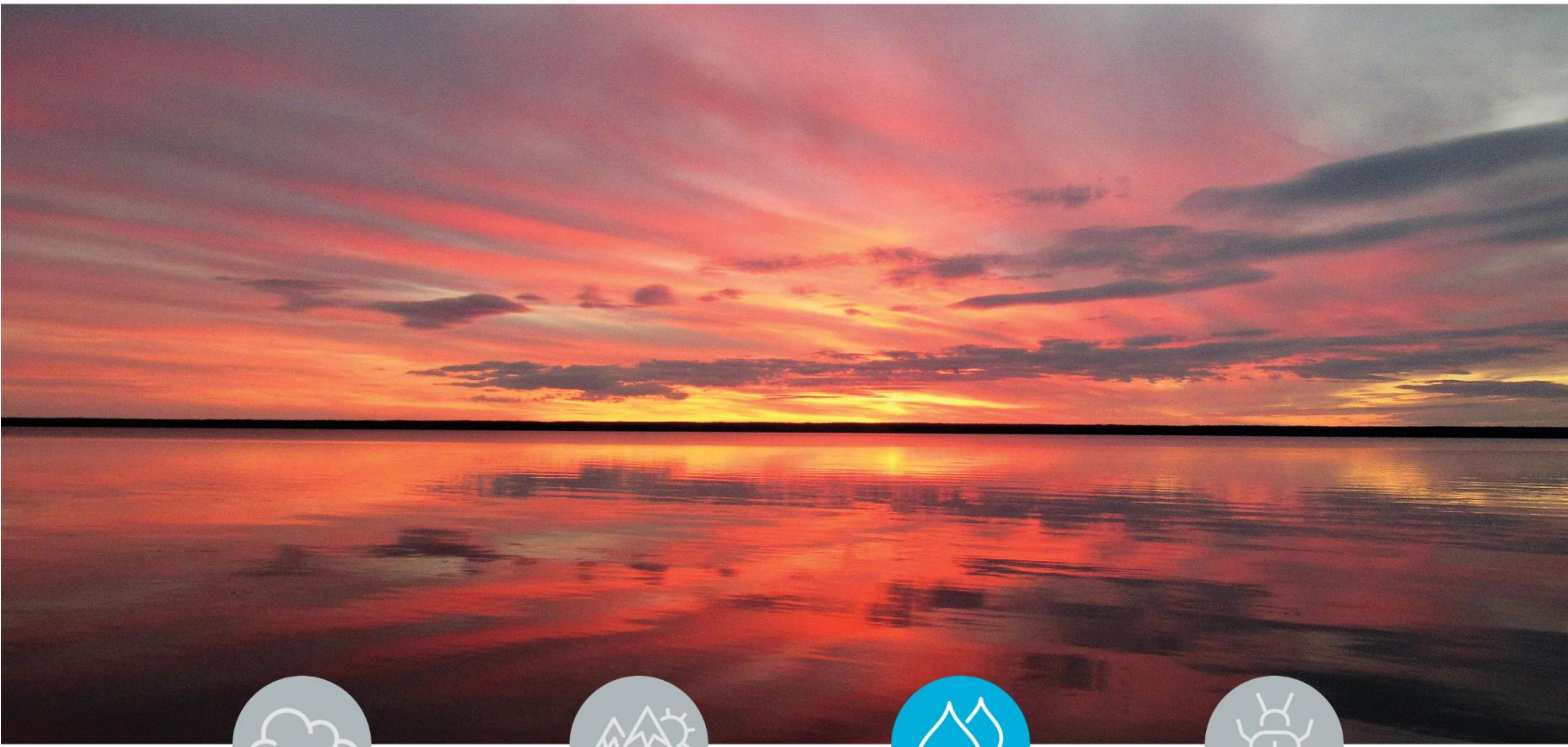
Wabasca Lake Monitoring Project Results Report



Air

Land

Water

Biodiversity

Wabasca Lake Monitoring Project Results Report

Ron Zurawell, Rebekah Adams and Craig Emmerton

Cover photo: Lynda Gray

This publication can be found at: open.alberta.ca/publications/9781460137239.

Comments, questions, or suggestions regarding the content of this document may be directed to:

Ministry of Environment and Parks, Environmental Monitoring and Science Division

10th Floor, 9888 Jasper Avenue NW, Edmonton, Alberta, T5J 5C6

Email: EMSD-Info@gov.ab.ca

Media Inquiries: AEP.mediainquiries@gov.ab.ca

Website: environmentalmonitoring.alberta.ca

Recommended citation:

Zurawell, R., Adams, R., and Emmerton, C. 2019. Wabasca Lake Monitoring Project Results Report. Government of Alberta, Ministry of Environment and Parks. ISBN 978-1-4601-3723-9. Available at: open.alberta.ca/publications/9781460137239.

Published March 2019

ISBN 978-1-4601-3723-9

Alberta’s Environmental Science Program

The Chief Scientist has a legislated responsibility for developing and implementing Alberta’s environmental science program for monitoring, evaluation and reporting on the condition of the environment in Alberta. The program seeks to meet the environmental information needs of multiple users in order to inform policy and decision-making processes. Two independent advisory panels, the Science Advisory Panel and the Indigenous Wisdom Advisory Panel, periodically review the integrity of the program and provide strategic advice on the respectful braiding of Indigenous Knowledge with conventional scientific knowledge.

Alberta’s environmental science program is grounded in the principles of:

- *Openness and Transparency.* Appropriate standards, procedures, and methodologies are employed and findings are reported in an open, honest and accountable manner.
- *Credibility.* Quality in the data and information are upheld through a comprehensive Quality Assurance and Quality Control program that invokes peer review processes when needed.
- *Scientific Integrity.* Standards, professional values, and practices of the scientific community are adopted to produce objective and reproducible investigations.
- *Accessible Monitoring Data and Science.* Scientifically-informed decision making is enabled through the public reporting of monitoring data and scientific findings in a timely, accessible, unaltered and unfettered manner.
- *Respect.* A multiple evidence-based approach is valued to generate an improved understanding of the condition of the environment, achieved through the braiding of multiple knowledge systems, including Indigenous Knowledge, together with science.

Learn more about the condition of Alberta’s environment at: environmentalmonitoring.alberta.ca.

Acknowledgements

This project is the result of new collaborative opportunities in environmental science and monitoring between Indigenous communities and Alberta Environment and Parks (AEP).

This collaboration was made possible with the commitment and in-kind support of Bigstone Cree Nation, the dedication and efforts of G. Cardinal (formerly with BCN Lands Department) and the foresight, persistence and hard work of Z. Wang, T. Howlett and others from Environmental Monitoring and Science Division's (EMSD) Indigenous Knowledge, Community Monitoring & Citizen Science Branch.

We acknowledge the efforts of: EMSD's Environmental Monitoring and Observation staff (especially, Project Lead Field Technologist S. Hustins) for their dedication to field sampling and *in situ* measurements, J. Pham (AEP Data Management) for timely data validation and management, P. Drevnick, J. Kerr, J. Orwin and B. Donahue (EMSD Science Branch) for critical report review and A. Lake (EMSD Science Branch) for data preparation. This study was funded by the Government of Alberta, Alberta Environment and Parks.

Executive summary

The Environmental Monitoring and Science Division of Alberta Environment and Parks in collaboration with Bigstone Cree Nation conducted water quality monitoring in North Wabasca Lake in 2016/2017. The North Wabasca Lake Monitoring Project originated, in part, from community concerns about general water quality degradation and the health of walleye in the lake and provided a unique opportunity to collect current water quality information in collaboration with indigenous communities. Lake water quality, including chemical, physical and biological measures, was monitored over the summer (June-September) and winter (February) periods. To better understand the influence of Desmarais (South Wabasca) Lake and Willow River on the water quality of North Wabasca Lake, samples were collected concurrently from the outlet of Desmarais Lake and Willow River upstream of North Wabasca Lake in the July-September period and February.

The Wabasca-Desmarais watershed comprises part of the south-central headwaters of the Peace River Drainage. The watershed is characterized by nutrient-rich, carbonate rock, deposits and organic soils that are largely forested or covered in shrubs and grassland. North Wabasca Lake is moderately deep and becomes only weakly stratified during the summer months. These characteristics and its relatively large surface area and long fetch (*i.e*., the length of water over which winds blow) suggest that North Wabasca Lake mixes (turns over) periodically during the open-water season (*i.e*., it is polymictic). While dissolved oxygen levels are depressed in the deepest parts of the lake in summer, periodic downward mixing results in sufficient oxygen at depth to support fish.

North Wabasca, along with upstream Desmarais Lake and Willow River, are alkaline and nutrient-enriched. Like other polymictic lakes in Alberta, phosphorus—the primary nutrient responsible for algae growth—that is normally stored in the sediment may undergo chemical transformations that cycle it back into the water column over the summer. Desmarais Lake Outlet and Willow River had higher nitrogen and phosphorus concentrations than North Wabasca Lake. Based on mean total phosphorus observed, Desmarais Lake Outlet is classified as hypereutrophic, Willow River as eutrophic and North Wabasca Lake as meso-eutrophic. The concentrations of metals were generally low in the water column of North Wabasca Lake, but slightly higher concentrations occurred near the sediments. The concentrations of dissolved iron and manganese were much lower in North Wabasca Lake than in either Desmarais Outlet or Willow River, which exceeded chronic (long-term) guidelines for the protection of aquatic health. There is no indication of metal contamination derived from human activities in the watershed (*i.e.*, guidelines values for total metals were not exceeded).

Like other moderately productive Alberta lakes, North Wabasca supports a large and relatively diverse phytoplankton community that is largely cyanobacteria-dominated during summer. However, levels of the cyanobacterial liver toxin, microcystin, were only detected at trace levels, indicating the dominant species/strains were not toxin-producers. Similarly, the lake supports a diverse zooplankton community that is important in the food web of the lake, feeding on the primary producers (*i.e.,* algae and cyanobacteria) and in turn providing food for larval and developing fish, bait fish and adult northern cisco that inhabit the lake. Walleye and northern pike are the primary predatory sportfish in the lake and fall index netting by Alberta Environment and Parks' Fish and Wildlife staff indicates recruitment overfishing is occurring in North Wabasca Lake. Lastly, skin tumors evident on recently caught walleye are caused by a natural virus, *Lymphocystis*, commonly found in Alberta's lakes, that is not usually fatal to fish and does not affect humans and other mammals.

Table of Contents

List of Tables

List of Figures

Introduction

North Wabasca Lake Monitoring Project

Water quality in North Wabasca Lake was sampled monthly from June–September (2016) and again under ice in February (2017) by Alberta Environment and Parks (AEP) and Bigstone Cree Nation (BCN). This lake monitoring effort was informed by community concerns about general water quality degradation and the health of walleye in North Wabasca Lake expressed by Gilmen Cardinal, a Lands/Environment Officer with BCN and graduate of the Alberta Environmental Monitoring and Environmental Reporting Agency (AEMERA)/Alberta Innovates Technology Futures (AITF) Pilot Environmental Monitoring Technician Training Program in 2015. The North Wabasca Lake monitoring project was part of the Province's (AEP, Environmental Monitoring and Science Division) regional lake monitoring program.

The goals of the North Wabasca Lake Monitoring Project were to: address the lack of recent water quality information for North Wabasca Lake; provide additional training in aquatic monitoring to the BCN Lands Officer; and, where possible, find opportunities to apply Traditional Ecological Knowledge (TEK) to AEP's western-science-based environmental monitoring. Furthermore, this was an opportunity for BCN to gather information to help address the community's interest in North Wabasca Lake, which included potential impacts of industrial activity and changing weather patterns (*e.g.,* warmer winters, perceived stronger summer wind velocities) on water quality, risk to drinking water quality, and fish health.

This report represents a summary of the water quality data collected including water chemistry and biological communities and invasive species. A companion report summarizing the engagement and training processes with BCN staff, as well as lessons learned is being prepared.

North Wabasca Lake and Watershed

North Wabasca Lake resides in the Peace River Drainage of north-central Alberta (Figure 1). It is the 15th largest lake in Alberta with a 101 km^2 surface area that can increase to nearly 112 km^2 during periods of high water (Table 1). The name Wabasca originates from the Cree word 'wapuskau', meaning 'white rapid', in reference to the Wabasca River flowing north out of the lake basin (Lesser Slave Lake Economic Alliance, 2013). North Wabasca Lake is located in the Municipal District of Opportunity No. 17, approximately 300 km north of the City of Edmonton. The lake supports the adjacent hamlet of Wabasca-Desmarais and BCN (Bands 166A, 166B, 166C and 166D) by providing subsistence fishing and water for treated drinking water. The lake also supports recreational activities, including sport-fishing, swimming, boating, camping and as well as providing water for golf course irrigation.

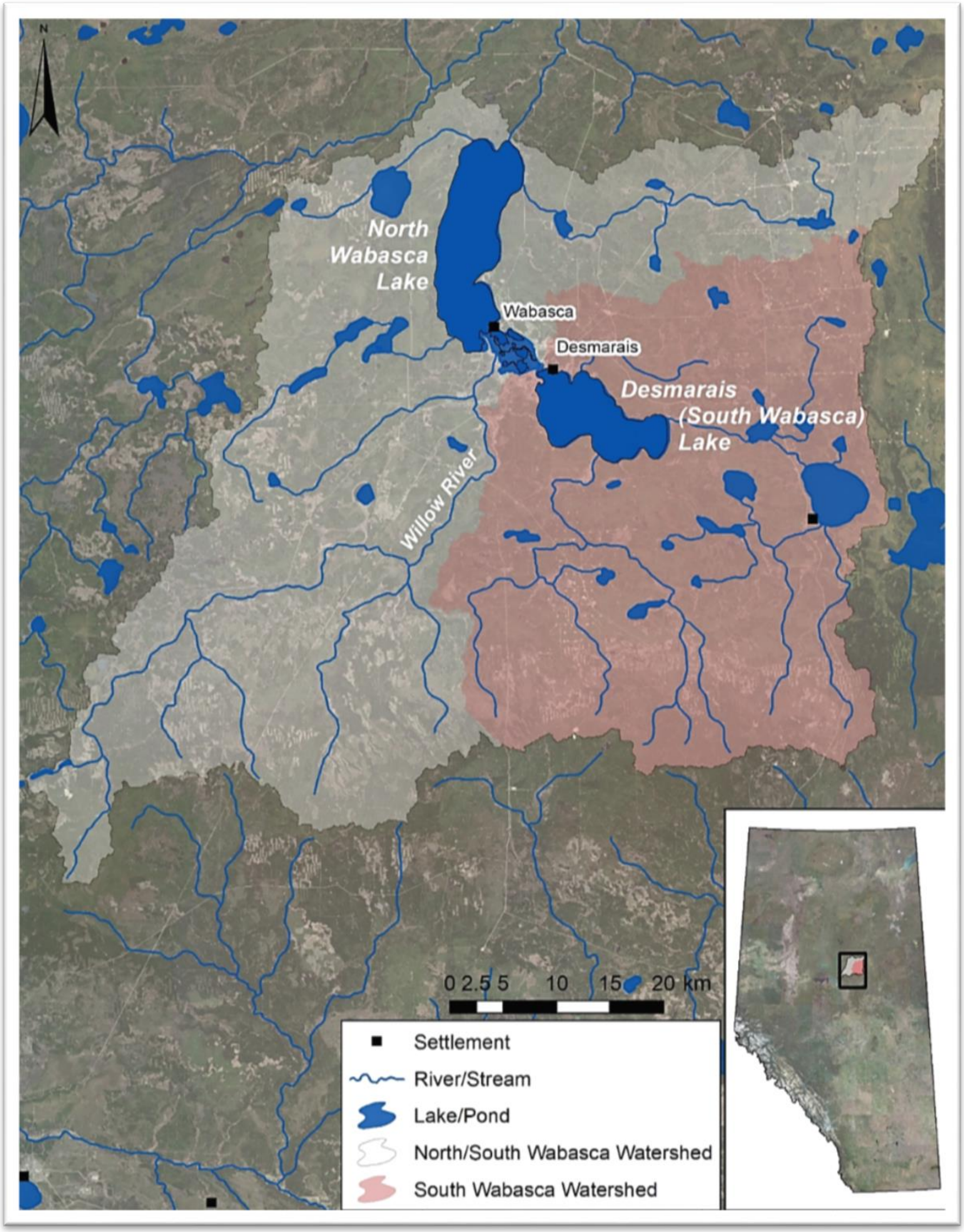


Figure 1. Wabasca-Desmarais Watersheds, Alberta, Canada.

North Wabasca Lake has a large drainage basin covering approximately 3,819 km^2 including the South Wabasca (a.k.a. Desmarais) Lake sub-basin (Table 1, Figure 1). The ratio of North Wabasca's watershed to lake area is approximately 38. This is greater than many other Alberta Lakes (average WA:LA ≈ 23 for recently sampled natural lakes in EMSD's database) and implies great potential for surface flow into the lake from the watershed. The lake receives five surface water inflows—most notably the outlet from Desmarais Lake and Willow River to the south—and several additional smaller, intermittent streams. Wabasca River, the primary outflow from North Wabasca Lake, flows northward to discharge into the Peace River west of Fort Vermilion.

The North Wabasca Lake watershed is located in the Wabasca Lowland Ecoregion (EcoRegions Working Group, 1989)/Central Mixed-wood Natural Sub-region (Natural Regions Committee, 2006) of Alberta. The region is part of the Western Canada Sedimentary Basin and underlying geology is of Cretaceous sedimentary bedrock mainly mudstones (e.g. shales), siltstones and sandstones of various fluvial, marine and estuarine origin; and notably, organic-rich oil deposits (i.e. heavy oil and oil sands) exist in several sandstone formations (Cant and Abrahamson 1997). Thick overlying surficial materials, which are varyingly comprised of medium-textured, loamy tills and fine-textured lacustrine, coarse-textured fluvial and aeolian, and organic deposits, reflect a complex history glaciation. The region is characterized by gently undulating, low-relief plains with organic soils dominating much of the area with poorly-drained black spruce fens and bogs (Natural Regions Committee, 2006). Upland areas are typically luvisolic soils dominated by aspen deciduous stands and aspen-white spruce stands, white spruce-dominate stands on till and lacustrine areas, and jack pine forests can occur on coarse soil materials. Given the low topographic position in fine-textured hydrogeological landforms, many Alberta boreal lakes receive phosphorus-rich, shallow groundwater from adjacent organic wetlands rather than deeper, phosphorus-depleted large-scale groundwater systems (Plach et al., 2016). A summary of geographical characteristics of North Wabasca Lake watershed is found in Table 1.

Most of the land in the North Wabasca Lake watershed is covered with vegetation including forests (≈ 63%), shrub-land (12%) and grasslands (≈ 13%). Urban and industrial development (mainly forestry and oil and gas exploration and extraction) covers approximately 3% of the watershed, with an additional 0.2% existing as exposed, un-vegetated lands. Agricultural land use is insignificant, comprising only 0.004% of the watershed area (ABMI, 2010; Table 1).

Table 1. Morphological/geographical characteristics of North Wabasca Lake and watershed.

Characteristic	
Maximum depth	17 m
Shoreline length (perimeter)*	55.690 km
Lake Area*	101.45 km^2 (111.94 km^2 high-water)
Watershed area*	3819.42 km^2
Watershed to Lake area ratio*	37.65
% Agriculture land use*	0.004
% Urban/industrial developed lands*	2.82
% Forested lands*	63.22
% Shrub-lands*	12.00
% Grass-lands*	12.95
% Exposed lands*	0.20
% Water*	8.81
Ecozone[1]	Boreal Plains
Ecoregion[1]	Wabasca Lowlands
Natural Region[2]	Boreal Forest
Subregion[2]	Central Mixedwood

*Derived from Alberta Biodiversity Monitoring Institute (ABMI) Wall-to-wall Land Cover Inventory, 2010; ([1]) Canada Ecoregion classification (EcoRegions Working Group, 1989); ([2]) Alberta Natural Region Classification (Natural Regions Committee, 2006).

Methodology

Water Quantity Methods

Currently, there is no lake level monitoring station located on North Wabasca Lake, making it difficult to understand historical changes in water level. However, water levels are monitored at the outlet of Desmarais (South Wabasca) Lake. Since Desmarais flows directly into North Wabasca Lake, changes in historical lake elevation at the outlet were used as a proxy for changes in North Wabasca Lake. It is also important to consider what influence other inflows—most notably Willow River—have on water levels in North Wabasca Lake. To provide this insight, discharge data were also obtained for the Willow River Flow Station (WSC #07JA003) upstream of North Wabasca Lake.

Water Quality Methods

Water depth was measured using a Humminbird model 160 Piranhamax depth sonar (dual beam; target separation 6.3 cm) along GPS-referenced (Garmin 76CSx; accuracy <3m with WAAS) transects across the lake, and the data used to determine coarse bathymetry (depth contours) and plotted in ArcGIS to produce a bathymetric map for the lake (Figure 2). Our goal was to collect water samples that were representative of overall or 'average' water quality within the lake basin and local knowledge provided by Gilmen Cardinal (with BCN) was critical to understanding potential influencing features of the lake basin (such as inflows and outflows) and inform sampling-site selection.

On each sampling event (day) we determined the euphotic depth—the depth in the water column where photosynthetically active radiation is approximately equal to 1% of the surface irradiance—at the deepest (primary) sampling site (Figure 3) using an electronic (Licor) light meter. We then recorded *in-situ* measurements with an electronic multi-probe meter (HydroLab Datasonde), including water temperature, dissolved oxygen, pH, and specific conductivity, at regular depth intervals (typically 0.5 m intervals through the euphotic zone, and 1 m intervals below that to the bottom sediment). These measures were used to construct depth-dependent temperature and oxygen profiles to determine the presence or extent of water column stratification (*i.e.,* development of discrete, vertical layers of water due to density differences) and oxygen depletion within the lake basin during the open-water season. Water color and transparency, indicating the quantity of planktonic algae (phytoplankton) in the water column, was determined with a Secchi disk, and a 63-µm mesh plankton net was raised vertically through the euphotic zone to collect zooplankton for identification and enumeration.

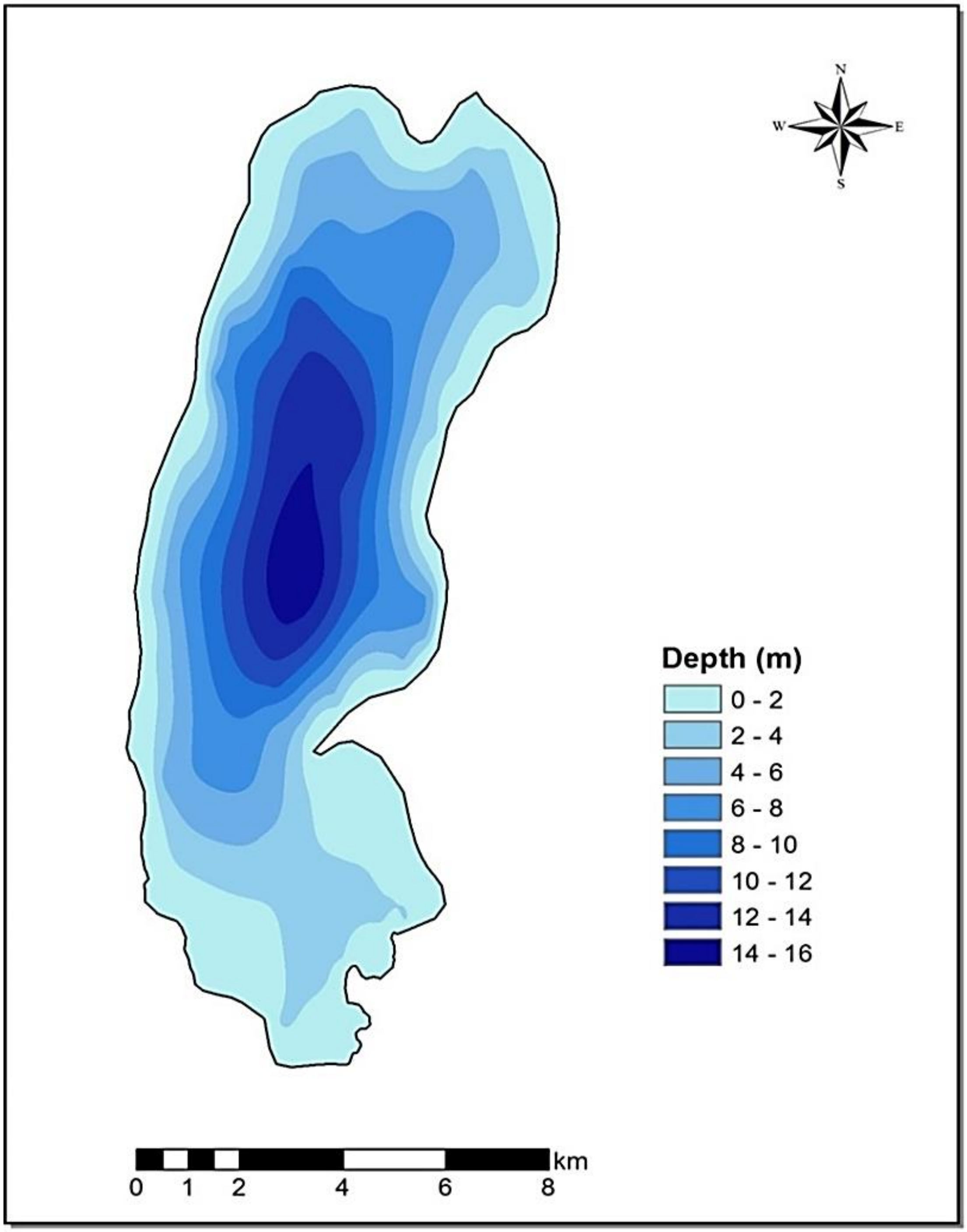


Figure 2. Coarse bathymetry of North Wabasca Lake as determined by GPS-referenced sonar.

