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Environmental Sciences Ltd.

District of Muskoka Water Quality Indicators
Water Quality Monitoring Program Design

Prepared for: District of Muskoka
Job #: J220010

October 16, 2023

Final Report

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October 16, 2023 HESL Job #: J220010

Glenn Cunnington
District of Muskoka

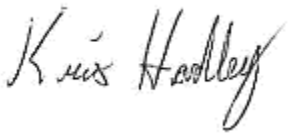
Dear Mr. Cunnington:

Re: Draft Report for the District of Muskoka - Water Quality Monitoring Program Design Project

We are pleased to submit the Draft Report for the District of Muskoka – Guidance for Long-term Monitoring Programs Project. This report was completed to provide in-depth background information to aid in the development of citizen science-led monitoring programs and includes a review of emerging threats to water quality discussed during the Water Quality Indicators Report, a discussion on various water quality parameters, monitoring program development guidance and a review of technology options for monitoring, data management and monitoring program costs.

We thank you for the opportunity to undertake this assignment and look forward to receiving your comments.

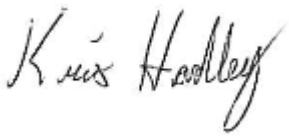
Sincerely,
Per. Hutchinson Environmental Sciences Ltd.



Kris Hadley, Ph. D.
Senior Aquatic Scientist

Signatures

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Executive Summary

Based on the recommendations provided by Hutchinson Environmental Sciences (HESL) to the District Municipality of Muskoka (DMM) in the final report for the Water Quality Indicators Project to inform ongoing Integrated Watershed Management in the Muskoka River Watershed, The DMM requested that HESL provide an in-depth guidance document to aid lake associations and other citizen led organizations in the development of monitoring programs.

This report includes:

- A brief summary of current and emerging threats to water quality (Section 1)
- Plain-language discussion of the importance of each water quality parameter (Section 2)
- Recommendations on the best practices and methods for monitoring lake health (Section 3)
- A layered approach to developing a monitoring program (Section 3)
    - Discussion of program resources needed for monitoring at each Phase
- A brief review of technology options for monitoring water quality and lake health (Section 4)
- Recommendations for data management and analysis (Section 5)
- Cost estimates for the collection and analysis of water quality data

The Lake Partner Program (LPP), coordinated by the Ministry of the Environment, Conservation and Parks (MECP) provides the best possible entry point to lake monitoring for lake associations with limited resources. Water quality sampling beyond the LPP will require lake associations to develop more in-depth monitoring objectives and associated water quality parameters. Lake associations interested in moving beyond data collection as part of the LPP are advised to seek lake specific guidance on the best allocation of resources from qualified experts, to ensure that specific equipment, training and analysis needs can be met, and resources are allocated efficiently.

Automated sensors and other advanced instrumentation can provide much higher data resolution through space and time than is achievable via manual sample collection. Consequently, high-frequency sensors can reveal processes and water quality issues that manual surveys may miss including the development of harmful algal blooms. We have summarized various options available for monitoring local weather, water temperature, water quality, shoreline characteristics, and tributary inputs; these range significantly in price. In addition to sensors, several rapid chemical test kits/systems which can also be useful for certain applications, have been included.

A water quality monitoring program requires the determination of timing and frequency of data collection, number and location of sites, as well as monitoring components that were reviewed in detail here-in: what parameters are to be measured, as well as the selection of technologies and data management to be employed. Potential monitoring programs range from relatively simple, such as involvement with the Lake Partner Program (LPP), to in-depth and complex programs that rely on the latest technological advancements. The determination of all monitoring components is dictated by lake characteristics, known water quality issues, resources available and specific goals of the monitoring program.

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Acronyms and Definitions

CWQG – Canadian Water Quality Guidelines
DO – Dissolved Oxygen
DOC – Dissolved Organic Carbon
ENM – Engineered Nanomaterials
HAB – Harmful Algae Bloom
MECP – Ministry of the Environment, Conservation and Parks
N – Nitrogen
P or TP – Phosphorus or Total Phosphorus
PWQO – Provincial Water Quality Objective
TDP – Total Dissolved Phosphorus
UV – Ultraviolet

- Abiotic - physical rather than biological; not derived from living organisms.
- Antimicrobial - A substance that kills microorganisms such as bacteria or mold
- Bioaccumulate - describes the buildup of (often harmful) substances in living organisms, such as animals and plants.
- Calcified carapace - a calcium based chitinous case or shield covering the back or part of the back of an animal.
- Chelating agent - A chemical compound that binds tightly to metal ions.
- Cyanobacteria - a division of microorganisms that are related to the bacteria but are capable of photosynthesis.
- Detritivores - an animal which feeds on dead organic material, especially plant detritus.
- Diel changes - refers to variation in organism abundance and density over a 24-hour period due to the influence of water movement, physical or chemical.
- Dreissenid mussels - zebra mussel (*Dreissena polymorpha*) is a small freshwater mussel.
- Dry deposition - the free fall to Earth directly from the atmosphere of atmospheric trace gases and particulate matter.
- Engineered nanomaterials - chemical substances or materials that are engineered with particle sizes between 1 to 100 nanometers.
- Epilimnion - Top layer of warm water in a stratified lake or other body of water
- Eutrophication - excessive richness of nutrients in a lake or other body of water.
- Fluorometer (Fluoroprobe) - A submersible spectrofluorometer for measurement of chlorophyll content in water
- Hypolimnetic anoxia - depletion of dissolved oxygen (anoxia) in the bottom waters (the hypolimnion) of a lake.
- Limnology - the study of the biological, chemical, and physical features of lakes and other bodies of fresh water
- Macrophytes - a plant, especially an aquatic plant, large enough to be seen by the naked eye.
- Microcystin - a class of toxins produced by certain freshwater cyanobacteria
- Nearshore - a band of varying width around the perimeter of each lake between the land and the deeper offshore waters of the lake.

- Oligotrophic – Low nutrient lakes, generally does not support large populations of aquatic plants, animals, or algae.
- Pathogens - a bacterium, virus, or other microorganism that can cause disease.
- Phytoplankton biomass - the amount of algal material present.
- Pseudomonas aeruginosa - a bacteria found widely in nature, in soil and water.
- Microplastics - extremely small pieces of plastic debris in the environment resulting from the disposal and breakdown of consumer products and industrial waste.
- Salmonid fish communities - is any of a family of elongate bony fishes (such as a salmon or trout)
- Sediment biogeochemistry - the mutual interactions (two-way) between the biology and chemistry of the lake sediment.
- Specific conductance - a measure of the ability to conduct electricity.
- Taxa - a group of one or more populations of an organism or organisms
- Toxicants - a toxic substance introduced into the environment, e.g. a pesticide.
- Water column - a vertical expanse of water stretching between the surface and the floor of a lake.
- YSI sonde - a multiparameter instrument that collects water quality data.

1. Introduction

Based on the recommendations provided by HESL to the DMM in the final report for the Water Quality Indicators Project to inform ongoing Integrated Watershed Management in the Muskoka River Watershed, the DMM requested that HESL provide an in-depth guidance document to aid lake associations and other citizen led organizations in the development of monitoring programs.

Lakes in the Muskoka River Watershed are under stress from a variety of emerging issues in water quality. The stressors on lakes in the region are minimal compared to urban lakes but impacts from traditional stressors such as waterfront development are being combined with impacts associated with emerging issues such as climate change to create a myriad of biotic and abiotic changes in lakes. Insightful water quality monitoring programs are required to characterize water quality conditions now more than ever to characterize lake health, determine changes over time, and inform management options such as stewardship, related planning policy or active in-lake or watershed management. Lake health monitoring programs share many commonalities; the specifics will depend on several factors:

- lake characteristics (size, productivity, shoreline development, catchment influences)
- known water quality issues (e.g., algal blooms, historical sources of contamination)
- resources available (funding, personnel, equipment)
- specific goals of the monitoring (what question(s) must be answered?)

These factors will dictate the timing and frequency of sample collection, number and location of sites, what parameters are measured (both chemical and biological), technologies that should be implemented and data management techniques. This report was completed to provide in-depth background information to aid in the development of citizen science-led monitoring programs. The report includes:

- A brief summary of current and emerging threats to water quality (Section 2)
- Plain-language discussion of the importance of each water quality parameter (Section 3)
- Recommendations on the best practices and methods for monitoring lake health, including a layered approach to developing a monitoring program (Section 4)
- A brief review of technology options for monitoring water quality and lake health (i.e., options for continuous monitoring) (Section 5)
- Recommendations for data management and analysis (Section 6)
- Summary and conclusions (Section 8)

2. Emerging Issues in Water Quality

A recent review on emerging threats to freshwater biodiversity identified twelve global ecological stressors deemed responsible for global freshwater biodiversity decline (Reid et al. 2019). While the researchers noted that this list is not exhaustive of all threats to freshwater biodiversity, they sought to highlight the most pressing concerns based on their expert opinion and the literature available at the time of writing. Threats identified included changing climate, harmful algal blooms, invasive species, emerging contaminants, microplastic pollution, light and noise, salinization, declining calcium, engineered nanomaterials and

cumulative impacts (Reid et al. 2019). We have briefly reviewed these threats in the paragraphs below as they pertain to the Muskoka River watershed to provide an understanding of current issues in water quality and the importance of monitoring. A more fulsome review of each water quality issue was included in the Water Quality Indicators Report (HESL, 2023).

Across the Northern Hemisphere, climate change has exerted discernible effects on lake ecosystems, inducing changes in their physical, chemical, and biological conditions. For example, increases in annual-mean air temperature in south-central Ontario have resulted in significant increases in the duration of the ice-free period since the mid-1970s (Futter 2003). Reid et al. (2019) noted that changing climate is expected to continue and is anticipated to exacerbate other emerging threats to water quality including invasive species (Rahel and Olden 2008), harmful algal blooms (Huisman et al. 2018), salinization (Henman and Poultier 2008), and eutrophication (Elliot 2012).

Climate, eutrophication, brownification (i.e., increased dissolved organics) and changes to hydrology have resulted in conditions conducive to the proliferation of nuisance and harmful algal blooms. In Central Ontario, this includes a marked recent increase in algal blooms in low nutrient lakes. The existing scientific body of literature suggests that the conventional understanding and management of algal blooms, that is based on controlling phosphorus concentrations in the water column, is not adequate to manage the development of oligotrophic blooms in nutrient-poor lakes (Reinl et al. 2021).

Invasive species are not a novel threat to freshwater biodiversity. Research on invasive mussels, aquatic plants, fish and invertebrates in the Muskoka River Watershed has been ongoing for decades (e.g., Hincks and Mackie 1997, Jacobs and MacIsaac 2009; Yan et al. 2011, MWC 2010; Edwards et al. 2013). The Muskoka Watershed Council (2010) summarized invasive species in Central Ontario, which includes 6 aquatic plants, 3 invertebrates, and 3 fish (Table 1). Over the past 30 years, aquatic invasive species (AIS) have become a prominent concern and focus in managing North America's freshwaters. The invasion of dreissenid mussels into the Great Lakes system in the 1980s had significant ecological, economic and management consequences that are still unresolved, and which raised awareness of the need for prevention and management programs. Increased surveillance of freshwater ecosystems since then has identified many new invasive species across the country, as well as range extensions of established invaders (e.g., rusty crayfish, *Orconectes rusticus*; spiny waterflea, *Bythotrephes longimanus*; European common reed, *Phragmites australis australis*; Eurasian watermilfoil, *Myriophyllum spicatum*). Rising international trade and travel, combined with climate change will continue to provide many opportunities for AIS to arrive alive, survive and thrive in Canadian freshwater ecosystems. Many past invasions have been associated with ballast water releases to the Great Lakes, leading to new regulations to control invasions. However, Reid et al. (2019) identified e-commerce as an emerging novel vector of concern for species invasions, noting that direct unregulated purchase of exotic species through the internet allows individuals the opportunity to import non-native plant and animal species. If released into the wild, these species often have the potential to become established and pose a substantial threat to native species.

Table 1. Inventory of Invasive Species Threatening the Muskoka River Watershed.

Aquatic Plants	Invertebrates	Fish
Eurasian water-milfoil (*Myriophyllum spicatum*)	Rusty crayfish (*Orconectes rusticus*)	Round goby (*Neogobius melanostomus*)

European frog-bit (*Hydrocharis morsus-ranae*)	Zebra mussel (*Dreissena polymorpha*)	Rainbow smelt (*Osmerus mordax*)
Yellow Iris (*Iris pseudacorus*)	Spiny water flea (*Bythotrephes longimanus*)	White perch (*Morone americana*)
Purple loosestrife (*Lythrum salicaria*)		
European common reed (*Phragmites australis subsp. australis*)		
Curly-leaved pondweed (*Potamogeton crispus*)		

A long-term consequence of acidification during the latter half of the 20th century by regional acid deposition from industrial smelting is that calcium concentrations in softwater lakes on the boreal shield have declined (Stoddard et al. 1999, Watmough et al. 2003). Numerous biological consequences have been linked to declining calcium in lakes. In Algonquin Park, regional calcium decline has had a significant negative effect on crayfish populations resulting in in the near extirpation of crayfish in four long-term study lakes (Hadley et al. 2014). Lower calcium availability also provides a competitive advantage to *Holopedium glacialis* (a planktonic water flea), which forms a jelly-capsule instead of a calcified carapace as its primary defence against predators (Jeziorski et al. 2015). *Holopedium* blooms are a nuisance for water intakes, are a less efficient food source for fish (lower phosphorus content), and are more difficult for invertebrate predators to catch, which may alter the food web within a lake and put additional stress on fish populations.

Emerging contaminants that are most relevant in the Muskoka River Watershed include active pharmaceutical ingredients, personal-care-product additives, pesticides, engineered nanomaterials and microplastics. Antibiotics, antimicrobials, antivirals, and antidepressants have been demonstrated to be broadly detectable in wastewater-impacted rivers (Hughes et al. 2013), however ongoing research is required to determine the impact of these compounds on the aquatic receiving environment.

Antimicrobial compounds have been demonstrated to affect natural microbial communities (Barra Caracciolo et al. 2015), as well as algal diversity and periphyton, and some primary consumers (Nietch et al. 2013). Likewise, anti-inflammatories and antidepressants have be shown to negatively impact species abundance and the composition algal communities (Bacsi et al., 2016; Richmond et al., 2016; Reid et al. 2019).

Microplastics became a topic of discussion in the early 2000s, when Thompson et al. (2004) demonstrated that microplastic particles were common pollutants in marine environments (beaches and estuarine sediments) and suggested that recovered microplastics were a result of the degradation of larger plastic debris. Due to their small size, microplastics can easily be ingested by biota. Microplastic ingestion can cause abrasion and blockage of the gastrointestinal tract and internal bleeding in aquatic organisms (Wright et al., 2013). It has been demonstrated in laboratory studies that microplastics can adsorb environmental contaminants on their surfaces and act as vectors for these contaminants (Rochman et al., 2013; Bakir et al., 2014; Velzeboer et al., 2014).

Engineered nanomaterials (ENMs) are synthetic materials, ranging in size from 1-100 nm, that are used in a myriad of applications. A marked increase in the number of ENM products listed in various global inventories has been recently noted, showing an increase from 54 in 2005 to above 5000 in 2020 (Moli et al. 2021). The market for ENMs is currently dominated by health and fitness products, including active wear, sunscreens, cleaning supplies, cosmetics, and sporting goods (Moloi et al. 2021). ENMs in these products are typically surface-bound or suspended in liquid and therefore have a medium to high potential for release into water (Moeta et al. 2019).

Major sources of impacts to lakes in the Muskoka River Watershed are faulty septic systems, road salt, and climate change. The risks associated with contaminants are lower than in more heavily developed urban areas and therefore sampling by independent citizen-science monitoring programs is not necessary. The District is currently working to develop a watershed-wide monitoring strategy for novel contaminants. Emerging issues such as calcium decline, and chloride from road salt are more easily incorporated into citizen-science programs and may be beneficial in informing our understanding of the extent and severity of these stressors.

3. Water Quality Parameters

General terms such as “lake health” or “water quality” are often used to summarize the numerous and sometimes complex physical, chemical, and biological characteristics of a lake’s water. From a recreational and aesthetic perspective, good water quality is usually associated with high clarity, low nutrient concentrations, the absence of toxins/toxicants and/or pathogens, and low phytoplankton biomass. The comprehensiveness of a water quality assessment depends on the number of lake characteristics (parameters) measured. The parameter suite used for a lake monitoring program may range from a couple of parameters (e.g., total phosphorus and Secchi depth) to potentially hundreds. The importance of a given parameter will depend to a certain extent on lake-specific issues (Section 4), and thus not all parameters can be assigned a simple, fixed rank in terms of priority. The paragraphs below summarize monitoring parameters in relation to lake management issues that are relevant in the Muskoka River Watershed, starting with water quality parameters that are typically included in monitoring programs to an expanded list of water quality parameters as well as phytoplankton and emerging contaminants.

3.1 Phosphorus

Phosphorus (P) is a natural element in the environment. It enters lakes predominantly from catchment inputs (streams and overland flow), as well as from the atmosphere (precipitation and dry deposition) and, to a lesser degree, through groundwater. Human sources to recreational lakes include storm-water runoff and erosion associated with altered land uses, fertilizers on manicured lawns, and faulty septic systems. Increases in P loads to lakes from human sources can result in increased growth of aquatic plants, algae, and cyanobacteria, which, in turn, can lead to a deterioration of water clarity and cold-water fish habitat through a decrease in deep-water oxygen concentrations. Phosphorus often limits phytoplankton growth in temperate lakes and is therefore the most commonly analyzed water quality indicator in Central Ontario. High levels of P can lead to phytoplankton blooms, and in some cases affect the habitat of cold-water fish such as lake trout. By sampling for P each year, it is possible to detect a change in the nutrient status of a

lake. It is important to note that several years of data (ideally 10 years or more) should be collected to distinguish a trend from normal, year-to-year variation in P concentration.

3.2 Water Clarity (Secchi Depth)

Water clarity (transparency) is a fundamental aspect of water quality. From a human perspective, high clarity is generally associated with high aesthetic appeal. From a limnological perspective, clarity reflects biological and chemical properties of lakes (phytoplankton biomass, dissolved organic carbon concentration) and controls light availability for photosynthesis (primary production) among other photochemical processes (e.g., DNA damage from UV radiation).

Water clarity is most often quantified as the Secchi Depth. Secchi Depth is determined by lowering a 20-cm black-and-white, weighted disc (Secchi disc) through the water column (on the shaded side of the boat) until it disappears, noting the depth, then raising the disc until it reappears – the Secchi Depth is the average of the two depths. The measurements are most accurate when made around midday, by an observer who is not wearing sunglasses. Secchi Depth ranges from only centimeters in highly turbid lakes to up to 40 m in a few very clear lakes; most Ontario lakes have a Secchi Depth in the 2-10 m range (LPP, unpublished data). Reasons for the common use of Secchi Depth as a measure of water clarity include its affordability and simplicity; more precise determinations of light transmission through the water column can be obtained by making direct measurements of the amount of light at multiple depths in the water column using a photometer/radiometer (e.g., LI-192 underwater quantum sensor by LI-COR, Inc.).

3.3 Bacteria

E. coli is a species of fecal coliform bacteria that comes from warm-blooded animals (including humans). Some strains are pathogenic and *E. coli* concentrations are a useful indicator of total potential pathogens in the water. They are the primary organism used by Health Canada in determining the safety of recreational waters for swimming and bathing.

Bacteria (*E. coli* and total coliform) levels are typically compared to the Provincial Water Quality Objectives (PWQOs) for recreational water use (MOEE, 1994). The PWQO for *E. coli* is 100 colony forming units (CFU) per 100 mL, based on a geometric mean of at least 5 samples taken from a site within one month. While sampling at this frequency is often not feasible for citizen science monitoring programs, comparison of a single sample to the guideline provides some indication of potential bacteria hotspots and can inform the planning of more rigorous sampling, if necessary. The nearshore is more likely to be impacted by contaminated runoff and therefore bacteria samples are typically collected in the nearshore environment rather than in a single central spot of a study lake. Site selection for bacteria sampling is lake specific but would generally focus on areas of high-development and recreational use.

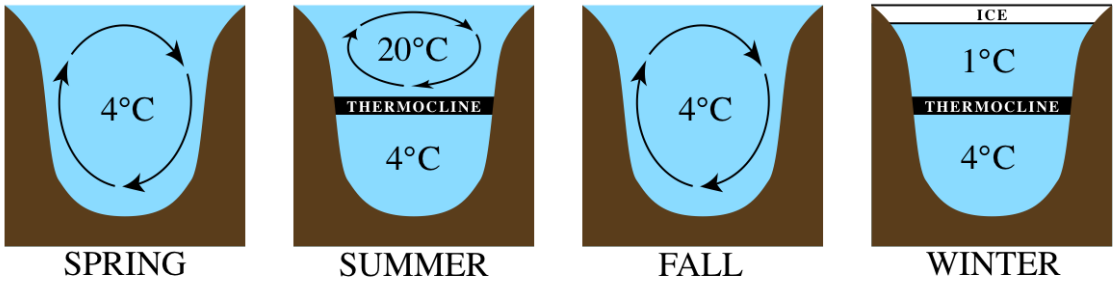
Monitoring of other varieties of bacteria in recreational waters is possible if there is reason to suspect contamination. *Streptococcus* and *Enterococcus*, which are commonly referred to as *Fecal streptococci*, are an index of fecal pollution used for recreational waters. *Pseudomonas aeruginosa* common in the environment and is often found in natural waters such as lakes and rivers. *Pseudomonas* levels in excess

of 100 organisms/100 mL can be measured in waters receiving surface drainage from urban areas but are unlikely to be a substantial threat in low population, central Ontario lakes.

