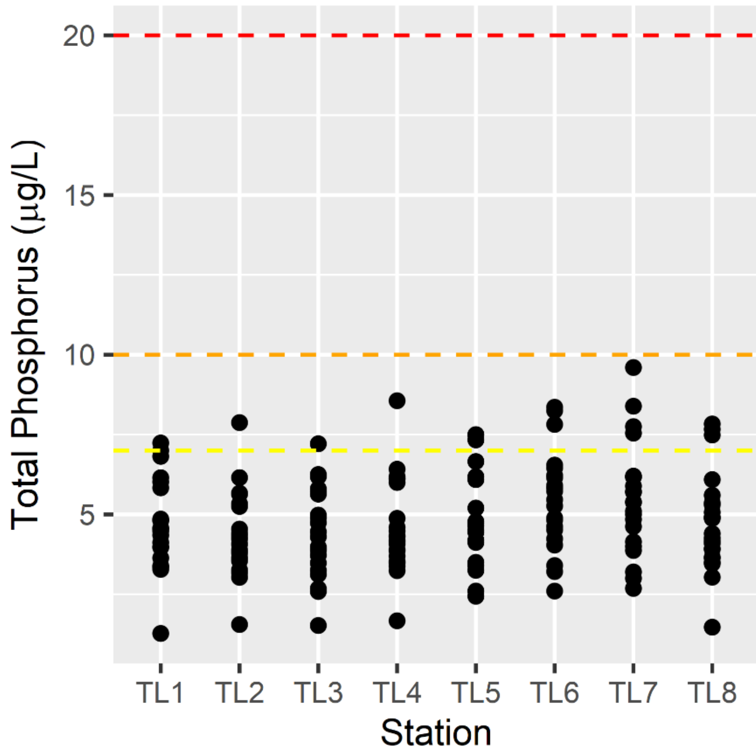


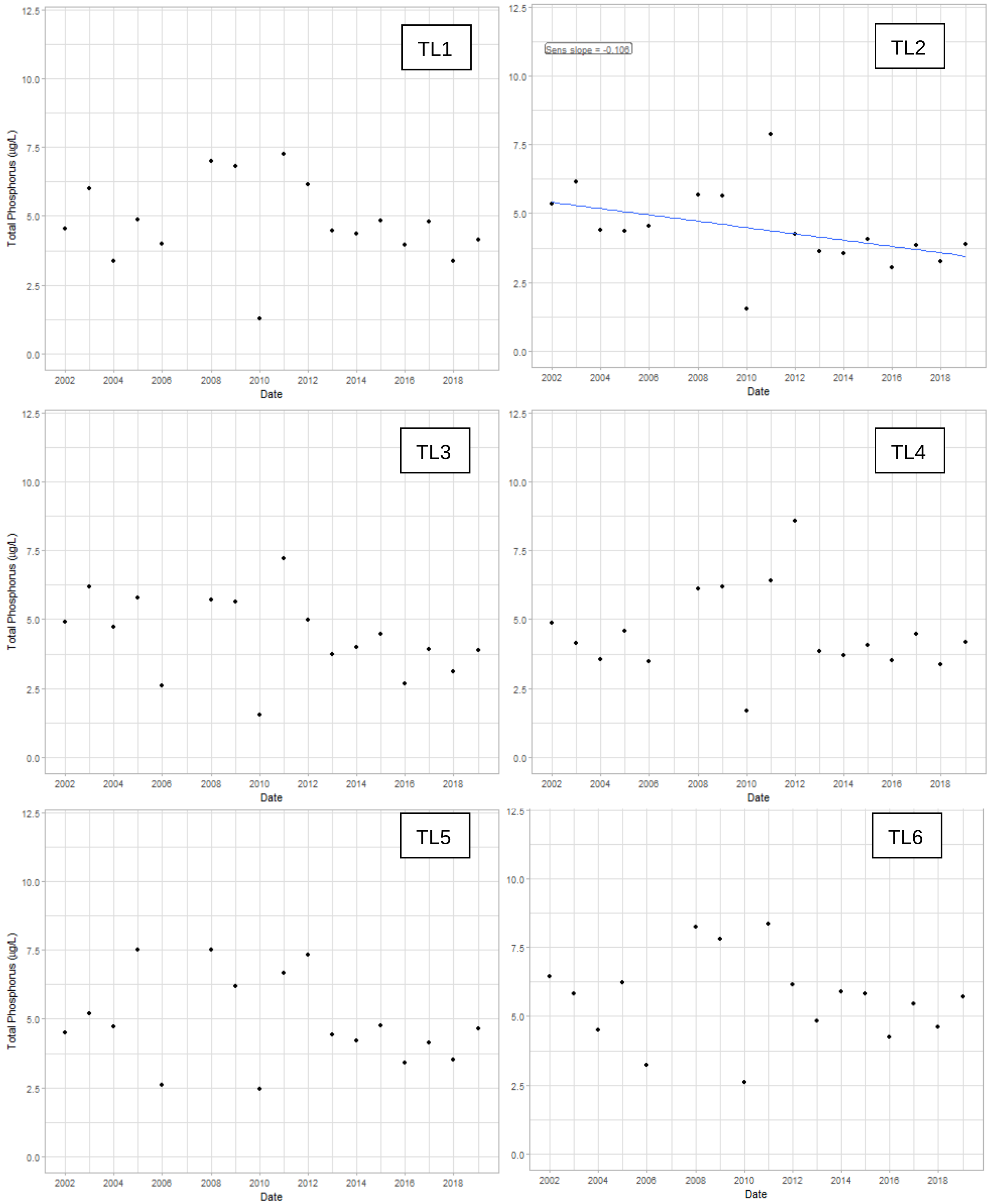
Figure 7. Comparison to Municipal Guidelines and Provincial Guidance.