For determining routine water chemistry, a Lund tube was used to collect depth-integrated water samples to the euphotic depth at 10 locations (primary + secondary sampling points; Figure 3). These 10 depth-integrated samples were combined into a single lake-composite water sample. The composite sample was poured into appropriate pre-rinsed containers (and in some cases preserved) for submission to the labs for the various chemical and biological analyses including: ion and nutrient chemistry, phytoplankton community enumeration; and concentrations of chlorophyll-a and the cyanobacteria (blue-green algae) liver toxin, microcystin (AENV, 2006). Depth-integrated sampling through the euphotic zone constrains vertical differences through the upper water column, while compositing (combining) samples from multiple sites moderates spatial differences throughout the lake. By combining water from 10 locations, we seek to identify average water quality conditions in a lake and do not consider or identify (spatial) variation in water quality occurring throughout the lake.

In addition to a composite water sample, water was also collected at the surface (0.1 m) and 1 m above the lake bottom (depth of 14.5 m) with a Teflon® discrete-depth sampler (called a Kemmerer sampler) during the August sampling event for determining metal and dissolved mercury concentrations (AENV, 2006). Lastly, sampling for invasive Dreissenid (zebra and quagga) mussel larvae and spiny water flea (*Bythotrephes longimanus*) was conducted in July, August and September, by vertically raising a 63-µm mesh net from the lake bottom to the surface several times at three sampling sites (corresponding to: an area receiving majority of inflows; an area nearest the main boat launch; and the area nearest the outflow), all of which were combined for a single sample for analysis. Approximately 500 L of water (total from the 3 sites) was passed through the net in turbid conditions (*i.e.,* Secchi disc less than 2.5m) and 1000 L of water (total from the 3 sites) passed through during clear conditions (*i.e.,* Secchi disc greater than 2.5m).

The shallow (< 1.5 m) depth of Willow River and the Desmarais Lake outlet required sampling by direct filling of pre-rinsed sample bottles below the water’s surface. Water temperature, dissolved oxygen, pH, and specific conductivity were recorded with a HydroLab Datasonde below the water’s surface on each visit. Biological samples were not collected from Willow River and Desmarais outlet during the study as we anticipated fundamental differences in communities resulting primarily from water flow rather than water quality—free-floating ‘planktonic’ communities are more evident in lentic (still water) systems rather than lotic (flowing) systems, which are dominated by attached or burrowing (benthic) plant and animal communities.

Winter sampling was conducted on February 22, 2017 at the primary site (Figure 3) in North Wabasca Lake. Water temperature, dissolved oxygen, pH, and specific conductivity were measured at 1 m depth intervals to the sediment’s surface with a HydroLab Datasonde. Water samples were collected at three discrete depths—at 1 m, 7 m and 14 m below the ice—by pumping water with the use of a peristaltic pump. Pre-rinsed bottles were directly filled (and in some cases preserved) for submission to the labs for the various chemical and biological analyses described above (AENV, 2006). Winter biological sampling was performed for chlorophyll-a, phytoplankton community analysis and microcystin, and did not include zooplankton, spiny water flea and invasive mussel larvae samples. Samples for water chemistry (including ions, nutrients and metals) were also collected from both Willow River and the outlet of Desmarais Lake by directly filling pre-rinsed sample bottles below the water's surface.

Samples collected for quality assurance/quality control (QA/QC) purposes accompanied all sample bottles being submitted to the labs for total recoverable metals and total and dissolved mercury in August and February. These 'field blank' samples consisted of laboratory grade reagent water poured into sample bottles in the field under the same environmental conditions as the regular sample containers. Field blank samples were submitted 'blind', meaning there was no indication the samples were for QA/QC purposes. Field blank results are presented Table 6.0 QA/QC Data, Appendix II.

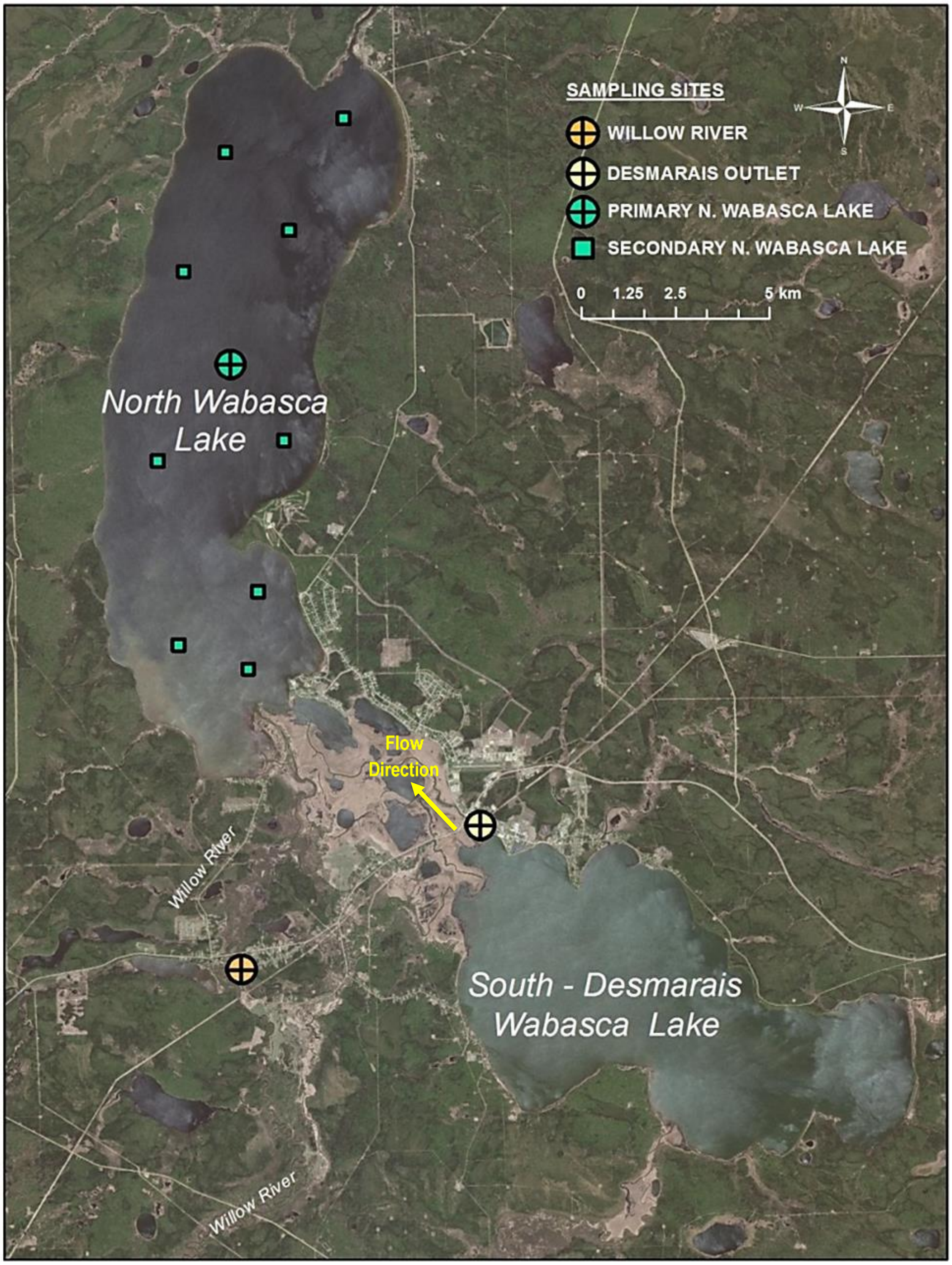


Figure 3. North Wabasca Lake, Desmarais Outlet and Willow River sampling sites

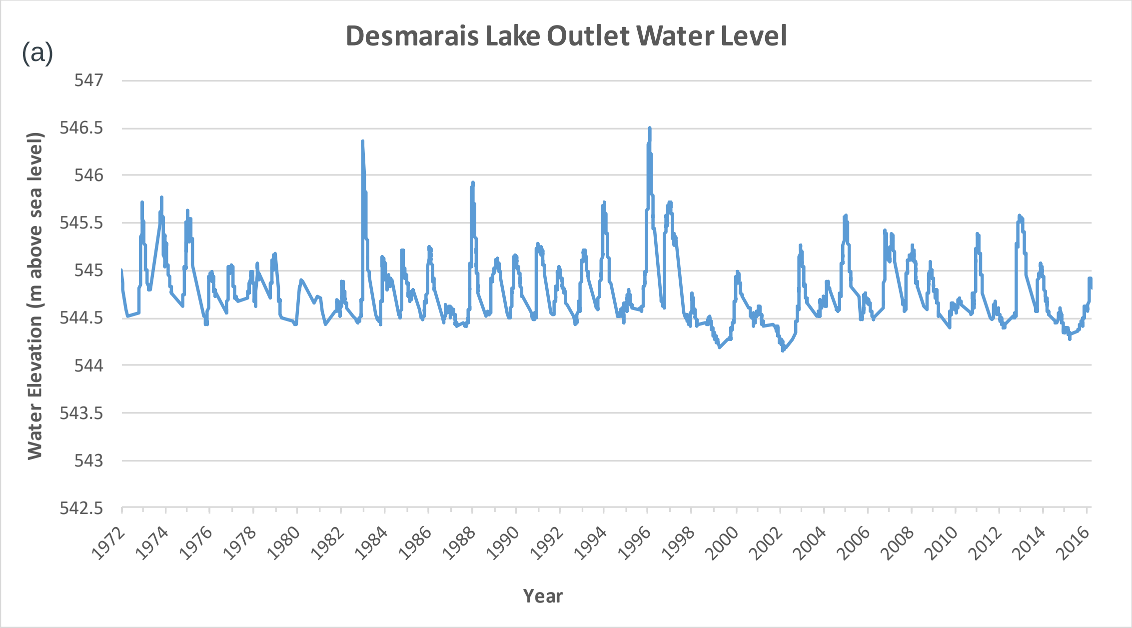
Results

Water Quantity

Water level data recorded by Water Survey of Canada at Station #07JA002 from 1972–2017 (ECCC, 2017; Figure 4a) indicate that water elevations at Desmarais outlet fluctuate seasonally by approximately 0.5 to 1m (from ≈ 544.4 to 545.4m) above sea level (ASL). Mean water level was 544.84m ASL, nevertheless, recorded levels have peaked as high as 546.5m (Aug, 1996) and has dropped as low as 544.2m (Sept, 2002) ASL in the past. Generally, it appears that water levels in Desmarais Lake (as measured at the outlet) have been stable over time.

Historical river discharge data for Willow River (WSC Station #07JA003; ECCC, 2017; Figure 4b) demonstrate seasonal peaks in river flow that are likely the result of spring snowmelt (run-off) and rainfall in the catchment. With a sub-watershed of about 1030 km^2, annual spring run-off/precipitation typically causes Willow River discharge to increase from < 1 m^3/s during winter low-flow periods to peaks of 20 to nearly 40 m^3/s during late spring and early summer. However, in some years (*e.g.* 1995, 1999, 2002, 2010 and 2012) discharge never exceeded 20 m^3/s; and in other years (*e.g.* 1988, 1994, 1996, 2003 and 2013), seasonal peak discharge has exceeded > 80 m^3/s (Figure 4b). The highest recorded value was 179 m^3/s in July, 1988. Except for Desmarais lake outlet, Willow River is the largest single inflow to North Wabasca Lake, but several permanent and ephemeral streams also flow directly into the lake from its catchment. These inputs have some seasonal (*i.e.* primarily spring run-off) impact on the water levels of North Wabasca Lake and influence discharge from the lake's primary outflow, the Wabasca River (Bigstone Cree, pers. comm.).

Boreal and parkland lakes in Alberta with large contributing watersheds and moderate to deep maximum depth (*i.e.* > 15–25m) tend to have relatively stable water levels (Gibson *et al.*, 2016). The numerous inflows to North Wabasca Lake help sustain water levels such that seasonal fluctuations in water elevation may be minimal. The water residence time of North Wabasca is not known. Other boreal and parkland lakes with similar depth and watershed areas (and large watershed to lake surface area ratios; > 15) generally have intermediate residence times (8–12 yrs; Gibson *et al.*, 2016), but some (*e.g.* Baptiste Lake South Basin) are even shorter (≈ 6 yrs; Trew *et al.*, 1987). Alberta lakes with large watersheds also receive large amounts of nutrients naturally from channelized inflows and diffuse run-off from the catchment. These lakes are usually quite productive (fertile) supporting elevated growth and reproduction of algae and large rooted aquatic vegetation (Gibson *et al.*, 2016; Trew *et al.*, 1987). Algal blooms are natural and common in these lakes (discussed in more detail below).



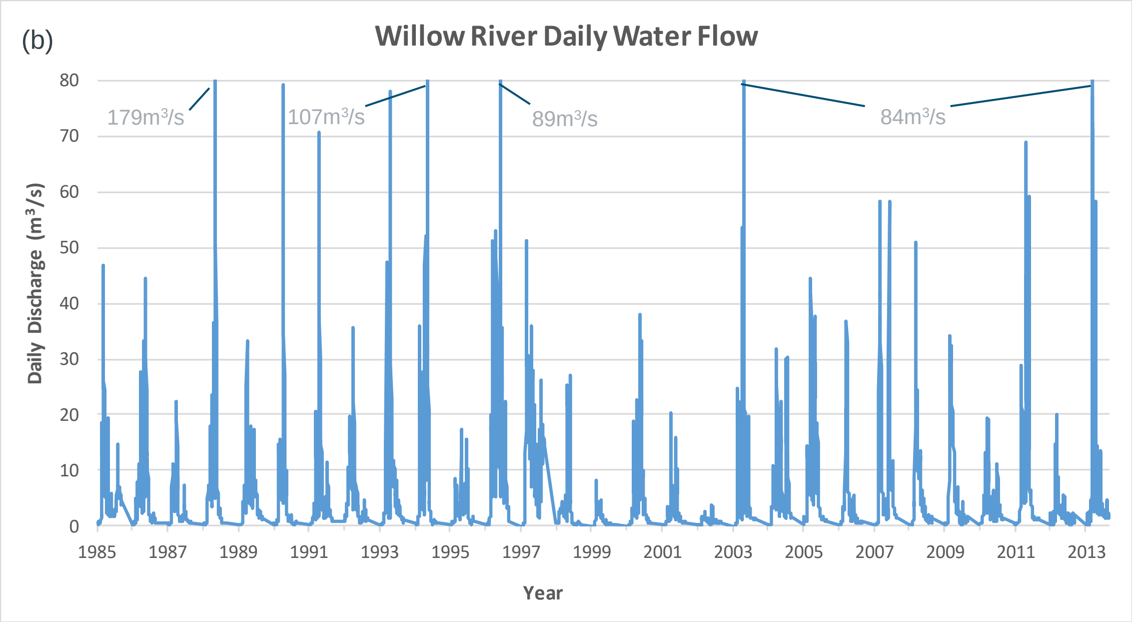


Figure 4. Historical water elevation of (a) Desmarais (South Wabasca) Lake outlet (m above sea level) and (b) Willow River discharge (cubic meters per second). Extracted from the Environment and Climate Change Canada Historical Hydrometric (HYDAT) Data web site (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html), Jan 2017.

Temperature and Dissolved Oxygen Depth Profiles

Water temperature-depth profiles (Figure 5) indicate that North Wabasca Lake became thermally stratified following ice-off and spring turn-over (see Figure A1, Appendix I). In June, the water column was weakly stratified, with temperatures of 16.3°C from the surface to a depth of 7 meters. Water temperature decreased gradually to 10.0°C between 7 and ≈ 12 meters, then remained isothermal (constant temperature) to the lake bottom. Stratification was strongest in July, as demonstrated by the most rapid decrease in temperature at depth of all months sampled. At this point, the temperature was 19.5°C in the epilimnion (warm, circulating and turbulent surface waters) to a depth of 7 meters, then decreased rapidly to 15.2°C at 9 m. Below 9 meters, temperatures in the hypolimnion (cold, relatively undisturbed deep waters) were approximately 14.3°C. In August the epilimnion was warmest, reaching 20.5°C. Approximately 14.0°C in the hypolimnion was similar to July, however, water column stratification was weaker (see Figure A1, Appendix I). By September, the lake was essentially isothermal, with temperatures 13.9°C throughout the water column indicating the lake had likely experienced Fall turnover (mixing of previously separated surface and deep waters). Under ice, the temperature profile in February was essentially isothermal, with temperatures increasing from ≈ 1.5 °C immediately below ice to 3.2°C at a depth of 15 meters.

Key Finding: Water Temperature

Due to its moderate depth and large area, North Wabasca Lake experiences weak 'thermal stratification' through summer. This means periods of windy conditions and cooler temperatures can cause the lake to mix completely over the open water season and can result in early fall turn-over.

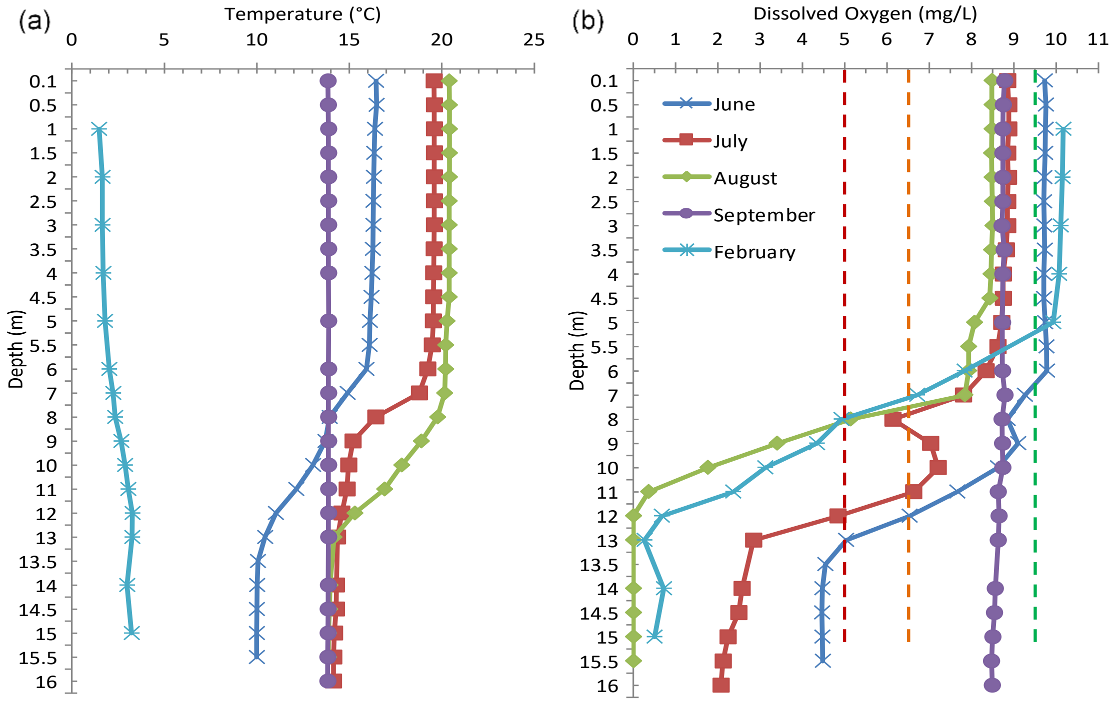


Figure 5. Depth-dependent water temperature (a) and dissolved oxygen (b) profiles for North Wabasca Lake. Vertical dashed lines indicate surface water quality DO guidelines: green = early life-stage development of fish; orange = long-term (chronic); and red = instantaneous (acute).

Dissolved oxygen (DO) profiles often mimic temperature profiles because water temperature influences DO concentrations in water. DO is critical for survival of fish and other aquatic organisms. The Alberta surface water quality guidelines for protection of aquatic life for DO are 5.0 mg/L (red dashed vertical line; Figure 5b and Figure 6) for instantaneous (*i.e.,* acute) exposure and 6.5 mg/L (orange dashed vertical line; Figure 5b and Figure 6) for long-term (*i.e.,* chronic) exposure (calculated as a 7-day mean; AENV, 1999). Additionally, the DO guideline for protection of early-life stage development of fish is 9.5 mg/L (green dashed vertical line; Figure 5b). In June, North Wabasca Lake had ample DO (≈ 9.7 mg/L) in the epilimnion to meet the early life stage requirements (9.5 mg/L) and sufficient DO (*i.e.,* > 6.5 mg/L) in the hypolimnion to 12 m to avoid chronic harm to fish (Figure 5b). Below 13 m, DO was below the acute guideline concentration (*i.e.,* < 5 mg/L). In summary, DO concentrations in North Wabasca met the early life stage requirements for spring spawning fish development to a depth of 6 m and sportfish could inhabit water from the surface down to about 13 m (Figure 6). However, DO was not sufficient for survival below 13 m. In July, the DO concentration in the epilimnion was slightly lower than in June (≈8.7 mg/L), decreased to less than 6.5 mg/L (Alberta chronic DO guideline) by 11 m and to less than 5 mg/L (Alberta acute DO guideline) at approximately 12 m (Figure 6). Although not sufficient for fish survival near the bottom sediment, DO remained at detectable levels (>2 mg/L). Surface DO in August was 8.5 mg/L, and declined to 6.5 mg/L (Alberta chronic DO guideline) at 7.2 m. Below 8 m, DO was below the chronic guideline and completely depleted in the lake below 12 m. Therefore, fish habitat was restricted to the uppermost 8 m of water in North Wabasca Lake in August (Figure 6). With complete mixing of lake waters by September, DO concentrations increased to 8.7 mg/L throughout the water column and were sufficient for fish survival in the entire lake.

Key Finding: Dissolved Oxygen

The amount of oxygen dissolved in North Wabasca Lake changes with water temperature and wind-induced mixing. While high DO levels may become restricted to the upper water column during late summer and winter, there is sufficient DO in the lake to support early life stage development and healthy sportfish populations in the spring and summer.

An early (September) Fall turnover is a result of the weak thermal stratification in North Wabasca Lake likely due to the relatively large surface area (*i.e.,* potentially more wind-induced mixing) and moderate depth of the lake basin. Deeper lakes (> 20 m) usually have stronger stratification and require more water cooling prior to turnover later in fall (*i.e.,* October; Figure A1, Appendix I). Concentrations of DO under ice in February were high (> 10 mg/L) to a depth of 5 m and gradually declined to 6.5 mg/L (chronic guideline) by 7.25 m and to 5 mg/L (acute guideline) at approximately 8 m depth. By 12 m depth, DO was less than 1 mg/L and remained so down to the bottom (Figure 6).

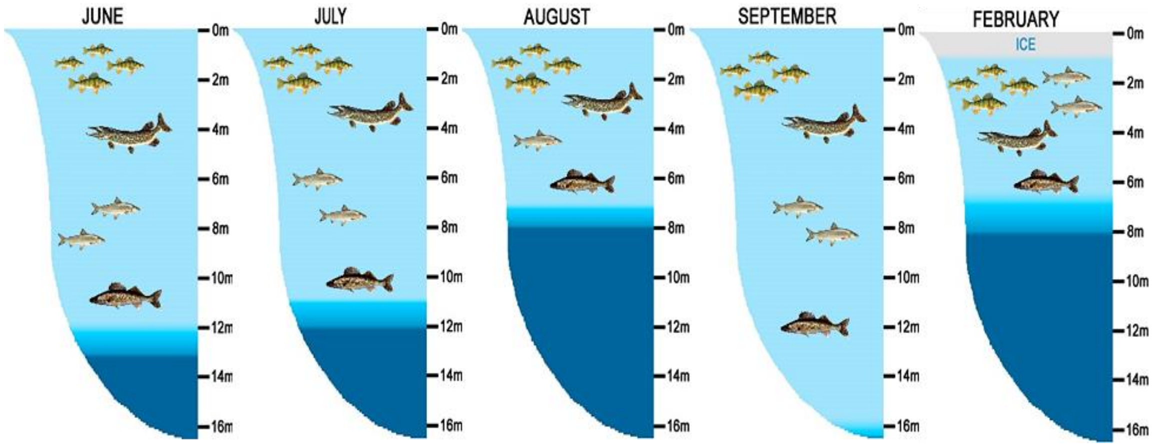


Figure 6. Depiction of dissolved oxygen availability for North Wabasca Lake, 2016. Light Blue exceeds chronic DO guideline (>6.5 mg/L), medium blue exceeds acute but not chronic DO guideline (>5 mg/L & < 6.5 mg/L), and dark blue does not meet acute DO guideline (< 5mg/L) (AENV, 1999).

Ion/Nutrient Chemistry and Trophic Status

Lake water contains numerous suspended particles and dissolved substances arising directly from precipitation (rain and snow) on the lake's surface, from groundwater and channelized surface flow (streams and rivers), and from diffuse run-off from the watershed. These substances include dissolved ions (*e.g*., sodium, calcium and chloride), metals (*e.g*., mercury, iron and aluminum) and nutrients (*e.g*., carbon, phosphorus and nitrogen) from weathering of minerals and dissolution of natural salts. In addition, substances like nutrients can also arise within the lake basin through microbial/biological activity of bacteria, fungi, algae and aquatic plants, as well as the resuspension of bottom sediments. In addition, many of these substances are mobilized through human activity and disturbance within the watershed, such as the use of road salts (*e.g*., calcium, sodium and chloride) and fertilizers (*e.g*., phosphorus) or the release of untreated sewage (*e.g*., nitrogen and phosphorus) and industrial chemicals or byproducts (*e.g.,* metals and organic contaminants).