3.4 Water Temperature and Climate Change

Temperature affects the density of water, its gas solubility (e.g., how much oxygen it can hold), the speed of chemical and biological reactions (e.g., bacterial metabolism), and habitat quality for aquatic life such as fish. Vertical temperature profiles reveal if a lake is thermally stratified (i.e., has layers that do not mix vertically), and if so, what depths the layers span (Figure 1).

Figure 1. Simplified representation of dimictic (twice per year) lake mixing.



Climate change has resulted in increased average air temperature, is impacting lake systems in Central Ontario and is expected to continue to exert an influence on lakes globally over the next few decades (e.g., Sharma et al. 2015). Increases in air temperatures over the past several decades in the Muskoka-Haliburton region have led to shortened ice-cover periods (e.g., Futter 2003, Yao et al. 2013), increased water temperatures (e.g., Dobiesz and Lester 2009), advanced onset of thermal stratification (e.g., Stainsby et al. 2011) and increased thermal stability in lakes (e.g., Stainsby et al. 2011, Hadley et al. 2014). Changes in thermal stratification and water column stability can have a major impact on physical and chemical properties in lakes, such as the redistribution of dissolved substances (e.g., nutrients and oxygen). These, in turn, may result in changes to biological communities, including the proliferation of nuisance cyanobacteria that release harmful toxins (Ferris and Lehman 2007, Paerl and Huisman 2008, O'Neal et al. 2012). The ability of certain cyanobacteria to store P, fix nitrogen and regulate their position in the water column could be particularly advantageous for these phytoplankton, as climate change brings stronger thermal stratification, sequestering nutrients outside the epilimnion.

The monitoring programs that measure water temperature typically collect profiles in the late-summer (typically mid to late August) or, in programs that lack a YSI sonde to measure profiles, collect surface water temperature during sampling. Surface measurements of water temperature alone provide little information on the impact of climate on the physical properties of study lakes, including the strength of stratification and risk of hypolimnetic anoxia. Water temperature impacts in lakes tend to be interactive with other stressors rather than directly lethal to most aquatic organisms. Timing of profile sampling for citizen-science programs is often determined by the end of the recreational water use season ending in late August. However, August sampling of temperature profiles often fails to capture peak water temperature and stratification as

consistent increases in the length of the ice-free season over the past several decades in Central Ontario lakes has pushed the timing of thermal maxima later in the year. If the goal of temperature and dissolved oxygen profile sampling is to determine if bottom water oxygen depletion is an issue in the study lake, sampling should take place just prior to mixing of the water column. Alternatively, high frequency automated monitoring of water temperature (i.e., continuous data loggers, daisy-chained at 1-m depth intervals; specific logger needs may vary depending on individual lake characteristics) would provide robust temperature profile data but at a significantly increased cost (as discussed in more detail in Section 5).

3.5 Dissolved Oxygen

Dissolved oxygen (DO) has many important effects on lake ecosystems. As noted above, DO solubility in lakes is primarily determined by water temperature, cold water can hold more DO than warm water. DO concentration controls habitat quality for aerobic organisms such as fish. The Provincial Water Quality Objective for DO is dependent upon temperature, ranging from 5 mg/L at 25°C to 8 mg/L at 0°C for cold-water biota such as salmonid fish communities (e.g., lake trout) and 4–7 mg/L (for 25-0°C) for warm-water biota (e.g., bass). DO is generated by photosynthesis during the day (by plants, algae, and cyanobacteria) and consumed by cellular respiration (by all organisms) during the day and night. For this reason, DO tends to vary on a 24-hour (“diel”) timescale, and the magnitude of these diel changes can provide information on lake metabolism (rates of ecosystem primary production and respiration). DO also has important indirect effects on the cycling and bioavailability of nutrients, notably phosphorus. Under oxygenated conditions, phosphate forms an insoluble precipitate with iron and sinks out of the water column to the sediments where it is not readily available to support phytoplankton growth, including cyanobacterial blooms. However, in a lake with an anoxic (oxygen-depleted) hypolimnion (bottom layer), P separates from iron and becomes soluble (dissolved) in the water where it is available for uptake by plankton. DO also mediates other aspects of sediment biogeochemistry and nitrogen cycling (e.g., nitrification and denitrification).

Monitoring programs that measure dissolved oxygen typically collect profiles in the late summer (mid to late August) to determine if low oxygen concentrations in bottom waters may result in the release of nutrients that feed phytoplankton growth and may result in cyanobacteria blooms or to characterize deep-water lake trout habitat under the most stressful period for reduced DO. Ideally, sampling should take place just prior to mixing of the water column to capture the lowest bottom water DO concentrations of the year as release of phosphorus during low oxygen conditions occurs quickly and may be missed. High frequency automated monitoring of DO (i.e., a continuous data logger) would provide the most robust DO data but at a significantly increased cost (Section 5).

3.6 Calcium and Chloride

Calcium (Ca) decline in Central Ontario lakes is a long-term consequence of acidification (Watmough et al. 2003). Acid rain caused by smelting of nickel and other metal ores stripped calcium from thin soils, which are underlain by weather-resistant granite rock. As a result, the amount of calcium moving from the watershed to freshwater lakes has decreased as have calcium concentrations in the lake water (Watmough et al. 2005). A variety of site-specific mechanisms can also contribute to declining concentrations of Ca including local geology and timber harvesting (Stoddard et al. 1999; Kirchner and Lydersen 1995; Watmough and Aherne 2008).

Numerous biological consequences have been linked to declining Ca in lakes. For example, crayfish, like other crustaceans, depend on lake-water Ca, particularly during their molting period (Rukke 2002). The range of lowest hypothesized requirements for freshwater crayfish is between 2 and 10 mg/L (Greenaway 1974, France 1987, Rukke 2002, Hammond et al. 2006, Cairns and Yan 2009). In Algonquin Park, regional Ca decline has had a significant negative effect on crayfish populations resulting in the near extirpation of crayfish in 4 long-term study lakes (Hadley et al. 2015). Crayfish are an integral component of energy flow in aquatic food webs because they can act as detritivores, herbivores, or keystone benthic predators (Momot 1995) and they are a key element of some fish diets (Saiki and Ziebell 1976, Stein 1977).

Ca decline has also resulted in a shift in microscopic herbivore communities in soft-water lakes across eastern North America. Lower Ca availability provides a competitive advantage to the zooplankton *Holopedium glacialis* (Jeziorski et al. 2015). *Holopedium* has a low Ca requirement because it has a jelly-capsule instead of a calcified carapace as its primary defence against predators (e.g., fish).

Salinization of freshwaters in Ontario has been an ongoing area of research and remains one of the most pressing environmental issues for recreational lakes near roadways. Analysis of spatial patterns in long-term chloride data from the Lake Partner Program and broad-scale monitoring data collected by the Ministry of the Environment, Conservation and Parks (MECP) has shown that proximity to urban centres and major roadways was a substantial factor in determining chloride concentrations of freshwaters; this suggests that winter road maintenance and urban land use are the primary drivers of chloride concentrations in Central Ontario lakes (Sorichetti et al. 2022). Elevated concentrations of chloride are toxic to freshwater biota, with the current guideline for the protection of aquatic life being set at 120 mg/L. However, recent research has shown that the Canadian Water Quality Guideline (CWQG) is not sufficient to protect lake food webs and should be reassessed (Hintz et al. 2022). Development in the Muskoka River Watershed and a shift from temporary summer use to year-round use of properties has the potential to increase the need for road treatment. Monitoring of chloride concentrations should therefore be considered a high priority for water quality monitoring programs near roadways which receive winter de-icing treatment.

Monitoring for calcium and chloride in the Muskoka River watershed is collected through the District's Recreational Water Quality Monitoring Program but can be provided to small scale monitoring programs through the Lake Partner Program alongside phosphorus with little expense and coordination required and is therefore an accessible component of all water quality monitoring programs.

3.7 Expanded Baseline Water Chemistry

Several standard limnological monitoring parameters are discussed in the following paragraphs which should be considered that are in addition to the core parameters described in Sections 3.1 to 3.6.

3.7.1 Nitrogen

Nitrogen (N) is important to quantify in the context of understanding lake trophic status and, to a lesser extent, aquatic toxicology. While phosphorus (P) often limits primary production in lakes, N can also be limiting, especially where/when P concentrations are already high. Indeed, the predominance of cyanobacteria in eutrophic lakes is likely due at least in part to the ability of certain cyanobacteria to "fix" nitrogen (i.e., to convert atmospheric N_2 to (bioavailable) NH_4^+) when high P availability makes N the

limiting nutrient. N-to-P ratios (e.g., TN:TP) can be examined to understand the nature of nutrient limitation in a particular lake and whether seasonal N limitation may be driving an increase in the biomass of N-fixing cyanobacteria, several of which can produce toxins (e.g., *Dolichospermum, Aphanizomenon)*. In addition to its role as an essential macronutrient for phytoplankton growth, several N species can be toxic to aquatic life: nitrate (NO_{3}-) has a Canadian Water Quality Guideline (CWQG) concentration of 3 mg-N/L, nitrite (NO_2^-) has a CWQG of 60 µg-N/L, and ammonia (NH_3) has a PWQO of 20 µg/L (16.4 µg/L as N).

3.7.2 Dissolved P

The importance of phosphorus as a macronutrient that controls lake productivity has previously been noted (Section 3.1). While total phosphorus is representative of lake trophic status and is the most important P parameter to monitor, dissolved P parameters provide additional information related to bioavailability and P cycling, and thus also deserve consideration. Total dissolved P (TDP) and dissolved reactive P (DRP) are the two dissolved P parameters typically quantified. The synonymous term "soluble" is often used in place of "dissolved", in which case these same parameters are known as TSP and SRP (either nomenclature is correct). TDP represents all the P contained in substances small enough to pass through a filter (~0.5 µm)[1]. Except in highly polluted waters or anoxic hypolimnia (i.e., the bottom thermal layer of a lake), most of this P is associated with dissolved organic molecules. In contrast, DRP is assumed to represent only orthophosphate (PO_4^{3-}), the form of P that is most easily taken up by organisms such as algae and bacteria (i.e., is most bioavailable). In practice, the DRP concentration usually overestimates the actual PO_4^{3-} concentration because other P-containing molecules react in the laboratory assay (Kalff 2002). Furthermore, it should be noted that ambient PO_4^{3-} concentrations would be expected to be negligible (zero or close to zero) in upper mixed layers of strongly P-limited lakes because this highly bioavailable fraction should be rapidly assimilated by the plankton. For these reasons, the interpretation of DRP (=SRP) data is not straightforward. However, DRP data can be valuable when monitoring lakes with high phosphate inputs (e.g., minimally treated wastewater) or anoxic hypolimnia, or where P concentrations are high enough to cause N limitation of primary production. TDP can be viewed as intermediate between TP and DRP in terms of both bioavailability and complexity of interpretation. The quantification of TDP allows the concentration of particulate P (PP) to be calculated by difference from TP (PP = TP – TDP).

3.7.3 Conductivity

The electrical conductivity (EC) of water is of interest because it is correlated with the total concentration of dissolved ions. EC can be measured easily with a sensor and thus provides a rapid assessment of water hardness (i.e., total ion (e.g., calcium, magnesium, sodium, potassium, chloride, nitrate, etc.) content). Moreover, where a single ion (e.g., chloride) dominates the ion pool, EC can be used as a tracer for this ion and multiple sensor readings can be taken through time or across space to characterize its source and controls (e.g., is chloride coming from surface inputs or seeping in with the groundwater?). EC depends on the temperature of the water, and thus the estimated value at 25°C is often reported, in which case it is known as "specific conductance".

[1] *The term "dissolved" is an operational term in limnology; it refers to substances that pass through a filter. Filter pore size typically ranges from 0.2 µm to 1.2 µm, with 0.45 µm or 0.8 µm being common choices. Because there are few substances/cells in the 0.2-1.2 µm size range this lack of standardization is not considered to be of great importance.*

3.7.4 Dissolved organic carbon

Most of the organic carbon in lakes is present as dissolved organic carbon (DOC). DOC refers to the pool of hydrocarbon compounds (of varying sizes) in water that are dissolved (i.e., that will pass through a filter with pores approximately 0.5-µm in diameter). Especially in small, wetland-influenced lakes, DOC can be highly coloured and impart a "tea-stained" character to the water due to its high absorbance of short-wavelength (UV and blue) light. Thus, DOC has an influence on the aesthetic quality of water (altering its colour and clarity) and can also limit the growth of phytoplankton and/or macrophytes by controlling the quantity and quality of light available for photosynthesis. Because it originates from the breakdown of organic matter (e.g., leaf litter, aquatic plants, etc.), DOC is typically associated with macronutrients such as N and P. DOC acts as a chelating agent for iron, affecting both iron and phosphorus bioavailability in surface waters (Maranger and Pullin, 2003). Likewise, DOC binds toxic metals, and has, for example, been found to control the concentration and bioavailability of total and methylmercury in Adirondack lakes (Driscoll et al. 1994). While DOC can limit primary production (Karlsson et al., 2009), it can also protect aquatic organisms from exposure to harmful UV radiation (Hansson and Hylander, 2009; Harrison and Smith, 2011) and directly supports the growth and metabolism of heterotrophic (non-photosynthetic) bacteria (Kalff, 2002).

3.7.5 Alkalinity

Alkalinity is the acid-neutralizing capacity of water due to the presence of weak-acid anions. High-alkalinity waters have a high "buffering capacity" and thus are less sensitive to (i.e., pH will change less in response to) the addition of acids (or bases) relative to less-alkaline waters. Catchment geology has a large influence on alkalinity. Where limestone is abundant, lakes tend to have high concentrations of bicarbonate and thus high alkalinity; conversely, lakes of the Canadian Shield such as those in the Muskoka River Watershed (largely underlain by bedrock) tend to have much lower alkalinity and are thus much more sensitive to acidification (a decrease in pH).

3.7.6 pH

The pH ("*puissance d'hydrogène*" or "strength of hydrogen") of water ranges from <1 to 14 on a logarithmic (nonlinear) scale; thus, the hydrogen ion concentration of water is 100-times higher at a pH of 2 than at a pH of 4. Most lakes have a pH in the range of 6.0 to 8.5 (a pH of 7 is neutral). The diversity (species richness) of aquatic ecosystems tends to decline at extreme pH levels (<6 or >8.5); the PWQO for pH is 6.5-8.5 to protect aquatic life and to avoid skin irritation for swimmers. pH has many indirect effects in lakes. For instance, it affects toxic metal (e.g., aluminum) solubility and the speciation of N (i.e., fraction of NH_3+NH_4^+ that is present as the more toxic NH_3).

3.7.7 Turbidity

High water quality is generally associated with low turbidity. Turbidity is the scattering (and absorbance) of light by suspended matter in water (e.g., clay, silt, carbonate particles, fine organic particulate matter, small organisms such as phytoplankton, etc.). There is generally a positive correlation between turbidity and the mass of suspended particles in natural waters (i.e., total suspended solids), though the strength of this

correlation can vary considerably. As with conductivity and pH (see above), turbidity is easily measured in the field, often by one of several probes of a multi-parameter sonde (e.g., YSI EXO2).

3.7.8 Metals

Metals play a number of different roles in aquatic ecosystems. Many metals can be toxic to aquatic life; PWQOs exist for aluminum, antimony, arsenic, beryllium, boron, cadmium, chromium, cobalt, copper, iron, lead, mercury, molybdenum, nickel, selenium, silver, thallium, tungsten, uranium, vanadium, zinc, and zirconium. Mercury, a potent neurotoxin, is known to bioaccumulate in aquatic foodwebs and thus is a potential human health concern for those who eat fish.

A number of metals (e.g., iron, manganese, zinc, copper, nickel, boron, molybdenum, selenium, cobalt) are essential micronutrients for primary producers such as plants and algae. Because concentrations in ionic form are usually low, iron can occasionally limit phytoplankton growth (Kalff 2002) and it has been suggested that the availability of ferrous iron (Fe^{2+}) may be a key factor in allowing cyanobacteria to dominate the phytoplankton community (Molot et al. 2014). Iron is of particular importance because it plays indirect roles in the cycling of nutrients and organic matter in lakes. Iron tends to form complexes with various organic compounds and thus is usually elevated where DOC concentrations are high (Wetzel 2001). Iron also has major effects on P availability, as previously noted, because it binds with phosphate in the presence of oxygen, which has the ultimate effect of storing much of the lake's P in the sediments where it is unavailable to the plankton under oxygenated conditions. Under "reducing" (very low oxygen or anoxic) conditions, these precipitates dissolve and (soluble) phosphate is released to the overlying water where it is available to algae and cyanobacteria. Sulfur is indirectly involved because it binds with iron (to form FeS) making that iron unavailable to bind P. The cycling of manganese in lakes is similar in many ways to that of iron. Sediment biogeochemistry is a relatively complex topic, and we will limit our consideration of it to the above text; a more detailed overview can be found in Wetzel (2001).

3.8 Phytoplankton (including harmful cyanobacteria)

The term phytoplankton refers to a diverse group of photosynthetic organisms (algae and cyanobacteria/blue-green algae) that are suspended in the water column (i.e., are planktonic). They can exist as single cells or as substantial groups (colonies or filaments), and thus range in size from less than 1 micron to large (macroscopic) aggregations of up to several millimeters in diameter. Phytoplankton are important primary producers: they use the energy of sunlight to convert carbon dioxide into organic matter, ultimately feeding higher trophic levels (e.g., phytoplankton→zooplankton→fish→humans). Phytoplankton have existed for billions of years and are a healthy and integral component of aquatic ecosystems. However, at high biomass certain species of phytoplankton can negatively affect lakes, both as ecosystems and as resources for human use.

Harmful algal blooms (HABs)[2] are often accompanied by unpleasant odours and the production of toxins. HABs degrade the quality of water for drinking and reduce the aesthetic and recreational appeal of lakes. From an ecological perspective, HAB taxa are not generally preferred by grazers (e.g., zooplankton), and the mineralization of HAB biomass in lake sediments consumes oxygen, decreasing the quality of cold-

[2] *The term "harmful algal bloom" is something of a misnomer in the context of limnology because most phytoplankton blooms in lakes are made up of cyanobacteria (prokaryotes) not algae (eukaryotes).*

water fish habitat and potentially causing hypolimnetic anoxia and internal phosphorus loading. HAB taxa commonly found in temperate lakes include the cyanobacteria *Dolichospermum*, *Microcystis*, *Gloeotrichia*, *Oscillatoria/Planktothrix,* and *Aphanizomenon*, among others. In general, filamentous and colonial cyanobacteria are more likely to dominate the phytoplankton of nutrient-enriched (eutrophic) lakes, though they can be observed in oligotrophic systems as well and this may become more common due to climate change (HESL 2020; Reinl et al. 2021). It is not fully understood why cyanobacteria tend to outcompete eukaryotic phytoplankton (algae) in eutrophic lakes. As previously noted, one plausible explanation is that at high P concentrations N may limit phytoplankton growth, which gives a competitive advantage to the "N-fixing" cyanobacteria (i.e., taxa with specialized cells (heterocysts/heterocytes) that allow them to incorporate N from N_2 gas into their biomass). Another potential explanation is that many cyanobacteria have both buoyancy control (i.e., can form gas vacuoles) and have an initial benthic life stage (i.e., grow at the sediment-water interface) which gives them better access to nutrients than phytoplankton that are limited to the upper mixed layer.

Much of the concern regarding cyanobacterial blooms is due to the ability of some taxa to produce toxins. It should be noted that cyanobacterial blooms are not always associated with detectable levels of toxins, and that the factors controlling toxin production are not fully understood. Cyanotoxins can affect the liver (e.g., microcystins), nervous system (e.g., anatoxins), and skin (e.g., lyngbyatoxins). It is not feasible to assess all types of cyanotoxins – there are over 250 different variants within the microcystin family alone (Fastner and Humpage 2021) so a small subset of parameters is typically measured, including microcystin-LR and total microcystins (the aggregate concentrations of all microcystin variants). Health Canada has established a total microcystins guideline value of 10 µg/L for "primary contact recreation" and estimates that waters may exceed this threshold where the chlorophyll-a concentration exceeds 33 µg/L (Health Canada, 2022). A stricter guideline value of 1.5 µg/L has been established for drinking water (Health Canada, 2021).

3.9 Emerging Contaminants

Synthetic contaminants are another potential source of concern in lakes. There are a large number of parameters in this class that can be measured by a commercial environmental laboratory. Quantifying a suite of chemicals in a certain class can be expensive (e.g., $700 for just Dioxins and Furans at ALS Labs; Appendix A). In most Central Ontario lakes, the concentrations of most of these chemicals will usually be reported as "below detection", meaning that the concentration is too low to be measured by the laboratory with confidence (i.e., is close to zero). Thus, contaminants are not generally included in lake water quality monitoring programs unless there is a reason to believe that concentrations could be of concern (e.g., known industrial activity, significant wastewater seepage, etc.). If baseline contaminant concentrations are not known with sufficient confidence but routine monitoring for contaminants is deemed too costly, a compromise would be to sample for a broad suite of contaminants once initially (upon commencement of the monitoring program) and use the results to direct future sampling; parameters that were consistently below the method detection limit in the first year of monitoring could be either omitted (if the source is generally in decline, e.g., heavy metals or PCBs) or sampled at a reduced frequency of once every 2-5 years (if the source may be on the increase, e.g., pharmaceuticals & personal care products).