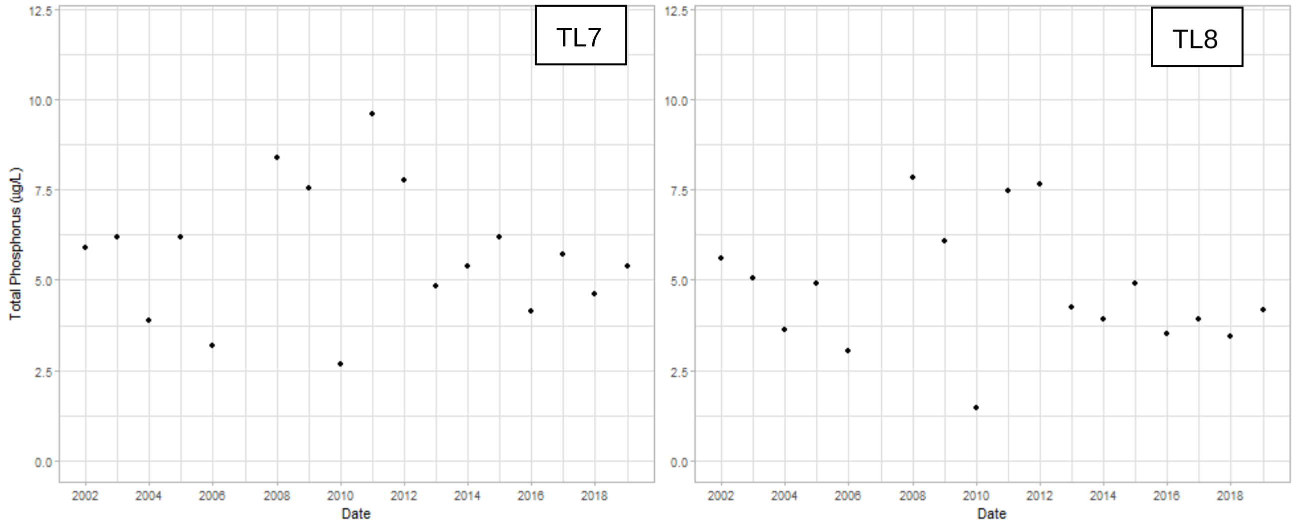


Notes: Yellow = Municipal guidance 7 mg/L; Orange = Provincial Water Quality Objective

Temporal trend analysis of long-term monitoring data was also performed station-by-station as described in Section 2.1.2. We found no significant increases in average annual total phosphorus concentrations at any of the water quality stations (Figure 8). Analysis of long-term trends in total phosphorus data excluding 2010 resulted in an additional decreasing trend in TP at site TL3, however this does no change our interpretation of these data, nor the recommendations that follow.

Figure 8. Temporal Trends in Total Phosphorus Concentrations in Trout Lake at Individual Sites.





3.4 Mean Volume-Weighted Hypolimnetic Dissolved Oxygen

Mean Volume-Weighted Hypolimnetic Dissolved Oxygen (MVWHDO) is the average concentration of dissolved oxygen measured in late summer in the hypolimnion that has been volume-weighted to account for the morphometry of the lake. MVWHDO concentrations have ranged between 7.8 and 11.1 mg/L in the 9 years of monitoring data available (MECP undated). Data collected and presented in the MECP Lake Capacity Assessment of Trout Lake were collected at every other metre depth from the surface to ~60m depth at the deepest basin of Trout Lake in 1987, 1989, 1994, 2001, and 2002 (TL4). Data between measured intervals were interpolated for the purpose of MVWHDO calculations to increase the resolution of the dataset to include data for each 1m of water depth. In 2006, data were collected every 1m from the surface to 25 m depth and then collected every 5 m to 57 m and interpolated. In 2014 and 2015 data were collected at 1m intervals from the surface to 53 m and 58 m depth respectively. In all sampling years, data were extrapolated beyond the maximum measured depth to a depth of 72 m, despite a reported maximum depth in the basin of 63 m. It is unclear how data were extrapolated or why this extrapolation took place. In Four Mile Bay, oxygen profile data were collected every 1 m from the surface to 30 m depth in 2014 and 2015, however in 1993 data were only collected to 28 m depth. In 1994 and 2002 profiles were collected at 2m intervals from the surface to 30 m and 29 m depths respectively and then interpolated.