Key Finding: Alkalinity and pH

The surrounding watershed influences the water chemistry of North Wabasca Lake. Like others in the region, the pH of the lake is mildly basic (mean pH 7.9) and sufficiently alkaline (from the carbonate-rich watershed) to buffer impacts of acid deposition (rain) or snowmelt.

The pH of water (degree of acidity) is an important determining factor in lake water quality as it influences the solubility (amount dissolved in the water) and biological availability (amount available for uptake by aquatic life) of chemical constituents including nutrients (*e.g*., phosphorus, nitrogen, and carbon) and heavy metals (*e.g.,* lead, copper, mercury) in water. pH can be altered by natural causes (*e.g.* run-off events and photosynthesis by aquatic plants and algae) and human activity (*e.g.* mining development, industrial discharges). In Alberta's lakes, pH tends to be naturally elevated (about 7.5–8.5) near the surface, where temperature and biological activity (*e.g.,* photosynthesis by algae and plants) are highest. In highly productive—'hypereutrophic'—lakes, pH can exceed 9 (and in some cases be as high as 10) during algal blooms (Kann and Smith, 1999). Spikes in pH can occur during daylight hours as aquatic plants and algae consume dissolved carbon dioxide in the process of photosynthesis. Levels will decrease at night as photosynthesis ceases. Although, most aquatic organisms are able to withstand small changes to environmental pH, rapid drastic change can be detrimental and changes in community structure will occur over time. The Alberta surface water quality guideline for pH is between 6.0 and 9.0 pH units.

During 2016, the pH of North Wabasca Lake varied little (Figure 7a), ranging only from 7.35 to 7.94 (see Table 2.0 Raw Data, Appendix II) and had a mean value of 7.87 over the summer sampling season (see Table c, Appendix I). This means that pH in North Wabasca Lake was relatively stable and close to neutral and fell within the normal range for lakes. In contrast, the pH measured at the Desmarais Lake outlet was significantly more alkaline (Figure 7a) and varied greatly during the study ranging from 7.29 in February to 9.67 in July (Table 2.0 Raw Data, Appendix II) with a summer mean of 9.21 (Table c, Appendix I). This elevated summer pH is common in hypereutrophic systems and exceeds the Alberta Surface Water Quality guideline of 9.0 (Alberta chronic pH guideline; AESRD, 2014). This exceedance was likely due, in part, to increased photosynthesis by dense aquatic vegetation and algal communities (Kann and Smith, 1999) evident in Desmarais Lake (severe weed growth across the lake obstructs boat access). The pH of Willow River was similar to North Wabasca Lake ranging from 7.2 (in winter) to 7.7 in August and had a mean summer value of 7.56. The more neutral pH in Willow River is likely due to humic acids—weak acids produced during the decomposition of plant residues (Hruška *et al*., 2001). Humic acids would enter the stream through the many wetlands populating this heavily forested region of Northern Alberta.

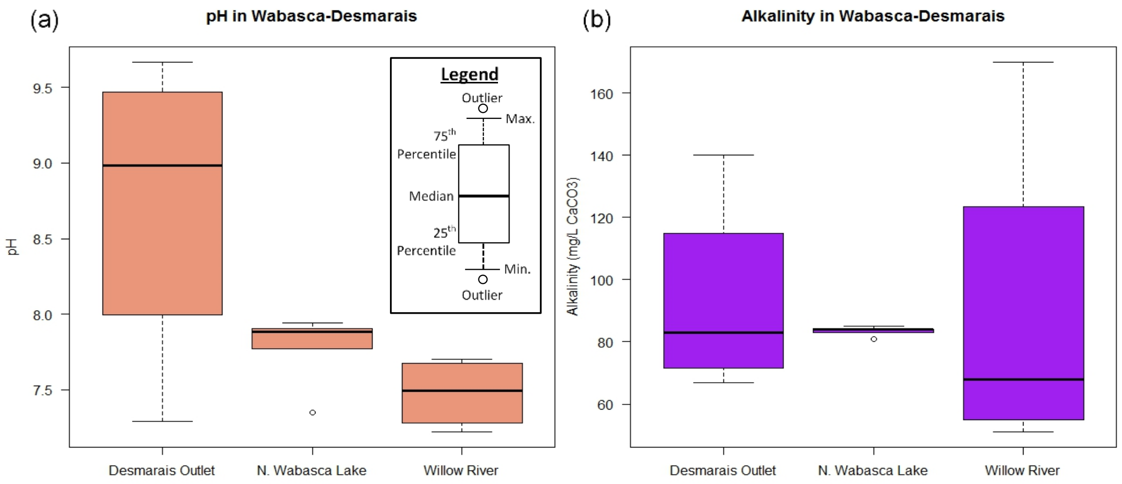


Figure 7. Box plots comparing pH (a) and alkalinity (b) in Desmarais Lake Outlet, North Wabasca Lake and Willow River.

Alkalinity refers to the capacity of water to neutralize or buffer acidity (hydrogen ions). Alkalinity of surface waters is determined by the presence carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) arising naturally from weathering of carbonate-rich soils and bedrock often comprised of calcium and magnesium carbonate rock (*e.g.* limestones and some sandstones) (Mattson, 2009). Because the main source of alkalinity (in the absence of industrial sources) is from calcium and magnesium carbonate rocks, it is often closely related to water hardness (*i.e.,* the amount of dissolved calcium and magnesium in the water). Alberta's water quality guidelines recommend that a habitat suitable for aquatic life should have a minimum of alkalinity 20 mg/L ($CaCO_3$) (AESRD, 2014; Table c, Appendix I).

All three waterbodies had moderate alkalinity in 2016, which can likely be attributed to the naturally occurring carbonate-rich parent bedrock within the watershed including primarily siltstones and sandstones with some shales (MPWA, 2015). For North Wabasca Lake, the variability in alkalinity was low, ranging from 81–85 mg/L $CaCO_3$ (Table 2.0 Raw Data, Appendix II) with a summer mean of 83.5 mg/L $CaCO_3$ (Figure 7b; Table c, Appendix I). This suggests the lake has a strong buffering capacity and would not be susceptible to acidification if the lake became subject to acid deposition (rain) or snowmelt. Alkalinity at Desmarais outlet was far more variable than in North Wabasca ranging from 67 to 90 mg/L $CaCO_3$ through summer and peaking at 140 mg/L $CaCO_3$ in February (Figure 7b; Table d, Appendix I). It is possible the winter peak in alkalinity may be attributed to low winter flows and an increasing proportion of groundwater contributions (and not surface water flow from the catchment) during winter. Alkalinity in Willow

River was the most varied of the three waterbodies. Alkalinity was low in July (59 mg/L $CaCO_3$), increased in August (to 77 mg/L $CaCO_3$), dropped to its lowest value in September (51 mg/L $CaCO_3$), and then increased sharply to 150 mg/L in February. Again, it is likely that groundwater mostly contributed to low winter (base) flows (Peralta-Tapia *et al*., 2015) and the peak in alkalinity. In general, base cation (Mg, Ca) concentrations and alkalinity tend to increase in these water bodies during periods of low flow (Lidman *et al*. 2017).

Nitrogen and phosphorus are essential nutrients for the production and growth of algae (and plants) that form the base of a lake's food chain. Nitrogen is naturally abundant in the environment and can enter rivers and lakes in inorganic and organic forms. Common inorganic forms include nitrate, nitrite and ammonia (Wetzel, 1983). Another important source of inorganic nitrogen—especially in Alberta's lakes—comes from the fixation of atmospheric nitrogen gas by several species of cyanobacteria (also called blue-green algae) (Stewart, 1969; Marino *et al*., 1990). Organic nitrogen comes from the decomposition of plant and animal matter by bacteria. Nitrogen is also found in fertilizers, human and animal wastes and these sources contribute to excess growth of algae and plants in some Alberta lakes (Prepas, 1990). In this study, inorganic nitrogen was measured as nitrate + nitrite and ammonia. Organic nitrogen was calculated as total Kjeldahl nitrogen minus ammonia (TKN; includes organic nitrogen and ammonia). For simplicity, we will focus on the total concentration of nitrogen, which is the sum of nitrate, nitrite and TKN.

In contrast to nitrogen (the most abundant gas in the earth's atmosphere), there are fewer natural sources of phosphorus and as a result it is far less abundant in lakes and rivers (Golterman, 1973). The primary natural source of phosphorus is phosphate minerals derived from metamorphic and sedimentary bedrock. Phosphate-rich minerals occur throughout Alberta and explain why phosphorus levels are naturally higher in many Alberta lakes compared to some eastern parts of Canada where igneous rocks (*e.g.* granite) form lake basins. Like nitrogen, phosphorus is also found at high concentrations in fertilizers, human and animal wastes. Because phosphorus is relatively scarce compared to nitrogen, it is often the main limiting nutrient for the growth of aquatic plants and algae (Schindler, 1977). Even a slight increase in phosphorus can cause significant increases in the growth of algae and aquatic plants.

One goal of this study was to understand how Desmarais Lake and Willow River—primary water sources to North Wabasca Lake—might influence nutrient concentrations. Nitrogen was highest and most variable in Desmarais Lake Outlet (Figure 8a; Table 3.0 Raw Data, Appendix II) ranging from 1.3 mg/L total nitrogen (TN) in July to 2.9 mg/L under ice in February (Table b, Appendix I). Mean TN over the summer was 1.96 mg/L (Table a, Appendix I). Nitrogen was also variable in Willow River (Figure 8a) ranging from 0.93 mg/L TN in July to 1.9 mg/L under ice in February, but concentrations were generally lower (than Desmarais Lake Outlet) with a summer mean concentration of 0.92 mg/L. Nitrogen concentrations were lowest and least variable in North

Wabasca Lake ranging from 0.66 mg/L TN in June to 1.29 mg/L under ice in February. Mean TN over the summer was 0.78 mg/L.

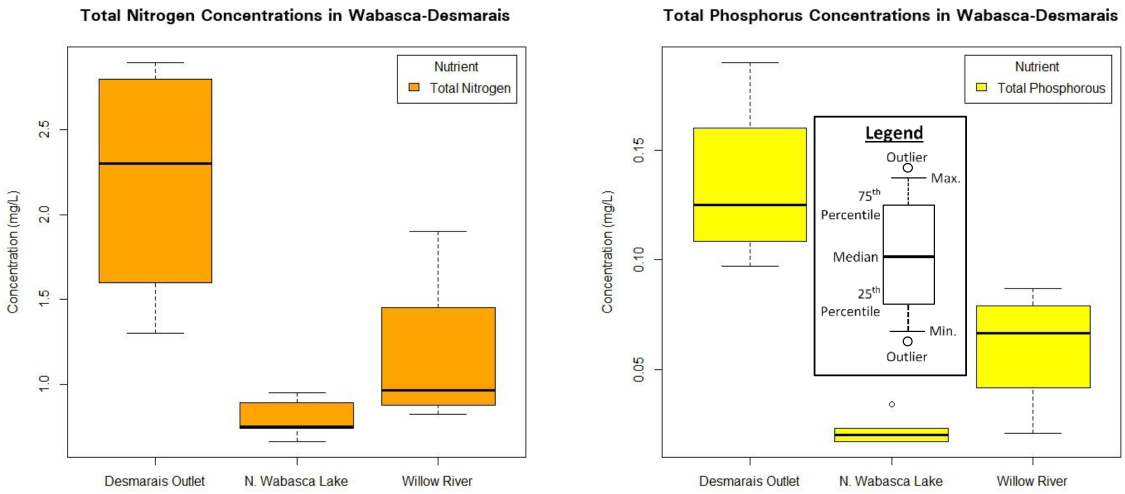


Figure 8. Box-plots comparing total nitrogen (a) and total phosphorus (b) concentrations in Desmarais Lake Outlet, North Wabasca Lake and Willow River.

In all locations, the primary component of nitrogen was attributed to organic forms. However, ammonia was detected at all sites in winter, in North Wabasca Lake during August, and in Desmarais Lake Outlet during August and September. Ammonia comes from the decomposition of algae and plant matter and animal and human wastes and it is commonly detected in winter as oxygen becomes depleted near the lake bottom (Domogalla *et al*., 1925; Geadah, 1985). Ammonia can be toxic to fish at sufficient concentrations, but toxicity is dependent of water pH and temperature (Emerson *et al*., 1975). The level of ammonia (0.08 mg/L; Table 3.0 Raw Data, Appendix II) in North Wabasca Lake in August did not exceed guidelines for protection of aquatic health suggesting little risk to fish. However, concentrations in Desmarais Lake Outlet did exceed guidelines for the protection of aquatic health (AESRD, 2014; Table a, Appendix I) and may reflect anoxic conditions and significant decomposition of organic matter in Desmarais Lake. Ammonia was only detected near the bottom (most oxygen depleted zone) of North Wabasca Lake during winter and was not detected immediately below the ice or mid-column (*i.e.,* 7 m). The concentration of ammonia (0.44 mg/L; Table 3.0 Raw Data, Appendix II) did not exceed guidelines. Similarly, winter concentrations of ammonia in Desmarais Lake Outlet and Willow River did not exceed guidelines (Table b, Appendix I).

Nitrate is the most oxidized form of nitrogen occurring naturally or leaching from soils, manure, domestic sewage and agricultural fertilizer and can be produced from nitrification (bacterial conversion of ammonia and nitrite to nitrate) of excess ammonia in the environment (Stoddard, 1994). Nitrate can cause chronic health effects especially in infants. The Canadian drinking water quality guideline for nitrate ion is 45 mg/L (or 10 mg/L nitrate expressed as nitrogen; Health Canada, 2017); and the guideline for the protection of aquatic health (Long-term exposure in freshwater; CCME, 2017) is 13 mg/L (or 3 mg/L nitrate expressed as nitrogen). Nitrate was detected at all sites during February, in Desmarais Lake Outlet during August, and in Willow River during July (Table 3.0 Raw Data, Appendix II). It was detected immediately below the ice, at 7 m depth and near the bottom of North Wabasca Lake during winter at 0.18, 0.24 and 0.41 mg/L, respectively. The highest concentration of nitrate occurred in the Willow River during winter. This may be a result of lower winter nitrate uptake by plants/microbes with or without enhanced nitrate deposition in winter or perhaps due to a pulse of nitrate that is known to be exported to streams during early stages of snowmelt (for discussion, see Stoddard, 1994). The concentrations detected in this study indicate nitrate is not of concern for drinking water (since water treatment effectively removes nitrate) or protection of aquatic health, as concentrations were much lower than guideline values.

As mentioned above, phosphorus is generally less abundant in lakes and rivers than nitrogen and is often the main limiting nutrient for algae and aquatic plant growth (Schindler, 1977). Total Phosphorus (TP) was highest in Desmarais Lake Outlet, with a mean concentration of 0.136 mg/L (0.10 to 0.19 mg/L) between July and September, and 0.13 mg/L under ice in February (Figure 8b; Table a, Appendix I; Table 3.0 Raw Data, Appendix II) Table b, Appendix I). Due to the shallow depth and severe density of aquatic vegetation across its lake basin, we were unable to navigate and directly sample Desmarais Lake. In Willow River, summer mean TP was 0.057 mg/L (0.021 to 0.087 mg/L; Figure 8b). The peak TP values in July may reflect phosphorus loading from the watershed (*i.e*. run-off from rain in June), which carries suspended soil- and sediment-bound phosphorus. Similarly, the high value in winter (*i.e.,* 0.071 mg/L), indicates possible loading from the watershed during snowmelt and is not uncommon in small streams. Like nitrogen, TP concentrations were lowest in North Wabasca Lake: TP ranged from 0.017 in June and July to 0.034 in September with a summer mean concentration of 0.022 mg/L; and concentrations immediately below the ice, at 7 m depth and near the bottom during winter were 0.023, 0.025 and 0.058 mg/L, respectively.

Because phosphorus is typically the main limited nutrient for algal growth, scientists often use TP concentration to classify or rank the degree of nutrient enrichment and biological productivity (or ‘trophic state’) within lakes. Lake trophic status can be classified into four categories: oligotrophic (low nutrient inputs and organic production), mesotrophic (moderate nutrient inputs and organic production), eutrophic (high nutrient inputs and organic production), and hypereutrophic (very high nutrient inputs and organic production; Vollenweider and Kerekes, 1982). Recognizing these historic classification categories are broad and can reflect large observable gradients in algal and aquatic plant community composition and biomass, Environment Canada (2004) suggested a modified system including 6 categories (Table 2). Based on mean TP over the study period, Desmarais Lake Outlet was classified as hypereutrophic, Willow River as eutrophic, and North Wabasca Lake as meso-eutrophic. This means the potential for growth of algae and aquatic plants is very high in Desmarais Lake Outlet and only moderately-high in North Wabasca Lake.

Table 2. Modified trophic classifications of lakes based on total phosphorus (adapted from Environment Canada, 2004).

Trophic State	Total Phosphorus (mg/L)
Ultra-oligotrophic	< 0.004
Oligotrophic	0.004–0.010
Mesotrophic	0.010–0.020
Meso-eutrophic	0.020–0.035
Eutrophic	0.035–0.100
Hypereutrophic	> 0.100

It is apparent that Desmarais Lake Outlet and (to a lesser extent) Willow River, are important sources of phosphorus to North Wabasca Lake. Given North Wabasca Lake's size and the co-location of the inlets from Desmarais Lake and Willow River in the southern end of the lake, it is reasonable to suspect phosphorus concentrations may vary spatially across North Wabasca Lake, with TP concentrations higher in the south end of the lake and lower in the north end. However, our sampling strategy was not designed to capture spatial differences in TP across North Wabasca Lake, but rather to understand average conditions for the entire lake. Casual observations during sampling did indicate lower water transparency (due to greater turbidity and color) in the south end of the lake extending several kilometers northward. This southern portion of the lake appears to be a shallow depositional area where fine sediments (including particlebound nutrients) from Desmarais Lake and Willow River settle. The south end of North Wabasca Lake also supports significant growth of aquatic plants over the summer.

An important factor in understanding the potential of a lake to support algal growth, is the ratio of nitrogen to phosphorus (TN:TP) in the water. In practice, freshwater lakes with TN:TP mass ratios greater than 20 indicates a potential phosphorus deficiency (*i.e.,* phosphorus is most likely limiting algal growth) and lakes with TN:TP below 10 indicate nitrogen deficiency (*i.e.,* nitrogen as the likely nutrient limiting algal growth) (Galvez-Cloutier and Sanchez, 2007). Eutrophic lakes often have lower TN:TP ratios (*i.e.,* TN:TP < 30), while mesotrophic and oligotrophic lakes have higher ratios of TN:TP (*i.e.,* TN:TP > 30). The summer mean TN:TP ratio in Desmarais Lake Outlet was 14.5, Willow River was 16.2 and North Wabasca Lake was 35.2 (Table a, Appendix I). This corresponds to the trophic status of each waterbody and indicates both Desmarais Lake and Willow River contain significant phosphorus and are close to nitrogen limiting conditions, while North Wabasca Lake is phosphorus limited. This could mean any inputs of phosphorus into North Wabasca could cause noticeable increases in algal growth.

Key Finding: Trophic Status

The North Wabasca Lake watershed contains high levels of phosphorus. While Desmaris Lake outflow and Willow Creek are key sources of nutrients to the Lake, internal loading of phosphorus from the sediment is another important source.

Based on mean phosphorus over the study period, North Wabasca Lake was classified as meso-eutrophic and can support excessive algae and plant growth and a likelihood of localized algal blooms during summer.

In this study we estimated algal biomass by measuring the chlorophyll-a (Chl-a) pigment in water samples. Chl-a is the primary pigment responsible for photosynthesis in algae and plants and its concentration in water is roughly proportional to the concentration of planktonic (free-floating) algae (Tolstoy, 1979). Chl-a concentrations varied greatly over the study in Desmarais Lake Outlet and North Wabasca Lake, while those in Willow River remained relatively stable (Figure 9; Table 3.0 Raw Data, Appendix II). This is expected, as lake environments (like Desmarais and North Wabasca Lakes) have distinct growing seasons for algae with peaks typically occurring in August or September and lowest growth under ice during winter months. In contrast, Willow River is a flowing-water environment that tends to support fewer planktonic algae in favor of algal forms attached to rooted plants, rocks and sediments, which we did not quantify in this study. Summer mean Chl-a (25.87 µg/L) and winter (5.5 µg/L) concentrations were highest in Desmarais Lake

Outlet (Table a & b, Appendix I), with values reaching a maximum concentration of 39.3 µg/L in August (Figure 9). Chl-a in North Wabasca Lake ranged from a winter low of 0.17 µg/L under ice to a peak of 35.4 µg/L in September (Figure 9; Table 3.0 Raw Data, Appendix II) with a summer mean value of 17.55 µg/L (Table a, Appendix I). In contrast, Chl-a in Willow River ranged from a winter low of 0.9 µg/L to a peak of 4.7 µg/L in July and had a summer mean value of 3.5 µg/L.

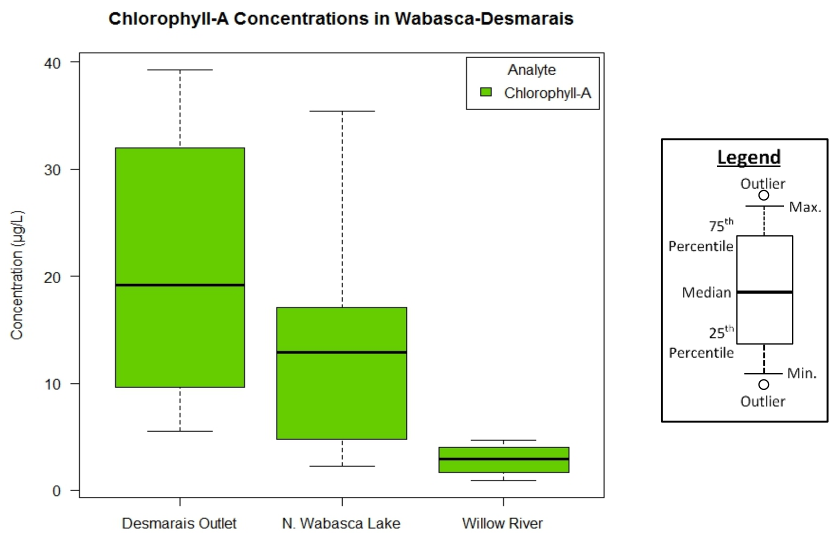


Figure 9. Box-plots comparing chlorophyll-a concentrations in Desmarais Lake Outlet, North Wabasca Lake and Willow River.

Similar to phosphorus, scientists often classify or rank lake trophic status based on the degree of actual biological productivity in a lake. Summer mean (and sometimes peak) algal biomass—as estimated by measured Chl-a concentration—is typically used to categorize lakes as Oligotrophic (low Chl-a concentrations), Mesotrophic (moderate Chl-a concentrations), Eutrophic (high Chl-a concentrations), and Hypereutrophic (very high Chl-a concentrations). In regions with low nutrients and hence low algal productivity, lakes may also be categorized as Ultra-oligotrophic or very low Chl-a concentrations (Table 3). Based on mean summer Chl-a, Desmarais Lake Outlet was classified as hypereutrophic (very high TP), but that was mostly due to the August peak of 39.3 µg/L influencing the mean value. For the most part however, Chl-a concentrations fell in the eutrophic range through most of summer. North Wabasca Lake was eutrophic (high Chl-a) based on summer mean Chl-a, but was mesotrophic (moderate Chl-a) in June and hypereutrophic (very high Chl-a) in September when Chl-a was 4.8 µg/L and 35.4 µg/L, respectively. Willow River was mesotrophic through the summer period and ultra-oligotrophic in winter.

Table 3. Trophic classifications of lakes with corresponding chlorophyll-a concentrations and Secchi disc transparency (adapted from Vollenweider and Kerekes, 1982).

Trophic State	Mean Chlorophyll-a (µg/L)	Mean Secchi Depth (m)
Ultra-oligotrophic	< 1	> 12
Oligotrophic	< 2.5	> 6
Mesotrophic	2.5–8	6–3
Eutrophic	8–25	3–1.5
Hypereutrophic	> 25	< 1.5

In this study, we measured water clarity (transparency) of North Wabasca Lake at the primary (deepest) sampling site (Figure 3) using a Secchi disc. The Secchi depth is a measure of light penetration in a lake. With the exception of very shallow (*i.e.,* <2 m depth) lakes that are susceptible to wave-induced suspension of sediments or lakes receiving direct loading of sediment and/or dissolved colored substances from the watershed, the biomass of planktonic algae largely dictates transparency of a lake's water column (Preisendorfer, 1986). In these cases, the Secchi depth is closely correlated to algal biomass measured as Chl-a concentration. In fact, both Secchi depth and Chl-a are correlated to TP in many lakes and thus, simply measuring the Secchi depth allows scientists to quickly and inexpensively surmise the Chl-a and TP levels in lakes. The Secchi depth of North Wabasca Lake was 1.8 m, 2.7 m, 2.75 m and 1.9 m in June, July, August and September, respectively, with a mean value of 2.3 m. This indicates that North Wabasca Lake was eutrophic throughout the summer period largely agreeing with the trophic classification based on both Chl-a and TP concentrations (Table 3 & 2, respectively).

Phytoplankton (Algae)

While Chl-a provided an estimate of overall phytoplankton (planktonic algae) biomass in North Wabasca Lake, we also collected samples for the direct identification and enumeration of planktonic algae. Generally, healthy lakes support diverse algal communities where no single species or group of algae dominates—oligotrophic lakes have lower overall algal biomass, but are typically more diverse (*i.e.,* more species) than hypereutrophic systems (Wetzel, 1983). The phytoplankton communities of eutrophic lakes like North Wabasca are more diverse early in the growing season when environmental conditions fluctuate and become less diverse later in summer as the lake's water column stabilizes allowing some groups—usually cyanobacteria—to dominate.