4. Monitoring Guidance

Lake monitoring is essential to understanding the health of aquatic ecosystems and how water quality changes over time. Lake health monitoring programs share many commonalities; the specifics will depend on several factors such as lake characteristics, water quality issues, resources available, and specific goals of the monitoring program.

4.1 Sampling Frequency

To detect long-term changes in water quality, lake monitoring is typically conducted annually. Within each year, the timing and frequency of sample collection will depend on available resources, the type of lake, and questions of interest. A biweekly or monthly sampling frequency during the open-water period (between ice off and ice on) is ideal to assess seasonal water quality changes in relatively low-productivity temperate lakes such as those in the Muskoka River Watershed, however such high frequency sampling may not be possible as part of a volunteer citizen-science based program.

4.2 Number of Sampling Locations

The adequate number and location(s) of sampling sites will depend on lake area, depth, and shape. For instance, a small, round lake may require only a single, central sampling site, whereas a large, deep lake with multiple bays (e.g., Kawagama Lake or Lake of Bays) will benefit from multiple sites because water quality may vary in isolated bays depending on incoming streams and rivers, and the level of development or other water quality stressors.

4.3 Selection of Parameters

Most lake monitoring programs assess a core set of parameters designed to address current and emerging issues in water quality such as water clarity, nutrient concentrations, and changes in temperature and oxygen with depth in the water column. Other common parameters include major ions (e.g., calcium, chloride), alkalinity, pH, conductivity, and chlorophyll concentrations and a measure of suspended particles (i.e., turbidity or total suspended solids). When of interest, the biological community is often assessed using net tows to sample plankton, sediment grabs or kick-and-sweep techniques to sample benthic invertebrates, and “rake on a rope” tosses to gather macrophytes.

More intensive monitoring may involve taking water column profiles with a multi-parameter sonde (e.g., YSI EXO2), light (“PAR”) profiles, and discrete depth sampling below the mixed layer (e.g., sampling of the hypolimnion) to assess vertical differences in water quality and the influence of the sediments (e.g., internal phosphorus loading). Lakes with a history of cyanobacteria (“blue-green algae”) blooms are often monitored for cyanotoxins such as microcystins and depending on the nutrient status of the lake, and species of algae, monitoring of meteorological data near the lake may also be desirable in an effort to understand and manage cyanobacterial blooms.

Small, shallow lakes frequented by animals (geese, livestock, etc.) or influenced by sewage may require monitoring for heterotrophic bacteria (e.g., *E. coli*). Many lake association monitoring programs in central Ontario include bacteria sampling as a measure of safety for recreational uses like swimming. Bacteria

sampling testing kits employing the “coliplate technique” can be purchased for under $20 (http://bluewaterbiosciences.com/) and used to collect bacteria data in the field with minimal training. Bacteria sampling by this method is generally not intended to follow Health Canada guidance for comparison to water quality guidelines, which requires 5 samples in a month, but rather to act as an early warning indicator of potential areas of concern in nearshore, high use areas.

Toxic heavy metals, pesticides, PCBs, PAHs, dioxins, furans, pharmaceuticals, and other contaminants are typically of low concentration in relatively unpolluted central Ontario lakes such as those located in the Muskoka River Watershed but should be quantified where concern exists (e.g., knowledge of historical or current industrial or wastewater pollution). Pharmaceuticals may be measured at environmentally relevant concentrations in proximity to areas of higher population density and/or intensive agriculture. Occasional targeted sampling of key contaminants (i.e., every 2 or 3 years) in high-risk areas near wastewater treatment plant (WWTP) outfalls, and the highest population densities in the watershed, would allow some assessment of potential impacts. These contaminants are often found below laboratory method detection limits and Federal and Ontario wastewater regulations have no specific requirements pertaining to managing pharmaceutical pollutants; however, changes in the frequency of detections may provide a basis for addressing any changes over time. Key steps to developing a monitoring strategy for contaminants should include:

- Develop a list of priority Active Pharmaceutical ingredients (APIs) requiring further investigation
- Identify high risk areas
- Implement a pilot monitoring program for priority APIs in waters identified as high risk
- Target worst case scenarios during periods of low natural flow and high wastewater discharge

In dynamic lakes where short-term changes are of interest, high-frequency sensor data can be obtained by mooring single sensors, sensor chains, or complete automated vertical profiling systems (e.g., YSI Pontoon Vertical Profiler). Many parameters can be measured at high frequency by sensors including water temperature, dissolved oxygen, conductivity, turbidity, pH, chlorophyll-a, phycocyanin, dissolved organic matter, chloride, and nitrate, among others.

4.4 Basic Monitoring - Lake Partner Program

The Lake Partner Program (LPP), coordinated by the Ministry of the Environment, Conservation and Parks (MECP) provides the best possible entry point to lake monitoring for lake associations with limited resources. The stated goal of the LPP is to protect and understand the water quality of Ontario’s inland lakes. This is accomplished by involving citizens in a volunteer-based monitoring program.

Water quality monitoring and assessment in cooperation with the LPP addresses several of the highest priority water quality issues in the Muskoka River Watershed area (i.e., phosphorus, calcium, and chloride), eliminates several logistical challenges (i.e., acquiring sampling equipment and laboratory analysis) and provides support on sampling methods and strategy (i.e., where, when, and how to sample). In addition, the LPP maintains a central database of all data collected and has recently begun storing those data on DataStream (See Section 6), an online platform for sharing information about freshwater health.

The MECP provides sampling instructions and the equipment needed to participate in the LPP (https://www.ontario.ca/page/lake-partner-program-sampling-instructions). This includes a basic sampling bottle, plastic funnel with Nitex mesh (to screen out large particles), Secchi disk, pre-paid Canada Post labels for sample return, prepaid envelope for Secchi data return, sample containers and instructions. It is the responsibility of the partner to access the sampling site – so a boat is needed to sample offshore lake sites. If new to the program, it is recommended to first check the locations of existing sites on the lake of interest[3] and, if possible, to reactivate a historical site rather than create a new site; this not only minimizes confusion at the LPP database level, but also produces a larger site-specific dataset, increasing the likelihood that there will be sufficient data to perform analyses of change over time (i.e., to determine whether present conditions differ from prior conditions). Water samples are collected once annually, at least 2 weeks following ice off (i.e., in April or May), and water clarity measurements with a Secchi disk are performed 1-2 times per month during the ice-free period.

Lake associations interested in participating in the Lake Partner Program should contact the Program Coordinator at lakepartner@ontario.ca for new registrations or questions.

4.5 Expanded Independent Monitoring

Lake associations interested in moving beyond data collection as part of the Lake Partner Program are advised to seek lake specific guidance on the best allocation of resources from qualified experts, to ensure that specific equipment, training and analysis needs can be met, and resources are allocated efficiently.

4.5.1 Additional Equipment and Data Recording

For lake associations that are participating in the Lake Partner Program (Section 4.4) most basic equipment required for collecting samples should already be provided by the MECP (Secchi disc with rope marked in 1-m increments) or owned by the LPP participant (e.g., a means to access the sampling site and appropriate safety equipment). It is recommended for health and safety considerations that a minimum of 2 field personnel be present at all times when sampling, regardless of lake conditions.

Water quality sampling beyond the LPP will require lake associations to decide on a list of parameters prior to sampling as well as contacting an accredited laboratory (e.g., ALS Environmental, Caduceon Environmental Laboratories) to acquire the appropriate sampling bottles for the parameters of interest. In some cases, bottles may contain a small amount of liquid preservative provided by the lab and should not be filled directly from the lake or river. Laboratories will provide coolers to contain and ship the bottles once sampling is complete, most parameters have maximum hold time (i.e., the time between sampling and analysis), it is therefore always good practice to ensure samples are shipped to the lab as soon after sampling as possible and are kept stored in a cold and dark place.

A hand-held GPS unit may be of value for finding and returning to sampling sites each year. The location of sampling should be recorded during each sampling visit to ensure consistency in the data. For sampling programs that have sufficient resources to collect temperature and dissolved oxygen profiles an appropriate multiparameter water quality sonde as well as training in its calibration and use will be necessary. Section

[3] https://www.ontario.ca/page/map-lake-partner

5.3 provides costing for purchase of a YSI EXO2 sonde, however lake associations should also consider equipment rental options (e.g., Pine Environmental; pineenvironmental.ca) as investing in the purchase of a multiparameter sonde is a significant financial investment and require ongoing care and maintenance of the equipment.

Once on-site for sampling it is important to collect all the necessary site data to accompany water quality samples and profiles. Metadata ("data about the data") is crucially important and must accompany the primary data for it to be interpretable (i.e., useful). The following types of metadata should accompany lake monitoring data:

- water body name
- site code
- site description
- site latitude & longitude
- sampling depth (or depth range, if integrated)
- sample collection method (e.g., Van Dorn bottle)
- date-time of sample collection (incl. time zone)
- date-time of sample analysis (incl. time zone)
- parameter name
- parameter units
- names of field personnel
- laboratory name
- laboratory sample number
- analytical precision of lab method
- any additional information from laboratory
- any additional information from field crew

4.5.2 Biological Communities

4.5.2.1 Phytoplankton

Cyanobacteria blooms are one of the leading concerns amongst property owners and recreational users in Central Ontario lakes. Cyanobacteria blooms have become an ongoing issue in both high and low nutrient lakes in Ontario and we therefore recommend that lake associations plan to ensure blooms, if they occur, are properly documented. Citizen scientists should be prepared to record the onset, extent and severity of cyanobacterial blooms for comparison against other environmental data to help characterize the conditions contributing to blooms. Potential options for collecting and storing data on blooms are numerous, from simple paper data sheets to more sophisticated options that could be coordinated through the county or CHA; for example, the EPA current employs several smartphone applications (i.e., CYAN and Bloomwatch) to allow citizens to document harmful algae blooms including location, photos and other meta data. If a bloom is suspected, it is important to contact the Ontario Ministry of the Environment's Spills Action Centre (1-800-268-6060 or 416-325-3000) to report the incident.

Phytoplankton abundance can be monitored in several ways. The most accurate assessment of biomass and community composition is accomplished by manually inspecting samples using an inverted microscope. Comprehensive assessment of the phytoplankton community (i.e., biovolume and species composition) typically involves microscopic examination of biweekly or monthly samples by a trained

taxonomist (~$300/sample). While a comprehensive assessment may be prohibitively expensive (several thousand dollars/year), for lakes subject to HABs, a single sample collected during a bloom can be invaluable. Often a single taxon (type) of phytoplankton (usually one of a relatively small number of common HAB taxa) constitutes most of the bloom biomass; thus identifying this one taxon can help answer important questions such as:

- Can this taxon produce toxins?
- Has it bloomed in other, nearby lakes?
- What environmental factors favour its growth?

Algae identification (not including enumeration or biomass) screening from an accredited laboratory is available for ~$75 with results available within ~5 days.

Perhaps the most commonly reported measure of phytoplankton biomass is chlorophyll-a concentration. This is only an approximate measure of biomass, as the amount of chlorophyll-a in phytoplankton cells can vary appreciably due to factors such as nutrient limitation and light climate. The concentration of chlorophyll-a is usually determined based on its fluorescence. This can be measured in the laboratory (following extraction by solvent of the pigment from the cells) or assessed in the lake using a field fluorometer. The former approach provides a more accurate determination of the true chlorophyll-a concentration whereas the latter approach, though less accurate, allows for large amounts of data collection (e.g., vertical profiles, high-frequency time series, nearshore-offshore transects, etc.) for very low effort and cost (aside from the initial fluorometer purchase). Other pigments can also be measured fluorometrically to estimate the biomass of specific types of phytoplankton. Phycocyanin fluorescence is commonly measured in the field to estimate the biomass of cyanobacteria. Many multi-parameter sondes can be equipped with probes for both chlorophyll-a and phycocyanin to estimate the concentrations of both eukaryotic phytoplankton and cyanobacteria simultaneously (See Section 5.3). There are several commercially available multi-wavelength field fluorometers that can differentiate several groups. The most widely used of these is probably the FluoroProbe (bbe Moldaenke). Using its default software and settings, the FluoroProbe estimates chlorophyll-a concentrations for 4 phytoplankton groups: cryptophytes, green algae/euglenoids, cyanobacteria, and diatoms/chrysophytes/dinoflagellates. While chlorophyll-a fluorescence serves as a convenient and cost-efficient method by which to quantify phytoplankton, sample collection and phytoplankton identification provides high-resolution taxonomic information (e.g., to species level), but is typically costly and time consuming. An alternative is the use of an automated system that combines flow cytometry technology with image recognition algorithms (see Section 5). Examples are the FlowCam[4] and (the submersible) Imaging FlowCytobot[5]. Such technologies promise to hugely increase the efficiency of phytoplankton analysis. However, considerable resources are required to assemble the image libraries required to calibrate these instruments and their accuracy may be much lower than promised (J.W. Harrison, unpublished data from Lake George, NY). At present, manual sample identification by a professional phytoplankton taxonomist remains the “gold standard” approach.

[4] https://www.fluidimaging.com/applications/marine-and-freshwater-research/phytoplankton-and-zooplankton-research
[5] https://mclanelabs.com/imaging-flowcytobot/

4.5.2.2 Ontario Benthos Biomonitoring Network (OBBN)

The Ontario Benthos Biomonitoring Network (OBBN) was established to enable assessment of aquatic ecosystem condition by sampling benthic invertebrate communities and using results as bioindicators of water and habitat quality. The OBBN protocol (Jones et al. 2007) describes sampling and laboratory methods as well as data-interpretation options for prospective partners. The available guidance aims to ensure standardization with federal protocols and allow partners with limited financial and technical resources to participate.

The OBBN program is built on a reference condition approach (RCA), wherein the benthic invertebrate communities between test and reference sites are statistically compared. Reference sites are minimally impacted sites where natural benthic communities (unimpacted by development) are expected. Multiple reference sites, across a range of physiographic conditions, are selected and sampled. Establishing a normal range from numerous reference sites allows for assessment of a wider range of test sites.

Participation in the OBBN program provides a means to collect biological data on lake health while actively engaging the community in sample collection, identification providing not only data for scientific assessment but also education for lake users. The OBBN program is a welcome addition to any lake associations monitoring program as an overall metric of nearshore lake health, collection of samples requires a kick and sweep or “D-Net” (See Appendix A).

4.5.2.3 Zooplankton

The animal plankton (zooplankton) range in size from ~2 µm to several centimeters, including small organisms such as protozoa and rotifers, as well as larger crustaceans (Cladocerans, Copepods, Ostracods). Zooplankton are an important component of lake foodwebs: many (larger) species graze on phytoplankton and are themselves an important source of food for certain (planktivorous) fish. While zooplankton grazing can act to reduce the biomass of phytoplankton (and thus increase water clarity) at certain times (e.g., the spring clear-water phase), nutrient supply is arguably the more important determinant of phytoplankton biomass in most central Ontario lakes. This is, in part, because under nutrient-enriched conditions, the phytoplankton community often tends toward dominance by cyanobacteria, and these phytoplankton are not the preferred prey of herbivorous zooplankton. Two factors that may increasingly affect the zooplankton of Canadian Shield lakes include the invasive Spiny Waterflea (*Bythotrephes longimanus*) and declining Ca concentrations (Azan and Arnott, 2017).

Zooplankton can be sampled in several ways. A common approach is the vertical net haul: a conical net (usually made of Nitex©; ~60 µm is a popular mesh size) is lowered by a rope to just off the lakebed then raised rapidly to the surface. The zooplankton are collected in a bottle attached to the base of the net and preserved (often with neutralized formalin or Lugol’s iodine). Coarse taxonomic assessments (e.g., rotifers vs. cladocerans vs. copepods) can be performed under relatively low magnificent with modest training, and with the use of image-based taxonomic keys[6] even family-level assessments may be conducted by non-experts. As with phytoplankton, detailed assessments are best done by professionals.

[6] http://cfb.unh.edu/cfbkey/html/begin.html

4.5.2.4 Macrophytes

Large aquatic plants (macrophytes) are an important ecosystem component of shallow lakes and the nearshore (littoral) areas of larger lakes, especially where water clarity is high. Macrophytes contribute to primary production, provide habitat for invertebrates and animals (fish, waterfowl, amphibians, etc.), and reduce shoreline erosion. At dense concentrations, macrophytes can interfere with recreational uses such as swimming and boating. Certain invasive macrophytes, such as Eurasian watermilfoil (*Myriophyllum spicatum*), can reach nuisance densities in Ontario lakes and displace native species.

If macrophyte monitoring is to be undertaken, it is especially important to consider the temporal and spatial variability in macrophyte communities. Macrophyte assemblages shift seasonally and often exhibit patchy distributions within lakes (as well as more predicable depth-dependent gradients in biomass and species composition). For qualitative assessments, it is common to toss a rake tied to a rope to gather macrophytes from a boat. For quantitative assessments, macrophytes must be collected manually from a defined area (e.g., using a quadrat) – this is done by underwater divers for deep-water sampling. Interpretation of macrophyte biomass and community composition data can be somewhat complex, especially if the goal is to understand the indirect effects of macrophytes on the water quality of a particular lake.

4.5.2.5 NatureWatch Programs

The NatureWatch program consists of a network of citizen science monitoring program modules, including FrogWatch, and PlantWatch, that began in 2000 as a partnership between Environment Canada, the environmental NGO Nature Canada, and several other organizations. The goal of these programs is to encourage the public to assist researchers in tracking changes in the natural environment by recording their observations of the environment. FrogWatch focuses on frog populations and habitat, tracking changes in the population of frogs and toads in Canada, their geographic range, and the beginning and ending of their calling season. PlantWatch is focused on blooming times of plant species, citizen scientists record flowering times for selected plant species while researchers use these data to identify ecological changes that may be affecting our environment.

Additional modules under the NatureWatch program include IceWatch for monitoring freeze and thaw of lakes and rivers; WormWatch for learning about soil health and habitat; MilkweedWatch for monitoring the health of monarch butterfly populations by identifying the location of milkweed plants; and SnowTweets which is a University of Waterloo program that collects data on snow depth using social media.

All the NatureWatch programs have value in both the data they collect and in engaging and educating residents on the natural environment. Tracking the formation and break up of lake ice is a no cost method to track possible effects of increased air temperatures on lakes. We would recommend that all lake associations and interested residents participate in the IceWatch program.

5. Technology Options for Monitoring

Automated sensors and other advanced instrumentation can provide much higher data resolution through space and time than is achievable via manual sample collection. Consequently, high-frequency sensors can reveal processes and water quality issues that manual surveys may miss (e.g., Harrison et al. 2021)

including the development of harmful algal blooms (e.g., Moriarty et al. 2022). Various options are available for monitoring local weather, water temperature, water quality, shoreline characteristics, and tributary inputs; these range significantly in price, as indicated below. In addition to sensors, rapid chemical test kits/systems can also be useful for certain applications.

5.1 Technology to Monitor Local Meteorology

Weather can exhibit marked spatial variation due to small-scale differences in factors such as altitude and topography. Weather ultimately drives much of the variation in the physical, chemical, and biological properties of lakes. Weather data from Environment Canada or other established sources can provide an estimate of conditions if located nearby the study lake, however these weather stations are often located at airports or in other upland areas where key parameters such as wind speed may differ significantly from conditions on the water in a forested lake catchment (Hadley et al. 2014). A number of options are available for user-friendly meteorology stations to collect hyper-local meteorological data. For example, Davis Instruments[7] offers the Vantage Vue Weather Station for $460 USD (wireless version for $790 USD) which measures air temperature, humidity, barometric pressure, wind speed & direction and rainfall; the (wireless) Vantage Pro2™ Plus also includes solar radiation sensors ($1,295 USD).

5.2 Technology to Monitor Water Temperature/Stratification

Water temperature affects many important processes in lakes, as discussed in Section 3.4. Most lake monitoring programs measure temperature at multiple depths (i.e., obtain profiles) throughout the ice-free period by using a temperature & DO meter or a multiparameter sonde (see Section 5.3). Alternatively, or in addition to manual profiles, a relatively small number of temperature loggers can be strung from an anchor buoy to quantify variation in surface temperature and water column structure. Given the modest resources required for purchase and installation, a “thermistor string” is often a worthwhile component of a lake monitoring program. This is especially true for shallow lakes/bays that do not stably stratify for the entire summer; these “polymictic” systems undergo transitory (ephemeral) stratification on the timescale of hours to days and thus their stratification regime is poorly characterized by periodic (e.g., monthly) manual measurements. There are many commercial options for temperature loggers. A simple, rugged choice is the HOBO TidBit logger manufactured by Onset ($207 per logger + $321 for adapter, cable & software). Alternatively, readings from an Onset HOBO Pendant MX Temp logger ($83) can be viewed in real time via mobile device or computer.