Ontario has adopted a MVWHDO concentration of 7 mg/L (measured between August 15th and September 15th) as a criterion to protect lake trout habitat. The Municipal regulations for Trout Lake add a layer of conservatism to the Provincial Objective, setting an objective for MVWHDO at 8 mg/L. Based on data available from 9 years of monitoring (i.e., 1987, 1989, 1994, 2001, 2002, 2006, 2014, 2015 and 2018) in the main basin of Trout Lake only a single value in 1994 fell below the Municipal objective. No MVWHDO concentrations below provincial guidance have been recorded.

In Four Mile Bay, MVWHDO was recorded less frequently than in Trout Lake (Table 3). Concentrations ranged from 6.94 to 9.3 mg/L, were lower than the Provincial Objective in 1994 (6.9 mg/L) and lower than the municipal regulation in 4 out of 6 years. Mean Volume Weighted Hypolimnetic Dissolved Oxygen concentrations were consistently lower in Four Mile Bay than in Trout Lake, but the difference was not statistically significant based on the limited data available (Table 3; n=6).

In Trout Lake no significant change (p>0.05) in MVWHDO was measured over the period of record based on our temporal analysis of annual MVWHDO concentrations (Figure 9). A strong correlation between MVWHDO concentrations and sampling date is apparent in the current dataset with elevated concentrations being associated with earlier sampling dates (e.g., 2001, 2002 and 2006). Maintaining consistent sampling timing will be vital for long-term comparison of MVWHDO concentrations.

Figure 9. Temporal Assessment of MVWHDO in Trout Lake.

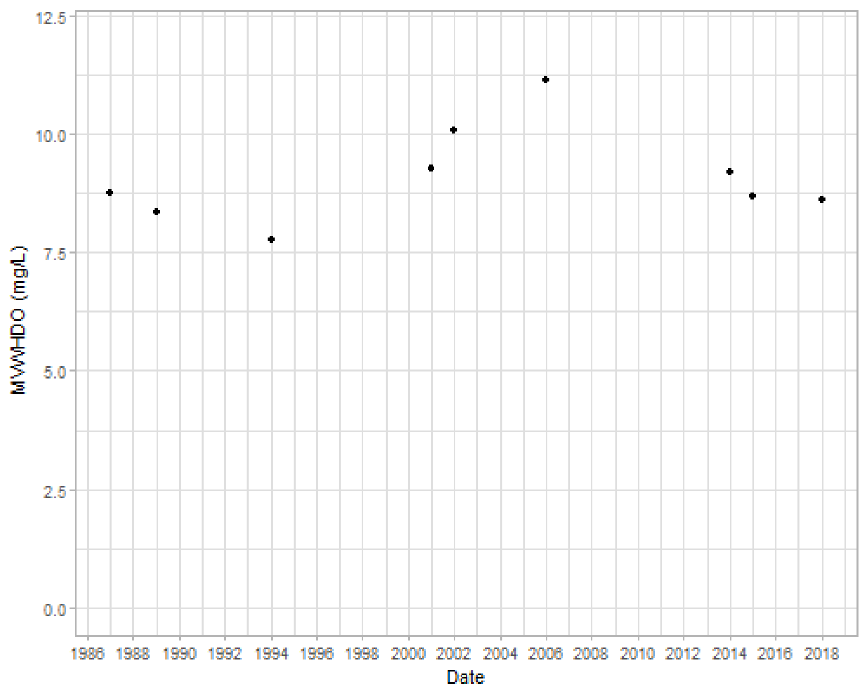


Table 3. MVWHDO Concentrations from Long-term Monitoring Data.

	MVWHDO (mg/L)	
Date	Four Mile Bay	Trout Lake
1987-09-14		8.77
1989-09-14		8.36
1993-09-15	7.94	
1994-09-14	6.94	7.78
2001-08-21		9.25
2002-08-27	9.3	10.07
2006-08-16		11.12
2014-09-02	8.4	9.18
2015-09-11	7.59	8.69
2018-09-11	7.61	8.6