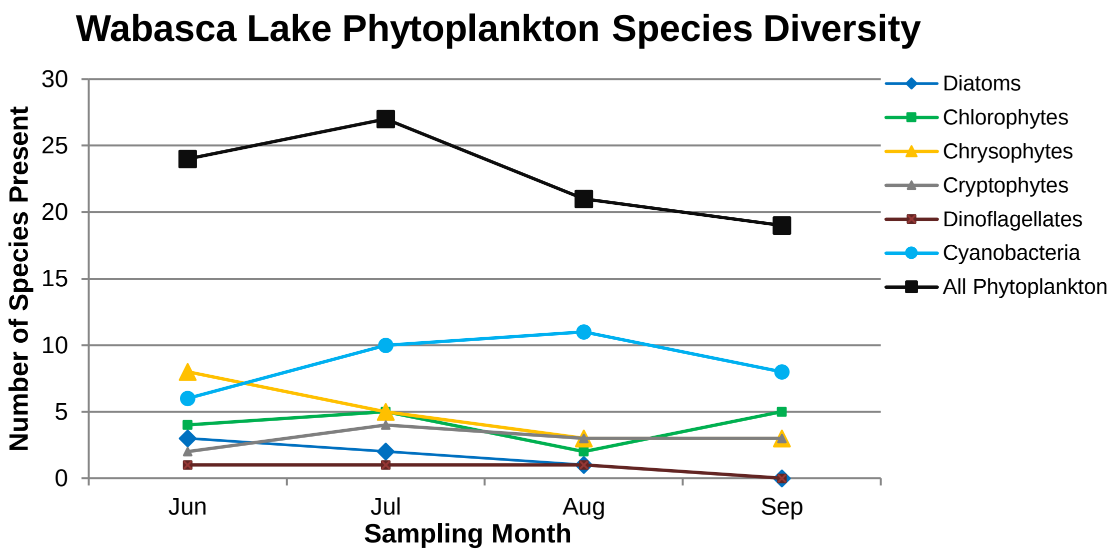


Figure 10. Phytoplankton (algae) species diversity in North Wabasca Lake during the open water season.

Phytoplankton species diversity (i.e., number of species present) was determined over the summer months (Figure 10). Results indicate the phytoplankton community was most diverse (most species of algae) in July becoming less diverse in August and September. Of the various groups of algae present in North Wabasca Lake, the cyanobacteria (commonly called blue-green algae) were the most diverse group through the summer with the exception of June when chrysophyte (golden-brown) algae were most numerous.

Species diversity is only one measure of aquatic ecosystem health. Another important measure is the abundance or density of algae. Oligo- and mesotrophic lakes have low and moderate phytoplankton biomass, respectively, and as a result do not typically support algal blooms, have greater water clarity and are less susceptible to oxygen depletion from microbial decomposition. In contrast, eutrophic and hypereutrophic lakes support large phytoplankton communities including localized to widespread cyanobacteria blooms (Wetzel, 1983). Aquatic plant growth may also be significant if young plants can grow close to the water's surface before algal blooms shade them from sunlight (limiting further growth). Water clarity becomes impaired as algal density increases and this can further stimulate cyanobacteria to migrate towards the surface seeking ideal sunlight for photosynthesis and growth—thus intensifying blooms.

Lakes suffering blooms experience drastic fluctuations in dissolved oxygen (DO) with peaks occurring mid-day along with highest photosynthetic rates and depletion at night as plants and algae respire (consuming DO; Wetzel, 1983). While deeper lakes may contain enough DO for fish survival, shallow hypereutrophic lakes can suffer episodic summer fish kills and over time may not support fish populations at all. Also, oxygen becomes depleted during winter in very productive lakes as microbes consume oxygen while decomposing dead organic (*e.g.* algae and plants) matter. Again, oxygen depletion can result in fish mortality and winter fish kills do occur periodically in Alberta's highly productive (hypereutrophic) shallow lakes.

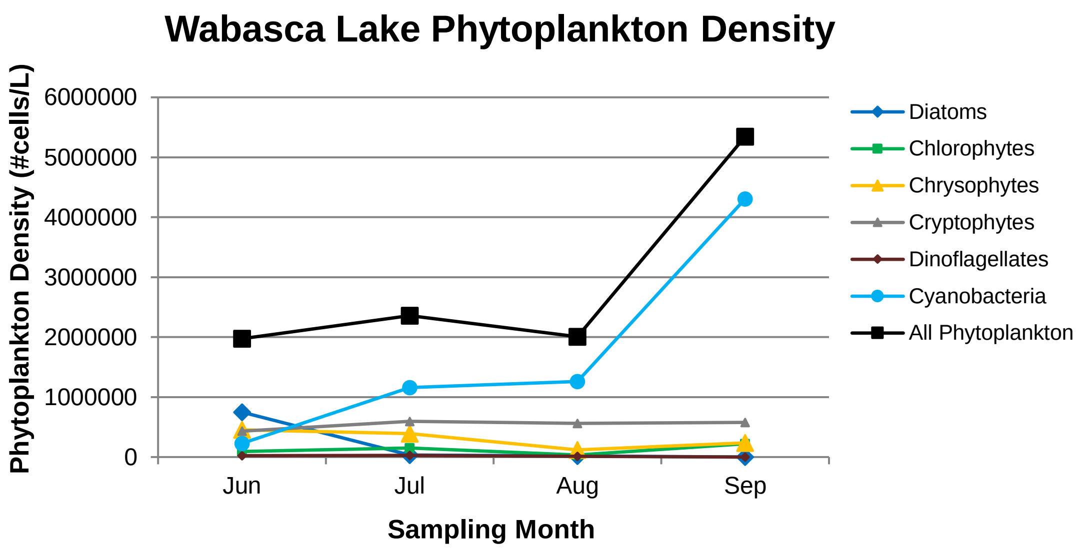


Figure 11. Phytoplankton (algae) density in North Wabasca Lake during the open water season.

Phytoplankton density (*i.e.,* number of algal cells present in a given volume of water) was determined over the summer months (Figure 11). As expected, overall density was lowest at the beginning of the growing season in June, increased slightly in July and after a slight decrease in August, increased significantly through September. Notably, the seasonal increase in algal density was largely due to increasing reproduction of cyanobacteria while other groups of algae either remained constant—including chlorophytes (green algae), cryptophytes (cryptomonads) and dinoflagellates—or declined over the summer—including chrysophytes (golden-brown algae) and diatoms (Figure 11). This indicates that based on cell abundance (density), cyanobacteria were the dominant group comprising the phytoplankton community of North Wabasca Lake over July through September period.

It is also important to consider algal community structure based on biomass (*i.e.,* total mass of algae in a volume of lake water) as algae vary greatly in body (cell) size. Some less-numerous or even rare species may have very large cell size and thus comprise a greater proportion of the overall algal crop. A good example is dinoflagellate algae common in most Alberta lakes. In North Wabasca Lake, dinoflagellates appeared only in low numbers in June, July and August (22689, 27227, 13613 cells/L, respectively; Figure 11) representing 1.1, 1.2, and 0.7% (respectively) of the total algal density. However, given their very large physical size, dinoflagellates represented as much as 7.4% (*i.e.,* 0.6, 7.4 and 2.1% in June, July and August, respectively; Figure 12) of the overall algal biomass during the summer. Diatoms were the dominant algal group in June comprising 67% of the overall biomass (Figure 12). Of that, two large-bodied species—*Asterionella formosa* and *Cyclotella sp.*—comprised 40.6 and 25% respectively, of the overall phytoplankton community. Diatoms often dominate Alberta lakes following ice-out as they are able to reproduce in cold water of the rapidly changing spring time environment. However, given the nutrient-rich conditions in North Wabasca Lake, cyanobacteria were already becoming an important group of algae in the lake in June, comprising 24.3% of the lake’s overall biomass. By the July sampling, cyanobacteria comprised the majority of the planktonic algal biomass in the lake (91.4%; Figure 12). Subsequently, the relative biomass of cyanobacteria increased to 97.4% in August and peaked at 99.7% in September.

The nearly complete dominance of the algal community by cyanobacteria is characteristic of eutrophic and hypereutrophic lakes. In the scientific sense, cyanobacteria (a.k.a. blue-green algae) are not algae, but rather comprise a group of photosynthetic bacteria that possess adaptations allowing them to thrive—and often dominate—in many of Alberta’s lakes (Kotak and Zurawell, 2007). For instance, many species of cyanobacteria produce resting stages (cells) that remain dormant on the bottom sediments until suitable environmental conditions arise. This represents a ‘seed bank’ and allows cyanobacteria to quickly re-populate a lake’s water column during favorable growing conditions. Another adaptation is the ability of cyanobacteria to utilize bicarbonate as an inorganic carbon source for photosynthesis. In contrast, most true algae require carbon dioxide as their main carbon source for photosynthesis. The primary form of inorganic carbon in lakes generally depends on pH with carbon dioxide levels increasing with decreasing pH and bicarbonate being the primary form at higher pH (*i.e.,* pH ≥ 8). Unlike algae, cyanobacteria are not limited by carbon dioxide availability in alkaline (high pH) lakes that are common in Alberta. While the pH of North Wabasca Lake was only 7.87 (mean) over the summer, the relatively high bicarbonate concentration (summer mean of 99.5 mg/L; Table c, Appendix I) suggests conditions were well-suited to cyanobacteria.

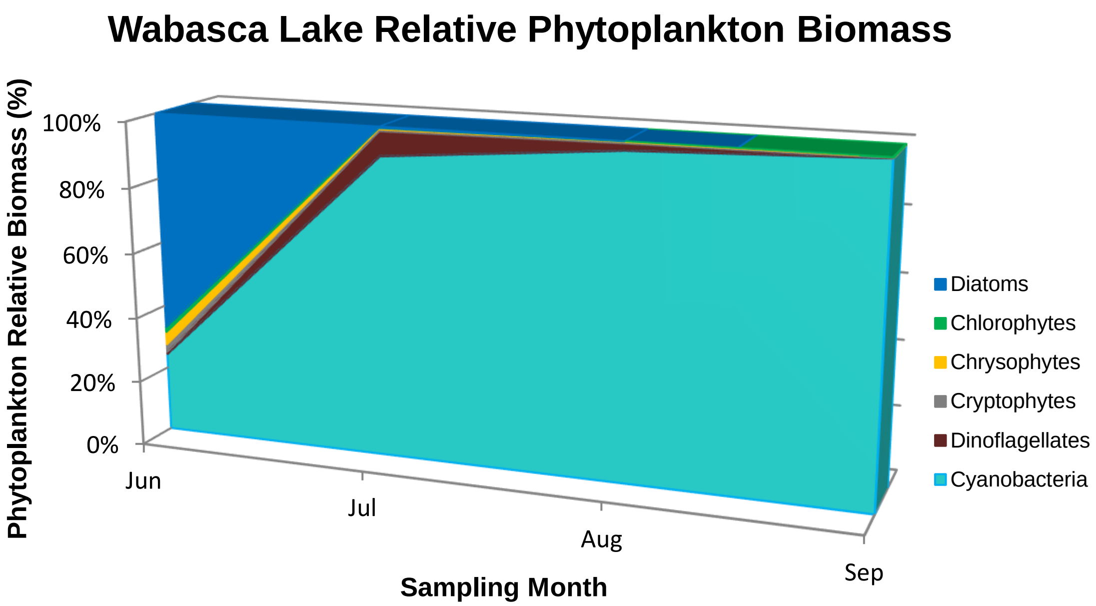


Figure 12. Relative biomass of phytoplankton (algae) in North Wabasca Lake during the open water season.

Plants, including algae, typically satisfy their nitrogen requirement by absorbing nitrate and/or ammonium from the water, but some bloom-forming species of cyanobacteria are able to fix atmospheric nitrogen gas (N_2). It has been reasoned that cyanobacteria should dominate at a low ratio of nitrogen to phosphorus (*i.e.,* inorganic nitrogen may not limit their growth as it would other groups of algae). It has been shown that cyanobacteria often dominate lakes with low TN:TP compared to lakes with higher ratios—cyanobacteria being rare when the TN:TP ratio is greater than 29 (by mass) and more often dominating when the ratio is less (Smith, 1983). Smith *et al.*

(1995) also concluded that a TN:TP ratio of 22:1 provides a distinct boundary between lakes dominated by nitrogen-fixing cyanobacteria and lakes with low occurrence of these species.

As presented above, the seasonal mean TN:TP of North Wabasca Lake was 35.2 (Table a, Appendix I), which suggests cyanobacteria—and especially N-fixing species—should be rare. Data from our summer sampling indicate that both nitrogen-fixing and non-nitrogen-fixing species of cyanobacteria populated the lake as early as June. The most abundant species in June was *Aphanocapsa delicatissima*, a small-celled colonial, non-nitrogen-fixing species (Figure 13a). Based on biomass, large, colonial, non-nitrogen-fixing *Woronichinia naegeliana* and *Planktothrix agardhii* (Figures 13b,c) were the dominant cyanobacteria comprising 13 and 5.2% of the overall phytoplankton community. By July, the phytoplankton community was largely dominated by the nitrogen-fixing species, *Aphanizomenon flos-aquae* (Figure 13d) and to lesser extent, *Dolichospermum flos-aquae* (Figure 13e). *Aphanizomenon flos-aquae* remained the single most important species over summer comprising 81.6, 95.1 and 97.1% of the overall phytoplankton biomass in July, August and September, respectively.

Key Finding: Phytoplankton

The phytoplankton community of North Wabasca Lake is largely dominated by cyanobacteria during the summer months. As is typical in Alberta's eutrophic lakes, the nitrogen-fixing cyanobacteria *Aphanizomenon flos-aquae*, was the predominant species.

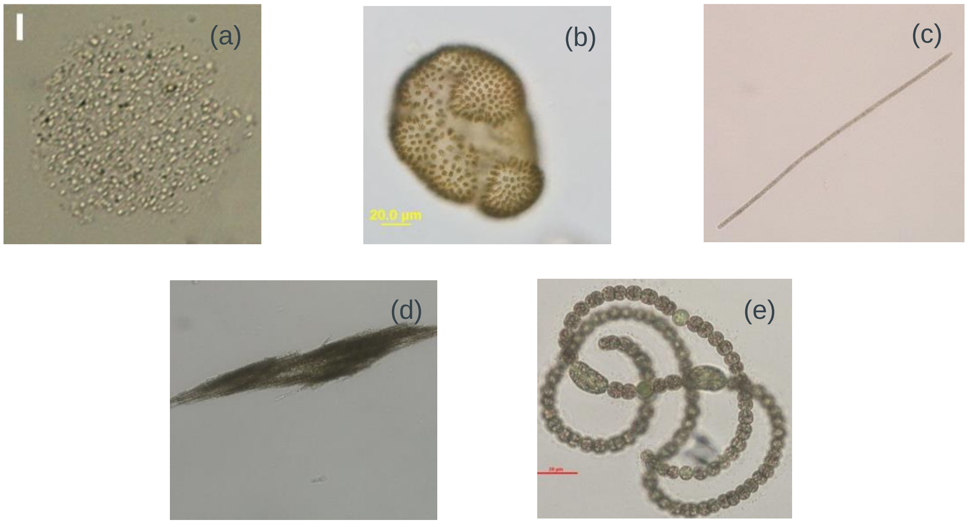


Figure 13. Examples of dominant cyanobacteria in North Wabasca Lake. (a) *Aphanocapsa delicatissima* (bar = 10 µm, credit: Palacio *et al.*, 2015); (b) *Woronichinia naegeliana* (credit: Rosen, 2017); (c) *Planktothrix agardhii*; (d) *Aphanizomenon flos-aquae*; and (e) *Dolichospermum flos-aquae* (bar = 20 µm, credit: GreenWater Lab, 2014).

Researchers have shown that concentrations of individual nutrients—primarily phosphorus—are more important than nutrient ratios in predicting cyanobacteria dominance in lakes (Schindler, 1977; Trimbee and Prepas, 1987; Downing *et al.*, 2001). It is also generally accepted that other factors (*e.g.* water temperature, pH, light intensity, carbon dioxide concentration, and water column transparency/turbulence) are important such that a single factor rarely determines algal dominance, but rather a combination of them will (Dokulil and Teubner, 2000).

An adaptation believed largely responsible for the success of cyanobacteria and the formation of blooms is the regulation of buoyancy (Reynolds *et al*., 1987). Cyanobacteria (including *Aph. flos-aquae*) produce gas-filled vesicles that reduce cell/colony density making them buoyant and allowing for vertical migration through the water column. It is particularly effective at affording access to optimal levels of light intensity and spectrum and nutrients during calm conditions. The formation of gas vesicles increases during windy periods to counter the downward drag of water currents. When stable conditions ensue, the buoyant colonies rise in the water column *en masse*, becoming visible near the surface as a scum (described in: Zurawell, 2000). Blooms worsen if wind/waves further concentrate these scums into bays or along the shorelines. Once established in the water column, cyanobacteria may further alter water conditions to favor their own growth while reducing that of other algae. For instance, cyanobacteria can limit light availability through shading, impacting photosynthesis and restricting growth of other algae and submerged aquatic plants. Also, cyanobacteria can elevate the pH of lake water by consuming carbon dioxide during photosynthesis, resulting in bicarbonate as the primary inorganic carbon source (only cyanobacteria are capable of utilizing bicarbonate for photosynthesis).

Many species of cyanobacteria produce large colonies, of which some are enclosed in a protective mucilage. These adaptations are thought to inhibit predation by zooplankton—small microscopic animals that typically graze on planktonic algae in lakes. Hence, algae (rather than cyanobacteria) are more susceptible to predation and usually the preferred food source for zooplankton. *Aphanizomenon flos-aquae* are a good example of large, colony-forming, predation-resistant species of cyanobacteria. Its colonies—up to a centimeter in length—are bundles of filaments comprised of numerous cells that resemble ‘grass clippings’ floating in the water (Figures 14a,b,c). In addition to the production of large predation-resistant colonies, this species possesses numerous adaptions for successful growth and reproduction in phosphorus-rich lakes including: production of buoyancy-regulating gas vesicles and specialized dormant over-wintering cells and the ability to utilize bicarbonate for photosynthesis, fix atmospheric nitrogen and reproduce at relatively cool temperatures (*i.e.,* less than 20°C). The clear dominance of *Aph. flos-aquae* over the summer in North Wabasca Lake is not unusual. *Aph. flos-aquae* are common inhabitants of Alberta’s nutrient-rich lakes and are known to dominate phytoplankton communities often resulting in intense and persistent algal blooms during summer months.

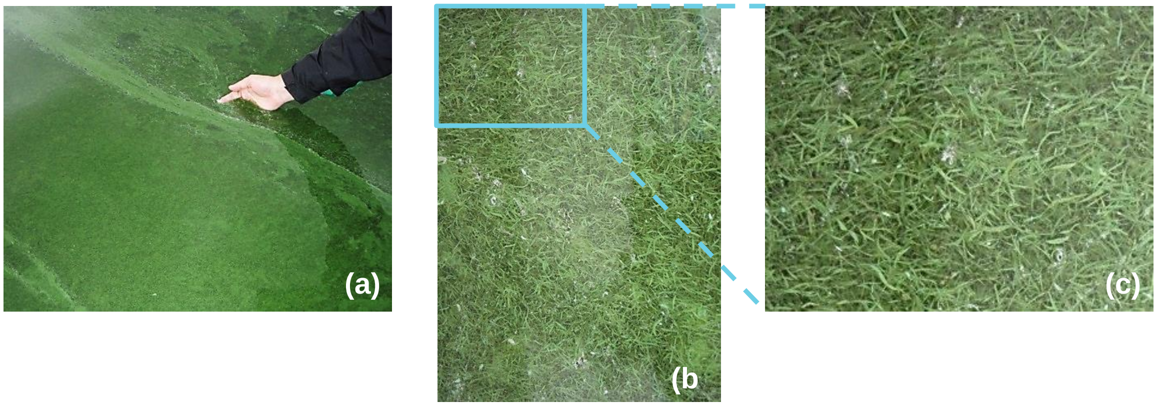


Figure 14. (a) *Aphanizomenon flos-aquae* bloom on an Alberta lake; (b) close-up showing dense *Aphanizomenon flos-aquae* colonies; (c) inset showing colony 'grass-clipping' form. Photos from AEP archives (not North Wabasca Lake).

It is well known that some common species of cyanobacteria produce potent liver and/or nerve toxins (Table 4). In some areas around the world, genetic strains of *Aph. flos-aquae* have been found to produce saxitoxin—a potent nerve (neuro) toxin belonging to the Paralytic Shellfish Poisoning (PSP) family of toxins (Table 4). Fortunately, the strains found in Alberta have never been linked to any toxic events involving humans, pets, livestock or wildlife and limited testing have never detected the presence of saxitoxin in Alberta's lakes. Neurotoxins also include anatoxin-a and anatoxin-a(s). These impact the transmission of nerve impulses to muscles causing paralysis and death in acutely affect humans and animals. Limited testing has shown that anatoxins are not commonly occurring in Alberta lakes, but this could be due to difficulty in preserving the toxin upon collection as it degrades rapidly. Regardless, anatoxins have occasionally been linked to mortality in waterfowl (including: gulls, terns, ducks, and grebes), bats and livestock and dogs in Alberta.

Of the cyanobacteria collected from North Wabasca Lake, *Dolichospermum flos-aquae* (occurring in July and September) and *Planktothrix agardhii* (occurring only in June) are potentially capable of producing anatoxin-a and/or anatoxin-a(s). There were also small populations of *D. mendotae* occurring from June to September that could have produced both anatoxin-a and the liver/kidney toxin cylindrospermopsin (Table 4). Recognizing these cyanobacteria generally do not dominate blooms and given the difficulty in preserving anatoxins (for lab analysis), routine sampling for these toxins is not typical in Provincial lake monitoring programs. Thus, anatoxins (and cylindrospermopsin) were not analyzed in water samples during this study.

Table 4. Toxins produced by freshwater cyanobacteria (adapted from Zurawell, 2015).

Toxin	Cyanobacteria genera/species	Health Effects
Microcystins	*Microcystis aeruginosa, M. flos-aquae, M. viridis, M. wesenbergii, Dolichospermum flos-aquae, D. circinalis, D. lemmermannii, Planktothrix agardhii, P. rubescens* and (possibly) *Woronichinia naegeliana*	Liver lesions, tumor promoter, possible carcinogen
Anatoxin-a	*D. flos-aquae, D. circinalis, D. lemmermannii, D. macrosporum, D. mendotae, D. planctonicum, D. spiroides, Cylindrospermum sp., P. agardhii, Raphidiopsis sp.* and *Oscillatoria sp.*	Affects nerve synapse interrupting nerve impulses to muscles
Anatoxin-a(S)	*D. flos-aquae, D. lemmermannii*, *D. spiroides* and (possibly) *P. agardhii*	Affects nerve synapse interrupting nerve impulses to muscles
Saxitoxin, neo-saxitoxin	*Aphanizomenon flos-aquae*, *Chrysosporum ovalisporum*, *D. circinalis, Cylindrospermopsis raciborskii* and *Lyngbya wollei*	Affects nerve axons
Cylindrospermopsin	*Ch. bergii, Ch. ovalisporum, C. raciborskii, D. mendotae, Raphidiopsis curvata*, *R. mediterranea* and *Umezakia natans*	Affects liver/kidney; possible carcinogen
Lyngbyatoxin-a, aplysiatoxins	*Lyngbya*	Skin/eye irritation, gastrointestinal symptoms

Microcystins (MCYSTs) are the most common group of toxins produced by cyanobacteria and are highly prevalent at wide-ranging concentrations over the summer in Alberta's lakes and reservoirs (Zurawell, 2010). MCYSTs exert toxicity by inhibiting specific cellular enzymes ultimately causing severe liver dysfunction and damage. They are tumor promoters and chronic exposure to MCYSTs has been linked to high incidence of primary liver (hepatocellular carcinoma) and colorectal cancers in rural human populations around the world (Zhou *et al.*, 2002). To date, more than 80 toxin analogues of MCYST have been isolated and described globally and several bloom-forming species of cyanobacteria (most notably *Microcystis aeruginosa, M. flos-aquae*, *Dolichospermum flos-aquae, D. circinalis, D. lemmermannii, Planktothrix agardhii* and *P. rubescens*) produce MCYSTs (Table 4). Given the widespread occurrence of MCYSTs and potential risk to human health, Health Canada has developed both drinking and recreational water quality guidelines for this family of toxins.

Key Finding: Algal Toxins

Although North Wabasca Lake is dominated by cyanobacteria during the summer months, the concentrations of microcystin (cyanobacterial liver toxin) were only detected at trace levels. This indicates the predominant cyanobacteria are not microcystin-producing species.

Of the cyanobacteria collected from North Wabasca Lake, *D. flos-aquae* (occurring in July and September), *P. agardhii* (occurring only in June) are potentially capable of producing MCYSTs. In addition, some research suggests that some genetic strains of *Woronichinia naegeliana* are capable of producing MCYSTs. This species was present in water samples throughout the summer sampling, but its biomass was greatest in June. Testing for total MCYST concentration was integrated into Provincial lake monitoring in 2005 and was part of routine testing in this study. MCYST was not detected in June (limit of detection 0.1 µg/L by protein phosphatase inhibition assay), but was detected at trace levels (0.13, 0.12 and 0.14 µg/L) in July, August and September, respectively (Table 3.0 Raw Data, Appendix II). This suggests the cyanobacteria species dominating North Wabasca Lake during summer of 2016 were not MCYST-producing species. Considering MCYST concentrations were below the drinking water quality guideline (1.5 µg/L/day) and far below the recreational water quality guideline (20 µg/L), there was very low risk to human health during 2016.