5.3 Technology to Monitor Lake Water Quality

Loggers are available for most water quality parameters (Table 2). There are circumstances where continuous high-frequency logger data from a small number of parameters are particularly valuable. For instance, it is common to pair an “off-bottom” oxygen logger with a thermistor chain (see Section 5.2) so that high-frequency measurements of water column stratification and its effect on hypolimnetic oxygen concentration can be characterized; this would be especially useful in a polymictic (shallow) lake where internal nutrient loading is a concern.

[7] *https://www.davisinstruments.com/collections/weather-stations*

Table 2. Water quality loggers

Parameters	Description	Price (CAD)
pH & Temperature	Onset HOBO MX2501 Bluetooth Low Energy pH and Temperature Data Logger	$1,025
Conductivity & Temperature	Onset HOBO U24 Conductivity Data Logger + USB Base Station	$1,357
Dissolved Oxygen & Temperature	PME miniDOT Logger + USB cable	$1,903
	PME miniDOT Logger + USB cable + Wiper & Attachment Bracket	$3,388
Turbidity	Observator Turbidity Logger with battery, case, USB cable + calibration kit	$6,508
Chlorophyll-a & Phycocyanin	Turner Designs C-FLUOR with Chlorophyll Optics + C-FLUOR with Phycocyanin Options + USB Logger + cable + testing fee + benchtop connection tool	$12,078

Note: Prices are from Hoskin Scientific (July 2022) exclusive of shipping and HST.

Given the aggregate cost of multiple individual sensors/loggers, it can be more economical and efficient to use a multi-parameter sonde rather than to purchase a large suite of loggers. There are numerous sonde manufacturers (e.g., OTT-HydroMet, In-Situ Inc., etc.); a common choice for lake monitoring is the EXO2 manufactured by YSI. The EXO2 can accommodate up to 6 different sensors for parameters such as pH, conductivity, dissolved oxygen, chlorophyll-a/phycocyanin, fluorescent dissolved organic matter, turbidity, nitrate, and chloride, in addition to logging temperature and depth. Pricing for a comprehensive suite of sensors and accessories is provided below (Table 3).

Table 3. Cost of EXO2 sonde and accessories

Item	Price (CAD)
EXO2 sonde (with depth sensor)	$10,646
chlorophyll-a & phycocyanin sensors	$5,362
handheld display unit	$4,381
dissolved organic matter (fDOM) sensor	$4,155
dissolved oxygen sensor	$3,098
turbidity sensor	$2,871
33 m cable	$1,643
conductivity/temp sensor	$1,455
pH sensor	$926
signal output adapter	$678
calibration cup	$338
guard assembly kit	$141
TOTAL	**$35,694**

Note: Prices are from Hoskin Scientific (July 2022) exclusive of shipping and HST.

For intensive monitoring of a priority lake, a YSI Pontoon Vertical Profiler can provide high-frequency multi-parameter sonde data from multiple depths in the water column (e.g., Lucius et al. 2020). This provides very-high-resolution data through both space and time. YSI EXO2 sondes can accommodate up to 7 probes for parameters such as temperature, oxygen, conductivity, turbidity, dissolved organic matter, chlorophyll-a & phycocyanin, chloride and nitrate. The YSI Pontoon Vertical Profilers can also be equipped with weather sensors (see Section 5.1). While it provides a comprehensive dataset, the YSI Pontoon Vertical Profiler is unlikely to be a standard component of most lake monitoring programs because the cost per unit (including sonde) is approximately $170,000, and a certain level of technical expertise is required to maintain the Vertical Profiler (e.g., troubleshoot mechanical or electrical issues, etc.).

It should be noted that most water quality sensors (whether as stand-alone loggers or attached to sondes) require periodic calibration. This involves a certain degree of expertise and the ongoing expense of calibration standards (e.g., $135 for 4 L of each of pH 4, 7, 10; $522 for 4 L of turbidity standard; $19 for 0.5 L of conductivity standard). The frequency of calibration needed varies from approximately monthly for specific conductance and pH to annually for optical parameters such as turbidity, chlorophyll-a, and phycocyanin[8].

Water quality testing kits for several basic parameters are available at relatively low cost. For instance, the Freshwater explorer test kit by Water Rangers[9] costs $360 and provides basic instrumentation and supplies for determining temperature, conductivity, pH, alkalinity, hardness, chlorine, dissolved oxygen, and Secchi depth. Such kits are ideal for involving multiple participants in water quality monitoring in an economical way, and thus for increasing community engagement and education related to water quality monitoring. The limitations of this approach are that it (1) is manual (vs. automated sensors/loggers), (2) involves the use of meters that are not of professional quality, (3) only includes a basic set of parameters, and (4) cannot be used for profiling the water column, i.e., taking multiple depth-specific measurements (e.g., with respect to dissolved oxygen, surface concentrations are rarely of interest).

5.4 Technology to Monitor Phytoplankton

High-frequency assessment of lake phytoplankton biomass is commonly accomplished using sensors for chlorophyll-a and phycocyanin fluorescence, as previously discussed (Sections 3.8 & 5.3). In most cases, a profiling sonde or fluorometer will be most useful, as phytoplankton distributions can vary appreciably with depth. The FluoroProbe (by bbe Moldaenke; ~$40,000 CAD) is a commonly used instrument for quantifying broad groups of phytoplankton at different depths, as discussed in Section 3.8. In certain situations, a fixed-depth deployment may be warranted (e.g., at the water's surface to detect blooms), in which case the Turner Designs sensors (Table 2) could be utilized. The FluoroProbe reports concentrations of different phytoplankton groups in common units (i.e., as µg/L of chlorophyll-a). This is an advantage over simple stand-alone sensors (that report relative fluorescence units) because the calibrated data can be compared among phytoplankton groups (e.g., to determine what fraction of the phytoplankton are

[8] *These recommendations are based on HESL's professional judgement; vendors of calibration standards may recommend more frequent calibration schedules.*

[9] *https://waterrangers.ca/product/freshwater-explorer-testkit/*

cyanobacteria) and the total chlorophyll-a concentration can be compared quantitatively to water quality guidelines and to chlorophyll-a data determined in the laboratory.

As previously noted, there are several instruments (FlowCam, Imaging FlowCytoBot) that combine flow cytometry with image recognition technology in an attempt to automate the identification of different phytoplankton species (see Section 3.8). Based on professional experience, HESL does not recommend the use of these technologies for the monitoring of lake phytoplankton communities at the present time; this is due to their cost, the resources required for calibration, and direct observation of poor performance (i.e., high rate of misidentifications).

Where HABs are a concern, testing systems such as the LightDeck MINI by HACH[10] offer rapid (<10 min) quantification of cyanotoxins. Test strips for microcystins are available from Eurofins Abraxis[11].

5.5 Technology to Monitor Shoreline Characteristics

Visual surveys of lake shorelines can be useful in characterizing the extent of shoreline development and associated Best Management Practices as well as in identifying potential point sources of nutrients. The District of Muskoka Shoreline Land Use Survey program has performed extensive shoreline classifications on lakes in the region since 2002. Shoreline land use assessments collect data on shoreline vegetation, structures and other information on the first 20m of land around a lake. Shoreline land use surveying is a labour-intensive process. Currently, the District of Muskoka surveys the shorelines of at most four to five small lakes a year, suggesting that methods to improve the rate of data collection or to involve the community in collecting shoreline data may be valuable.

Drone imagery may be useful in this regard, using high resolution video footage of the shoreline collected during the summer months. Trained citizen-science volunteers could analyze this footage during the off season. Drones vary widely in price from several hundred to several thousand dollars and require a trained pilot and appropriate licence and clearance to operate, alternatively, hiring an experienced drone pilot may be possible. Our experience hiring a drone operator costs ~$1,800 CAD per hour (ca. 2018), which may be prohibitive in most typical monitoring programs.

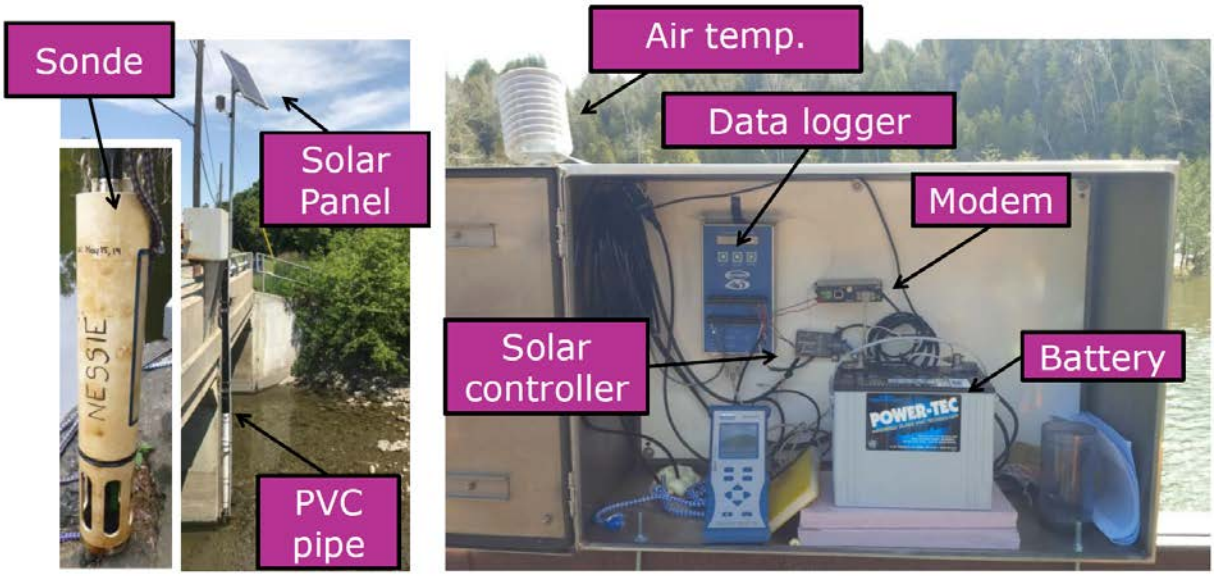
5.6 Technology to Monitor Tributary Inputs

Tributaries (inflowing watercourses) are often major sources of nutrients and contaminants to lakes. For this reason, lake monitoring programs often include tributary sampling and gauging the major tributaries (measuring water levels and flow) so that chemical loadings (the mass of a chemical entering the lake per unit time) can be calculated. Manual sample collection is typically done at a monthly frequency (or less). Because stream flow and nutrients are highly variable (due to seasonality, rainstorms, etc.), it is beneficial to augment the manual sampling with continuous monitoring. This can be done using sondes and/or loggers (Table 2, Table 3). Sonde-based continuous water quality monitoring set-ups have been deployed with success by Conservation Authorities with estimated initial set-up costs of ~$30,000 (in 2018) and

[10] *https://www.hach.com/lightdeck-mini-algal-toxin-testing-system/product?id=60752257837*
[11] *https://abraxis.eurofins-technologies.com/home/products/rapid-test-kits/algal-toxins/*

annual estimated cost of $10,000, however these costs will vary depending on the parameters desired and the current market (Figure 2).

Figure 2. Example set-up of a sonde-based continuous monitoring station. (Murison et al. 2018)



Suspended solids and nutrients (e.g., P) are often elevated during high-flow events (i.e., severe storms), and concentrations can vary substantially with stream flow over relatively short periods (often <24 h). In this context, autosamplers (e.g., by Teledyne-ISCO; ~$5,000) can be programmed or remotely triggered to collect a series of samples (up to 24) over the course of a storm event. If paired datasets are established between (laboratory) water chemistry information and continuous sensor data from the field, statistical and/or machine-learning models can be used to predict water chemistry on a continuous basis (e.g., Harrison et al. 2021). Note that deployment of these specialized equipment set-ups requires significant training to ensure data integrity.

6. Data Management

6.1 Data collection and storage

Water quality monitoring can be a significant undertaking for a lake association both in terms of cost, coordination and time invested. Obtaining and maintaining a high-quality dataset requires Quality Assurance/Quality Control (QA/QC) protocols and collecting and storing detailed metadata to ensure that the environmental data can be properly interpreted.

QA/QC involves proper calibration of all sensors/meters, careful sample collection procedures (e.g., avoiding sample contamination), review of data for outliers (extreme/strange values), and in the case of continuous sensor data, signal drift or step changes that may indicate hardware issues or probes in need of recalibration. QA/QC for chemistry data collected and sent to the lab should also include a number of duplicate samples. For example, Lake Partner Program water samples for analysis of total phosphorus are

taken into duplicate laboratory-provided glass tubes. Contamination of samples can occur during sample collection which can produce elevated TP concentrations and 'bad splits' between the field duplicates. Even with careful sampling, bad splits occur in approximately 10% of sample submissions to DESC (pers. comm., Bev Clark, MECP retired). Review of duplicate samples provides information on the success of the sampling methods and the training of volunteers and helps identify problems in the dataset prior to analysis.

Many software options are available for storing lake monitoring data. Commercial database software designed specifically for aquatic environmental data such as WISKI (by Kisters) can offer secure storage of large datasets, remote data access and visualizations, and responsive technical support; however, such software is unnecessary for a lake association monitoring program, can be expensive, and the learning curve can be steep. A common approach is to store lake monitoring data in Microsoft Excel or Access, Excel being the most common and likely best option for most programs. The Microsoft suite of products has the advantage of ease of use, and relatively low cost. However, the onus is on the user to ensure that the database is logically structured, includes the necessary metadata, and is not accidentally altered (corrupted).

Online data management and sharing options are also available and could be considered. For example, DataStream (by The Gordon Foundation) offers a free, open-source option for storing, accessing, and visualizing (graphing) Canadian water data. The data must be formatted according to DataStream's criteria and are uploaded via either their Excel or Google Sheets template. Once uploaded, the information is freely available to the public. We recommend lake associations maintain an offline database of water quality data regardless of if the DataStream option is considered for added security.

6.2 Data Analysis

In general, it is recommended that lake associations engage with a private consulting firm or science partner to provide specialized water quality analysis and reporting. Data analysis and visualization (graphing/plotting) should begin early in the monitoring process and be done regularly. Frequent data analysis increases the likelihood that changes in water quality will be detected and allows issues in the monitoring program design to be corrected before a large amount of data is affected or to focus efforts on an issue of concern. Plotting data helps to identify outliers (part of the QA/QC process) and allows any methodological issues (e.g., sample contamination, improper sensor calibration, etc.) to be resolved. Scatterplots and boxplots are both useful for this purpose. Early identification of patterns in the data can aid in adapting the structure of the monitoring; for instance, regular plotting of temperature and oxygen profiles may suggest a lake develops an anoxic hypolimnia and trigger targeted sampling to characterize internal nutrient loading.

Data analysis options will change over the course of a long-term monitoring program. For example, new programs will not have sufficient data for meaningful statistical analysis of trends over time until at least 10 years of data have been collected. Early in a monitoring program, assessment of water quality data to answer management questions will likely rely on summary statistics and comparison to provincial and/or federal water quality guidelines. Summary statistics should be calculated for each parameter, including measures of central tendency (e.g., average, median) and dispersion (e.g., range, standard deviation, interquartile range). Time series analysis should be performed, once a sufficient period of record (>=10 years) is available, to assess trends in water quality.

7. Summary and Conclusions

Lakes in the Muskoka River Watershed are under stress from a variety of emerging issues in water quality such as changing climate, harmful algal blooms, invasive species, emerging contaminants, microplastic pollution, light and noise, salinization, declining calcium, engineered nanomaterials and cumulative impacts. The stressors on lakes in the region are minimal compared to urban lakes but impacts from traditional stressors such as waterfront development are being combined with impacts associated with emerging issues such as climate change to create a myriad of biotic and abiotic changes in lakes. Insightful water quality monitoring programs are required to characterize water quality conditions now more than ever to characterize lake health, determine changes over time, and inform management options such as stewardship, related planning policy or active in-lake or watershed management.

Water quality monitoring programs often include phosphorus, water clarity, bacteria, water temperature, calcium and chloride, while other parameters such as nitrogen, dissolved phosphorus, conductivity, dissolved organic carbon, pH, turbidity, metals and biological monitoring provide additional information on lake health. Chemical and biological parameters can be interpretated independently against guidelines, as trends over time, or as surrogate information along with other data to provide additional insights on lake health.

Automated sensors and other advanced instrumentation can provide higher data resolution, both spatially and temporally, than is achieved with manual sample collection. High-frequency sensors can reveal processes and water quality issues that manual surveys may miss including the development of harmful algal blooms and other impacts in multi-stressor systems. Technologies are available to monitor local meteorology, water temperature/stratification, water quality, phytoplankton, shoreline character and tributary inputs.

Monitoring programs must also implement appropriate data management techniques such as QA/QC protocols for collecting and storing data, and data analysis to ensure that monitoring programs develop precise and accurate results.

A water quality monitoring program requires the determination of timing and frequency of data collection, number and location of sites, as well as monitoring components that were reviewed in detail here-in: what parameters are to be measured, as well as the selection of technologies and data management to be employed. Potential monitoring programs range from relatively simple, such as involvement with the Lake Partner Program, to in-depth and complex programs that rely on the latest technological advancements. The determination of all monitoring components is dictated by lake characteristics, known water quality issues, resources available and specific goals of the monitoring program.

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Appendix A. Cost Estimates for the Collection and Analysis of Water Quality Data

Subcategory	Parameter	Estimated Cost
Water Quality Parameters[12]		
Major Ions	Alkalinity	$ 12.00
	Chloride	$ 12.00
	Sulfate	$ 5.00
	Chlorophyll a	$ 35.00
Nutrients	Ammonia	$ 12.00
	Nitrate and Nitrite	$ 15.00
	TKN and Total Phosphorus	$ 35.00
	Dissolved Organic Carbon	$ 20.50
Physical Parameters	pH	$ 5.50
	Suspended Solids	$ 12.00
Total Metals	Aluminum (Al)-Total	$ 40.00
	Antimony (Sb)-Total	
	Arsenic (As)-Total	
	Barium (Ba)-Total	
	Beryllium (Be)-Total	
	Bismuth (Bi)-Total	
	Boron (B)-Total	
	Cadmium (Cd)-Total	
	Calcium (Ca)-Total	
	Cesium (Cs)-Total	
	Chromium (Cr)-Total	
	Cobalt (Co)-Total	
	Copper (Cu)-Total	
	Iron (Fe)-Total	
	Lead (Pb)-Total	
	Lithium (Li)-Total	
	Magnesium (Mg)-Total	
	Manganese (Mn)-Total	
	Molybdenum (Mo)-Total	
	Nickel (Ni)-Total	
	Phosphorus (P)-Total	
	Potassium (K)-Total	

[12] *Prices from ALS Environmental*

	Rubidium (Rb)-Total	
	Selenium (Se)-Total	
	Silicon (Si)-Total	
	Silver (Ag)-Total	
	Sodium (Na)-Total	
	Strontium (Sr)-Total	
	Sulfur (S)-Total	
	Tellurium (Te)-Total	
	Thallium (Tl)-Total	
	Thorium (Th)-Total	
	Tin (Sn)-Total	
	Titanium (Ti)-Total	
	Tungsten (W)-Total	
	Uranium (U)-Total	
	Vanadium (V)-Total	
	Zinc (Zn)-Total	
	Zirconium (Zr)-Total	
Contaminants	Dioxins and Furans	$ 700.00
	BTEX	$ 87.50
	Microcystin	$ 180.00
	PAHs (Hydrocarbons)	$ 85.00
	PCB	$ 55.00
	Pesticides	$ 105.00
	Handling and Disposal Fees	$ 3.50
Continuous Monitoring		
Loggers	Temperature Logger HOBO Pendant MX[13]	$ 83.00
	Temperature Logger HOBO TidBit logger[13]	$ 207.00 per logger + $ 321.00 for adapter, cable & software
	pH & Temperature[13]	$ 1,025.00
	Conductivity & Temperature[13]	$ 1,357.00
	Dissolved Oxygen & Temperature[14]	$ 1,903.00 to $ 3,388.00 per logger
	Turbidity[15]	$ 6,508.00 per logger

[13] *https://www.onsetcomp.com/*
[14] *https://www.pme.com/*
[15] *https://observator.com/*

	Chlorophyll-a & Phycocyanin[16]	$ 12,078 per logger
Sonde-based continuous water quality monitoring	Dependant on the Sonde (Rough cost based on Conservation Authority estimate ca. 2018)	~$ 30,000 set-up ~$ 10,000 annual
Autosampler	Suspended Solids and Phosphorus[17]	~$ 5,000
Vertical Profiler	high-frequency multi-parameter sonde data[18]	$ 170,000
Phytoplankton	FluoroProbe[19]	$ 40,000
Biological Parameters[12]		
Phytoplankton lab analysis	Biovolume and Species composition	$ 280 per sample
	Dominant Species Identification	$75
Benthic Invertebrate Sampling	D-Net (Equipment)	$310
Bacteria Sampling	E. coli	$10
	Fecal Coliforms	$15
	Fecal Streptococcus	$22
	Pseudomonas aeruginosa	$15
Zooplankton	Vertical Net Haul Equipment	$600
Climate Monitoring	Meteorological Station[20]	$700 - 2,000
Shoreline Land use Assessments	Drone based data collection	$ 1,800 per hour

Note: Prices are exclusive of shipping and HST.