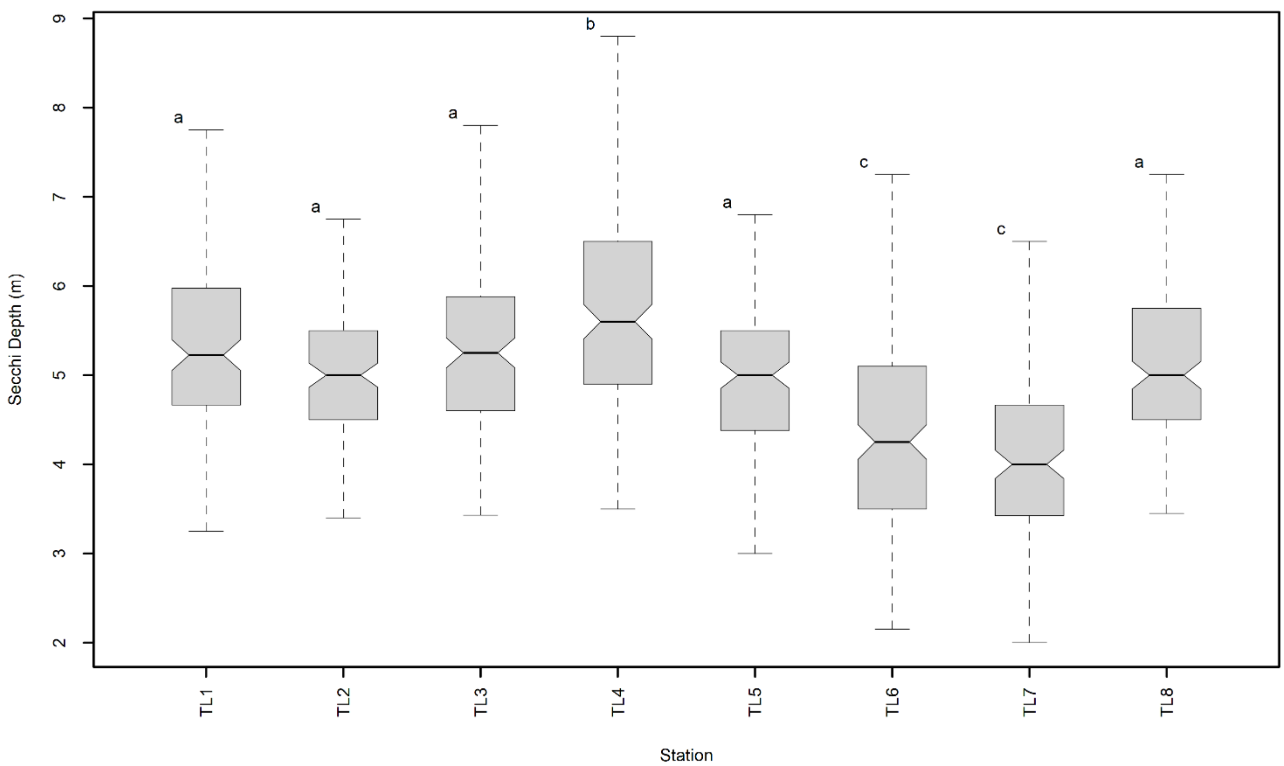
3.5 Secchi Disk Depth

Secchi depth is a measure of water transparency and is often applied in lake management as an indicator of productivity and trophic status in lakes. We assessed spatial and long-term linear trends in Secchi depth as part of our assessment of the current and historical water quality in Trout Lake.

3.5.1 Spatial Trends in Secchi Depth

Assessment of spatial trends in Secchi depth in Trout Lake showed consistent water clarity across the majority of monitoring stations in Trout Lake. The deep-water station at TL4 had significantly higher water clarity than any other site, as it is less likely to be directly impacted by run-off from storm activity or other watershed disturbances or inputs. Secchi depth in Four Mile Bay (TL6 and 7) was significantly lower than elsewhere on the lake, likely as a result of either higher productivity of algal assemblages, higher DOC concentrations, or as a result of suspended sediments from the inflow of Four Mile Creek. Median Secchi depth measurements in Four Mile Bay were 3.9 - 4.0 m and ranged between 5.0 and 5.4 m at the six other long-term monitoring stations (Figure 9).