Zooplankton

Zooplankton are small (≈ 5mm) to microscopic animals that live drifting or weakly swimming in the open water of oceans, seas, lakes and reservoirs. Freshwater zooplankton includes rotifers and two subclasses of micro-crustaceans, the cladocerans (water fleas) and copepods. In addition, microscopic, single-celled, ‘animal-like’ heterotrophic organisms called protozoans that feed on algae and other protozoans may also be included (*e.g.* amoeba, ciliates etc.). As a group, zooplankton are a very important link in the food web of lakes grazing on the primary producers—algae and cyanobacteria (some larger species may actually consume other zooplankton)—and in turn, being preyed upon by aquatic invertebrates (*i.e.,* worms, mollusks, insects, crustaceans) and planktivorous fish including small baitfish species and juvenile sport fish (fry). Like phytoplankton, zooplankton communities also experience succession over seasons in response to changing environmental (*i.e.,* physical and chemical properties of the lake) and biological (*i.e.,* food availability) conditions, as well as pressure from predators in a given lake ecosystem; and zooplankton communities vary with lake trophic status. Generally, healthy lakes support diverse zooplankton communities and like phytoplankton, oligotrophic lakes have lower overall biomass and greater species diversity than hypereutrophic systems.

Samples for the enumeration and identification of zooplankton were collected during the summer season from North Wabasca Lake. Only rotifers and micro-crustaceans (*i.e.,* cladocerans and copepods) were identified and quantified—microscopic protozoans were not included in the analysis. Results indicate that zooplankton species diversity (total number of species present) was stable in June through August (about 23 species) and increased slightly in September to 26 species (Figure 15). Small-bodied rotifers were the most diverse group throughout the study (14, 10, 10 11 species in June, July, August and September, respectively). Diversity of cladocerans (water fleas) and copepods were similar over the open-water season indicating very little variation in the number of species present in North Wabasca Lake (Figure 15). The copepods within the lake were further distinguished into either calanoid or cyclopoid groups. Calanoid copepods are herbivores that usually live entirely planktonic. Compared to cyclopoid copepods, they are the larger in physical size and as a result are frequently preyed upon by planktivorous and juvenile fish. Cyclopoid copepods are omnivores feeding on anything from fine particulate organic matter to bacteria and other plankton. Most cyclopoids are completely planktonic, but benthic (bottom-dwelling) forms do exist. Because of their smaller size, they are less susceptible to predation by fish. Diversity of calanoid and cyclopoid copepods were similar throughout the study with one species in each group present in June and increasing to 2 calanoid species and 3 cyclopoid species, respectively, throughout the summer season (Figure 15).

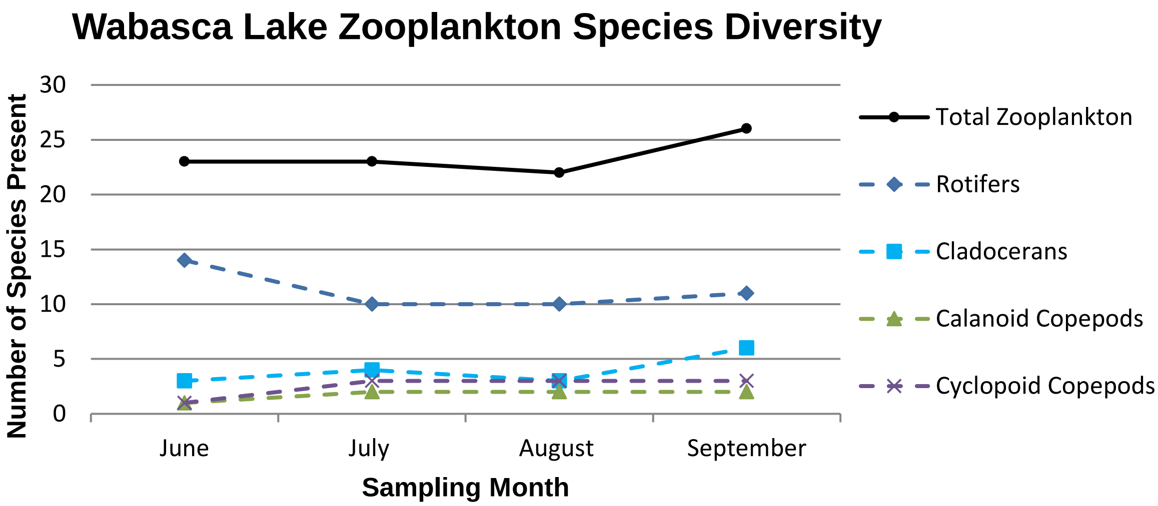


Figure 15. Zooplankton species diversity in North Wabasca Lake during the open water season.

Zooplankton density was greatest in June (1201 organisms/L) attributed mainly to a large abundance of rotifers and secondly, to juvenile copepods. Zooplankton density decreased dramatically in July (321 organisms/L) coincident with a decline in rotifer population and remained stable through the rest of summer (142 organisms/L in August and 164 organisms/L in September; Figure 16). Adult cladocerans were most abundant in July (≈ 24 individuals/L) and continued to decrease in density into September coinciding with the end of their growing season. Adult copepods were present in low numbers in June, but densities of both copepod groups increased over the summer with cyclopoid copepods reaching peak density in August (≈ 7 individuals/L) and calanoid copepods reaching highest density in September (≈ 9 individuals/L). Not surprisingly, juvenile cladocerans and copepods were generally more abundant than adults particularly early in the growing season (*i.e.,* June and July). Juvenile cyclopoid copepods were most abundant in June (≈ 7 juveniles/L), while juvenile calanoid copepods were especially numerous in July (≈ 150 juveniles/L).

Lastly, nauplii, were present throughout the summer. These are the early, larval form of most crustaceans (including cladocerans, copepods, shrimp, crabs, etc.) that are essentially indistinguishable amongst species (Figure 16). Nauplii were most abundant in June and September. The June peak likely reflects the primary reproductive season for many cladoceran and copepod species. The September peak could possibly reflect the production of male cladocerans near the end of growing season. Cladocerans (and other zooplankton) reproduce by parthenogenesis—a natural form of asexual reproduction in which growth and development of embryos occur without fertilization—so most adults in early growing season are reproductive females. As the growing season nears fall and water temperatures decrease, females begin producing male off-spring. Males are necessary for sexual reproduction, which yields specialized eggs (called ephippia) capable of over-wintering or withstanding unfavorable conditions.

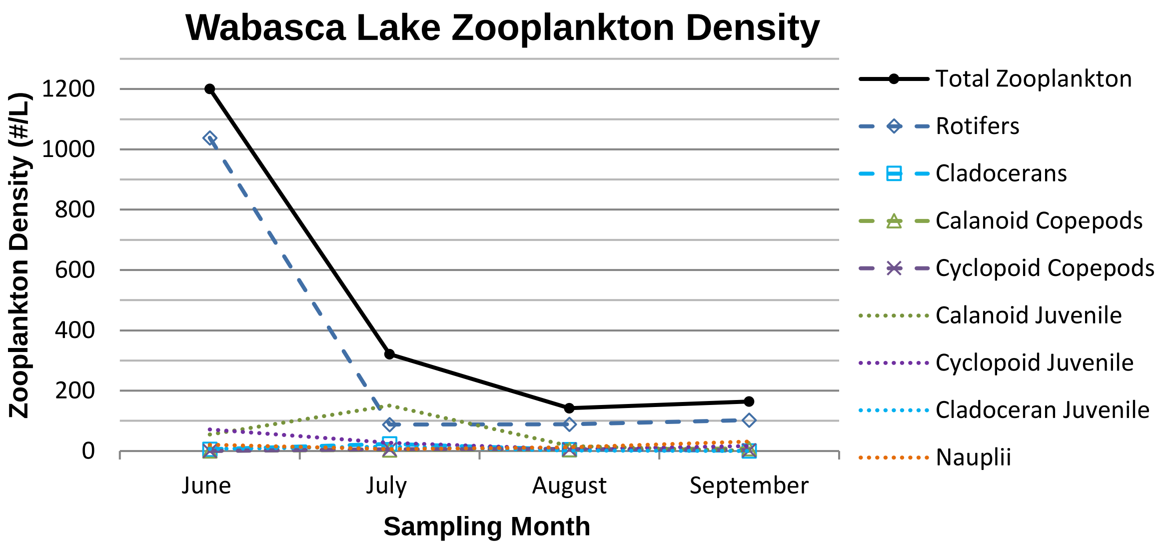


Figure 16. Zooplankton density in North Wabasca Lake during the open water season.

Zooplankton groups vary greatly in body size. Rotifers were the smallest zooplankton with species ranging from 0.1–0.5 mm mean length in this study (Figure 17a–c). Copepods were larger with cyclopoid species ranging from 0.84–1.38 mm mean length (Figure 17e) and calanoid species ranging from 0.90–1.56 mm mean length (Figure 17d). As a group, cladocerans are often the largest-bodied zooplankton of freshwater temperate lakes and often easily viewed without aid of a microscope. However, species can vary greatly in size and in this study we recorded smaller-bodied *Bosmina sp.* (0.33 mm mean length), moderately-sized *Daphnia sp*. (ranging from 1.08–1.42 mm mean length; Figure 17f) and large-bodied *Leptodora sp*. (ranging from 2.43–5.21 mm mean length).

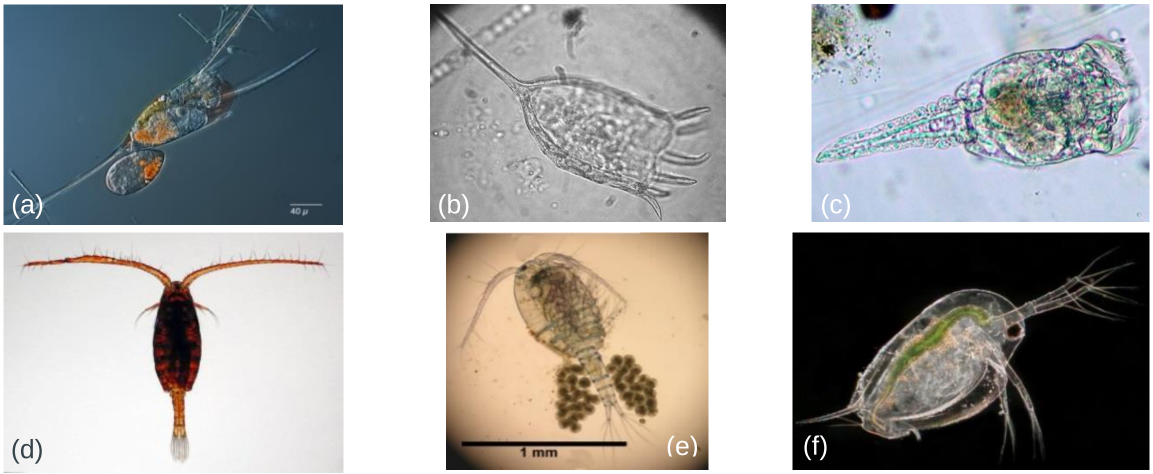


Figure 17. Examples of zooplankton in North Wabasca Lake: Rotifers (a) †*Kellicottia longispina*, with egg (b) *Keratella cochlearis*, and (c) *Conochilus sp.*; Calanoid Copepod (d) ‡*Leptodiaptomus sicilis*; Cyclopoid Copepod (e) **Mesocyclops edax*, bearing eggs; and Cladocera (f) †*Daphnia pulex*. Credit: †Michael Plewka, (http://www.plingfactory.de); ‡Ian Gardiner, E-Fauna, BC, 2012; *Center for Freshwater Biology, UNH, 2013.

Like phytoplankton, to better understand the overall biological health and food-web (*i.e.,* implications for fish production) of a lake ecosystem it is important to consider zooplankton community structure based on overall biomass (*i.e.,* total mass of zooplankton in a volume of lake water). Rotifers were the most numerous group of zooplankton (Figure 16), but due to their microscopic size they comprised an extremely small proportion of the overall zooplankton biomass; and their relative contribution was so small they do not show up in Figure 18.

Key Finding: Zooplankton

The zooplankton community of North Wabasca Lake is diverse and dynamic – ever changing over the summer in response to food availability and predation. Zooplankton are a key level in the food chain supporting lake's fishery.

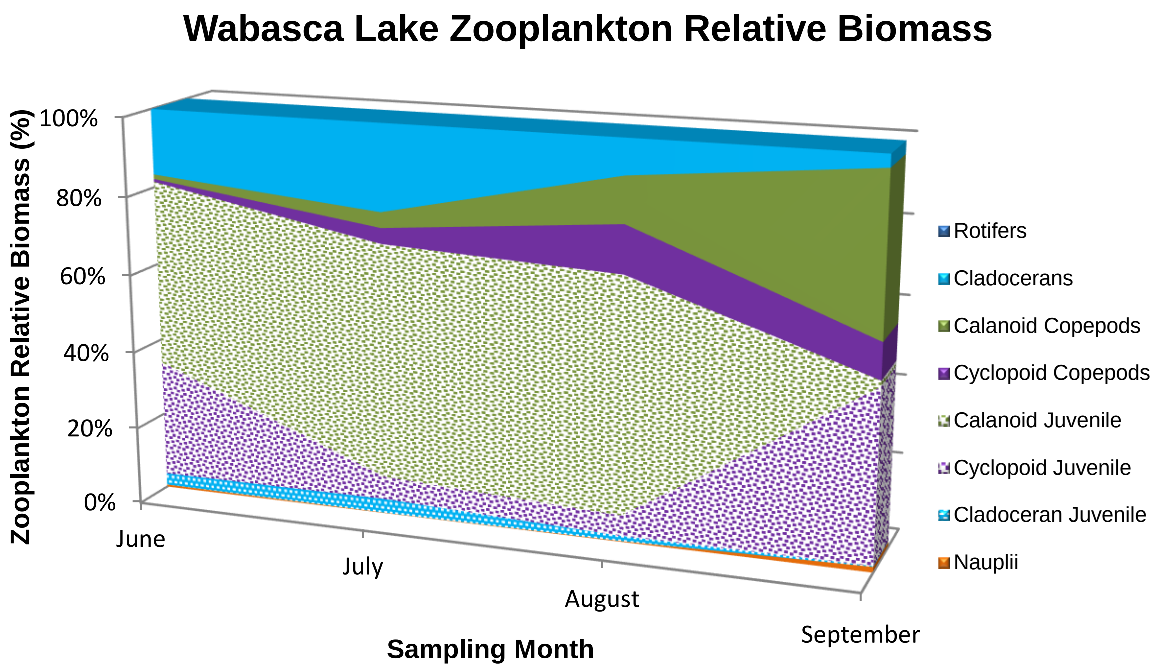


Figure 18. Relative biomass of zooplankton in North Wabasca Lake during the open water season.

Juvenile copepods comprised a majority of the biomass throughout summer (Figure 18). Juvenile calanoid copepods were especially important in June, July and August comprising 47.5, 60.2 and 60.3% of the overall zooplankton biomass, respectively. Juvenile cyclopoid copepods comprised 30.2% of the zooplankton biomass in June, declined to 6 and 5.4% in July and August (respectively) and then dominated overall biomass in September at 44.1%. Adult calanoid copepods constituted only 1.2 and 4% of the biomass in June and July, but increased to 11.6% in August and peaked at 40.4% in September. Relative biomass of adult cyclopoid copepods was very low in June (0.7%), low July (4%) and increased to 12.2 and 9.2% in August and September (respectively). Nauplii—the indistinguishable microscopic larvae—comprised only a very small proportion of the zooplankton biomass (typically less than 1%) and reached its highest level in September (at 1.4%) likely due to increased sexual reproduction by cladocerans in preparation for over-wintering. Owing to their large body size, adult cladocerans were an important component of the zooplankton community throughout the study, comprising 16.7, 22.1, 8.9 and 3.2% of the overall biomass in June, July, August and September (respectively; Figure 18).

In general, rotifers are prey for a variety of predatory invertebrates including other predatory rotifers (*e.g. Asplanchna*), cyclopoid copepods (*e.g. Mesocyclops*; Figure 17e), predatory cladocerans (*e.g. Leptodora*) and midge (*Chaoborus*) and fish larvae, which can be numerous in productive eutrophic lakes. The abundance and biomass of rotifers is usually small in winter, reaches a maximum in spring or summer and decreases to a winter minimum as was the case for North Wabasca Lake. It is evident that enough rotifers are present to sustain healthy copepod and other invertebrate populations that are important to the overall food chain of the lake. Smaller copepods are primarily prey for other predatory copepods, macro-invertebrates and larval fish. In fact the early-life-stage diet of most fish include zooplankton and preferred prey changes from small-bodied species to larger forms as mouth gape increases in developing fish. For example, larval yellow perch (*Perca flavescens*) begin feeding on rotifers and copepod nauplii and shift to adult copepods and small cladocerans (*e.g. Bosmina sp.)* and to larger cladocerans as they develop from fry to juveniles (Graeb *et al.*, 2004). Large-bodied cladocerans (*i.e., Daphnia sp*.) are not only important prey for developing piscivorous (fish-eating) fish, but are also consumed by adult bait fish (a.k.a. minnows) and even large, planktivorous Northern Cisco (a.k.a. tulibee; *Coregonus artedi*).

While some cyclopoid copepods are predators, most others including the calanoid copepods are herbivorous grazers. Along with the much larger cladocerans, these grazers feed predominantly on phytoplankton (both algae and cyanobacteria). However, various herbivorous zooplankton display species-specific selectivity for different classes of phytoplankton prey. Zooplankton grazing can effectively control the standing crop of some (preferred) algal species, but may lead to less desirable algae dominating the phytoplankton community. Due to their large colonial forms, protective mucilage and potential toxicity, cyanobacteria are generally not the preferred food source for most zooplankton. While efficient grazing by zooplankton may control algae in less productive lakes, selective grazing may actually contribute to a cyanobacteria-dominated phytoplankton community and the eventual production of surface blooms. Shifting the phytoplankton community to primarily cyanobacteria can cause a shift in the zooplankton community from large-bodied cladocerans to smaller-bodied copepods capable of selective feeding on smaller algae and solitary (non-colonial), non-toxic cyanobacteria. Large-bodied cladocerans like *Daphnia* decreased in North Wabasca Lake after July, coincident with a marked increase in large colonial cyanobacteria species. However, the Lake also supports a large fish population including northern cisco, which primarily feed on large cladocerans through its lifetime. So the reduction in large-bodied cladocerans could be a result of selective predation by juvenile fish and planktivorous cisco.

Invasive Mussel Monitoring

> ### Key Finding: Invasive Species
>
> Invasive Dreissenid (zebra and quagga) mussel larvae and spiny water flea were not detected in North Wabasca Lake.

As part of the Provincial lake monitoring network and Aquatic Invasive Species Program, samples were collected from North Wabasca Lake in July, August and September to determine if invasive Dreissenid (zebra and quagga) mussels were present. Monitoring focused on the planktonic 'veliger' (larval) stage responsible for dispersal throughout the water-body and not fixed populations of attached adult invasive mussels. In addition, samples were also analyzed for the presence of spiny water flea (*Bythotrephes longimanus*), a very large predatory cladoceran that feeds on other zooplankton like *Daphnia*. Spiny water flea competes with juvenile fish, including walleye and perch fry, for zooplankton prey. However, due to their long spines, *Bythotrephes* may not be preyed upon by small fish so its population is not impacted by direct predation. While there are no known populations in Alberta, documented invasions of some Ontario lakes by Spiny water flea suggest long-term impacts (declines) in native zooplankton communities due to predation; and eventual declines in fish communities resulting from direct competition between *Bythotrephes* and juvenile fish for native zooplankton prey. No evidence of invasive mussel veligers or spiny water flea was found in any of the samples collect from North Wabasca Lake during the study.

Fish Community

To understand the overall biological health of North Wabasca Lake, it is important to consider the fish community. While our lake monitoring program did not include an assessment of fish populations in North Wabasca Lake, fall index netting (FIN) was previously conducted by AEP Fishery Biologists in 2006, 2010 and 2013 (AEP, 2017). FIN is standardized index netting method used by AEP to monitor walleye and northern pike abundance in Alberta lakes by determining catch rates (i.e., number of fish captured per net night). In addition, the sizes and age of fish are also recorded to determine if potential overharvest (*e.g.* too few fish living to old age) or habitat (*e.g.* poor spawning success) problems exist. AEP Fisheries Biologists combine this information with data on water quality, lake access, watershed development, and habitat threats to determine a Fish Sustainability Index (FSI) that are compared to risk thresholds (Table 5).

Table 5. Alberta fish sustainability index risk thresholds for walleye and northern pike (adapted from AEP, 2017).

Mature Walleye/net	Mature Pike/net	Risk to Sustainability
>29	>22	Very Low
20–29	15–22	Low
15–20	11–14	Moderate
6–15	4–10	High
<6	<4	Very High

FIN was conducted from September 23rd–26th, 2013. A total of 17 gill nets captured 252 northern cisco (*Coregonus artedi*), 2 longnose sucker (*Catostomus catostomus*), 2 spot-tail shiners (*Notropis hudsonius*), 26 white suckers (*Catostomus commersonii*), 59 lake whitefish (*Coregonus clupeaformis*), 74 northern pike (*Esox lucius*), 114 walleye (*Sander vitreus*), and 66 yellow perch (*Perca flavescens*) from North Wabasca Lake. Mean catch rates of mature walleye were 3.5/net-night and correspond to an FSI score of Very High risk to sustainability (Table 5). Moreover, the low abundance of "280 to 530 mm walleye, and an abundance of walleye larger than 530 mm" indicate a recruitment overfished population (AEP, 2017). The mean catch rate of mature northern pike was 4.2/net-night and corresponds to an FSI score of High (Table 5). The length distribution of pike shows a "low abundance of 490 to 750 mm pike and an abundance of 760 to 1050 mm fish" suggesting that, like walleye, the northern pike population in North Wabasca Lake has experienced recruitment overfishing (AEP, 2017).

Recruitment overfishing occurs when the populations of mature, spawning-aged fish are depleted through over-harvesting to a level no longer capable of sustaining itself (*i.e.,* too few reproducing adults to spawn offspring). Both walleye and northern pike lack abundances of spawning-aged fish in North Wabasca Lake, yet very large individuals of each species were documented. Large fish are usually the oldest fish in a lake and while they continue to feed on smaller (young) fish—reducing the stock of fish reaching spawning age—they no longer contribute to spawning success of their species. Removal of older non-spawning fish has been used as a management strategy by AEP to allow more young fish to reach spawning age. Over-harvesting of spawning-aged fish not only results in fewer offspring produced annually, but reduces predation on planktivorous fish (*i.e.,* baitfish and cisco) that feed specifically on zooplankton. Since zooplankton availability "is strongly linked with the growth, survival, and ultimately recruitment of fish during their early life history" (Graeb *et al.*, 2004), a reduction in large-bodied zooplankton populations (*i.e.,* specifically cladocerans) in North Wabasca by baitfish and cisco could negatively impact growth and survival of larval and juvenile sportfish. Furthermore, a decrease in the population of herbivorous zooplankton could result in reduced grazing pressure and ultimately greater algal and cyanobacterial standing crops. A reduction in cladocerans (and other large zooplankton) resulting from excessive growth of large, colonial cyanobacteria, could further contribute to reduced growth and survival of newly hatched fish. The control of the lake's food chain by influencing the top predatory fish (top consumer) is referred to as top-down trophic cascade. It has been suggested that over-harvesting of predatory sportfish may ultimately lead to blooms of cyanobacteria (Agrawal, 1998).

The discussion regarding monitoring of North Wabasca Lake began with concerns expressed by BCN over reports of mature walleye exhibiting disease (unusual wart-like growths or tumors; Figure 19). Some residents have suspected the disease was linked to impacts from local industry or municipal waste water. In most cases, unusual growths such as this, are caused by natural viruses in the water. *Lymphocystis* is a virus that commonly infects more than one hundred species of freshwater and marine fishes around the world. The virus infects skin cells through cuts or abrasions causing wart-like irregular growths to appear on the fish's body. *Lymphocystis* is spread between fish through physical contact or water transmission and while infections can occur throughout the year, it is more prevalent during spawning season as fish congregate and interact in large numbers. Tumor growth is generally self-limited and eventually dies and may fall off the fish or be replaced with white scar tissue (ASRD, 2004). Infections are usually not fatal to fish, but severe infections can cause damage to vital organs and possibly death. *Lymphocystis* does not affect humans and other mammals. It is commonly found in Alberta's northern lakes.

Figure 19. Walleye from North Wabasca Lake showing disease appearing as unusual growths or tumors (photo provided by G. Cardinal, BCN).

Metal Chemistry

Metals occur naturally in lakes and are typically derived from the weathering and erosion of rocks and soils in the watershed. However, human activities both within the watershed (*i.e.,* industrial and municipal discharges, urban runoff, landfill leachates, surface mining and pesticide use) and abroad (*i.e.,* deposition of emissions associated with oil, gas and steel production and burning of fossil fuels) can greatly influence the concentrations of metals in lakes. The concentrations of naturally derived metals are usually low in the water column of lakes, as most are bound to silicates and other primary (*e.g.* oxide, sulfate and phosphate) minerals. These metal-mineral complexes are generally insoluble and tend to sink to the bottom sediments of lakes. Similarly, metals derived from human activities accumulate in sediments and are usually the primary site of metal contamination in lakes and rivers. To a lesser extent, some metals (*e.g.* manganese, molybdenum, zinc, etc.) are naturally taken up by bacteria, algae and plants as they are essential for biological processes.