[16] *https://www.turnerdesigns.com/*
[17] *https://www.teledyneisco.com/*
[18] *https://www.ysi.com/*
[19] *https://www.bbe-moldaenke.de/en/products/chlorophyll/details/fluoroprobe.html*
[20] *https://www.davisinstruments.com/collections/weather-stations*

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Memorandum

Date: **October 24th, 2023**

To: **Glenn Cunnington and Alana Perez, District Municipality of Muskoka**

From: **Kristopher Hadley, Hutchinson Environmental Sciences Ltd.**

Re: **Water Quality Indicators – Implementation of Recommendations**

Hutchinson Environmental Sciences Ltd. (HESL) provided a series of recommendations to the District Municipality of Muskoka (DMM) in the final report for the Water Quality Indicators Project to inform ongoing Integrated Watershed Management in the Muskoka River Watershed. The DMM subsequently requested that HESL provide an additional scope of work including a technical memo to provide guidance on implementation of recommendations made in the Water Quality Indicators Report.

The purpose of this memo is to fulfil the DMM request for guidance on the recommendations made in the initial Water Quality Indicators report. Findings from the literature review of emerging threats to water quality and the review of current water quality monitoring programs informed our analysis of gaps in the current monitoring and led to 15 recommendations to improve or expand the monitoring in the Muskoka River Watershed:

1. ***Agencies need to coordinate their efforts and where possible resources to address emerging issues.***

2. ***Include consideration of beneficial long-term research projects and the resources required at the Dorset Environmental Science Centre (DESC) to facilitate that research.***

3. ***Develop a training program lead by experienced Science Partners at DESC and DMM in the necessary sampling equipment for citizen-science partners.***

4. ***Develop guidance for lake associations and other coalitions participating in monitoring.***

5. ***Develop Provincial Water Quality Monitoring Network (PWQMN) partnership or re-implementation to establish long-term monitoring stations on rivers in the watershed.***

6. ***Consider preserving and archiving samples as part of a long-term monitoring strategy.***

7. ***Make Integrated Watershed Management (IWM) data available alongside Lake Partner Program (LPP) data on DataStream.***

8. ***Expand data analysis and reporting on additional parameters (e.g., Ca and Cl) and assess trends over time in water quality.***

9. ***Re-assess program every 5 years maximum to make necessary changes from lessons learned.***

10. **Expand lake temperature and dissolved oxygen profile collection by coordinating with other monitoring programs.**

11. **Include high frequency continuous monitoring of temperature and dissolved oxygen, particularly in lakes with frequent recurring HABs.**

12. **Invest in improved meteorological data collection within the sub-watersheds of the Muskoka River to better inform HAB investigations.**

13. **Develop a watershed-wide Citizen science-based bloom watch program to collect and archive detailed data on cyanobacteria and other nuisance algal blooms.**

14. ***Engage with university partners to investigate the feasibility of using diatoms (either from periphyton or surface sediment samples) as a road salt indicator.***

15. ***Develop a monitoring strategy for emerging contaminants, including pharmaceuticals and pesticides.***

Below we have highlighted ideas for the implementation of each of these recommendations or where applicable highlighted where recommendations are being addressed by follow-up work underway as part of the WQI Project. Where appropriate recommendations have been grouped by common theme.

Agencies need to coordinate their efforts and where possible resources to address emerging issues.

Our recommendation for coordination amongst programs and agencies in the watershed was made based on interviews with subject matter experts and the understanding that lake management questions in the watershed are becoming increasingly complex. Coordination between agencies however may be the most difficult recommendation to implement as it assumes that provincial and municipal agencies responsible for monitoring in the watershed are focused on similar goals and share a mutual desire to work together. Gauging the willingness of the Ministrisy of the Environment, Conservation and Parks (MECP) and Ministry of Northern Development, Mines, Natural Resources and Forestry (MNDMNRF) to work with the IWM Program would be the first step in coordinating effort. Coordination efforts would then likely require a formal agreement between the IWM project and the agencies that outlined their goals, resources and approach to monitoring the Muskoka River watershed including specific roles and responsibilities of each participant.

Engage with university partners to investigate the feasibility of using diatoms (either from periphyton or surface sediment samples) as a road salt indicator.

Dr. John Smol and Dr. Brian Cummings at Queen's University in Kingston have both recently worked with Master and Ph.D. students exploring chloride concentrations in Ontario. Both scientists work with diatoms as indicators of environmental change and would be able to provide expert opinion on the use of diatoms as a road salt indicator in the Muskoka River watershed.

Include consideration of beneficial long-term research projects and the resources required at the DESC to facilitate that research.

Consideration of beneficial long-term research projects may be partially addressed under the current review of the District's Official Plan policy relating to Causation Studies and harmful algae blooms. The intent of that project is to address the current Causation Study format and explore alternative methods for managing lakes in the District.

Develop guidance for lake associations and other coalitions participating in monitoring.

This recommendation was made during the water quality indicators project recognizing that the size of the Muskoka River watershed and the logistical challenges faced by the District which limits the number of lakes it can sample. Lake associations, property owners and other stakeholders could potentially expand the regional coverage of lake monitoring in the District and/or improve the frequency with which lakes can be sampled, i.e., annual instead of every 2-3 years. The potential trade-off of this approach is the need to ensure consistency in sampling methods across all participating organizations and individuals. A report was prepared to standardize, as much as possible the parameters and approach to monitoring for lake associations and individuals interested in participating in monitoring[1] that addresses this recommendation. Providing this guidance document to interested parties and ensuring that any data collected are gathered in a consistent manner helps to increase the compatibility of data across the watershed.

Develop PWQMN partnership or re-implementation to establish long-term monitoring stations on rivers in the watershed.

This recommendation was made during the water quality indicators project recognizing that monitoring data on the Muskoka River and major tributaries has not taken place since the early 1990s. The current DMM program collects high quality monitoring data across the watershed from lakes on a rotational basis, however no river monitoring is currently included as part of the program due to resource limitations. The PWQMN program that monitors rivers across Ontario is connected directly to Conservation Authorities, however no Conservation Authority currently exists for the Muskoka River Watershed or any sub-watersheds within.

As part of the follow-up work being conducted as part of the Watershed Indicators Project, a plan for the implementation of a river water quality monitoring program is being developed. This plan includes sampling locations and parameter recommendations for monitoring watercourses across the Muskoka River Watershed. This plan, if adopted, would satisfy this recommendation.

Consider preserving and archiving samples as part of a long-term monitoring strategy.

This recommendation was made as a part of the interview process that took place during the Watershed and Water Quality Indicators projects. Preserving water quality and other samples from field monitoring would potentially allow future research in the watershed to reanalyze samples in the future if necessary.

[1] *HESL 2023. District of Muskoka Water Quality Indicators - Water Quality Monitoring Program Design.*

For example, novel contaminants could be measured that may not currently be considered a current priority or if methodological developments are made in monitoring contaminants that improve the detection limit.

Implementing this recommendation would involve selecting monitoring stations where archiving of samples would be considered highest priority. For example, upstream and downstream of a treatment plant, urban development area or other local stressor.

Expand data analysis and reporting on additional parameters (e.g., Ca and Cl) and assess trends over time in water quality

We recommended that analysis of calcium and chloride data collected by the Recreational Water Quality monitoring program be included in annual reports as part of the Recreational Water Quality Monitoring Program. This could be included alongside phosphorus and secchi depth analysis and would include a summary of calcium concentrations across site sampled and comparison against literature values identifying areas in the watershed that may be vulnerable to the impacts of low calcium concentrations.

Make IWM data available alongside LPP data on DataStream.

Raw data from the IWM and District monitoring could be uploaded to the Datastream service annually to allow stakeholders, government agencies and researchers working in the area to use these data as needed. Lake partner program data collected by the MECP are stored on the Great Lakes Datastream, storing District and other watershed data in the same format would facilitate analysis of these data as a whole. This would involve developing and implementing a universal format for water quality data that includes both raw data (e.g., chemical concentrations) and meta data to identify duplicates, field and trip blanks and other information that inform where and how data were collected. Once data are formatted Datastream provides an open platform for organizing, storing, visualizing and sharing data. Working with the MECP Lake Partner Program when developing a format would greatly increase the compatibility between datasets. Contacting the LPP and Datastream would be the first step in implementing this recommendation.

Include high frequency continuous monitoring of temperature and dissolved oxygen, particularly in lakes with frequent recurring HABs.

The Watershed Health Indicators – Muskoka River Watershed - Implementation Report (HESL 2023) includes recommendations on the implementation of continuous monitoring of temperature and dissolved oxygen with a focus on lakes with recurring HABs[2].

Expand lake temperature and dissolved oxygen profile collection by coordinating with other monitoring programs. Develop a training program lead by experienced Science Partners at DESC and DMM in the necessary sampling equipment for citizen-science partners.

Expanding lake temperature and dissolved oxygen profile collection could be accomplished in several ways. Data collected by the Township of Seguin has some overlap with the Muskoka River Watershed, although many of their sample sites lay outside the watershed area. A data sharing agreement with Seguin may allow the IWM monitoring program access to temperature profiles from several lakes monitored by the

[2] *HESL. 2023. Watershed Health Indicators – Muskoka River Watershed Implementation Report.*

Seguin to include in the IWM water quality reporting. Further expansion would involve including and possibly supporting citizen science-based monitoring programs to collect additional data. For example, the Muskoka Lakes Association collects water quality data from numerous locations on the three largest Muskoka Lakes (i.e., Lake Joseph, Rosseau and Muskoka) and from several nearby smaller lakes. This program however only collects temperature data from the surface not depth profiles. For a collaboration to work effectively we believe the IWM program would need to:

1. Gauge interest in participating in expanded monitoring from one or more Citizen science-based programs in the watershed (e.g., Muskoka Lakes Association, Lake of Bays Association)

2. Facilitate equipment and training in equipment use to measure temperature and oxygen profiles including prioritizing site selection.

    a. Other monitoring programs in the watershed led by citizen science do not currently incorporate temperature or dissolved oxygen sampling. If they wish to do so The IWM and citizen program may need to find funding for renting sampling equipment.

    b. DMM staff are knowledgeable in sampling methods with YSI meters for temperature and dissolved oxygen. Expansion of the sampling, if desired, would almost certainly require the development of a training program and in-person or online training sessions with interested citizen science partners in the use, calibration and troubleshooting of sampling equipment. Developing a training program should be relatively straight forward as the DMM already trains summer students as part of the Recreational Water Quality Program. It is possible that expanded training could be offered to interested parties online via video conference to reduce the logistical difficulty and cost of training.

3. Provide a centralized repository for data collected including QA/QC of incoming data from third party samplers.

Invest in improved meteorological data collection within the sub-watersheds of the Muskoka River to better inform HAB investigations.

Previous reporting as part of the IWM program produced guidance for monitoring in the Muskoka River Watershed[3]. This guidance highlighted the importance of local meteorological data, particularly when assessing harmful algal blooms and included options for improved monitoring beyond reliance on the existing weather stations in the watershed.

Re-assess program every 5 years maximum to make necessary changes from lessons learned.

The increased scope and effort being proposed for the Recreational Water Quality Monitoring Program and the Muskoka Riverine Monitoring Program will require ongoing adjustment to sites, sampling schedule and parameter list as lessons are learned from sampling and analysis of data. We recommended a five-year re-assessment period in the Water Quality Indicators Report and as part of the Muskoka Riverine and Contaminants Monitoring Programs. Implementation of this recommendation would require a third-party

[3] *HESL 2023. District of Muskoka Water Quality Indicators Water Quality Monitoring Program Design*

review of the water quality monitoring being undertaken by the District including an annual in-depth analysis of these data (e.g., summary statistics) to determine if they are providing appropriate spatial and temporal resolution to discern watershed condition. Every two to five years, we recommended that field monitoring data be analyzed and interpreted in a monitoring report summarizing trends and patterns in watershed health.

Develop a watershed-wide Citizen science-based bloom watch program to collect and archive detailed data on cyanobacteria and other nuisance algal blooms.

A report is currently being prepared to outline options for app-based citizen science monitoring of algae blooms within the watershed as part of ongoing work with the IWM program. That report is expected to be submitted and reviewed by the IWM team in October.

Develop a monitoring strategy for emerging contaminants, including pharmaceuticals and pesticides.

A report is currently being prepared to outline the locations, schedule and parameters of interest for monitoring urban and agricultural contaminants within the watershed as part of ongoing work with the IWM program. That report is expected to be submitted and reviewed by the IWM team in October.

Hutchinson

Environmental Sciences Ltd.

Water Quality Indicators – Muskoka River Watershed Contaminants Monitoring

Prepared for: The District Municipality of Muskoka
Job #: J220010

October 31, 2023

Final Report

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October 31, 2023 HESL Job #: J220010

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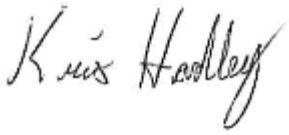
Dear Mr. Cunnington:

Re: Draft Report for the Water Quality Indicators – Muskoka River Watershed Contaminants Monitoring Project

We are pleased to submit the Draft Report for the Water Quality Indicators – Muskoka River Watershed Contaminants Monitoring Project. The report provides a brief review of the current and emerging issues in water quality in the region, identifies key regions for a focused contaminants monitoring program, including recommendations for the District on integrating contaminants monitoring into the comprehensive long-term monitoring strategy in the watershed.

We thank you for the opportunity to undertake this assignment and look forward to receiving your comments.

Sincerely,
Per. Hutchinson Environmental Sciences Ltd.



Kris Hadley, Ph. D.
Senior Aquatic Scientist

Signatures

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1. Introduction

1.1 Background

Integrated Watershed Management (IWM) is increasingly being recognized as an effective way to sustainably manage human activities and protect the natural environment. IWM takes a holistic approach to environmental management and land use planning, incorporating environmental, social, and economic considerations into a continuously adaptive process. It provides a science-based framework for community planning and decision-making, which acknowledges that ecosystem features and functions are complex, inter-connected, and best addressed at meaningful ecological scales, such as watersheds, rather than political boundaries. IWM further acknowledges that watershed health is influenced by a dynamic interplay of environmental (e.g., water quality, biodiversity etc.) and socio-economic (e.g., human health, economic activities) factors. Promoting watershed health thus requires a collaborative process, which depends on participation from a broad cross-section of society, so that community interests and concerns are fully represented, and inform the identification of issues, goals, and actions, and the subsequent implementation of plans and strategies.

In 2020, the Muskoka Watershed Council (MWC) released a report entitled *The Case for Integrated Watershed Management in Muskoka* (Sale et al. 2020), recommending that IWM be applied to all aspects of environmental management and land use planning in the Muskoka River Watershed. The report emphasized that IWM was particularly needed to address climate change in the watershed, which, among other impacts, has led to more variable water flow both spatially and temporally, challenging traditional approaches to flow regulation. The report illustrated the iterative adaptive management nature of IWM (Figure 1).

In 2021, the Province of Ontario provided funding to the District Municipality of Muskoka (DMM) to support a series of IWM initiatives to reduce the impacts of flooding in, and protect the health of, the Muskoka River Watershed. These projects include the development of a hydrological model, flood plain mapping, a natural capital inventory, water quality indicators, and watershed health indicators.

Integrated Watershed Management relies on an adaptive management approach, which establishes a management plan, monitors for changes to the environment, and then re-evaluates and updates the plan. Scientifically defensible monitoring of the environment is essential to the adaptative management process and to that end the DMM undertakes several monitoring programs, while a variety of other citizen-science and government-led monitoring programs are also completed in the watershed.



Figure 1. The IWM iterative process.

IWM typically proceeds by describing the watershed, identifying local issues, developing plans and strategies to address those issues, implementing actions locally, monitoring for changes and responses to management actions, and refining or modifying the approach based on monitoring results (From Sale et al. 2020).

1.2 Purpose

One of the long-term focal points of the overarching IWM project is to assist in the development of a comprehensive water quality monitoring program for the Muskoka River Watershed. The DMM recognizes that numerous successful programs are currently in place within the watershed and seeks to build on the successes of those programs. The primary focus of this project was to

- Document emerging threats to water quality based on a literature review with emphasis on relevant issues in the Muskoka River watershed (Section 2);
- Develop a list of priority parameters (Section 3.2); and
- Provide guidance for incorporating emerging contaminants into the Muskoka Riverine Monitoring Program (Section 3) and associated reporting recommendations (Section 4).

2. Emerging Threats to Water Quality

2.1 Contaminants of Potential Long-term Concern

Emerging contaminants that are most relevant in the Muskoka River watershed include active pharmaceutical ingredients, personal-care-product additives, pesticides, engineered nanomaterials and microplastics. All have garnered widespread attention because of their unexpected or unknown biological activity and/or stability (or pseudo-persistence) in aquatic environments. Antibiotics, antimicrobials, antivirals and antidepressants have been demonstrated to be broadly detectable in wastewater-impacted rivers (Hughes et al. 2013), however additional research is needed to better determine the impact of these compounds on the aquatic receiving environment. Contaminants, including pharmaceuticals, microplastics and nanomaterials are ubiquitous, being found in influent and effluent of Wastewater Treatment Plants (WWTPs), surface water, groundwater and drinking water (Gomes et al. 2020).

The Ontario Ministry of the Environment, Conservation and Parks (MECP) found 27 different pharmaceutical and hormones in source and drinking water (Kleywegt et al. 2011). The pharmaceuticals most frequently detected in drinking water included carbamazepine (medication for epilepsy), gemfibrozil (lipid-regulating medication), and ibuprofen (anti-inflammatory medication). Metcalfe et al. (2014) found carbamazepine, trimethoprim (antibiotic), ibuprofen, estrone (hormone) and gemfibrozil in treated drinking water from five different water treatment plants (WTPs) in Ontario.

WWTP effluent is a primary source of human pharmaceutical pollution in surface waters (Grabarczyk et al. 2020). WWTP effluent contains unmetabolized and unused drugs from hospitals, households and the pharmacological industry. Conventional activated sludge treatment used in WWTPs are not typically tailored to remove pharmaceuticals resulting in high variability in removal efficiencies between WWTPs. Leaching from domestic septic tanks has been found to be a significant source of pharmaceuticals in rural environments. Veterinary pharmaceuticals are released into waterways through leaching or surface runoff from unmetabolized drugs and/or metabolites contained in animal feces (often used in fertilizer) and urine (O'Flynn et al. 2021). Pharmaceuticals are considered pseudo-persistent contaminants as the continuous emission of human pharmaceuticals from sewage into the aquatic environment exceeds the rate of degradation (Bu et al., 2016 and O'Flynn et al. 2021).

Diclofenac, naproxen and ibuprofen are anti-inflammatory, antipyretic and analgesic agents that are used worldwide (Grabarcyzy et al. 2020). Concentrations of diclofenac measured in surface waters include 1.16 ng/L in Italy (Riva et al. 2015), 170-1,400 ng/L in Germany (Kunkel and Radke, 2012 and Schwientek et al. 2016) and 15-83 ng/L in Canadian surface waters within and nearby First Nations (Schwartz et al. 2020). Schwartz et al. (2020) reported concentrations of ibuprofen of 27-367 ng/L and concentrations of naproxen of 5.5 and 120 ng/L in Canadian surface waters. Grabarczyk et al. (2020) found diclofenac, naproxen and ibuprofen to exert a toxic effect on *Raphidocelis subcapitata* (microalgae), *Lemma minor* (Common Duckweed), *Daphnia similis* (zooplankton) and *Hydra attenuate* (freshwater hydra) at concentrations between 13.25 mg/L (13,250,000 ng/L) (*L. minor*) and 93.26 mg/L (93,260,000 ng/L) (*R. subcapitata*). Mehinto et al. (2010) found diclofenac to damage kidney tissue and villi in the intestine of *Oncorhynchus mykiss* (Rainbow Trout) starting at concentrations of 1,000 ng/L.

Sulfamethoxazole, azithromycin, and ciprofloxacin are antibiotics. Sulfamethoxzole is used to treat both gram-positive and gram-negative bacteria in human and veterinary medicine (Grabarczyk et al. 2020). Concentrations found in the environment include 0.51-149 ng/L in Spain and 140-469 ng/L in Germany for sulfamethoxazole, 1-71.67 ng/L for azithromycin and 1-93.3 ng/L for ciprofloxacin in Spain (O'Flynn et al. 2021). Ciprofloxacin has been found in concentrations between 20 and 37.7 ng/L, and sulfamethoxazole between 2 and 87 ng/L in Canadian surface waters within and near First Nations communities (Schwartz et al. 2020). Sulfamethoxazole has been found to be toxic to algae, aquatic plants and cyanobacteria (O'Flynn et al. 2021). Grabarczyk et al. (2020) found EC_{50} values below 10,000,000 ng/L for both *R. subcapitata* and *L. minor*. They also noted growth inhibition at 3,000,000 ng/L for *L. minor* and 5,000,000 ng/L for *R. subcapitata* with the sulfamethoxazole human metabolite N_4-acetylsulfamethoxazole. Antibiotics have also been linked to the promotion and maintenance of resistance genes in microbial communities in natural environments (Balcázar et al. 2015).

Gemfibrozil is a lipid-regulating medication and used for cardiovascular disease. Concentrations between 1.1 to 16.8 ng/L have been found in waterways within and nearby First Nations in Canada (Schwartz et al. 2020) and a maximum concentration of 4 ng/L in Canadian drinking water (Khan and Nicell 2015). Concentrations of gemfibrozil in Spain ranged from 0.91 to 326 ng/L (O'Flynn et al. 2021). Mimeault et al. (2005) noted that gemfibrozil was taken up from water through the gills and reduced plasma testosterone by over 50% in *Carassius auratus* (Goldfish) at environmentally relevant concentrations.