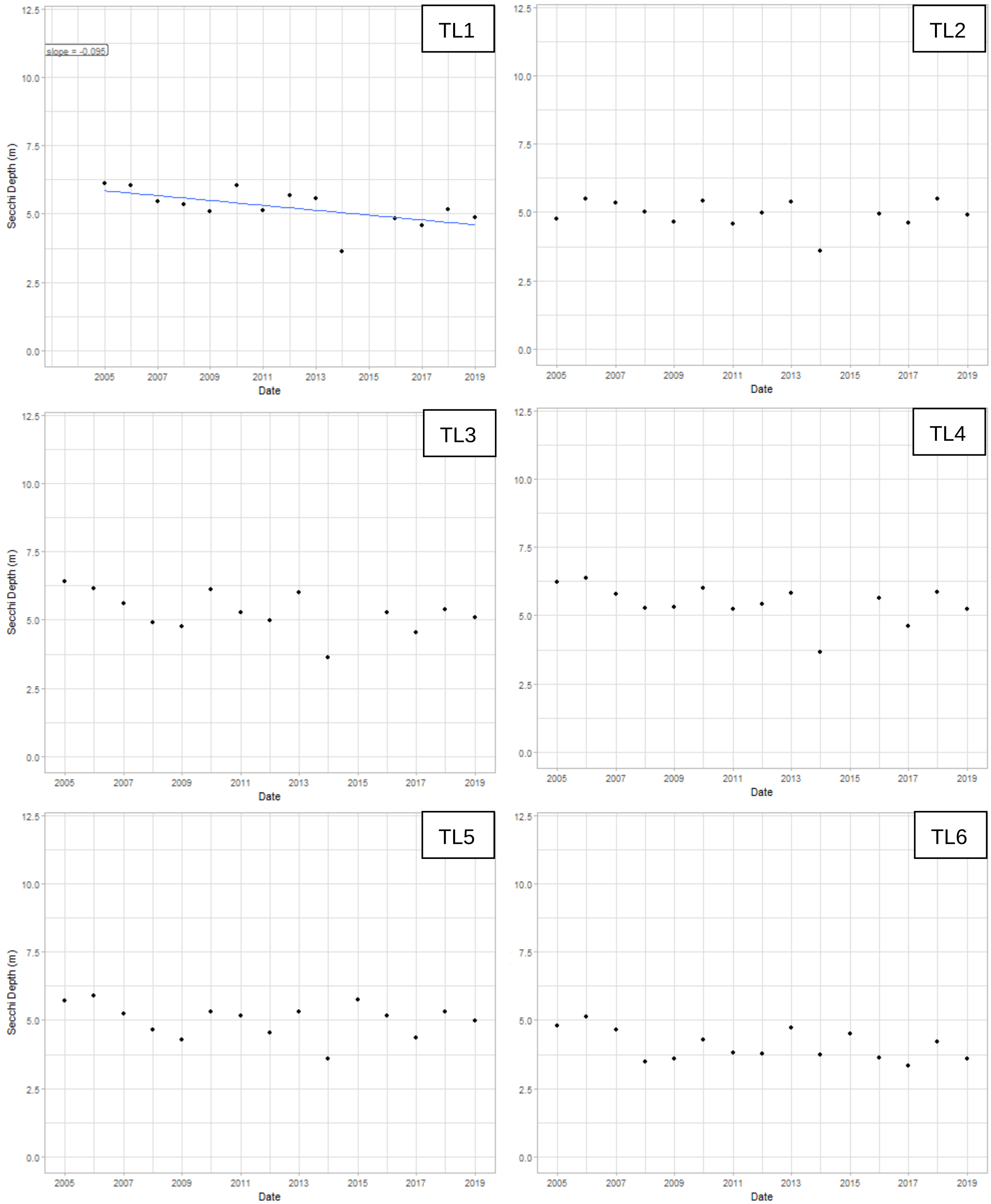
Figure 10. Spatial Trends in Secchi Disk Depth on Trout Lake.

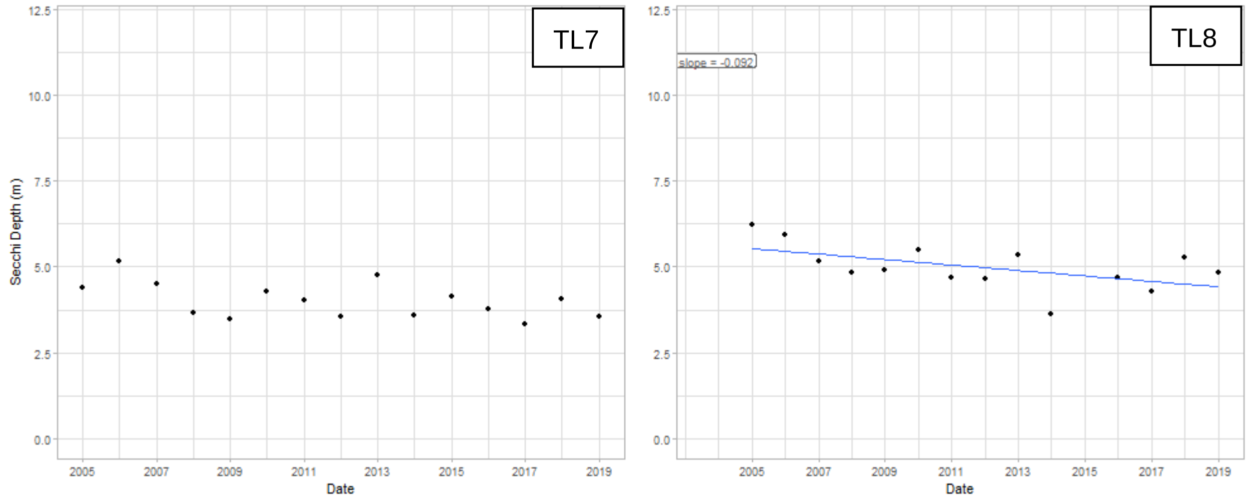


3.5.2 Temporal Trends in Secchi Depth

Temporal trend analysis of long-term monitoring data on Trout Lake was performed as described in Section 2.1.2. We found significant ($p<0.05$) long-term decreases in average annual Secchi depth at Delaney Bay (TL1) and One Mile Bay since 2005 (TL8; Figure 11). These trends appear to be driven in part by a marked decline in water clarity in 2014, reanalyzing the data without the 2014 data did not change the results at TL1, however the decreasing trend at TL8 was no longer significant when the 2014 data were removed.