The concentrations of metals (measured as total recoverable metal) were determined in samples collected from the surface (0.1 m) and bottom (14.5 m) of North Wabasca Lake during August and below ice (1 m), mid-water column (7 m) and near bottom (14 m) in February. In addition, dissolved mercury was also determined at these depths due to its potential conversion to organic methylmercury and subsequent accumulation in the food chain. The reason for collecting separate, near-surface and bottom samples is due to the influence of dissolved oxygen on metal chemistry—oxygen influences the oxidation (and conversely, reduction) state and consequently, the form and solubility (and availability) of metals in lakes. For example, iron exists in its ferric ion form (Fe^{+3}, *i.e.,* oxidation state +3) in well-oxygenated lakes and readily bonds with phosphorus (specifically, phosphate) in water causing precipitation of the newly formed iron-phosphate to the sediment. In the absence of oxygen as is often the case near the sediments of deep lakes, iron is reduced to its ferrous ion form (Fe^{+2}, *i.e.,* oxidation state +2) and dissociates from phosphate causing them to migrate back into the water column. Dissolved oxygen was 8.48 mg/L at the surface (0.1 m) and 0 mg/L near the lake bottom (14.5 m depth) in August and was 10.17, 6.71 and 0.72 mg/L at 1 m below ice, mid-column (7 m) and near the bottom (14 m), respectively, in February. This indicates potential for oxidizing/reducing conditions to influence concentrations of some metals in North Wabasca Lake.

For some metals, the oxidation state influences potential toxicity, such that non-toxic elements can become highly toxic. An example of this is chromium where in its trivalent ion form (Cr^{+3} or Cr(III)), is essentially non-toxic—and in trace amounts is used in the body to enhance the role of insulin in regulating blood glucose levels. However, in its hexavalent (Cr^{+6} or Cr(VI)) ion form, chromium can be highly toxic at both acute and chronic exposures (it is carcinogenic and can be transported to cells whereas trivalent chromium cannot). The pH of water may also determine the form (speciation) of metals in lakes and ultimately influence the solubility and toxicity of some metals. For instance, aluminum is the most abundant metal and third most abundant element in the earth's crust comprising about 8.8% by weight (ATSDR, 2008). At pH > 5.5 naturally occurring aluminum exists mainly as insoluble aluminosilicate and aluminum hydroxide minerals. However, the presence of naturally occurring dissolved organic acid compounds (oxalic, humic or fulvic acids from decomposition of plant matter) or decreasing environmental pH below 5.5 through acidification (from acidic rain/snow or mining discharge), can cause the dissociation of these minerals and the mobilization of aluminum ion (Al^{+3}). In its ionic form, aluminum inhibits root growth in plants and can be directly toxic to fish by binding to and disrupting ion regulation and oxygen transport in gills (Sparling & Lowe, 1996).

Lastly, some metals undergo biochemical modification into potentially toxic organometallic compounds by natural microbes. A relevant example in Alberta lakes is the conversion of natural and anthropogenic inorganic mercury to methylmercury compounds through a process known as methylation, by some sulfur- and iron-reducing bacteria. In lakes, methylmercury is taken up by primary producers like cyanobacteria and algae and accumulates in primary consumers including zooplankton and other invertebrates (insects, mollusks). Secondary consumers like planktivorous fish (including small baitfish and larval and juvenile sportfish) further consume and accumulate methylmercury. Because of its rather long half-life and difficulty being eliminated from the body, methylmercury increases with every subsequent (trophic) level of the food chain—this is known as biomagnification. Methylmercury reaches highest levels at the top of the food chain in predatory fish, which in Alberta are commonly the primary sportfish like northern pike and walleye. Methylmercury levels in sportfish can be more than a million times higher than in lake water and thus pose a risk to humans consuming fish. Mercury is a neurotoxin that can cause muscle weakness and can result in damage to many parts of the brain and peripheral nervous system—it is particularly harmful to developing fetuses, as well as to infants (Berlin *et al.*, 2007). Fish-mercury consumption guidelines exist for many of Alberta's surface waters and given the potential toxicity of other metals, Federal and Provincial Health and Environment agencies have developed drinking water guidelines, recreation and aesthetic water quality guidelines and guidelines for the preservation of aquatic life.

Results for total recoverable metals indicate beryllium and silver were too low in concentration to be detected in North Wabasca Lake during summer or winter (Table e, Appendix I; Table 5.0 Raw Data, Appendix II). Bismuth and cadmium were only detected in trace amounts (0.003–0.007 µg/L and 0.007 µg/L, respectively) during summer, but not at all under ice during winter. Metals including chromium (<0. 03–0.07 µg/L), thallium (<0. 0009–0.0038 µg/L) and thorium (<0. 0009–0.044 µg/L) were only detected at trace levels and at some (but not all) depths throughout the study. For some metals, concentrations near the bottom sediments were certainly higher than in surface waters indicating mobilization from sediments with changes in oxidation/reduction states.

Key Finding: Metals

No significant or unusually high concentrations of metals were found in North Wabasca Lake. Although concentrations of certain metals increased with depth, most were detected at or below trace and none exceeded water quality guidelines.

For instance, the concentration of molybdenum was 0. 442 µg/L at surface and 0.474 µg/L near bottom in August and was below detection <0.446 µg/L under ice, 0.516 µg/L at mid-column and 0.663 µg/L near bottom during February. Iron was 26.4 µg/L at surface and 123 µg/L near bottom in August and 30.4 µg/L under ice, 55 µg/L mid-column and 603 µg/L near bottom during February. Manganese, which showed even greater differences in concentration with depth, was 62.1 µg/L at surface and 3180 µg/L near bottom in August and 5.75 µg/L under ice, 21.6 µg/L mid-column and 1590 µg/L near bottom during February. Other metals displaying an increasing concentration with depth and a concomitant decrease in oxygen include antimony, barium, cobalt, mercury, nickel, strontium and titanium (Table e, Appendix I; Table 5.0 Raw Data, Appendix II). Several metals showed an increase with depth only in August, but either similar (*e.g.* arsenic) or no consistent pattern (*e.g.* aluminum) in concentrations with depth under ice; and others decreased with depth in August and either increased (*e.g.* boron, copper, lithium and uranium) or showed no consistent pattern (*e.g.* lead, selenium, vanadium and zinc) with depth under ice. Tin was the only metal that was consistently higher in concentration near the surface compared to mid-column (sampled winter only) or near the bottom.

Due to its potential for accumulating in aquatic food webs, total and dissolved mercury were determined in North Wabasca Lake (methylmercury was not determined in this study). Mercury exists in three oxidation states: Hg^0—as reduced elemental (metallic) mercury; Hg^{+1}—an unstable, intermediate oxidized monovalent (mercurous) ion; and Hg^{+2}—a highly oxidized divalent (mercuric) ion. Reduced metallic Hg^0 is the primary vaporous form that enters the atmosphere from natural off-gassing of soils, volcanoes, hydrothermal vents and surface waters (Batrakova *et al.*, 2014). Elemental mercury vapor can be transported very long distances (in fact, globally transported) in the atmosphere and can re-enter lakes through air-water exchange. It can also be oxidized into mercuric ion (Hg^{+2}) in the atmosphere, which can be deposited back to surface waters through wet (rain and snow) deposition or bound to particulates and deposited directly onto surface waters through dry deposition. Total mercury analysis includes: insoluble Hg^0 vapor; low solubility, colloidal and particulate inorganic Hg^{+2} (*e.g.* mercury sulfide, HgS) and organic (*e.g.* methylmercury chloride, CH_3HgCl) complexes; and dissolved forms. Dissolved mercury analysis primarily quantifies soluble inorganic mercury compounds (*e.g.* mercuric chloride, $HgCl_2$, and mercuric hydroxide, $Hg(OH)_2$), but also those organic methylmercury compounds that are relatively soluble (*e.g.* methylmercury nitrate, CH_3HgNO_3).

The concentrations of total mercury were 0.4 ng/L at the surface and 0.55 ng/L near bottom in August and were 0.45 ng/L under ice, 0.59 ng/L at mid-column and 0.81 ng/L near bottom during February. In comparison, concentrations of dissolved mercury were 0.36 ng/L at the surface and 0.18 ng/L near bottom in August and were 0.34 ng/L under ice, 0.36 ng/L at mid-column and 0.77 ng/L near bottom during February. The concentrations of mercury (both total and dissolved Hg) varied little over summer and winter (Figure 20); and generally, the dissolved fraction comprised 61–95% of the total mercury concentration likely due to prevalence of soluble inorganic Hg^{+2} compounds (*e.g.* mercuric chloride, $HgCl_2$). However, the concentration of dissolved mercury was lowest near the lake bottom in summer (August) comprising only 33% of the total mercury concentration. A complete lack of oxygen near the lake bottom in August likely caused the reduction of Hg^{+2} containing compounds to insoluble Hg^0 vapor and the formation of insoluble mercury-sulfide complexes, thus reducing dissolved mercury content.

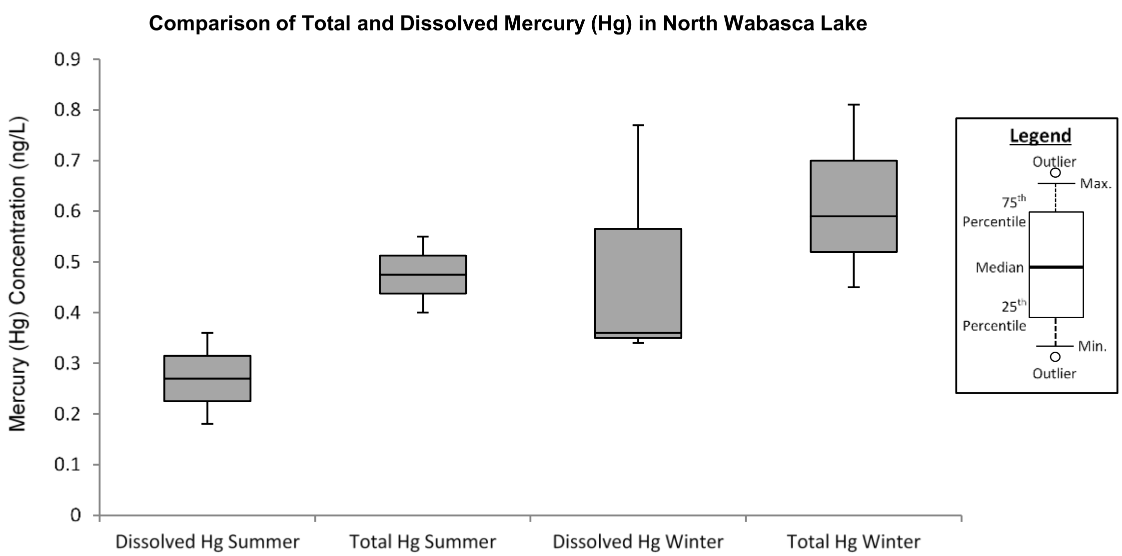


Figure 20. Box plots comparing range in summer (August) and winter (February) dissolved and total mercury concentrations in North Wabasca Lake.

In addition to determining total recoverable metals and dissolved mercury concentrations at discrete depths in August and February, dissolved manganese and iron were also measured in composite samples collected from North Wabasca Lake (June–September) and both incoming tributaries (July–September). Dissolved manganese was not detected during the summer in North Wabasca Lake (Figure 21a; Table c, Appendix I; Table 4.0 Raw Data, Appendix II), but was detected in near the bottom sediment in winter (Table d, Appendix I; Table 4.0 Raw Data, Appendix II). Dissolved manganese was detected in summer and winter in samples collected from Desmarais Outlet and Willow River (Figure 21a). Desmarais Outlet contained only slightly higher concentrations of dissolved manganese than Willow River (summer means 0.053 and 0.033 mg/L, respectively), but both tributaries are potential sources of this metal to North Wabasca Lake. Biological uptake of dissolved manganese by phytoplankton (both algae and cyanobacteria), in addition to strong oxidizing conditions in the lake (*i.e.,* precipitation to sediments as manganese oxides etc.), may have resulted in concentrations below our reliable limit of detection.

Dissolved iron was not detected in North Wabasca Lake from June–August, but was 0.078 mg/L in September (Figure 21b; Table c, Appendix I; Table 4.0 Raw Data, Appendix II) and 0.42 mg/L near the bottom sediment in winter (Table d, Appendix I). Dissolved iron was detected in summer (Figure 21b; Table c, Appendix I) and winter (Table d, Appendix I) in Desmarais Outlet and Willow River. Concentrations in Desmarais Outlet exceeded chronic (long-term) guidelines for the protection of aquatic health during summer (mean 0.326 mg/L; Table c, Appendix I) and winter (0.8 mg/L; Table d, Appendix I). Dissolved iron in Willow River was similar to Desmarais Outlet in winter (0.78 mg/L) and even was higher in summer (mean 1.23 mg/L). Like manganese, these tributaries may be sources of iron to North Wabasca Lake, but again, lower levels in the Lake likely reflect greater iron-phosphate binding under oxidizing conditions (*i.e.,* increased precipitation to sediments)—a common phenomenon in nutrient-rich lakes. Additionally, the elevated dissolved iron in Willow River may be attributed to greater ground water inputs and to low biological uptake compared to North Wabasca Lake.

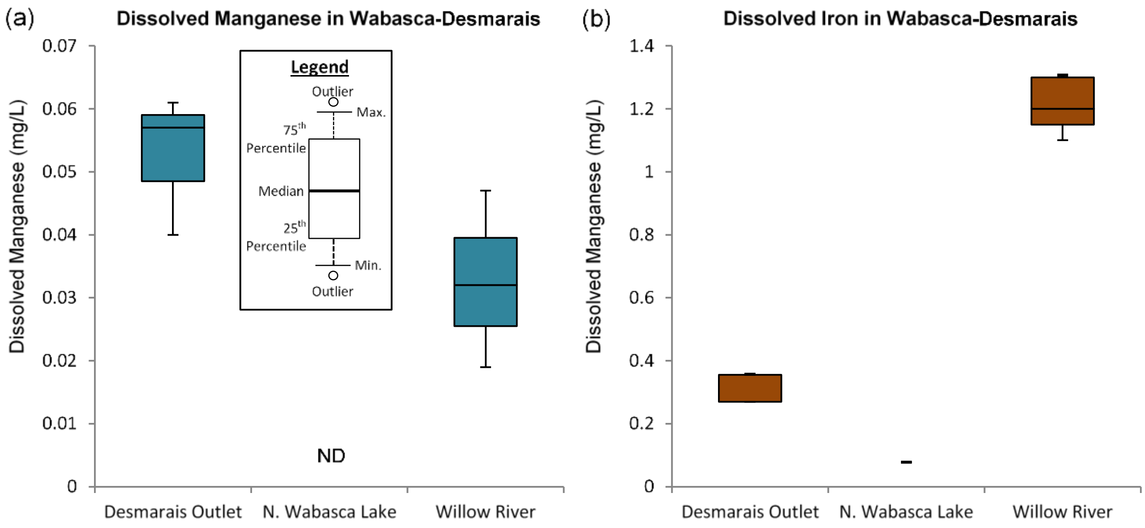


Figure 21. Box plots comparing dissolved manganese (a) and dissolved iron (b) concentrations in North Wabasca Lake, Desmarais Outlet and Willow River. ND = not detected.

Summary

North Wabasca Lake is the 15th largest (101.45 km^2) lake in Alberta and is located in the Central Mixed-wood sub-region of the Boreal Forest Region. It is part of the Peace River Drainage and has a large watershed (3819.42 km^2) that is mostly dominated by forested (≈ 63%), shrub- (12%) and natural grass-lands (≈ 13%) with relatively low proportions of developed lands (≈ 3% urban/industrial and 0.004% agricultural land uses). The lake has several inflows—the most notable being the outlet from Desmarais Lake and Willow River to the south. Wabasca River is the main outflow from the lake, which flows northward to Peace River west of Fort Vermillion. Like other lakes within the region, the large contributing watershed of North Wabasca Lake results in stable water levels.

The lake is moderately deep (maximum depth of 17 m) and became thermally stratified following spring turn-over. Given its relatively large size and long fetch (*i.e.,* greater potential for wind-induced mixing), however, the lake only weakly stratified during the summer months and became isothermal by late summer (September). Water temperature in the deepest part of the water column rarely dropped below 10°C during the summer indicating the lake may actually be polymictic—the water column thoroughly mixes periodically over the summer. North Wabasca Lake generally had sufficient dissolved oxygen (DO) to support large (*e.g.* pike and walleye) or sensitive (*e.g.* cisco and lake whitefish) sportfish through summer in the uppermost depths (13 m in June, 8 m in July/August). The early fall turnover resulted in higher (8.7 mg/L) DO levels throughout the water column in September providing adequate DO to support fall spawning fish. Concentrations of DO under ice in February was high (> 10 mg/L) to a depth of 5m possibly indicating some photosynthetic activity (oxygen production) by phytoplankton. This suggests adequate DO to support over-wintering of fish in the lake.

The water quality in North Wabasca Lake appears to be quite stable and varied to a lesser degree than Desmarais Lake outlet. The mean pH of North Wabasca Lake was 7.87 (ranged 7.35–7.94) over the summer, which is close to neutral and falls within the normal range for lakes. In contrast, the pH of Desmarais Lake outlet varied greatly (from 7.29 in February to 9.67 in July) and was significantly more alkaline during summer (mean = 9.21) indicating hypereutrophic conditions and increased photosynthesis by dense aquatic vegetation and algal communities. The pH of Willow River was similar to North Wabasca Lake (summer mean = 7.56) and was typical of boreal streams in the region.

North Wabasca Lake is a moderately alkaline system (summer mean = 83.5 mg/L $CaCO_3$), which can be attributed to the naturally occurring carbonate-rich parent bedrock within the watershed. Although mean alkalinity was similar in Desmarais outlet, it was more variable over the study period and peaked at 140 mg/L $CaCO_3$ in February. Alkalinity in Willow River was the most varied

of the three waterbodies ranging from 51 mg/L in September to 77 mg/L ($CaCO_3$) in August) and was very high 150 mg/L in February. The high winter alkalinity likely reflects the proportional increase in groundwater contributions (and decreasing precipitation and surface water contributions) during low winter flows. Moderate alkalinity suggests these systems have a strong buffering capacity and would not be susceptible to acidification from acid deposition (rain) or snowmelt.

The low topographic position, nature of surficial deposits and soils, hydraulic connection to organic shallow groundwater from adjacent organic wetlands and shallow basin depth contribute to North Wabasca Lake's moderate to somewhat high levels of phosphorus and nitrogen. Total nitrogen (TN) was lowest in North Wabasca Lake (summer mean 0.78 mg/L), higher in Willow River (0.92 mg/L) and highest and most variable in Desmarais Lake Outlet (1.96 mg/L). Similarly, total phosphorus was highest in Desmarais Lake Outlet (summer mean 0.136 mg/L), somewhat lower in Willow River (0.057 mg/L) and lowest North Wabasca Lake (0.022 mg/L). Based on mean TP over the study period, Desmarais Lake Outlet was classified as hypereutrophic, Willow River was eutrophic and North Wabasca Lake was meso-eutrophic. The summer mean TN:TP ratio indicates both Desmarais Lake and Willow River contain significant phosphorus and are close to nitrogen limiting conditions, while North Wabasca Lake is likely to be phosphorus limited; and this implies North Wabasca Lake could be susceptible to increased algal growth with additional inputs of phosphorus. Corroborating nutrient-based trophic status, summer mean Chl-a also indicated Desmarais Lake Outlet was hypereutrophic and North Wabasca Lake was eutrophic.

North Wabasca Lake supported a large and relatively diverse phytoplankton community. Species diversity and overall biomass changed over the summer months from high species diversity and lower overall biomass in early summer to a high-biomass, cyanobacteria dominated system into September. Non-nitrogen-fixing species of cyanobacteria were the most abundant (*Aphanocapsa delicatissima*) and comprised the majority of the biomass (*Woronichinia naegeliana* and *Planktothrix agardhii*) in June. These gave way to nitrogen-fixing species (*Aphanizomenon flos-aquae* and to lesser extent, *Dolichospermum flos-aquae*) through the rest of summer. Although, cyanobacteria dominated the phytoplankton over summer, levels of the cyanobacterial liver toxin, microcystin, were only detected at trace levels indicating the dominant species were not toxin-producers.

The zooplankton community of North Wabasca Lake was comprised of rotifers, cyclopoid and calanoid copepods and cladocerans. These organisms are important in the food web of the lake, feeding on the primary producers (*i.e.,* algae and cyanobacteria) and in turn providing food for other macro-invertebrates (insect larvae), larval and developing fish, adult bait fish and even large, planktivorous northern cisco that inhabit the lake. The abundance of large-bodied cladocerans (like *Daphnia* sp.) decreased after July coincident with increasing biomass of large, colonial cyanobacteria. This may indicate direct (toxic effects) and/or indirect (reduced grazing effects) negative impacts of cyanobacteria on this group of zooplankters occurred in the lake. However, the reduction of *Daphnia* could also be (partly) attributed to predation by developing juvenile and planktivorous bait fish and cisco inhabiting the lake. There was no evidence of the presence of invasive Dreissenid mussels in North Wabasca Lake.

It has been determined by Fish and Wildlife that recruitment overfishing is occurring in North Wabasca Lake, as both walleye and northern pike lack abundances (due to over-harvesting) of spawning-aged fish required to support self-sustaining populations. Over-harvesting of spawning-aged fish not only results in fewer offspring produced annually, but over-time, reduces predation on planktivorous fish (*i.e.,* baitfish and cisco) that feed specifically on zooplankton. Zooplankton availability is strongly linked with the growth and survival of sport fish during their early life history and a reduction in large-bodied zooplankton populations (*i.e.,* specifically cladocerans) in North Wabasca by baitfish and cisco could negatively impact growth and survival of larval and juvenile sportfish. Decreasing herbivorous zooplankton populations could result in reduced grazing pressure and ultimately greater algal and cyanobacterial standing crops. Over-harvesting of predatory sportfish may ultimately lead to increased blooms of cyanobacteria through top-down control of the lake's food chain—known as top-down trophic cascade.

Furthermore, concerns have been expressed by BCN over reports of mature walleye exhibiting disease appearing as unusual wart-like growths or tumors. In most cases, the skin tumors depicted are caused by natural virus, Lymphocystis in the water. Lymphocystis infects skin cells and is spread from fish to fish through physical contact or water transmission typically during spawning season as fish congregate and interact in large numbers. Tumor growth is generally self-limited and is usually not fatal to fish. Lymphocystis does not affect humans and other mammals and is commonly found in Alberta's northern lakes.

The concentrations of dissolved iron and manganese are much lower in North Wabasca Lake than in either Desmarais Outlet or Willow River. Concentrations of dissolved iron in Desmarais Outlet and Willow River exceeded chronic (long-term) guidelines for the protection of aquatic health. While these tributaries may be sources of iron and manganese to North Wabasca Lake, lower levels in lake likely reflect greater biological uptake of dissolved iron and manganese by phytoplankton and precipitation of metal-mineral complexes to the sediments (*i.e.,* as manganese oxides and iron-phosphate) under strong oxidizing conditions—a common phenomenon in nutrient-rich lakes.

The concentrations of other metals were generally low in the water column of North Wabasca Lake, but slightly higher concentrations often occurred near the sediments. There is no indication of metal contamination derived from human activities in the watershed (*i.e.,* guidelines values for total metals were not exceeded). The concentrations of both total and dissolved mercury varied little over summer and winter. The dissolved fraction usually comprised more than 60% of the total mercury concentration likely due to prevalence of soluble inorganic Hg^{+2} compounds. While methylmercury was not determined in this study, it is naturally produced by sulfate-reducing and other bacteria and likely present in low concentrations in North Wabasca Lake. Methylmercury biomagnifies up the food chain and is detectable primarily in sport fish. Fish-mercury consumption guidelines exist and human health risk advisories have been posted for the consumption of pike and walleye.

References

ABMI (Alberta Biodiversity Monitoring Institute), 2010. Wall-to-wall Land Cover Inventory. http://www.abmi.ca/home/data-analytics/da-top/da-product-overview/GIS-Land-Surface/Land-Cover.html

AENV (Alberta Environment), 2006. Aquatic ecosystems field sampling protocols. Environmental Assurance Division, Environmental Monitoring and Evaluation Branch, Edmonton. Report #W0605, 149 pp.

AENV (Alberta Environment), 1999. Surface Water Quality Guidelines for Use in Alberta. Environmental Sciences Division, Environmental Services Branch. Edmonton. Pub No. T/483, 25 pp.

AEP (Alberta Environment & Parks), 2017. North Wabasca Lake FIN Summary, 2013. http://aep.alberta.ca/fish-wildlife/fisheries-management/fall-index-netting/fall-index-netting-summaries/documents/NWabascaLake-FallIndexNettingReport-2013.pdf

AESRD (Alberta Environment & Sustainable Resource Development), 2014. Environmental Quality Guidelines for Alberta Surface Waters. Water Policy Branch, Policy Division. Edmonton. 48 pp.

ASRD (Alberta Sustainable Resource Development), 2004. Skin tumours of fishes (various viruses) in Alberta—What's Bugging Wild Critters? Fact sheet #26: Lymphosarcoma. Fish & Wildlife Division. Edmonton. http://aep.alberta.ca/fish-wildlife/wildlife-diseases/documents/SkinTumoursFish-2004.pdf.

Agrawal, A.A., 1998. Algal defense, grazers, and their interactions in aquatic trophic cascades. Acta Oecologica, 19:331–337.