In addition to the native form of pharmaceuticals, their transformation products including metabolites exerted from organisms and degradation products from hydrolysis, photolysis and biodegradation can also pose a risk to nontarget aquatic biota (Grabarczyk et al. 2020). Transformation products can pose a greater threat than native forms as they may be more toxic, stable, and abundant in the receiving environment (Fatta-Kassinos et al. 2011). In addition to transformation products there is also the potential for significantly different toxic effects to chiral (i.e., mirror) forms of the same drug in aquatic biota (Grabarczyk et al. 2020).

Mixtures of pharmaceuticals and their transformation products can cause synergistic, additive, or antagonistic effects; however, multiple chemicals must be tested as effects can be unique to a specific chemical cocktail (O'Flynn et al. 2021). This remains a knowledge gap in the environmental assessment of pharmaceuticals.

2.1.1 Microplastics

Plastic pollution is a key environmental concern because (1) plastic production and use are widespread, and (2) plastic is persistent in the environment for long time periods due to its stability. Therefore, plastics pose a threat to biota in both terrestrial and aquatic ecosystems. Microplastics (MPs) became a topic of discussion in the early 2000s, when Thompson et al. (2004) demonstrated that MP particles were common pollutants in marine environments (beaches and estuarine sediments) and suggested that recovered microplastics were a result of the degradation of larger plastic debris (Thompson et al., 2004; Ryan, 2015). This seminal study initiated more in-depth research on the environmental impact of plastic pollution in marine environments. Extensive research has been conducted on shorelines and open oceans (Barnes et al., 2009; Claessens et al., 2011; Leslie et al., 2013; Lusher et al., 2015; Schmidt et al., 2017; Zobkov and Esiukova, 2017), although freshwater studies have become an important area of research due to the dominance of land-based and urban (anthropogenic) sources of plastic pollution that can ultimately make

their way to oceans (Andrady, 2011). Moreover, urban inputs of MPs have a greater impact on freshwater bodies due to varying seasonal conditions, elevated populations in urban centers situated close to water bodies, and the heightened impact of plastic inputs on relatively small bodies of water such as lakes and rivers (Corcoran et al., 2015).

Microplastics are broadly defined as any plastic fragment 1-5 mm in size (Arthur et al., 2009; Triebskorn et al., 2019). Common sources of MPs to the environment include synthetic and semi-synthetic clothing fibres (e.g., polyester, nylon, acrylic, cellulose acetate), household and industrial paints, car tires (i.e., polypropylene), fishing nets and ropes, industrial abrasives, and personal care products (i.e., microbeads). MPs are often classified as fibres, fragments, foams, films, and beads. MPs are defined as either primary (produced for an intended use, i.e., microbeads) or secondary (originating from fragmentation in the environment) (Wagner et al., 2014).

Due to their small size, MPs can easily be ingested by biota. Microplastic ingestion can cause abrasion and blockage of the gastrointestinal tract and internal bleeding in aquatic organisms (Wright et al., 2013). Concerns have also arisen over the slurry of environmental contaminants that MPs encounter in nearshore and offshore waters. It has been demonstrated in laboratory studies that microplastics can adsorb environmental contaminants on their surfaces and act as vectors for these contaminants (Rochman et al., 2013; Bakir et al., 2014; Velzeboer et al., 2014). Gut conditions, such as temperature and pH, can influence the transfer of sorbed contaminants to organisms (Bakir et al., 2014; Triebskorn et al., 2019). Additionally, as the surface area of MPs increase due to degradation, the potential contaminant adsorption capacity also increases, as demonstrated by Hartmann et al. (2017) and Brennecke et al. (2016).

Nanoplastics (NPs), defined as plastic particles 1-1000 µm in diameter, are also a key concern. Translocation of NPs into organism tissues, which appears to increase with decreasing particle size, is of significant concern, especially as NPs have greater potential for sorption of environmental contaminants due to their high surface ratios (Triebskorn et al., 2019).

The major pathways of MPs to ecosystems include rivers, drainage systems, car tire abrasion (Wagner et al., 2018), agricultural runoff (Nizzetto et al., 2016), wastewater treatment plant (WWTP) effluent, and erosion by wind and currents (Zalasiewicz et al., 2016). A major urban pathway through which MPs have proliferated in the aquatic and terrestrial environment is the wastewater treatment system. During wastewater treatment, 90% of MPs are sequestered in sludge or biosolids during secondary treatment, these MPs can reach the environment when biosolids are commodified and applied to agricultural soils as fertilizer. In 1996, the Canadian Ministry of the Environment stated that up to 8 tonnes of biosolids may be applied per hectare of agricultural fields (Garofolo, 1996). Up to 99% of MPs (and other anthropogenic litter) removed during wastewater treatment can then reach adjacent water bodies via non-point source runoff (Michielssen et al., 2016). The potential impact of MP application to crops may also have consequences for crop quality and physical soil properties (Rillig, 2012), potentially leading to increased pesticide runoff and/or adherence of agrochemicals to MP surfaces (Steinmetz et al., 2016). MPs have also been found to accumulate in agricultural runoff (Nizzetto et al., 2016) and may enter nearby streams. This suggests that MPs could migrate through the soil column and contaminate groundwater and nearby surface water (Panno et al., 2019; Hurley and Nizzetto, 2018).

In urban environments, WWTPs are well-documented pathways for MPs, facilitating their transport and release into the environment. Washing machine effluent has been identified as a dominant source of MPs to WWTPs, as the laundering of synthetic clothing fibres releases >1900 microfibres per wash (Browne et al., 2011). Napper and Thompson (2016) estimated that over 700,000 microfibres could be released per 6 kg load of acrylic textiles (Napper and Thompson, 2016). As WWTPs are typically not equipped to remove small particles and microfibres, WWTPs are potentially introducing MPs to tributaries, especially via high sewage outflows during heavy precipitation (Eriksen et al., 2013). Numerous studies have investigated the effectiveness of WWTPs in removing these MPs, as well as daily and annual rates of discharge of MPs into adjacent water bodies via effluent (Magnussen and Noren, 2014; Mason et al., 2016; Michielssen et al., 2016; Mintenig et al., 2017). WWTP technology is also taken into consideration in these studies, as the type of treatment process often influences the dominant MP morphologies found in the system.

2.1.2 Nanomaterials

Engineered nanomaterials (ENMs) are synthetic materials, raging in size from 1-100 nm, that are used in a myriad of applications. A marked increase in the number of ENM products listed in various global inventories has been recently noted, showing an increase from 54 in 2005 to above 5000 in 2020 (Moli et al. 2021). The market for ENMs is currently dominated by health and fitness products, including active wear, sunscreens, cleaning supplies, cosmetics, and sporting goods where ENMs are surface-bound or suspended in liquid and therefore have a medium to high potential for release into water (Foss Hansen et al., 2016; Moeta et al., 2019; Amorim et al., 2018 and Lehutso et al., 2021).

ENMs (e.g., titanium dioxide (nTiO2), zinc oxide nanoparticles (nZnO), silicon dioxide nanoparticles ($nSiO_2$) and silver (nAg)) are incorporated into products due to beneficial properties such as blockage and protection from UV radiation ($nTiO_2$ and nZnO), absorption ($nSiO_2$) and antimicrobial properties (nAg). ENMs have the potential to be released into the aquatic environment during the various stages of their life cycle including manufacturing, usage, washing, weathering and elimination at the end of their lifecycle (Andreani et al. 2020). These ENMs have been categorized as having medium to high environmental release potential in various inventories (Vance et al., 2015; Moeta et al. 2019; Zhang et al. 2015, The Ecological Council, DTU Environment Department of Environmental Engineering and Forbrugerrådet Tænk Danish Consumer Council, 2021, and Woodrow Wilson Center, 2021), indicating that they could be emitted into the environment with ease.

Reed et al. (2017) investigated titanium dioxide in a Colorado, U.S.A. creek during a busy holiday weekend and found an increase of ~10 ng/L during peak periods of recreational use. Product release of titanium dioxide and nZnO (protection from UV radiation) from sunscreen was also detected in the French Mediterranean region in surface waters (70-500 and 10-15 µg/L, respectively) and the water column (10-30 and 3 µg/L, respectively) during high recreational activity (Labille et al. 2020). Andreani et al. (2020) assessed the toxicity of commercially available zinc oxide nanoparticles and functionalized titanium dioxide (anatase form) to *Raphidocelis subcapitata* (micro algae), *Daphnia magna* (zooplankton) and *Lemna minor* (Common Duckweed). The EC_{50} for the growth inhibition *R. subcapitata* test with zinc oxide nanoparticles was 4.86 mg/L. The EC_{50} for the acute 48-h *D. magna* immobilization test with zinc oxide nanoparticles was 1.33 mg/L. The EC_{50} for the growth inhibition *R. subcapitata* and 48-h *D. magna* immobilization tests with $nTiO_2$ were above the tested concentration of 20 mg/L. Andreani et al. (2020) also reviewed the most current toxicological data available for titanium dioxide and zinc oxide nanoparticles to determine the hazard

concentration for 5% of the species (HC_5). For titanium dioxide in the anatase form less than 25 nm the HC_5 was 1.89 mg/L. The HC_5 value for zinc oxide nanoparticles with a primary particle average size of less than 100 nm was calculated as 0.063 mg/L.

Sediments may act as a sink for ENMs (Kuehr et al. 2021a), therefore, benthic biota are likely to be exposed to higher concentrations over a longer duration. Most toxicity data are acute and focus on pelagic species (Reid et al. 2019), however ENM concentrations found in sediment are typically low (µg/kg; Gottschalk et al., 2013), therefore, greater information is required on the chronic effects of ENMs on benthic organisms.

2.2 Contaminant Sources in the Muskoka River Watershed

2.2.1 Water and Wastewater Treatment Facilities

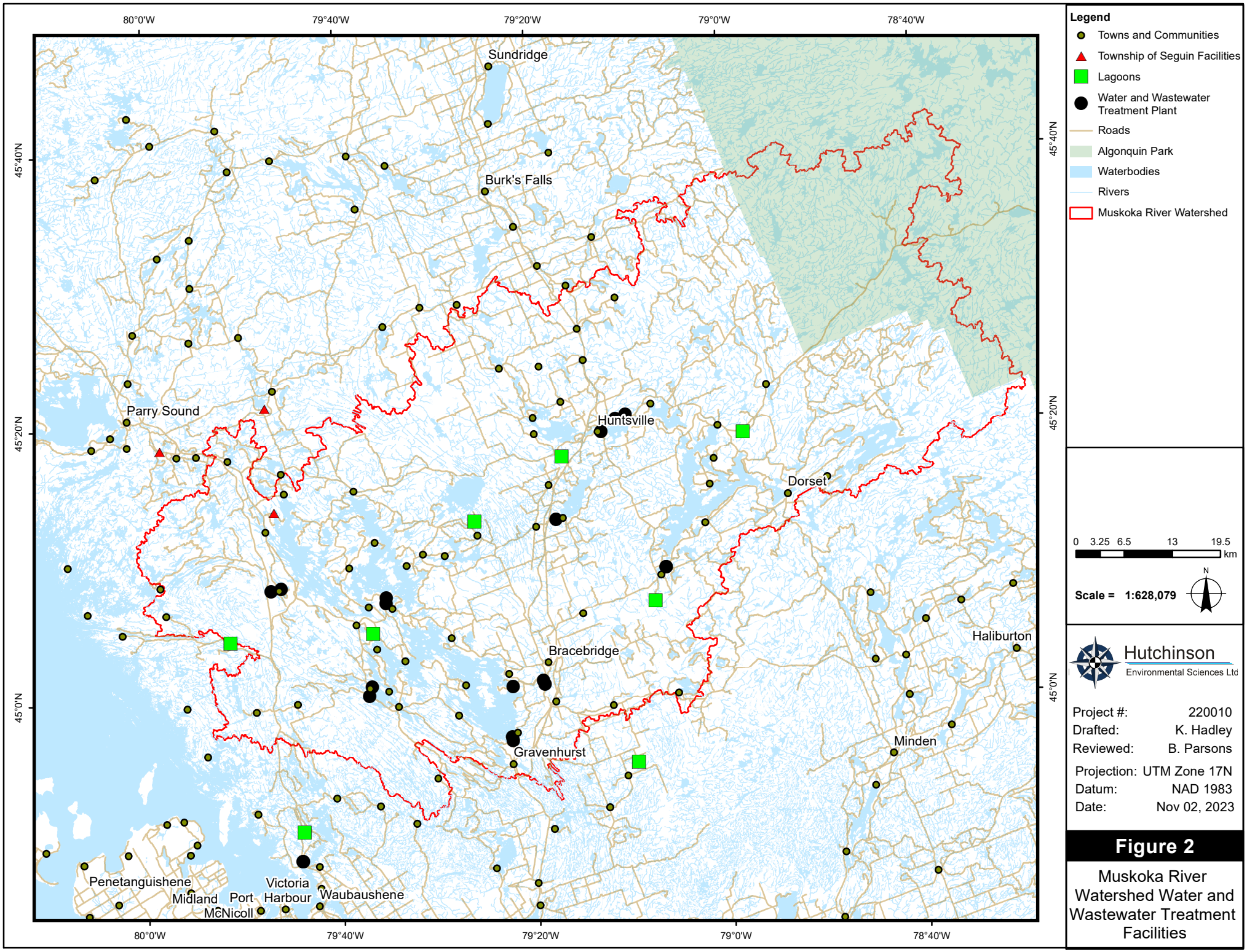
The District of Muskoka operates 9 drinking water systems, 8 wastewater facilities, and 9 septage lagoons. The Township of Seguin provided information on three WWTP sites as part of this project, one of which is in the Muskoka River watershed north of Hamer Bay at Rocky Crest Golf Club (Figure 2). WWTPs are considered both sinks and secondary sources of microplastics, and engineered nanomaterials (ENMs) to the aquatic environment (Figure 2; Moloi et al., 2021). ENMs are found both in the effluent of WWTPs and sludge. ENMs and microplastics have been found to be emitted from agricultural fields where sludge has been applied as fertilizer during runoff events (Zalasiewicz et al., 2016; Musee, 2011). Based on our review of District policy on treatment and use of biosolids it is not clear if the DMM's current program includes application of biosolids on agricultural lands (GHD, 2018), though agricultural lands in the Muskoka River watershed are limited.

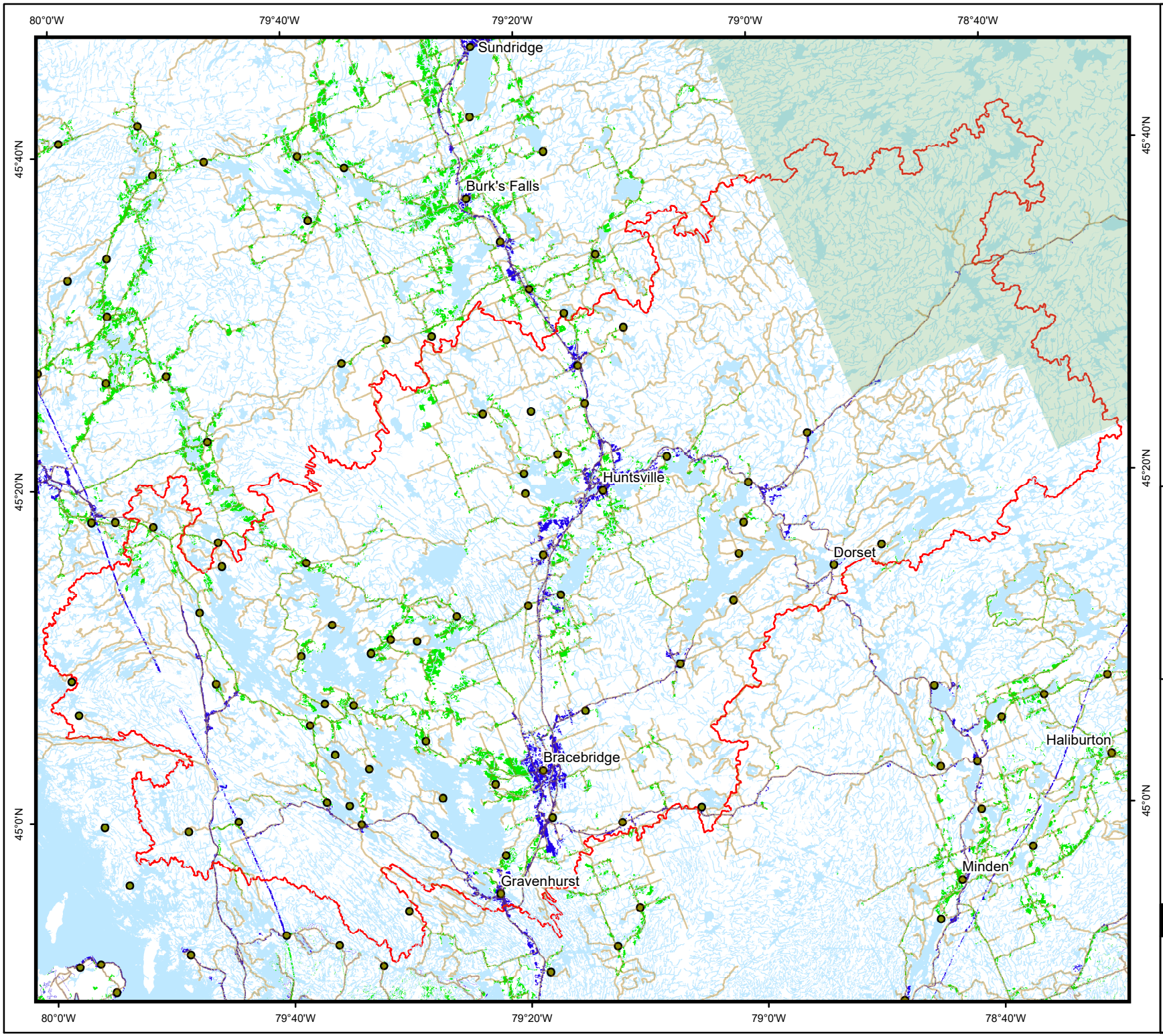
2.2.2 Agricultural Land Assessment

We mapped agricultural land use in the Muskoka River watershed to ensure that future sampling for agricultural contaminants (e.g., insecticides and herbicides) was focused in areas under the highest potential stress from agricultural runoff. In general, agricultural land in the Muskoka River watershed is limited, however the Ontario Watershed Information (OWIT) tool, which was used to identify agricultural areas, also includes golf courses under the same classification (i.e., Agricultural and other Rural Use). Golf courses are a potential source of similar contaminants as crop land due to the use of fertilizer as well as weed and pest control. OWIT land use is classified using the Ontario Land Cover Compilation v2.0 which is comprised of the Provincial Land Cover Database, Far North Land Cover, and the Southern Ontario Land Resource Information System. Agricultural land is classified as open grassland with sparse shrubs in rural land and areas of row crops and fallow fields. Undifferentiated land includes field and forage crops and rural properties along with urban brown fields and openings within forests. To our knowledge this is the best compilation of land use data available in the region and was therefore deemed suitable for use as a proxy for agricultural lands in the Muskoka River watershed. Land use mapping from the Natural Capital Inventory project may be beneficial but was not available at the time of reporting.

Our review of agricultural land in the watershed identified several locations, which we believe warrant investigation as part of the monitoring program updates being undertaken by the District (Figure 3). The watershed area of two of the main tributaries flowing into Three Mile Lake, one from the North and one from the South, contain 23% and 12% agricultural lands respectively (Figure 4). The Shadow River watershed,

which flows into northern Lake Rosseau at Rosseau Bay also contains significant agricultural lands (6%) along with potential runoff from the Village of Rosseau (Figure 5). The reach of the north branch of the Muskoka River between Fairy Lake and Mary Lake near Huntsville contains ~5.5 km^2 of agricultural land despite a small local watershed area of 44 km^2 (12%; Figure 6). Lastly, we identified the reach of the Muskoka River, downstream of the Town of Bracebridge as a key location for monitoring agricultural contaminants (Figure 7). This reach of the Muskoka River receives drainage from agricultural lands west of the Town of Bracebridge, and the Muskoka Highlands Golf Course via a small tributary stream and agricultural lands along the shore of the river between Bracebridge and Lake Muskoka.