Figure 11. Temporal Trends in Secchi Depth on Trout Lake.



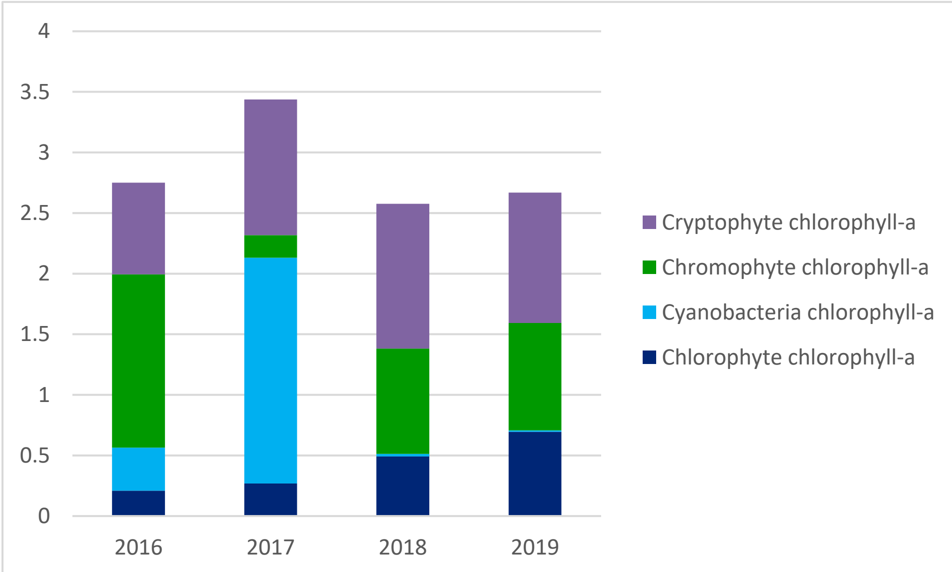


Reduced water clarity in the Delaney Bay basin could be the result of higher TSS loads from local roads, railroads and urban development in the area (Delaney Bay is the most developed area of the lake) or could be the result of higher local algae production or changes in Dissolved Organic Carbon (DOC). Palmer et al. (2011) documented increased DOC in south central Ontario lakes between 1981-1990 and 2004-2005 and linked the increases to a warmer climate with increased decomposition of organic matter. The NBMCA fluoroprobe data does not include results from prior to 2016 nor are long-term water quality data on suspended sediments or DOC available and therefore it is difficult to defensibly ascertain the cause of recent declines in water clarity in Delaney Bay.

3.6 Phytoplankton

Fluoroprobe data from 2016 to 2019 showed consistent algal pigment production and community composition results over the course of the four years of late August/Early-September measurements, with the exception of a marked increase in cyanobacterial production in 2017 (Figure 12). Total chlorophyll *a* concentrations ranged from 2.6 to 2.8 μg/L in 2016, 2018 and 2019 but increased to 3.4 μg/L in 2017 as cyanobacteria accounted for 54% of the algal production.

Figure 12. September Phytoplankton Data from Fluoroprobe Surveys of Trout Lake.



Seasonal phytoplankton succession in northern, temperate waterbodies is driven by changes in nutrients, water stability and light regime. Briefly, winter phytoplankton under the ice is commonly dominated by small motile algae which are adapted to low light, low water temperature and high water column stability, such as Chrysophytes (e.g., *Dinobryon*, *Mallomonas*, and *Synura*) and Cryptophytes (e.g, *Cryptomonas* and *Rhodomonas*).

In the late winter, light availability improves as the snowpack melts, resulting in increased abundance of dinoflagellates and small centric diatoms. As ice cover is lost in the spring, mixing in the water column creates conditions of low stability and high nutrient concentrations. This results in a marked increase in phytoplankton productivity, particularly diatoms, and is frequently the annual peak in phytoplankton biomass. This spring bloom is often dominated by a single species (e.g., *Asterionella*, or *Cyclotella*).

During initial summer stratification increased water temperature stabilizes the water column and light availability increases, while nutrient concentrations decline. Total phytoplankton biomass generally decreases as grazing pressure from zooplankton rapidly increases. By late summer high water temperatures and water column stability often favour chrysophytes and colonial green algae as observed in the fluoroprobe data in 2016, 2018 and 2019. When silica concentrations are high diatoms may replace green algae, however if silica becomes depleted dinoflagellates and cyanobacteria often dominate the late summer phytoplankton assemblage. As plankton consume available nitrogen resources to below detectable concentrations, cyanobacteria can become increasingly dominant. Cyanobacteria are capable of fixing molecular nitrogen from the atmosphere and regulating their buoyancy to take advantage of nutrients outside the photic zone. Certain species of cyanobacteria may also be recruited into the water column directly from resting stages in the sediments, drawing phosphorus directly from lake sediments rather than relying on the limited resources available in the lake water. The marked increase in cyanobacterial production in September of 2017 compared to the other three years on record may be the result of interannual climate variability, however climate data available from the North Bay meteorological station (climate id = 6085680) showed 2017 as the coldest and wettest year of the four, which does not generally support the enhanced growth of cyanobacteria. Water chemistry data on silica are not available to confirm the limiting nutrient hypothesis as a driver of increased cyanobacteria production in 2017.