ATSDR (Agency for Toxic Substances and Disease Registry), 2008. Toxicological profile for Aluminum. U.S. Department of Health and Human Services, Public Health Service, Atlanta, GA. 335 pp.

Batrakova, N., O. Travnikov and O. Rozovskaya, 2014. Chemical and physical transformations of mercury in the ocean: a review. Ocean Sci., 10:1047–1063.

Berlin, M., R.K. Zalups and B.A. Fowler, 2007. Mercury. In: Handbook on the Toxicology of Metals. 3rd edition. G.F. Nordberg, B.A. Fowler, M. Nordberg and L.T. Friberg, eds. Elsevier, New York, NY, USA

BCMOE (British Columbia Ministry of Environment), 2017. British Columbia approved water quality guidelines: aquatic life, wildlife & agriculture: summary report. Water Protection & Sustainability Branch, Environmental Sustainability and Strategic Policy Division. 36 pp.

BCMOE (British Columbia Ministry of Environment), 2006. British Columbia approved water quality guidelines, 2006 Ed. Science and Information Branch, Environment and Lands HQ Division. 71pp.

BCMOE (British Columbia Ministry of Environment), 1998. Guidelines for interpreting water quality data, Version 1.0. Lands And Parks Division, Pub No. 7680000553.

Cant, D.J. and B. Abrahamson. 1997. Regional stratigraphy, sedimentology, and petroleum geology of the Grand Rapids Formation, Mannville Group Northeastern Alberta. Bull. Can. Petrol. Geol., 45: 141–154.

CCME, 2017. Canadian Water Quality Guideline for the Protection of Aquatic Life Summary Table, Obtained June 20, 2017. http://st-ts.ccme.ca/en/index.html?chems=all&chapters=1

Domogalla, B.P., C. Juday and W.H. Peterson, 1925. The forms of nitrogen found in certain lake waters. J. Biol. Chem., 63: 269–285.

Downing, J.A., S.B. Watson and E. McCauley, 2001. Predicting cyanobacterial dominance in lakes. Can. J. Fish. Aquat. Sci., 58: 1905–1908.

Dokulil, M.T. and K. Teubner, 2000. Cyanobacterial dominance in lakes. Hydrobiologia, 438: 1–12.

EcoRegions Working Group, 1989. Ecoclimatic Regions of Canada, First Approximation. Ecological Land Classification Series, No. 23, Environment Canada, Ottawa 119p.

ECCC (Environment and Climate Change Canada), 2017. Historical Hydrometric Data web site: https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html.

Emerson, K., R.C. Russo, R.E. Lund and R.V. Thurston, 1975. Aqueous ammonia equilibrium calculations: effect of pH and temperature. J. Fish. Res. Bd of Can., 32: 2379–2383.

Env. Canada, 2004. Canadian guidance framework for the management of phosphorus in freshwater systems. National Guidelines and Standards Office, Water Policy and Coordination Directorate, Report No. 1–18. 133 pp.

Env. Canada, 2016. Canadian Environmental Protection Act, 1999, Federal Environmental Quality Guidelines: Vanadium. Environment and Climate Change Canada. 2017. 8 pp.

Galvez-Cloutier, R. and M. Sanchez, 2007. Trophic status evaluation for 154 lakes in Quebec, Canada: monitoring and recommendations. Water Qual. Res. J. Canada, 42: 252–268.

Geadah, M., 1985. National Inventory of Natural and Anthropogenic Sources and Emissions of Ammonia (1980). Environmental Protection Programs Directorate, Environmental Protection Service, Environment Canada Report EPS5/IC/1.

Gibson, J.J., S.J. Birks, Y. Yi, M.C. Moncur and P.M. McEachern, 2016. Stable isotope mass balance of fifty lakes in central Alberta: Assessing the role of water balance parameters in determining trophic status and lake level. Journal of Hydrology: Regional Studies, 6: 13–25.

Golterman, H.L., 1973. Natural phosphate sources in relation to phosphate budgets: a contribution to the understanding of eutrophication. In: Progress in Water Technology, Vol. 2: Phosphorus in Fresh Water and the Marine Environment. S.H. Jenkins and K.J. Ives, eds. Wat. Res. Pergamon Press 1973. Vol. 7, pp. 3–17.

Graeb, B.D.S., J.M. Dettmers, D.H Wahl. and C.E. Cáceres, 2004. Fish size and prey availability affect growth, survival, prey selection, and foraging behavior of larval yellow perch. Transactions of the Am. Fish. Soc., 133: 504–514.

GreenWater Lab, 2014. http://greenwaterlab.com/algal-id.html. Accessed 13 Sept 2017.

Health Canada, 2012. Guidelines for Canadian Recreational Water Quality, Third Ed. Federal-Provincial-Territorial Working Group on Recreational Water Quality, Federal-Provincial-Territorial Committee on Health and Environment. Ottawa, 161 pp.

Health Canada, 2017. Guidelines for Canadian Drinking Water Quality—Summary Table. Water and Air Quality Bureau, Healthy Environments and Consumer Safety Branch, Health Canada, Ottawa, Ontario.

Hruška, J., H. Laudon, S. Kohler, C.E. Johnson and K. Bishop, 2001. Acid/base character of organic acids in a boreal stream during snowmelt, Water Resour. Res., 37: 1043–1056.

Kann J. and V.H. Smith, 1999. Estimating the probability of exceeding elevated pH values critical to fish populations in a hypertrophic lake. Can. J. Fish Aquat. Sci., 56: 2262–2270.

Kotak, B.G. and R.W. Zurawell, 2007. Cyanobacterial toxins in Canadian freshwaters: A review. Lake and Reserv. Manage., 23:109–122.

Lesser Slave Lake Economic Alliance, 2013. http://www.lslea.ca/images/PDF/profiles/Wabasca Investment Profile.pdf. Accessed Sept 25, 2017.

Lidman, F., Å. Boily, H. Laudon and S.J. Köhler, 2017. From soil water to surface water—how the riparian zone controls element transport from a boreal forest to a stream. Biogeosciences, 14: 3001–3014.

Marino, R., R.W. Howarth, J. Shamess and E. Prepas, 1990. Molybdenum and sulfate as controls on the abundance of nitrogen-fixing cyanobacteria in saline lakes in Alberta. Limnol. Oceanogr., 35: 245–259.

Mattson, M.D., 2009. Alkalinity. In: Encyclopedia of Inland Waters. G.E. Likens ed. Elsevier, Oxford, pp.1–6.

MPWA (Mighty Peace Watershed Alliance), 2015. Background Report: Regional Hydrological Assessment of the Peace River Watershed. http://mightypeacesow.org/pdf/MPWA_Regional_Hydrological_Assessment.pdf. Accessed Feb, 2018.

Natural Regions Committee, 2006. Natural Regions and Subregions of Alberta. Compiled by D.J. Downing and W.W. Pettapiece. Government of Alberta. Pub. No. T/852.

Palacio H., J. Ramírez, R. Echenique, J. Palacio, C. Sant'Anna, 2015. Floristic composition of cyanobacteria in a neo-tropical, eutrophic reservoir. Braz. J. Bot., 38: 865–876.

Peralta-Tapia, A., R.A. Sponseller, A. Ågren, D. Tetzlaff, C. Soulsby and H. Laudon, 2015. Scale-dependent groundwater contributions influence patterns of winter baseflow stream chemistry in boreal catchments: BASEFLOW CHEMISTRY IN BOREAL CATCHMENTS. J. Geophys. Res. Biogeo., 2014JG002878, https://doi.org/10.1002/2014JG002878.

Plach, J.M., J.-M. Ferone, Z. Gibbons, B.D. Smerdon, A. Mertens, C.A. Mendoza, R.M. Petrone and K.J. Devito. 2016. Influence of glacial landform hydrology on phosphorus budgets of shallow lakes on the Boreal Plain, Canada. J. Hydrol. 535: 191–203. doi: 10.1016/j.jhydrol.2016.01.041.

Preisendorfer, R.W., 1986. Secchi disk science: Visual optics of natural waters. Limnol. Oceanogr. 31: 909–926.

Prepas, E.E., 1990. Water quality. In: Atlas of Alberta Lakes. P.A. Mitchell and E.E. Prepas, eds. University of Alberta Press, Edmonton.

Reynolds C.S., R. L. Oliver and A.E. Walsby, 1987. Cyanobacterial dominance: the role of buoyancy regulation in dynamic lake environments. N.Z. J. Mar. Freshwater Res., 21: 379–390.

Rosen, B., 2017. USGS Microbiological Image Gallery https://microbiology.usgs.gov/image_gallery_cyanobacteria_cnaegeliana_light.html. Accessed 14 Sept 2017.

Schindler, D.W., 1977. Evolution of phosphorus limitation in lakes. Science, 195: 260–262.

Smith, V.H., 1983. Low nitrogen to phosphorus ratios favour dominance by blue-green algae in lake phytoplankton. Science, 221: 669–671.

Smith, V.H., V.J. Bierman, B.L. Jones and K.E. Havens, 1995. Historical trends in the Lake Okeechobee ecosystem IV. Nitrogen:phosphorus ratios, cyanobacterial dominance, and nitrogen fixation potential. Archiv für Hydrobiologie, 107: 71–88.

Sparling, D.W. and T.P. Lowe, 1996. Reviews of Environmental Contamination and Toxicology. Springer Verlag, New York. Vol. 145.

Stewart, W.D.P., 1969. Biological and ecological aspects of nitrogen fixation by free-living micro-organisms. Proc. R. Soc. London. Ser. B, 172: 367–388.

Stoddard, J.L., 1994. Long-term changes in watershed retention of nitrogen. In: Environmental Chemistry of Lakes and Reservoirs, L.A. Baker ed., Adv. in Chem., Am. Chem. Soc., Washington, D.C. Ser. 237: 223–284.

Trew, D.O., D. J. Beliveau and E.I. Yonge, 1987. The Baptiste Lake Study Technical Report. Alberta Environment, Edmonton, Alberta. 380 pp.

Trimbee, A.M. and E.E. Prepas, 1987. Evaluation of total phosphorus as a predictor of the relative biomass of blue-green algae with emphasis on Alberta lakes. Can. J. Fish. Aquat. Sci., 14:1337–1342.

Tolstoy, A., 1979. Chlorophyll a in relation to phytoplankton volume in some Swedish lakes. Arch. Hydrobiol., 85: 133–151.

Vollenweider, R.A. and J. Kerekes, 1982. Eutrophication of waters. Monitoring Assessment and Control. Organization for Economic Co-Operation and Development (OECD), Paris. 156 pp.

Wetzel, R.G., 1983. Limnology. 2nd ed. Saunders College Publishing, Toronto. 767 p.

Zhou, L., H. Yu and K. Chen, 2002. Relationship between microcystin in drinking water and colorectal cancer. Biomed. Environ. Sci., 15:166–71.

Zurawell, R., 2000. Cyanobacteria: A review toward understanding. Lakeline, 20 (4): 29–33.

Zurawell, R.W., 2010. Alberta Environment Cyanotoxin Program Status Report. https://open.alberta.ca/publications/9780778590149.

Zurawell, R.W., 2015. Toxic Cyanobacteria. In: Routledge Handbook of Water and Health, 1st ed. J. Bartram ed. Routledge, London and New York. ISBN: 978-1-138-91007-2, pp. 98–106.

Appendix I

Figure A1: Lake Stratification

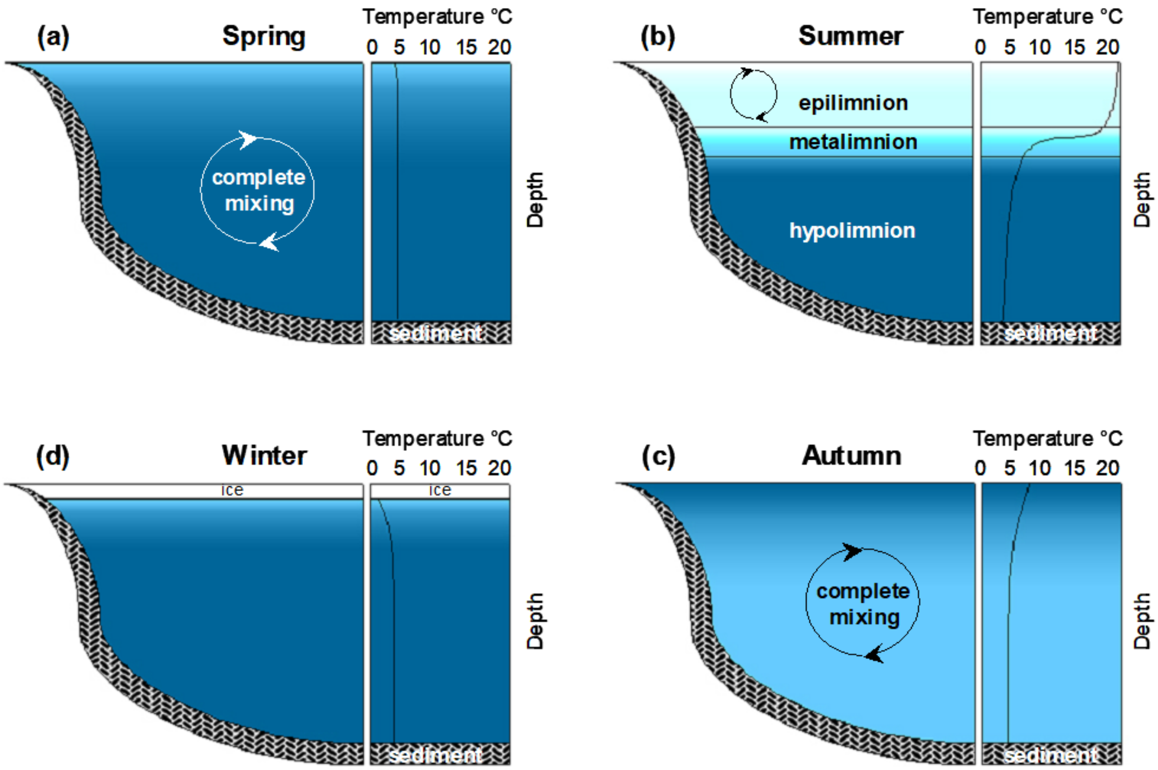


Figure A1. Depiction of annual lake mixing and thermal stratification within Alberta's dimictic (stratified) lakes.

Tabulated Data

Table a. Mean (and median) concentrations of nutrients and chlorophyll-a in samples collected during the open-water season from Desmarais Lake Outlet, North Wabasca Lake and Willow River. [TP–total phosphorus, TDP–total dissolved phosphorus, TKN–total Kjeldahl (organic) nitrogen, NO2 + NO3–nitrite + nitrate, NH3–ammonia, TN–total nitrogen, TN:TP–ratio of total nitrogen to total phosphorus].

Nutrient	Desmarais Lake Outlet	North Wabasca Lake	Willow River	Guideline: Preservation of Aquatic Life
TP (mg/L)	0.136 (0.12)	0.022 (0.0185)	0.057 (0.062)	
TDP (mg/L)	0.087 (0.072)	0.006 (0.006)	0.027 (0.03)	
TKN (mg/L)	1.93 (1.9)	0.91 (0.91)	0.91 (0.91)	
NO_2 + NO_3 (mg/L)	0.02 (0.02)	0.0025 (0.0025)	0.016 (0.016)	
NH3 (mg/L)	0.15 (0.11)^	0.038 (0.025)	ND	0.028–3.96[†a]
TN (mg/L)	1.967 (1.9)	0.775 (0.745)	0.917 (0.93)	
TN:TP	14.496 (15.833)	35.227 (40.270)	16.176 (15)	
Chlorophyll-a (µg/L)	25.87 (24.6)	17.55 (15)	3.5 (3.3)	

ND = not detected

^ exceeds guideline value

† Calculated at pH range of 7.0–9.5 and 20°C (concentration inversely proportional to water temperature and pH)

[a] Environmental Quality Guidelines for Alberta Surface Waters (AESRD, 2014)

Table b. Concentrations of nutrients and chlorophyll-a in samples collected at 1m depth (below surface or ice) during winter 2017 from Desmarais Lake Outlet, North Wabasca Lake and Willow River. [TP–total phosphorus, TDP–total dissolved phosphorus, TKN–total Kjeldahl nitrogen, NO_2 + NO_3–nitrite + nitrate, NH_3–ammonia, TN–total nitrogen, TN:TP–total nitrogen to total phosphorus].

Nutrient	Desmarais Lake Outlet	North Wabasca Lake	Willow River	Guideline: Preservation of Aquatic Life
TP (mg/L)	0.13	0.023	0.071	
TDP (mg/L)	0.073	0.019	0.011	
TKN (mg/L)	2.7	0.72	1.5	
NO_2 and NO_3 (mg/L)	0.21	0.18	0.49	
NH_3 (mg/L)	1.2	ND	0.28	1.76–17.5[†a]
TN (mg/L)	2.9	0.89	1.9	
TN:TP	22.31	38.70	26.76	
Chlorophyll-A	5.5	2.3	0.9	

ND = not detected

† Calculated at pH range of 7.0–8 and 1.5°C (concentration inversely proportional to water temperature and pH)

a Environmental Quality Guidelines for Alberta Surface Waters (AESRD, 2014)

Table c. Mean (and median) ion chemistry in samples collected during the open-water season from Desmarais Lake Outlet, North Wabasca Lake and Willow River. Guidelines for recreational/aesthetic quality and the preservation of aquatic life are provided as references.

Parameter	Desmarais Lake Outlet	North Wabasca Lake	Willow River	Guideline: Recreation/ Aesthetics	Guideline: Preservation of Aquatic Life (PAL)	
					Acute	Chronic
pH[#]	9.21 (9.27)^	7.87 (7.96)	7.56 (7.65)	5.0–9.0[c]		6.5–9.0[a]
Conductivity (uS/cm)[#]	184.5 (176.2)	205.28 (205)	144.3 (146.2)			
Total Alkalinity (mg/L $CaCO_3$)[#]	77.67 (76)	83.5 (84)	62.33 (59)			20*[a]
Dissolved O_2 (mg/L)[#]	6.927 (7.33)	7.2 (8.54)	8.537 (8.11)	2[d]	5*[a]	6.5* (8.3†,9.5‡)[a]
Dissolved Cations						
Potassium [K^+] (mg/L)	1.9 (2.1)	2.1 (2.15)	1.267 (1.2)			
Sodium [Na^+] (mg/L)	7.7 (8)	6.6 (6.6)	4.8 (4.7)			
Calcium [Ca^{2+}] (mg/L)	21.33 (21)	26.25 (26.5)	20.67 (19)			
Magnesium [Mg^{2+}] (mg/L)	7.53 (8.1)	7.33 (7.4)	5.47 (5.1)			
Manganese [Mn^{2+}] (mg/L)	0.053 (0.057)	ND	0.033 (0.032)			
Iron [$Fe^{2+/3+}$] (mg/L)	0.326 (0.27)^	0.042 (0.03)	1.23 (1.2)^			0.3[a]

Parameter	Desmarais Lake Outlet	North Wabasca Lake	Willow River	Guideline: Recreation/ Aesthetics	Guideline: Preservation of Aquatic Life (PAL)	
Dissolved Anions						
Chloride [Cl^-] (mg/L)	2.43 (2.4)	1.73 (1.75)	1.7 (1.7)		120[a]	640[a]
Hydroxide [OH^-] (mg/L)	ND	ND	ND			
Bicarbonate [HCO_3^-] (mg/L)	81.33 (81)	99.5 (100)	76 (72)			
Carbonate [CO_3^{2-}] (mg/L)	6.7 (5.5)	ND	ND			
Sulfate [SO_4^{2-}] (mg/L)	10.8 (9.9)	16 (16)	3.9 (3.9)			309[ab]
Silica [Si^-] (mg/L)	9.167 (9)	6.5 (6.4)	8.267 (8.7)			

ND = not detected

^ exceeds guideline value

† Values reported as minimum levels to protect mayfly emergence

‡ Values reported as minimum levels to protect larval fish development

* Minimum value (unless natural conditions are lower)

Value represents mean for discrete depths of entire water column (not only euphotic zone mean)

[a] Environmental Quality Guidelines for Alberta Surface Waters (AESRD, 2014)

[b] CCME Canadian Water Quality Guideline for the Protection of Aquatic Life

[c] Guidelines for Canadian Recreational Water Quality, Third Ed. (Health Canada. 2012)

[d] Guidelines for Interpreting Water Quality Data (BCMOE, 1998)

Table d. Surface (1-m below surface or ice) ion chemistry in samples collected during winter 2017 from Desmarais Lake Outlet, North Wabasca Lake and Willow River. Guidelines for recreational/aesthetic quality and the preservation of aquatic life are provided as references.

Parameter	Desmarais Outlet	North Wabasca Lake	Willow River	Guideline: Recreation/ Aesthetics	Guideline: Preservation of Aquatic Life	
					Acute	Chronic
pH[#]	7.29	7.58	7.22	5.0–9.0[c]		6.5–9.0[a]
Conductivity (uS/cm)[#]	307.4	199.9	260.4			
Total Alkalinity (mg/L $CaCO_3$)[#]	140	83	170			20*[a]
Dissolved O_2 (mg/L)[#]	7.79	10.17	6.64	2[d]	5*[a]	6.5* (8.3[†],9.5[‡])[a]
Dissolved Cations						
Potassium [K^+] (mg/L)	2.8	1.9	2.6			
Sodium [Na^+] (mg/L)	10	6.4	18			
Calcium [Ca^{2+}] (mg/L)	38	25	48			
Magnesium [Mg^{2+}] (mg/L)	11	7.3	15			
Manganese [Mn^{2+}] (mg/L)	0.54	ND	0.44			
Dissolved Iron [$Fe^{2+/3+}$] (mg/L)	0.8	ND	0.78			0.3[a]
Dissolved Anions						
Chloride [Cl^-] (mg/L)	2.9	2.3	9.7		120[a]	640[a]

Parameter	Desmarais Outlet	North Wabasca Lake	Willow River	Guideline: Recreation/ Aesthetics	Guideline: Preservation of Aquatic Life
Hydroxide [OH^-] (mg/L)	0.25	ND	0.25		
Bicarbonate [HCO_3^-] (mg/L)	170	100	200		
Carbonate [CO_3^{2-}] (mg/L)	0.25	ND	0.25		
Sulfate [SO_4^{2-}] (mg/L)	20	18	35		309[ab]
Silica [Si^-] (mg/L)	19	9.5	11		

ND = not detected

^ exceeds guideline value

† Values reported as minimum levels to protect mayfly emergence

‡ Values reported as minimum levels to protect larval fish development

* Minimum value (unless natural conditions are lower)

Value represents mean for discrete depths of entire water column (not only euphotic zone mean)

a Environmental Quality Guidelines for Alberta Surface Waters (AESRD, 2014)

b CCME Canadian Water Quality Guideline for the Protection of Aquatic Life

c Guidelines for Canadian Recreational Water Quality, Third Ed. (Health Canada. 2012)

d Guidelines for Interpreting Water Quality Data (BCMOE, 1998)

Table e. Total recoverable metals concentrations in samples collected from the surface (0.1 m) and near bottom (14.5 m) during August from North Wabasca Lake. Guidelines for recreation and aesthetic quality and preservation of aquatic life are provided as references.

Metals (Total Recoverable)	North Wabasca Lake	Guideline: Recreation/Aesthetics	Guideline: Preservation of Aquatic Life (PAL)	
	Concentration Surface/Bottom	Chronic	Acute	Chronic
Aluminum (µg/L)	22.2/24.1	200[d]	100*‡[a]	50*‡[a]
Antimony (µg/L)	0.062/0.063			
Arsenic (µg/L)	1.09/2.71			5[a]
Barium (µg/L)	35.6/86.9			
Beryllium (µg/L)	ND			
Bismuth (µg/L)	0.003/0.007			
Boron (µg/L)	34.6/32.2		29,000[a]	1,500[a]
Cadmium (µg/L)	0.007/0.007	10,000[e]	2.1†[a]	0.16†[a]
Chromium (µg/L)	0.05/0.05			1, 8.9§[a]
Cobalt (µg/L)	0.004/0.078			2.5[a]
Copper (µg/L)	0.93/0.59	1000[e]	16†[a]	7†[a]
Iron (µg/L)	26.4/123			300*[a]
Lead (µg/L)	0.014/0.009	10[e]		3.2†[a]
Lithium (µg/L)	10.1/9.25			
Manganese (µg/L)	62.1/3180		1600†b	1000†b
Mercury (ng/L)	0.4/0.55	1000e	13a	5a
Molybdenum (µg/L)	0.442/0.474			73a
Nickel (µg/L)	0.955/0.009		470†a	52†a
Selenium (µg/L)	0.15/0.14			1[a]
Silver (µg/L)	ND			0.1[a]

Metals (Total Recoverable)	North Wabasca Lake	Guideline: Recreation/Aesthetics	Guideline: Preservation of Aquatic Life (PAL)	
	Concentration Surface/Bottom	Chronic	Acute	Chronic
Strontium (µg/L)	133/149			
Thallium (µg/L)	0.0038/0.003			0.8[a]
Thorium (µg/L)	0.0099/0.044			
Tin (µg/L)	0.034/0.008			
Titanium (µg/L)	1.14/1.48			
Uranium (µg/L)	0.148/0.129		33[a]	15[a]
Vanadium (µg/L)	0.24/0.19			120[c]
Zinc (µg/L)	1/0.8	5000[e]		30[a]

ND = not detected

* Applies to dissolved (not total) fraction since most is attached to particles and not bioavailable

† Calculated based on water hardness ($CaCO_3$) of 100mg/L

‡ Based on pH ≥ 6.5

§ Hexavalent (Cr VI) and Trivalent (Cr III) respectively

[a] Environmental Quality Guidelines for Alberta Surface Waters (AESRD, 2014)

[b] British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture (BCMOE, 2017)

[c] CEPA Federal Environmental Quality Guidelines: Vanadium (Env Canada, 2016)

[d] Applies to dissolved (not total) aluminum, British Columbia Approved Water Quality Guidelines, 2006 Edition (BCMOE, 2006)

[e] Guidelines for Interpreting Water Quality Data (BCMOE, 1998)

Table f. Total recoverable metals concentrations in samples collected from the surface (1-m below surface or ice) during winter from North Wabasca Lake. Guidelines for recreation and aesthetic quality and preservation of aquatic life are provided as references.