80°0'W
79°40'W
79°20'W
79°0'W
78°40'W
45°40'N
45°20'N
45°0'N
Sundridge
Burk's Falls
Parry Sound
Huntsville
Dorset
Haliburton
Bracebridge
Gravenhurst
Minden
Penetanguishene
Midland
Port McNicoll
Victoria Harbour
Waubaushene
Legend
Towns and Communities
Township of Seguin Facilities
Lagoons
Water and Wastewater Treatment Plant
Roads
Algonquin Park
Waterbodies
Rivers
Muskoka River Watershed
0 3.25 6.5 13 19.5
km
N
Scale = 1:628,079
Hutchinson
Environmental Sciences Ltd
Project #: 220010
Drafted: K. Hadley
Reviewed: B. Parsons
Projection: UTM Zone 17N
Datum: NAD 1983
Date: Nov 02, 2023
Figure 2
Muskoka River Watershed Water and Wastewater Treatment Facilities



Legend

- Roads
- Towns and Communities
- Algonquin Park
- Waterbodies
- Rivers
- Muskoka River Watershed
- 27 - Community / Infrastructure
- 28 - Agriculture and Undifferentiated Rural Land Use

0 2.75 5.5 11 16.5 km

Scale = 1:563,934

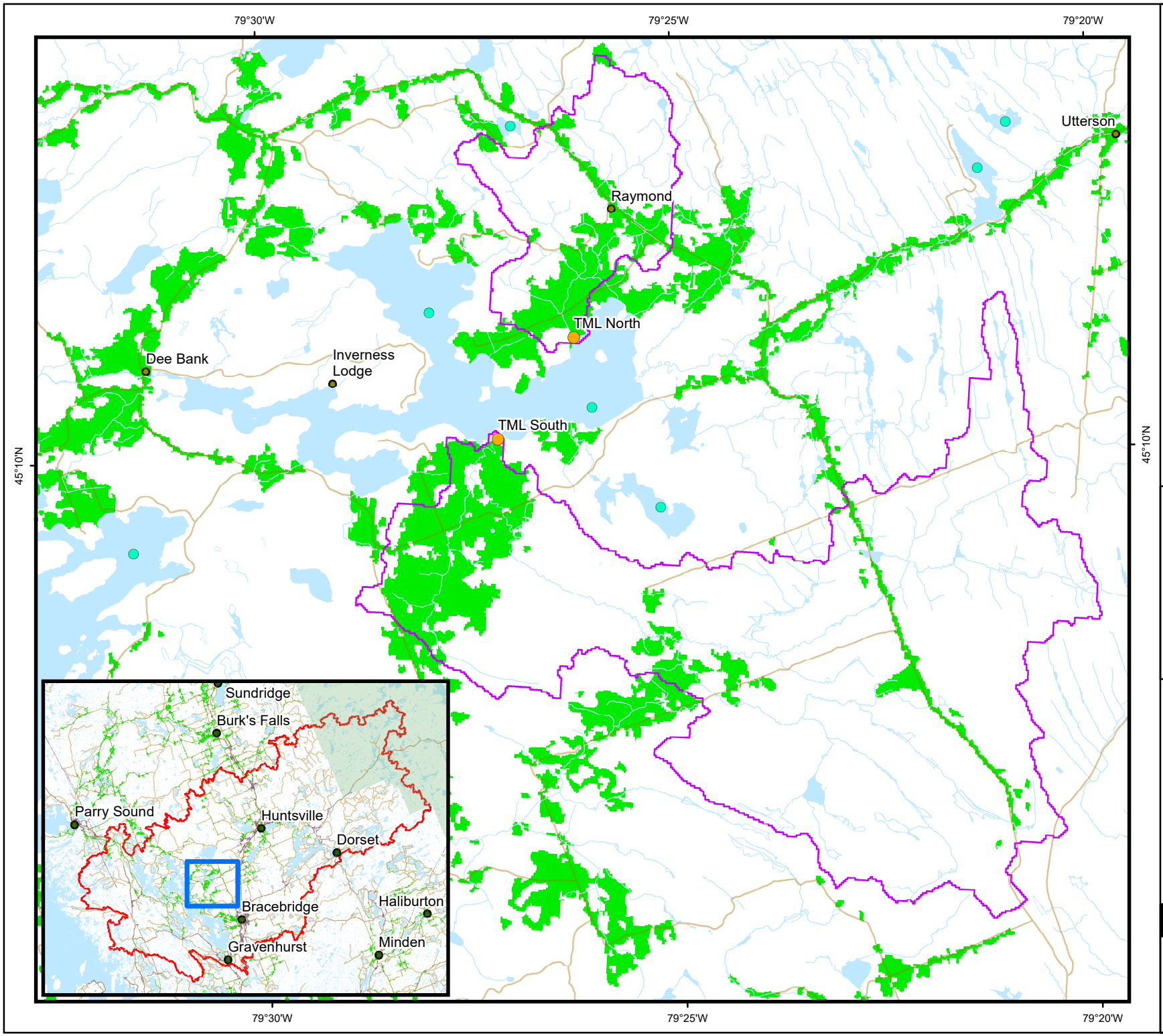
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Project #:	220010
Drafted:	K. Hadley
Reviewed:	B. Parsons
Projection:	UTM Zone 17N
Datum:	NAD 1983
Date:	Nov 02, 2023

Figure 3

Agricultural and Urban Areas in the Muskoka River Watershed



Legend

- Contaminants Monitoring Location
- District Sampling Sites
- Roads
- Towns and Communities
- Tributary Subwatershed Boundary
- Waterbodies
- Rivers
- Muskoka River Watershed
- 28 - Agriculture and Undifferentiated Rural Land Use

0 0.4 0.8 1.6 2.4 km

Scale = 1:80,000

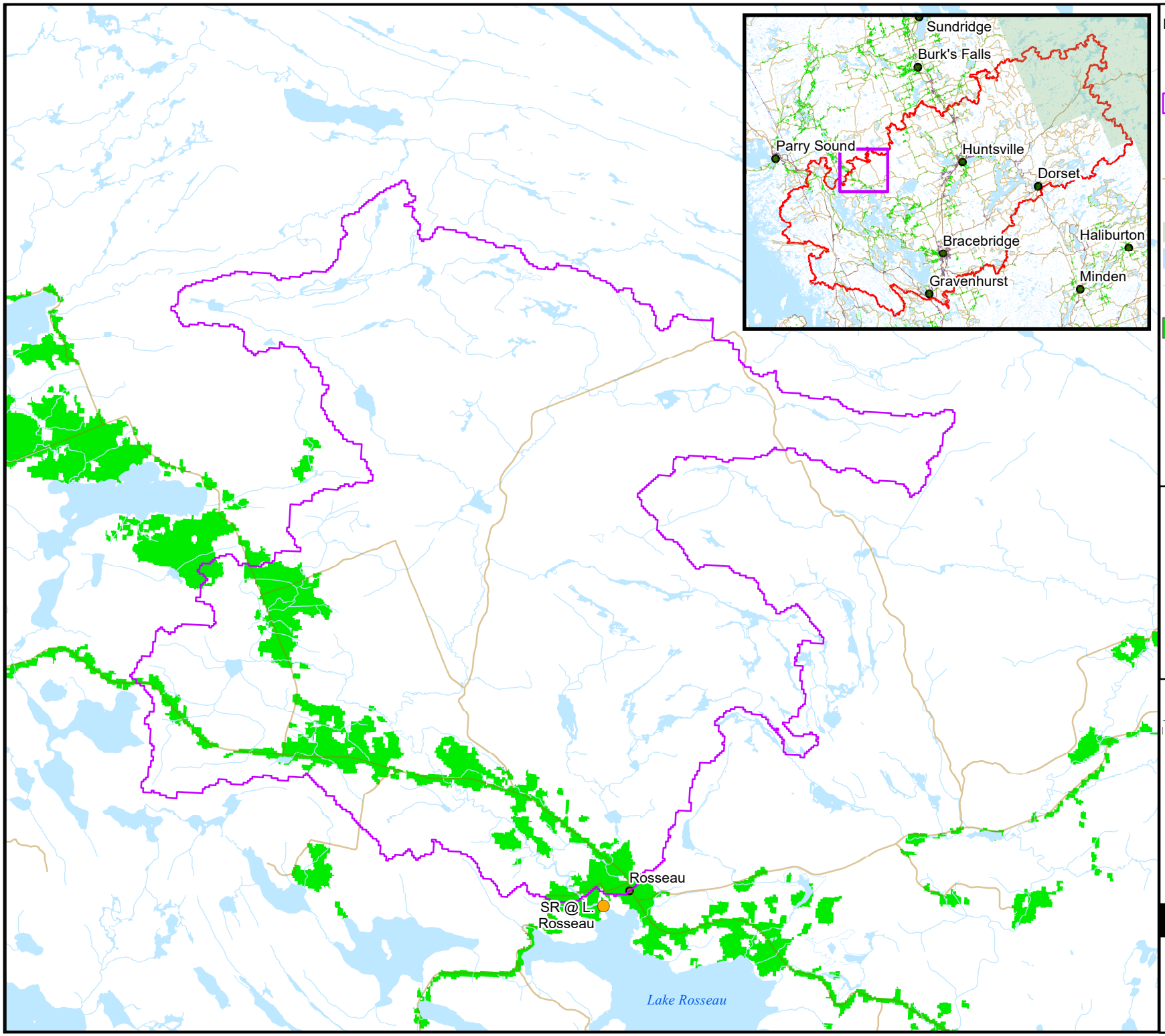
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Drafted:	K. Hadley
Reviewed:	B. Parsons
Projection:	UTM Zone 17N
Datum:	NAD 1983
Date:	Nov 02, 2023

Figure 4

Agricultural Areas near Three Mile Lake



Legend

- Contaminant Monitoring Location
- Shadow River Watershed
- District Sampling Sites
- Roads
- Towns and Cities
- Algonquin Park
- Waterbodies
- Rivers
- 28 - Agriculture and Undifferentiated Rural Land Use

0 5 10 20 30 km

Scale = 1:1,727,533

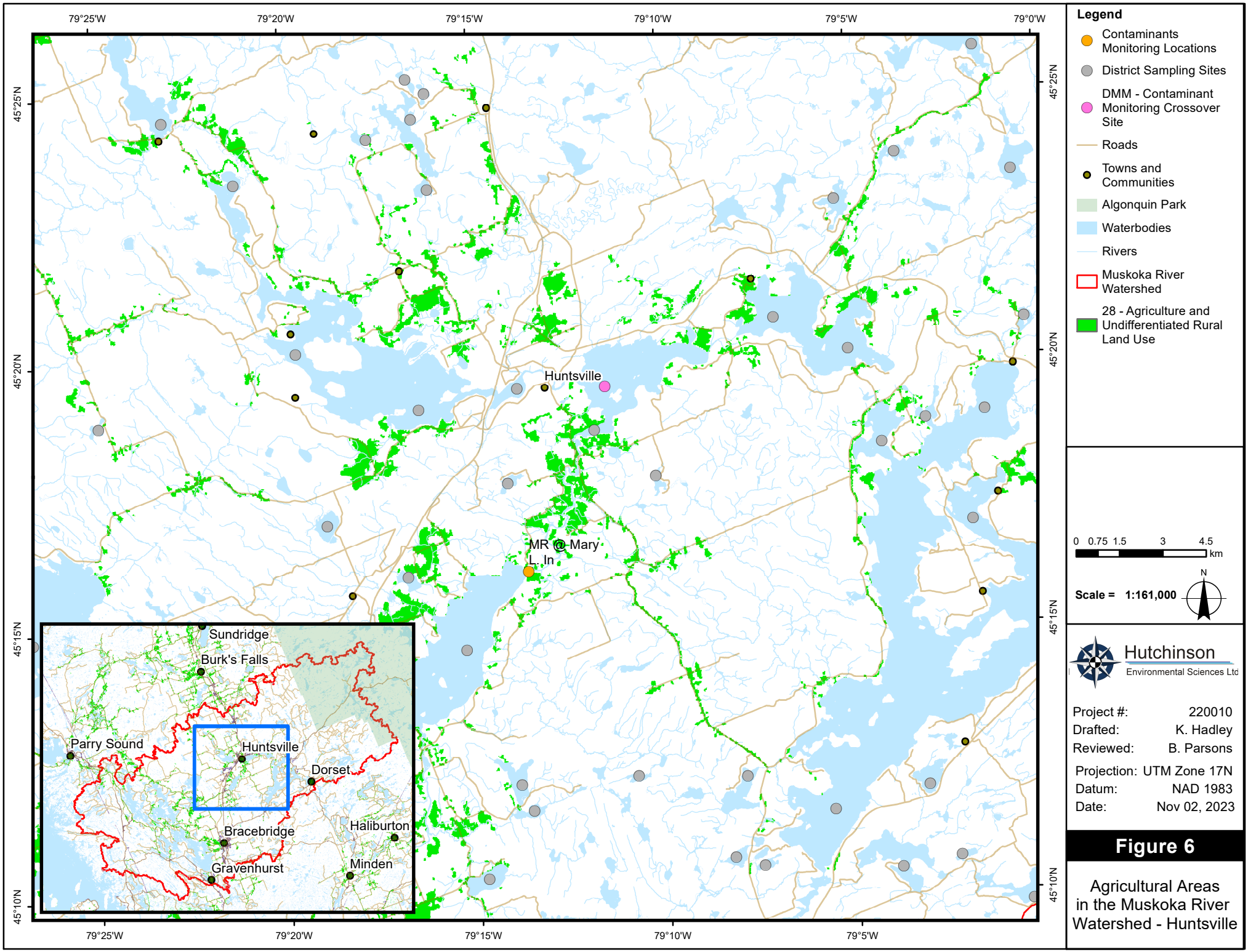
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Reviewed:	B. Parsons
Projection:	UTM Zone 17N
Datum:	NAD 1983
Date:	Nov 02, 2023

Figure 5

Agricultural Areas in Shadow River Watershed at Lake Rosseau


79°25'W
79°20'W
79°15'W
79°10'W
79°5'W
79°0'W
45°25'N
45°20'N
45°15'N
45°10'N
Huntsville
MR @ Mary L. In
Sundridge
Burk's Falls
Parry Sound
Huntsville
Dorset
Bracebridge
Haliburton
Gravenhurst
Minden
Legend
Contaminants Monitoring Locations
District Sampling Sites
DMM - Contaminant Monitoring Crossover Site
Roads
Towns and Communities
Algonquin Park
Waterbodies
Rivers
Muskoka River Watershed
28 - Agriculture and Undifferentiated Rural Land Use
0 0.75 1.5 3 4.5 km
Scale = 1:161,000
N
Hutchinson Environmental Sciences Ltd
Project #: 220010
Drafted: K. Hadley
Reviewed: B. Parsons
Projection: UTM Zone 17N
Datum: NAD 1983
Date: Nov 02, 2023
Figure 6
Agricultural Areas in the Muskoka River Watershed - Huntsville

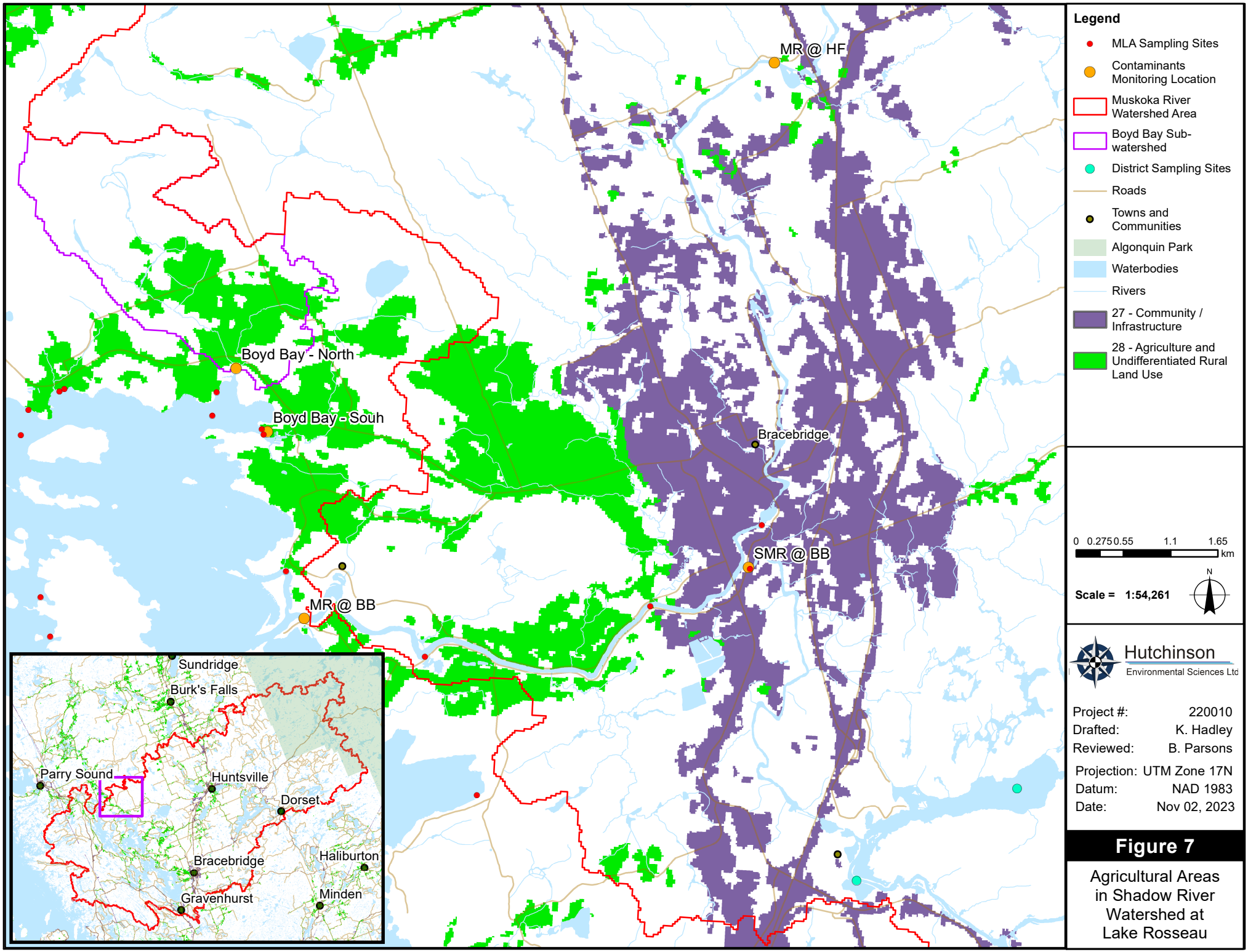


Figure 7

Agricultural Areas in Shadow River Watershed at Lake Rosseau

3. Incorporating Emerging Contaminants into the Muskoka Riverine Monitoring Program

3.1 Muskoka Watershed Riverine Monitoring Program

The DMM launched the Watershed Health Indicators Project in 2022, as part of its IWM Initiative. The aim of the project was to build on existing information and studies to identify environmental and ecological metrics to monitor watershed health in the Muskoka River watershed. The Watershed Health Project Report recommended a shortlist of watershed indicators based on survey results and consideration of additional criteria (HESL 2022), while additional guidance on implementation of the shortlist was provided in a separate report (HESL 2023) which included a list of potential sampling locations across the Muskoka River watershed. Every effort has been made to align the sampling locations of the contaminants monitoring program with sites recommended as part of the Muskoka Watershed Riverine Monitoring Program (HESL 2023) to improve logistics and data comparability. The proposed sampling locations for the Contaminants Monitoring Program, recommended parameters, any overlap with other sampling programs, and reasoning for the sampling locations, is discussed in Table 1.

Table 1. Contaminants Monitoring Program Sampling Station Overview.

Monitoring Location	Monitoring Location Identifier	Latitude Longitude	Agricultural or Urban Monitoring Location	Recommended Parameters	Overlap with other monitoring programs	Reasoning
Three Mile Lake – North Tributary	TML - North	45°11'0.43"N 79°26'12.98"W	Agricultural	• Glyphosate • 2,4-dichlorophenoxyacetic acid (2,4-D) • Neonicotinoids (imidacloprid, clothianidin, and thiamethoxam)	No	Downstream of agricultural lands
Three Mile Lake – South Tributary	TML - South	45°10'8.98"N 79°27'9.21"W	Agricultural	• Glyphosate • 2,4-dichlorophenoxyacetic acid (2,4-D) • Neonicotinoids (imidacloprid, clothianidin, and thiamethoxam)	No	
Shadow River	SR @ L. Rosseau	45°15'21.13"N 79°38'43.91"W	Agricultural	• Glyphosate • 2,4-dichlorophenoxyacetic acid (2,4-D) • Neonicotinoids (imidacloprid, clothianidin, and thiamethoxam)	Muskoka Riverine Monitoring Program (Optional)	
Mary Lake	MR @ Mary L. In	45°16'4.42"N 79°13'36.07"W	Agricultural	• Glyphosate • 2,4-dichlorophenoxyacetic acid (2,4-D)	Muskoka Riverine Monitoring Program	

				• Neonicotinoids (imidacloprid, clothianidin, and thiamethoxam)		
Muskoka River @ Bracebridge	MR @ BB	Muskoka River @ Lake Muskoka Inflow 45° 1'35.74"N 79°23'6.13"W	Agricultural and Urban	• Glyphosate • 2,4-dichlorophenoxyacetic acid (2,4-D) • Neonicotinoids (imidacloprid, clothianidin, and thiamethoxam) • Caffeine • Sulfamethoxazole	Muskoka Riverine Monitoring Program	Overlaps with Muskoka Riverine Monitoring Program Downstream of Town of Bracebridge Downstream of Lagoon Lane WWTP Downstream of Agricultural Lands
	MR @ HF	North Muskoka River @ High Falls 45° 5'23.37"N 79°18'23.03"W		• Glyphosate • 2,4-dichlorophenoxyacetic acid (2,4-D) • Neonicotinoids (imidacloprid, clothianidin, and thiamethoxam) • Caffeine	Muskoka Riverine Monitoring Program	Upstream Reference for Town of Bracebridge

				• Sulfamethoxazole		
	SMR @ BB	South Muskoka River @ Bracebridge 45° 1'53.27"N 79°18'44.56"W		• Glyphosate • 2,4-dichlorophenoxyacetic acid (2,4-D) • Neonicotinoids (imidacloprid, clothianidin, and thiamethoxam) • Caffeine • Sulfamethoxazole	Muskoka Riverine Monitoring Program	South Branch Muskoka River Site upstream of WWTP
Huntsville/Fairy Lake	Fairy L. DW		Urban	• Caffeine • Sulfamethoxazole	Recreational Water Quality Monitoring Program	Downstream of WWTP
Port Carling/Indian River	IR @ P. Carling	45° 6'51.13"N 79°34'55.10"W	Urban	• Caffeine • Sulfamethoxazole	Muskoka Riverine Monitoring Program	Downstream of Town of Port Carling Downstream of Port Carling Wastewater Treatment Plant
Moon River/Bala	Moon R. DS Bala	45° 1'18.17"N 79°40'31.84"W	Urban	• Caffeine • Sulfamethoxazole	Muskoka Riverine Monitoring Program	Downstream of Indian Road (Bala) Water

						Pollution Control Plant Downstream of Town of Bala
South Muskoka River @ Baysville	SMR @ Baysville	45° 8'25.52"N 79° 7'5.94"W	Urban	• Caffeine • Sulfamethoxazole	Muskoka Riverine Monitoring Program	Downstream of Village of Baysville Downstream of Baysville WWTP
Oxtongue River @ HWY 35	OTR @ HWY 35	45°18'41.63"N 78°59'19.91"W	Urban	• Caffeine • Sulfamethoxazole	Muskoka Riverine Monitoring Program	Downstream of Sewage Lagoons

3.2 Develop a list of priority parameters

3.2.1 Priority agricultural parameters

Pesticides are substances used to prevent or terminate pests, the most common of which in Canada are herbicides, insecticides, and fungicides for the control of weeds, insects and fungi, respectively. The active ingredients in many pesticides have changed over time due to improved understanding of environmental pollution and changes in the regulation of their use.