4. Monitoring Recommendations

Despite a multitude of monitoring programs that have been completed in Trout Lake, data to track and assess emerging limnological issues typical of temperate freshwater lakes in Ontario is limited. For example, decreased concentrations of calcium as a long-term consequence of industrial development, smelting and acid precipitation, and increased chloride concentrations due to salting of roadways have increasingly become issues in lakes across Ontario. Long-term records of calcium concentrations are not available in the Trout Lake monitoring data and were only collected, based on the data reviewed, during the Watershed Management Study in 1986. Data from 1986 suggest calcium concentrations may be depleted in Four Mile Bay and may warrant ongoing monitoring to assess the risk to aquatic organisms that are sensitive to calcium decline. Likewise, despite increased chloride concentrations between 1977 and 1986 discussed in the Watershed Management Study (CRA 1988); chloride has not been measured in the water quality data available since 1990.

Our assessment of water clarity in Trout Lake has demonstrated a significant decline in Delaney Bay near the City of North Bay between 2005 and 2019. Numerous potential causes may contribute to long-term changes in water quality however determining causation is difficult in the absence of recent monitoring data. Several key parameters that may inform of the changes in water clarity are not currently collected as part of routine monitoring on Trout Lake including suspended solids, DOC and ongoing phytoplankton monitoring.

Significant differences in total phosphorus between Four Mile Bay and the Main Basin of Trout Lake were observed. Regular monitoring of Four Mile Creek is part of the regular monitoring program on Trout Lake, however the Trout Lake Creeks monitored during the Watershed Management Study have not been sampled since 1990 according to our review. An updated assessment of the water quality of all Trout Lake creeks sampled during the last Watershed Management Study would inform the relative contributions of each sub-watershed to Trout Lake and may help focus and refine management objectives.

Lastly, dissolved oxygen and temperature measurements have been gathered from standardized locations, but the maximum depths of measurements have not been consistent between years. The variability of depth measurements limits the ability to calculate MVWHDO concentrations and compare concentrations over time. MVWHDO provides a means of tracking the impacts of watershed development, lake health and Lake Trout habitat quality over time so standardized profile locations and related depths should be implemented.

5. Conclusions and Next Steps

Water quality in Trout Lake is excellent, nutrient concentrations are low and there is no evidence of changing water quality. Significant monitoring effort has been invested in the management of water quality of Trout Lake, however little evidence of a marked impact of development on the lake is apparent. Long-term phosphorus data collected from 2000 to 2019 have not shown any significant change in nutrient concentration at the eight long-term monitoring locations on the lake, suggesting that any potential impacts of recent (i.e., 20 years) development have not occurred or have not been captured by the current monitoring program. Likewise historical data analysis (1975 – 2002) from previous reporting (1977 – 1986 [CRA 1988], 1975 – 2002 [GLL 2002]) has not recorded an increase of nutrients in the lake over time.

Ice free average total phosphorus concentrations have however exceeded the municipal Minimum Water Quality Objective of 7 μg/L at individual sites and in specific years when sites are combined. Total phosphorus concentrations are variable year-to-year but it is clear that TP concentrations are higher in Four Mile Bay, with annual MWQO exceedances in 2008 (8.32 μg/L), 2009 (7.69 μg/L) and 2011 (8.98 μg/L; Table 2). Mean Volume Weighted Hypolimnetic Dissolved Oxygen Concentrations were also different between Four Mile Bay and the Main Basin resulting in multiple concentrations lower than the municipal regulations (8 mg/L) in Four Mile Bay (1993, 1994, 2015, 2018) and only a single concentration lower than municipal regulations in the Main Basin (1994). Note however that the data which MECP used to complete these calculations were heavily interpolated.

A significant decrease in water clarity measured through Secchi Disk Depth in the most developed basin of Trout Lake (i.e., Delaney Bay) may suggest a localized impact of urban development, roads and railroads on water quality within the Bay or input of DOC from the catchment. Exploration of policies and practices to control sediment, erosion and runoff into the lake from urban areas may help to mitigate further reductions in water clarity within Delaney Bay.

Future project phases will include a more quantitative assessment of the impact of development on water quality through evaluation of water quality data in relation to development data at a broad scale as well as evaluation of more site-specific monitoring data associated with individual development applications (i.e., lot level or subdivision level). Subsequent stages will be focused on consultation and development of management recommendations and related reporting.