Metals (Total Recoverable)	North Wabasca Lake	Guideline: Recreation/Aesthetics	Guideline: Preservation of Aquatic Life (PAL)	
	Concentration Surface/Bottom	Chronic	Acute	Chronic
Aluminum (µg/L)	11.4	200[d]	100[*‡a]	50[*‡a]
Antimony (µg/L)	0.075			
Arsenic (µg/L)	1.21			5[a]
Barium (µg/L)	47.1			
Beryllium (µg/L)	ND			
Bismuth (µg/L)	ND			
Boron (µg/L)	41.7		29,000[a]	1,500[a]
Cadmium (µg/L)	ND	10,000[e]	2.1[†a]	0.16[†a]
Chromium (µg/L)	0.07			1, 8.9[§a]
Cobalt (µg/L)	ND			2.5[a]
Copper (µg/L)	0.86	1000[e]	16[†a]	7[†a]
Iron (µg/L)	30.4			300[*a]
Lead (µg/L)	0.077	10[e]		3.2[†a]
Lithium (µg/L)	12.4			
Manganese (µg/L)	5.75		1600[†b]	1000[†b]
Mercury (ng/L)	0.45	1000[e]	13[a]	5[a]
Molybdenum (µg/L)	0.466			73[a]
Nickel (µg/L)	1.48		470[†a]	52[†a]
Selenium (µg/L)	0.11			1[a]
Silver (µg/L)	ND			0.1[a]
Strontium (µg/L)	156			

Metals (Total Recoverable)	North Wabasca Lake	Guideline: Recreation/Aesthetics	Guideline: Preservation of Aquatic Life (PAL)	
	Concentration Surface/Bottom	Chronic	Acute	Chronic
Thallium (µg/L)	0.0018			0.8[a]
Thorium (µg/L)	ND			
Tin (µg/L)	0.05			
Titanium (µg/L)	1.04			
Uranium (µg/L)	0.171		33[a]	15[a]
Vanadium (µg/L)	0.21			120[c]
Zinc (µg/L)	2.3	5000[e]		30[a]

ND = not detected

* Applies to dissolved (not total) fraction since most is attached to particles and not bioavailable

† Calculated based on water hardness ($CaCO_3$) of 100mg/L

‡ Based on pH ≥ 6.5

§ Hexavalent (Cr VI) and Trivalent (Cr III) respectively

[a] Environmental Quality Guidelines for Alberta Surface Waters (AESRD, 2014)

[b] British Columbia Approved Water Quality Guidelines: Aquatic Life, Wildlife & Agriculture (BCMOE, 2017)

[c] CEPA Federal Environmental Quality Guidelines: Vanadium (Env Canada, 2016)

[d] Applies to dissolved (not total) aluminum, British Columbia Approved Water Quality Guidelines, 2006 Edition (BCMOE, 2006)

[e] Guidelines for Interpreting Water Quality Data (BCMOE, 1998)

Appendix II

1.0 Raw Data: *In-Situ* Parameters

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Temperature (°C)				
	07–Jun–16	Not sampled	14.02	Not sampled
	05–Jul–16	20.09	17.37	18.62
	09–Aug–16	19.39	18.47	18.69
	14–Sep–16	12.99	13.86	10.13
	22–Feb–17	1.41	2.41	-0.24
Total Water Depth (m)				
	07–Jun–16	Not sampled	16	Not sampled
	05–Jul–16	Not sampled	16.1	Not sampled
	09–Aug–16	Not sampled	15.7	Not sampled
	14–Sep–16	Not sampled	16.2	Not sampled
Euphotic Depth (m)				
	07–Jun–16	Not sampled	6.1	Not sampled
	05–Jul–16	Not sampled	4.95	Not sampled
	09–Aug–16	Not sampled	5.1	Not sampled
	14–Sep–16	Not sampled	3.2	Not sampled
Secchi Disk Depth (m)				
	07–Jun–16	Not sampled	1.8	Not sampled
	05–Jul–16	Not sampled	2.7	Not sampled
	09–Aug–16	Not sampled	2.75	Not sampled
	14–Sep–16	Not sampled	1.9	Not sampled

2.0 Raw Data: Water Chemistry

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Field pH				
	07–Jun–16	Not sampled	7.77	Not sampled
	05–Jul–16	9.67	7.9	7.65
	09–Aug–16	9.27	7.88	7.7
	14–Sep–16	8.7	7.94	7.34
	22–Feb–17	7.29	7.35	7.22
Specific Conductivity (Us/cm)				
	07–Jun–16	Not sampled	205.82	Not sampled
	05–Jul–16	175.9	205.136	146.2
	09–Aug–16	176.2	209.3	171.6
	14–Sep–16	201.4	200.65	114.9
	22–Feb–17	307.4	222.23	260.4
Dissolved oxygen (mg/L)				
	07–Jun–16	Not sampled	8.16	Not sampled
	05–Jul–16	8.18	6.72	8.11
	09–Aug–16	5.27	5.3	7.84
	14–Sep–16	7.33	8.68	9.66
	22–Feb–17	7.79	5.46	6.64
Alkalinity (mg/L CaCO3)				
	07–Jun–16	Not sampled	85	Not sampled
	05–Jul–16	67	81	59
	09–Aug–16	76	84	77
	14–Sep–16	90	84	51
	22–Feb–17	140	97	170

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Hardness (mg/L CaCO3)				
	07–Jun–16	Not sampled	99	Not sampled
	05–Jul–16	77	88	69
	09–Aug–16	88	100	94
	14–Sep–16	90	94	61
	22–Feb–17	140	107	180
Total Dissolved Solids (mg/L)				
	07–Jun–16	Not sampled	120	Not sampled
	05–Jul–16	98	110	76
	09–Aug–16	110	120	100
	14–Sep–16	120	120	74
	22–Feb–17	190	140	240
Residual Non filterable (mg/L)				
	07–Jun–16	Not sampled	3.3	Not sampled
	05–Jul–16	3.3	3.3	38
	09–Aug–16	5.3	2.7	17
	14–Sep–16	7.3	6.7	50
	22–Feb–17	3.3	L0.5	4.7

3.0 Raw Data: Nutrient Chemistry

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Microcystin (µg/L)				
	07–Jun–16	Not sampled	L0.1	Not sampled
	05–Jul–16	Not sampled	0.13	Not sampled
	09–Aug–16	Not sampled	0.12	Not sampled
	14–Sep–16	Not sampled	0.14	Not sampled
	22–Feb–17	Not sampled	Not sampled	Not sampled
Chlorophyll-A (µg/L)				
	07–Jun–16	Not sampled	4.8	Not sampled
	05–Jul–16	13.7	12.9	4.7
	09–Aug–16	39.3	17.1	3.3
	14–Sep–16	24.6	35.4	2.5
	22–Feb–17	5.5	1.17	0.9
Total Phosphorous (mg/L)				
	07–Jun–16	Not sampled	0.017	Not sampled
	05–Jul–16	0.097	0.017	0.087
	09–Aug–16	0.12	0.02	0.062
	14–Sep–16	0.19	0.034	0.021
	22–Feb–17	0.13	0.035	0.071
Total Dissolved Phosphorous (mg/L)				
	07–Jun–16	Not sampled	0.006	Not sampled
	05–Jul–16	0.06	0.006	0.03
	09–Aug–16	0.072	0.006	0.033
	14–Sep–16	0.13	0.006	0.02
	22–Feb–17	0.073	0.021	0.011

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Dissolved Organic Carbon (mg/L)				
	07–Jun–16	Not sampled	14	Not sampled
	05–Jul–16	25	17	34
	09–Aug–16	21	14	28
	14–Sep–16	24	14	33
	22–Feb–17	23	18	23
Total Nitrogen (mg/L)				
	07–Jun–16	Not sampled	0.66	Not sampled
	05–Jul–16	1.3	0.75	0.93
	09–Aug–16	1.9	0.74	0.82
	14–Sep–16	2.7	0.95	1
	22–Feb–17	2.9	1.29	1.9
Nitrate (mg/L)				
	07–Jun–16	Not sampled	L0.003	Not sampled
	05–Jul–16	L0.003	L0.003	0.016
	09–Aug–16	L0.003	L0.003	L0.003
	14–Sep–16	0.0081	L0.003	L0.003
	22–Feb–17	0.2	0.28	0.48
Nitrite (mg/L)				
	07–Jun–16	Not sampled	L0.003	Not sampled
	05–Jul–16	L0.003	L0.003	L0.003
	09–Aug–16	L0.003	L0.003	L0.003
	14–Sep–16	0.012	L0.003	L0.003
	22–Feb–17	0.0091	L 0.003	0.0085
NO2 & NO3 (mg/L)				
	07–Jun–16	Not sampled	L0.005	Not sampled

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
	05–Jul–16	L0.005	L0.005	0.016
	09–Aug–16	L0.005	L0.005	L0.005
	14–Sep–16	0.02	L0.005	L0.005
	22–Feb–17	0.21	0.28	0.49
TKN (organic N and ammonia) (mg/L)				
	07–Jun–16	Not sampled	0.66	Not sampled
	05–Jul–16	1.3	0.75	0.91
	09–Aug–16	1.9	0.74	0.82
	14–Sep–16	2.6	0.95	1
	22–Feb–17	2.7	1.02	1.5
Total ammonia (mg/L)				
	07–Jun–16	Not sampled	L0.05	Not sampled
	05–Jul–16	L0.05	L0.05	L0.05
	09–Aug–16	0.11	0.08	L0.05
	14–Sep–16	0.33	L0.05	L0.05
	22–Feb–17	1.2	0.44	0.28

4.0 Raw Data: Ion Chemistry

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Ionic Balance (meg/L)				
	07–Jun–16	Not sampled	1.1	Not sampled
	05–Jul–16	1.1	1	1.4
	09–Aug–16	1.2	1.2	1.4
	14–Sep–16	1.1	1.1	1.2
	22–Feb–17	1.1	1	1
Sum of Cations (meg/L)				
	07–Jun–16	Not sampled	2.3	Not sampled
	05–Jul–16	1.9	2.1	1.7
	09–Aug–16	2.2	2.4	2.2
	14–Sep–16	2.2	2.2	1.4
	22–Feb–17	3.5	2.57	4.5
Dissolved Calcium (mg/L)				
	07–Jun–16	Not sampled	27	Not sampled
	05–Jul–16	20	24	19
	09–Aug–16	21	28	26
	14–Sep–16	23	26	17
	22–Feb–17	38	28.67	48
Dissolved Iron (mg/L)				
	07–Jun–16	Not sampled	L0.06	Not sampled
	05–Jul–16	0.27	L0.06	1.1
	09–Aug–16	0.27	L0.06	1.4
	14–Sep–16	0.44	0.078	1.2
	22–Feb–17	0.8	0.42	0.78

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Dissolved Magnesium (mg/L)				
	07–Jun–16	Not sampled	7.7	Not sampled
	05–Jul–16	6.3	6.8	5.1
	09–Aug–16	8.2	7.6	6.7
	14–Sep–16	8.1	7.2	4.6
	22–Feb–17	11	8.3	15
Dissolved Manganese (mg/L)				
	07–Jun–16	Not sampled	L0.004	Not sampled
	05–Jul–16	0.057	L0.004	0.019
	09–Aug–16	0.04	L0.004	0.032
	14–Sep–16	0.061	L0.004	0.047
	22–Feb–17	0.54	1.2	0.44
Dissolved Potassium (mg/L)				
	07–Jun–16	Not sampled	2.2	Not sampled
	05–Jul–16	1.4	2.1	1.2
	09–Aug–16	2.1	2.2	1.5
	14–Sep–16	2.2	1.9	1.1
	22–Feb–17	2.8	2.1	2.6
Dissolved Sodium (mg/L)				
	07–Jun–16	Not sampled	6.8	Not sampled
	05–Jul–16	6.7	6.3	4.7
	09–Aug–16	8.5	6.9	6.3
	14–Sep–16	8	6.4	3.4
	22–Feb–17	10	7.3	18
Sum of Anions (meg/L)				
	07–Jun–16	Not sampled	2.1	Not sampled

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
	05–Jul–16	1.7	2	1.2
	09–Aug–16	1.8	2.1	1.6
	14–Sep–16	2.1	2	1.2
	22–Feb–17	3.2	2.43	4.4
Bicarbonate (mg/L)				
	07–Jun–16	Not sampled	100	Not sampled
	05–Jul–16	53	98	72
	09–Aug–16	81	100	94
	14–Sep–16	110	100	62
	22–Feb–17	170	120	200
Carbonate (mg/L)				
	07–Jun–16	Not sampled	L0.5	Not sampled
	05–Jul–16	14	L0.5	L0.5
	09–Aug–16	5.5	L0.5	L0.5
	14–Sep–16	0.67	L0.5	L0.5
	22–Feb–17	L0.5	L0.5	L0.5
Dissolved Chloride (mg/L)				
	07–Jun–16	Not sampled	1.6	Not sampled
	05–Jul–16	2.4	1.8	1.4
	09–Aug–16	2	1.7	1.7
	14–Sep–16	2.9	1.8	2
	22–Feb–17	2.9	2.5	9.7
Hydroxide (mg/L)				
	07–Jun–16	Not sampled	L0.5	Not sampled
	05–Jul–16	L0.5	L0.5	L0.5
	09–Aug–16	L0.5	L0.5	L0.5

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
	14–Sep–16	L0.5	L0.5	L0.5
	22–Feb–17	L0.5	L0.5	L0.5
Dissolved Silica (mg/L)				
	07–Jun–16	Not sampled	6	Not sampled
	05–Jul–16	7.5	5.1	7.3
	09–Aug–16	9	6.8	8.7
	14–Sep–16	11	8.1	8.8
	22–Feb–17	19	11.07	11
Dissolved Sulfate (mg/L)				
	07–Jun–16	Not sampled	17	Not sampled
	05–Jul–16	13	16	L1
	09–Aug–16	9.6	16	2.9
	14–Sep–16	9.9	15	4.9
	22–Feb–17	20	18.33	35

5.0 Raw Data: Metals Chemistry

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Aluminum µg/L				
	09–Aug–16 (0.1m)	Not sampled	22.2	Not sampled
	09–Aug–16 (14.5m)	Not sampled	24.1	Not sampled
	22–Feb–17 (1m)	Not sampled	11.4	Not sampled
	22–Feb–17 (7m)	Not sampled	6.7	Not sampled
	22–Feb–17 (14m)	Not sampled	12.2	Not sampled
Antimony µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.062	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.063	Not sampled
	22–Feb–17 (1m)	Not sampled	0.075	Not sampled
	22–Feb–17 (7m)	Not sampled	0.085	Not sampled
	22–Feb–17 (14m)	Not sampled	0.091	Not sampled
Arsenic µg/L				
	09–Aug–16 (0.1m)	Not sampled	1.09	Not sampled
	09–Aug–16 (14.5m)	Not sampled	2.71	Not sampled
	22–Feb–17 (1m)	Not sampled	1.21	Not sampled
	22–Feb–17 (7m)	Not sampled	1.31	Not sampled
	22–Feb–17 (14m)	Not sampled	1.3	Not sampled
Barium µg/L				
	09–Aug–16 (0.1m)	Not sampled	35.6	Not sampled
	09–Aug–16 (14.5m)	Not sampled	86.9	Not sampled
	22–Feb–17 (1m)	Not sampled	47.1	Not sampled
	22–Feb–17 (7m)	Not sampled	57.4	Not sampled
	22–Feb–17 (14m)	Not sampled	90.6	Not sampled

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Beryllium µg/L				
	09–Aug–16 (0.1m)	Not sampled	L0.008	Not sampled
	09–Aug–16 (14.5m)	Not sampled	L0.008	Not sampled
	22–Feb–17 (1m)	Not sampled	L0.008	Not sampled
	22–Feb–17 (7m)	Not sampled	L0.008	Not sampled
	22–Feb–17 (14m)	Not sampled	L0.008	Not sampled
Bismuth µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.003	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.007	Not sampled
	22–Feb–17 (1m)	Not sampled	L0.001	Not sampled
	22–Feb–17 (7m)	Not sampled	L0.001	Not sampled
	22–Feb–17 (14m)	Not sampled	L0.001	Not sampled
Boron µg/L				
	09–Aug–16 (0.1m)	Not sampled	34.6	Not sampled
	09–Aug–16 (14.5m)	Not sampled	32.2	Not sampled
	22–Feb–17 (1m)	Not sampled	41.7	Not sampled
	22–Feb–17 (7m)	Not sampled	46	Not sampled
	22–Feb–17 (14m)	Not sampled	49	Not sampled
Cadmium µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.007	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.007	Not sampled
	22–Feb–17 (1m)	Not sampled	L0.002	Not sampled
	22–Feb–17 (7m)	Not sampled	L0.002	Not sampled
	22–Feb–17 (14m)	Not sampled	L0.002	Not sampled
Chromium µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.05	Not sampled

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
	09–Aug–16 (14.5m)	Not sampled	0.05	Not sampled
	22–Feb–17 (1m)	Not sampled	0.07	Not sampled
	22–Feb–17 (7m)	Not sampled	0.03	Not sampled
	22–Feb–17 (14m)	Not sampled	L0.03	Not sampled
Cobalt µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.004	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.078	Not sampled
	22–Feb–17 (1m)	Not sampled	L0.002	Not sampled
	22–Feb–17 (7m)	Not sampled	0.007	Not sampled
	22–Feb–17 (14m)	Not sampled	0.276	Not sampled
Copper µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.93	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.59	Not sampled
	22–Feb–17 (1m)	Not sampled	0.86	Not sampled
	22–Feb–17 (7m)	Not sampled	1.06	Not sampled
	22–Feb–17 (14m)	Not sampled	1.21	Not sampled
Iron µg/L				
	09–Aug–16 (0.1m)	Not sampled	26.4	Not sampled
	09–Aug–16 (14.5m)	Not sampled	123	Not sampled
	22–Feb–17 (1m)	Not sampled	30.4	Not sampled
	22–Feb–17 (7m)	Not sampled	55	Not sampled
	22–Feb–17 (14m)	Not sampled	603	Not sampled
Lead µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.014	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.009	Not sampled
	22–Feb–17 (1m)	Not sampled	0.077	Not sampled

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
	22–Feb–17 (7m)	Not sampled	L0.003	Not sampled
	22–Feb–17 (14m)	Not sampled	0.026	Not sampled
Lithium µg/L				
	09–Aug–16 (0.1m)	Not sampled	10.1	Not sampled
	09–Aug–16 (14.5m)	Not sampled	9.25	Not sampled
	22–Feb–17 (1m)	Not sampled	12.4	Not sampled
	22–Feb–17 (7m)	Not sampled	13.6	Not sampled
	22–Feb–17 (14m)	Not sampled	16.3	Not sampled
Manganese µg/L				
	09–Aug–16 (0.1m)	Not sampled	62.1	Not sampled
	09–Aug–16 (14.5m)	Not sampled	3180	Not sampled
	22–Feb–17 (1m)	Not sampled	5.75	Not sampled
	22–Feb–17 (7m)	Not sampled	21.6	Not sampled
	22–Feb–17 (14m)	Not sampled	1590	Not sampled
Mercury ng/L				
	09–Aug–16 (0.1m)	Not sampled	0.4	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.55	Not sampled
	22–Feb–17 (1m)	Not sampled	0.45	Not sampled
	22–Feb–17 (7m)	Not sampled	0.59	Not sampled
	22–Feb–17 (14m)	Not sampled	0.81	Not sampled
Molybdenum µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.442	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.474	Not sampled
	22–Feb–17 (1m)	Not sampled	0.466	Not sampled
	22–Feb–17 (7m)	Not sampled	0.516	Not sampled
	22–Feb–17 (14m)	Not sampled	0.663	Not sampled

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
Nickel µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.955	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.991	Not sampled
	22–Feb–17 (1m)	Not sampled	1.48	Not sampled
	22–Feb–17 (7m)	Not sampled	1.87	Not sampled
	22–Feb–17 (14m)	Not sampled	2.98	Not sampled
Selenium µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.15	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.14	Not sampled
	22–Feb–17 (1m)	Not sampled	0.11	Not sampled
	22–Feb–17 (7m)	Not sampled	0.08	Not sampled
	22–Feb–17 (14m)	Not sampled	0.12	Not sampled
Silver µg/L				
	09–Aug–16 (0.1m)	Not sampled	L0.002	Not sampled
	09–Aug–16 (14.5m)	Not sampled	L0.002	Not sampled
	22–Feb–17 (1m)	Not sampled	L0.002	Not sampled
	22–Feb–17 (7m)	Not sampled	L0.002	Not sampled
	22–Feb–17 (14m)	Not sampled	L0.002	Not sampled
Strontium µg/L				
	09–Aug–16 (0.1m)	Not sampled	133	Not sampled
	09–Aug–16 (14.5m)	Not sampled	149	Not sampled
	22–Feb–17 (1m)	Not sampled	156	Not sampled
	22–Feb–17 (7m)	Not sampled	187	Not sampled
	22–Feb–17 (14m)	Not sampled	236	Not sampled
Thallium µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.0038	Not sampled

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
	09–Aug–16 (14.5m)	Not sampled	0.003	Not sampled
	22–Feb–17 (1m)	Not sampled	0.0018	Not sampled
	22–Feb–17 (7m)	Not sampled	L0.0009	Not sampled
	22–Feb–17 (14m)	Not sampled	0.001	Not sampled
Thorium µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.0099	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.044	Not sampled
	22–Feb–17 (1m)	Not sampled	L0.0009	Not sampled
	22–Feb–17 (7m)	Not sampled	L0.0009	Not sampled
	22–Feb–17 (14m)	Not sampled	0.0122	Not sampled
Tin µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.034	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.008	Not sampled
	22–Feb–17 (1m)	Not sampled	0.05	Not sampled
	22–Feb–17 (7m)	Not sampled	0.025	Not sampled
	22–Feb–17 (14m)	Not sampled	0.018	Not sampled
Titanium µg/L				
	09–Aug–16 (0.1m)	Not sampled	1.14	Not sampled
	09–Aug–16 (14.5m)	Not sampled	1.48	Not sampled
	22–Feb–17 (1m)	Not sampled	1.04	Not sampled
	22–Feb–17 (7m)	Not sampled	1.33	Not sampled
	22–Feb–17 (14m)	Not sampled	1.95	Not sampled
Uranium µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.148	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.129	Not sampled
	22–Feb–17 (1m)	Not sampled	0.171	Not sampled

Parameter	Date	Desmarais Lake Outlet	North Wabasca Lake	Willow River
	22–Feb–17 (7m)	Not sampled	0.2	Not sampled
	22–Feb–17 (14m)	Not sampled	0.301	Not sampled
Vanadium µg/L				
	09–Aug–16 (0.1m)	Not sampled	0.24	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.19	Not sampled
	22–Feb–17 (1m)	Not sampled	0.21	Not sampled
	22–Feb–17 (7m)	Not sampled	0.13	Not sampled
	22–Feb–17 (14m)	Not sampled	0.2	Not sampled
Zinc µg/L				
	09–Aug–16 (0.1m)	Not sampled	1	Not sampled
	09–Aug–16 (14.5m)	Not sampled	0.8	Not sampled
	22–Feb–17 (1m)	Not sampled	2.3	Not sampled
	22–Feb–17 (7m)	Not sampled	0.7	Not sampled
	22–Feb–17 (14m)	Not sampled	1	Not sampled

6.0 QA/QC Data: Field Blanks

Parameter	Summer (09–August–16)	Winter (22–February–17)
Aluminum (µg/L)	0.4	0.5
Antimony (µg/L)	0.001	L0.001
Arsenic (µg/L)	0.006	L0.004
Barium (µg/L)	0.012	0.011
Beryllium (µg/L)	L0.008	L0.008
Bismuth (µg/L)	0.002	L0.001
Boron (µg/L)	0.3	0.2
Cadmium (µg/L)	0.003	L0.002
Chromium (µg/L)	0.04	0.03
Cobalt (µg/L)	0.004	L0.002
Copper (µg/L)	L0.05	0.14
Iron (µg/L)	1.7	1.9
Lead (µg/L)	0.004	L0.003
Lithium (µg/L)	0.06	L0.05
Manganese (µg/L)	0.012	0.011
Mercury (ng/L)	0.11	L0.06
Molybdenum (µg/L)	0.003	L0.002
Nickel (µg/L)	0.017	L0.008
Selenium (µg/L)	L0.06	L0.06
Silver (µg/L)	0.002	L0.002
Strontium (µg/L)	0.002	0.003
Thallium (µg/L)	0.002	L0.0009
Thorium (µg/L)	0.002	L0.0009
Tin (µg/L)	0.008	0.004

Parameter	Summer (09–August–16)	Winter (22–February–17)
Titanium (µg/L)	0.14	0.08
Uranium (µg/L)	0.003	L0.003
Vanadium (µg/L)	0.02	0.02
Zinc (µg/L)	0.1	0.2