6. References

Australian and New Zealand Environment and Conservation Council (ANZECC) & Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ), 2000. Australian and New Zealand Guidelines for Fresh and Marine Water Quality.

Benjamini, Y., and Hochberg, Y. 1995. Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. Journal of the Royal Statistical Society. Series B (Methodological),57, 289-300.

Bowman, A.B. 1979. Impact assessment of Ontario Northland Railroad derailment (1967) into Four Mile Creek. Ontario Ministry of the Environment Technical Memorandum, Northeastern Region, Sudbury, Ontario.

Clark, B., Paterson, A.P., Jeziorski, A. and Kelsey, S. 2010. Assessing variability in total phosphorus measurements in Ontario lakes. Lake and Reservoir Management. 26. 63-72. 10.1080/07438141003712139.

Conestoga Rovers and Associates Ltd. 1988. Trout Lake Watershed Management Study. Prepared for the North Bay-Mattawa Conservation Authority.

Dillon, P.J., K.H. Nicholls, W.A. Scheider, N.D. Yan and D.S. Jeffries. 1986. Lakeshore Capacity Study, Trophic Status. Research and Special Projects Branch, Ontario Ministry of Municipal Affairs and Housing. Queen's Printer for Ontario. 89pp.

Dillon, P.J and L.A. Molot, 1997 Effect of landscape form on export of dissolved organic carbon, iron, and phosphorus from forested stream catchments, Water Resources Research, Vol 33, No. 11, pages 2591-2600.

Fitchko, J., Eakins, R.J., and A.R. Glasgow. 1996. Return of the Ouananiche to Trout Lake, near North Bay, Ontario. Unpublished manuscript. 32 pp.

Gartner Lee Limited. 2002. Water Quality Modelling and Assessment: Trout Lake. Prepared for List Planning Ltd.

Hutchinson Environmental Sciences Ltd. 2011. Phosphorus Control Site Plan – Lot 6 – Eastview Development.

McBean, E., T. Mereu, G. Gartshore, C. Kitchen & M. Benson 1992. An Integrated Approach to Watershed Management Planning for Trout Lake, Ontario, Canadian Water Resources Journal, 17:1, 33-48, DOI: 10.4296/cwrj1701033.

Millard, S. 2013. EnvStats, an R Package for Environmental Statistics. 10.1007/978-1-4614-8456-1.

Miller Environmental Services Inc. 2000. Trout Lake Parasite Study – Final Report. Prepared for the City of North Bay.

Ministry of the Environment, Conservation and Parks. 2019. Hydrodynamic and Water Quality Numerical Modelling in Trout Lake.

Ministry of the Environment, Conservation and Parks. Undated. Lake Capacity Assessment: Trout Lake.

Ministry of the Environment. 2010. Lakeshore Capacity Assessment Handbook. Protecting Water Quality in Inland Lakes on Ontario's Precambrian Shield. Queen's Printer for Ontario. PIBS 7642e.

Ministry of the Environment 1984. Water management: policies, guidelines, provincial water quality objectives

Ministry of the Environment. 1973. Preliminary Evaluation of the water Quality of Trout Lake.

North Bay-Mattawa Conservation Authority. 1985. Inventory Information for the Trout Lake Watershed.

North Bay-Mattawa Conservation Authority. 1987. Trout Lake Rainwater Water Quality Analysis for Phosphorus.

North Bay Parry Sound District Health Unit, 2012. Chemical Spill in Trout Lake. https://www.myhealthunit.ca/en/News/index.aspx?newsId=8fe44da6-069f-49dc-9126-09c9b8e87963.

Northland Engineering Limited and Beak Consultants Limited. 1992a. Trout Lake Pollution Control Plan Sewage Disposal Systems Inventory and Analysis. Prepared for the City of North Bay.

Northland Engineering Limited and Beak Consultants Limited. 1992b. Trout Lake Pollution Control Plan Limnology and Hydrology Analysis. Prepared for the City of North Bay.

Ogle, D. 2021. FSA: Simple Fisheries Stock Assessment Methods. https://cran.r-project.org/web/packages/FSA/index.html

Palmer, M.E., N.D. Yan, A.M. Paterson and R.E. Girard. 2011. Water quality changes in south-central Ontario lakes and the role of local factors in regulating lake response to regional stressors. Can. J. Fish. Aquat. Sci. 68:1038-1050

Pohlert, T. 2017. trend: Non-Parametric Trend Tests and Change-Point Detection. https://cran.r-project.org/web/packages/trend/index.html

R Core Team 2013. R: A language and environment for statistical computing.

Rees, D.L. 1974. The Trout Lake Reservoir – A Water Balance Study.

Rosner, B. 1983. Percentage Points for a Generalized ESD Many-Outlier Procedure. *Technometrics, 25*(2), 165-172. doi:10.2307/1268549

Trout Lake Conservation Association 2021. TLCA News – Summer 2021. The Glum Reality of PFAS Exposures.