Agriculture and urban developments (e.g., lawns and golf courses) that use pesticides contribute to the load of chemicals that pollute surface waters in Canada. Below we have summarized the three most commonly-used pesticides in Canada which we believe should be assessed as part of the Contaminants Monitoring Program.

Glyphosate is an organophosphate compound and the most widely used agricultural herbicide in Canada (and the U.S.A.), and is also employed in forestry, industrial, and commercial practices, as well as for home gardening and for aquatic plant control. Health Canada notes over 150 products listed with glyphosate as an active ingredient registered in Canada (Health Canada, 2016). 2,4-dichlorophenoxyacetic acid (2,4-D) is amongst the most commonly used of all pesticides in Canada as an herbicide to control broadleaf weeds (e.g., dandelions). 2,4-D is used on turf, forests, woodlots, terrestrial feed, and food crops. 2,4-D was on Health Canada's yearly list of "Top 10 Active Ingredients Sold in Canada" in 2018 with more than 1,000,000 kg of active ingredient and there are over 100 registered products that contain 2,4-D (Health Canada, 2020). In Ontario, Metcalf et al., (2016) reported detections of 2,4-D in samples from three out of six Lake Ontario urban river sites, however levels at these sites were recorded below the CWQG for the protection of aquatic life in freshwater ecosystems ().

Neonicotinoids are an insecticide comprised of nicotine-based systemic chemicals. Agricultural uses of these products in Ontario include corn and soybean (as a seed coating) to control beetles, fleas, some wood-boring pests, flies, and cockroaches. Use of neonicotinoids in Ontario is widespread; up to 100% of corn seed and 60% of soybean seed sold in Ontario were treated (MECP, 2018). There are three neonicotinoids currently approved for use in Canada: imidacloprid, clothianidin, and thiamethoxam.

Accredited laboratories often offer analysis of samples for a suite of herbicide and pesticide parameters for between $100-150 per sample; however, these packages do not necessarily include the key parameters reviewed here and, in some cases, may include pesticides and herbicides that are no longer registered for use in Canada. For example, many water quality analysis packages include aldrin + dieldrin, chlorodane, edrin and heptachlor, which have been banned for sale and use in Canada and have subsequently had their water quality guidelines withdrawn by the federal government. We recommend focusing the sampling and laboratory analysis on the most widely applied chemicals reviewed above, rather than assessing a wide array of pesticides and herbicides whose concentrations would be expected to fall below detection limits as they have been out of use for decades. Based on our review a short-list of agricultural parameters should be:

- Glyphosate (~$200)
- 2,4-dichlorophenoxyacetic acid (2,4-D; ~$110)

- Neonicotinoids (imidacloprid, clothianidin, and thiamethoxam; ~$300)

3.2.2 Priority water and wastewater treatment facility parameters

The criteria used for the selection of pharmaceuticals were based on the levels and frequency of detection of the pharmaceuticals in the aquatic environment noted in previous studies (e.g., Schwartz et al. 2021). Based on a study of pharmaceuticals in source waters across Canada, focused specifically on 95 First Nations communities, the most frequently detected pharmaceuticals were Atenolol (blood pressure medicine; 28.4% detection), caffeine (32.5% detection), Carbamazepine (epilepsy and bipolar disorder, 14% detection), Cotinine (nicotine metabolite, 17.4% detection), Metformin (diabetes treatment, 21.6% detection), and Sulfamethoxazole (antibiotic, 14% detection). All other pharmaceuticals measured were detected in less than 10% of the samples collected.

Microplastics in the environment have recently become an issue highlighted in scientific and environmental media resulting in increased public concern. Scientific assessment of microplastics in surface waters has proved challenging and studies have concluded that microplastics are difficult to identify and standardized methods do not exist (e.g., Mintenig et al., 2018). In their review of microplastics in peer reviewed literature Koelmans et al. (2019) concluded that the number of high-quality studies were limited and that standardization of microplastic analysis was needed, including methods of sampling, isolating, purifying and identifying microplastics. Long-term monitoring benefits greatly from standardization and stability of methods of collection and analysis. Standardization of methods for sampling and analysis of microplastics are currently being developed in an academic setting and until such a time that consistent sampling and analysis guidance are available, we recommend delaying sampling of microplastics in the Muskoka River watershed. Sampling sites described in Section 3.3 have been selected with future potential microplastics analysis in mind, however at this time, the analysis of microplastics is not the best use of the resources available as part of the Contaminants Monitoring Program.

A recent review on the detection of ENMs in the aquatic environment has highlighted the challenges associated with sampling and analysis of these materials (Zhang et al. 2019). The current focus of assessment on ENMs is on developing and standardizing laboratory methods for enrichment, separation and detection. This work has focused on laboratory environments and has highlighted the need for adaptation to the real aquatic environment. Surface water, sewage water and industrial wastewater have unique characteristics including pH, ionic strength and other factors that may impact the assessment of ENMs; we recommend delaying sampling of ENMs as part of the Contaminants Monitoring Program and revisiting the possibility and need for assessing these parameters during a future program review.

Caffeine and artificial sweeteners may serve as valuable chemical tracers as they are anthropogenic in origin and are predominantly associated with domestic wastewater (Lange et al., 2012; Spence 2015). The laboratory cost of assessing pharmaceutical chemicals as part of monitoring in the Muskoka River watershed is high relative to other standard water quality parameters, and in the case of microplastics and ENMs, methods are not well established. We recommend the use caffeine and artificial sweeteners as surrogates to characterize human influence and therefore identify the highest priority sampling locations for ENMs and microplastics in the future.

Based on our understanding of the challenges and priorities of sampling and analysis of novel contaminants we recommend that the early stages of the Contaminants Monitoring Program include the following parameters:

- Caffeine
- Sulfamethoxazole

Caffeine provides a good surrogate for human influence, while we believe Sulfamethoxazole is the most applicable to the Muskoka River watershed of the pharmaceuticals detected in source waters across Canada. Sampling of these parameters should be focused where concentrations are expected to be the highest, Section 3.4 will discuss in detail the sites where we recommend sampling and analysis of these contaminants.

3.3 Contaminants Sampling Frequency

Novel contaminants have been identified in the Water Quality Indicators and Watershed Health Indicators reports (HESL 2022a, b) as a gap in our current understanding and a potential issue of future concern in the Muskoka River watershed. We and other experts in the field however believe that the risk associated with novel contaminants remains low in the Muskoka River watershed and have made our recommendations accordingly. Pesticides are no doubt used in the watershed, however, there is not a large agricultural industry in Muskoka relative to other locations in Ontario (e.g., south-western Ontario). Likewise, population density within the District of Muskoka (17.4/km^2) watershed is low relative to other central Ontario regions (e.g., Simcoe County 110.6/km^2) suggesting that the risk from urban contaminants is also low.

We advise sampling a short-list of novel contaminants during the first year of the Contaminants Monitoring Program. Sampling of contaminants, both agricultural and urban, should occur following the schedule proposed for the Muskoka Riverine Monitoring Program (i.e., three sampling periods annually to capture concentrations during seasonal flow regimes in the spring (high flow following spring freshet), summer (low baseflow) and fall (moderate flow).

Following the first year of sampling, an assessment of data and the number of results above the laboratory's minimum detection limit should be completed to determine the most appropriate sampling frequency in future years. For example, if a significant number of results are greater than the minimum detection limit in year one, the District may wish to sample every year for the first five years to establish a baseline dataset, however if the vast majority of samples are non-detects, less frequent sampling will be warranted (e.g., once every 2-3 years).

3.4 Sampling locations and times

In an effort to ensure that the Contaminants Monitoring Program is scaled appropriately to the relatively small risk that we believe contaminants currently pose in the watershed, we have targeted sampling locations in the highest priority areas. If initial results indicate the parameters of interest are found in notable concentrations (i.e., above the minimum detection limit), the program could be easily expanded to include

other sampling locations. A total of 5-7 agricultural monitoring locations, and 6-8 urban monitoring locations have been proposed, respectively (Table 1).

3.4.1 Agricultural Priority Locations

3.4.1.1 Three Mile Lake Tributaries

We identified the tributaries of Three Mile Lake as potential sources of agricultural contaminants based on our review of the available GIS data in the watershed (Figure 4). Agricultural lands are more common in the Three Mile Lake area than other parts of the watershed, and the water quality of Three Mile is heavily scrutinized because of recurring algal blooms so additional information is welcome. Monitoring of Three Mile Lake is completed through the DMM's Recreational Water Quality Monitoring Program and the Lake Partner Program. Two sites are currently sampled annually due to Three Mile Lake's vulnerable status following the District's Official Plan policy, one site is in Hammell's Bay, and one is in the East basin. Both of these sites are deep water sampling locations designed to monitor long-term lake health. The southern and north-eastern tributaries to Three Mile Lake should be sampled as part of the Contaminants Monitoring Program (Figure 4). The Contaminants Monitoring Program should include the establishment of monitoring stations at the inflow from these two tributary streams to Three Mile Lake. These stations would be monitored for agricultural contaminants (Table 1) following the schedule described in Section 3.3 (i.e., spring, summer' and fall).

3.4.1.2 Shadow River

Based on our review of the available GIS data in the watershed, we identified lands in the Shadow River sub-watershed as a potential source of agricultural contaminants (Figure 5). Currently no monitoring by the District occurs in the Shadow River or in the Northern bay of Lake Rosseau where contaminants from these lands may be detected. The Muskoka Lakes Association maintains several long-term water quality monitoring stations in Rosseau Bay; however, these samples are not currently analyzed for contaminants of potential interest. The Contaminants Monitoring Program should include the establishment of a monitoring station at the inflow of the Shadow River to Lake Rosseau (Figure 5). This station would be monitored for agricultural contaminants (Table 1) following the schedule described in Section 3.3.

3.4.1.3 North Branch Muskoka River Upstream of Mary Lake

We identified the reach of the North Branch of the Muskoka River between Fairy Lake and Mary Lake as a potential target location for the monitoring of agricultural contaminants (Figure 6). District monitoring in the area occurs at the outflow from Fairy Lake upstream of the agricultural development. This station is a deep-water long-term lake monitoring site that is part of the Recreational Water Quality Monitoring Program.

The Contaminants Monitoring Program in the Muskoka River watershed should include the establishment of a monitoring station at the inflow of the Muskoka River to Mary Lake. This station would be monitored for agricultural contaminants (Table 1) following the schedule described in Section 3.3.

3.4.1.4 Muskoka River downstream of Bracebridge

Substantial agricultural lands were noted downstream of the Town of Bracebridge on the mainstem of the Muskoka River and on a northern tributary of the river (Figure 7). Currently no monitoring by the District occurs in the Muskoka River. The Muskoka Lakes Association maintains several long-term water quality monitoring stations in the Muskoka River; however, these samples are not currently analyzed for contaminants of potential interest.

Sampling for contaminants in the Muskoka River upstream of the inflow to Lake Muskoka could be approached in several ways depending on the resources available. We believe that the Contaminants Monitoring Program in the Muskoka River watershed should, at a minimum, include the establishment of a monitoring station at the inflow from the Muskoka River to Lake Muskoka. This station would be monitored for agricultural contaminants (Table 1) following the schedule described in Section 3.3. This single station would allow the concentrations of agricultural contaminants and flows to be measured to get an estimate of loading from the watershed to Lake Muskoka. Additional sampling sites could be included upstream of the Town at High Falls and on the South Branch of the Muskoka River upstream of the confluence with the North Branch. Assuming detectable concentrations of contaminants, these sites would allow the monitoring program to parse out the contribution of the Town and agricultural lands downstream, from background concentrations upstream of the Town. This may be useful in establishing the source of the contamination, if concentrations of concern are noted at the downstream site. We recommend that the monitoring program for agricultural contaminants include three sites in this region, listed in order of highest priority 1. Muskoka River at Lake Muskoka, 2. Muskoka River at High Falls, and 3. South Muskoka River at Muskoka River Confluence.

In addition, two tributaries with substantial agricultural development that drain into Boyd Bay have been highlighted. Currently, we believe that focusing the program on the Muskoka River site(s) is advisable given resources available for monitoring are likely to be limited, however if expansion of the program is possible in the future these tributaries should be considered as potential monitoring additions.

3.4.2 Water and Wastewater Treatment Facility Priority Locations

Recommended monitoring locations for urban contaminants are located in the highest priority locations with the understanding that should development patterns change in the watershed in the future, the program could be altered to relocate existing or include additional sampling locations. Urban contaminants are a relatively small risk within the watershed but an important part of a long-term comprehensive monitoring strategy. A total of 6-8 urban contaminant monitoring locations have been proposed to establish a baseline throughout the watershed.

3.4.2.1 Huntsville/Fairy Lake Monitoring Location

Using available GIS data in the watershed from the MECP and District, three water and wastewater treatment facilities in the Huntsville/Fairy Lake region were identified which could be potential sources of contaminants and downstream sampling of urban contaminants is recommended (Figure 8). Currently the District maintains two deepwater monitoring sites on Fairy Lake, one in the centre of the lake and one in the southern bay of the lake just upstream of the outflow. Ideally contaminants monitoring would take place

as close to the treatment facility discharge as possible (e.g., just downstream of the Mountview Wastewater Treatment Plant), however three sites at this location may not be feasible and therefore we have recommended that the District's long-term Fairy Lake monitoring station be used as the Contaminants Monitoring Program sampling site (Figure 8). In addition to ongoing monitoring as part of the Recreational Water Quality Monitoring Program, this station would include contaminants monitoring in spring, summer and fall.

3.4.2.2 Baysville Monitoring Location

Two water and wastewater treatment facilities managed by the District are located in the Baysville region, the downstream of which represents a valuable monitoring location for urban contaminants (Figure 9). The Baysville Wastewater Treatment Plant (WWTP) services a population of approximately 348 people with a permitted average daily flow of 475 m^3/day. The Birch-Glen Drinking Water System draws source water from Lake of Bays with a capacity of ~1,100 m^3/day. No current monitoring is completed downstream of these locations to our knowledge. The proposed contaminant monitoring location is downstream of both treatment facilities and the Village of Baysville. Ideally contaminants monitoring would take place as close to the treatment facility discharge as possible (e.g., upstream of Baysville near the Landscapes Resort), however this site would fail to capture runoff from the Village and the risk of contaminants in the region is not high enough to justify two sampling station in such close proximity. We have therefore selected a downstream location which overlaps with the proposed sampling location for Muskoka Riverine Monitoring Program and captures what we expect to be the most significant potential sources of contamination in the area. This station would be monitored for urban contaminants (Table 1) following the schedule described in Section 3.3.

3.4.2.3 Bala Monitoring Location

Based on our review of the available GIS data in the watershed, we identified two water and wastewater treatment facilities in the Bala region, the Minto Street Water Treatment Facility, and the Indian Road (Bala) Water Pollution Control Plant. The Indian Road (Bala) Water Pollution Control Plant services 390 accounts (ca. 2022) and an average daily flow of 550 m^3. We have recommended a single monitoring site near Bala which overlaps with a monitoring location proposed in the Muskoka Riverine Monitoring Program (HESL 2023) and would be a potential valuable monitoring location for urban contaminants (Figure 10). No current District monitoring is underway at these locations to our knowledge, however the Muskoka Lakes Association maintains several monitoring locations in the Moon River/Bala area. The site we have selected for monitoring is downstream of both treatment facilities and the Town of Bala. This station would be monitored for urban contaminants (Table 1) following the schedule described in Section 3.3.

3.4.2.4 Oxtongue River Monitoring Location

The Oxtongue River receives discharge from sewage lagoons upstream of Highway 35 (Figure 11). A monitoring location has been recommended on the Oxtongue River as part of the Muskoka Riverine Monitoring Program. We recommend that this station also be sampled as part of the Contaminants Monitoring Program.

3.4.2.5 Bracebridge and Muskoka Beach

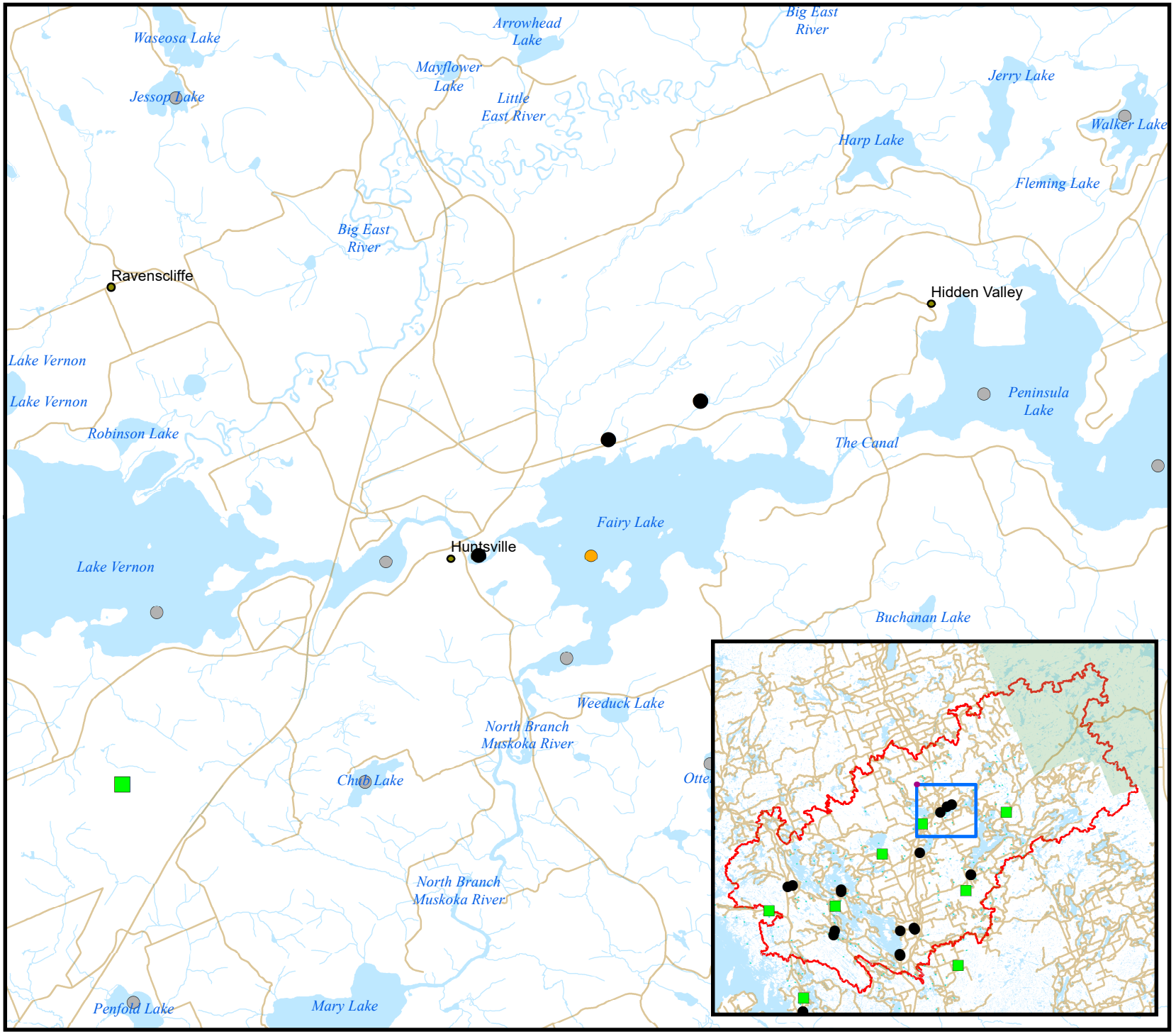
Four water and wastewater treatment facilities discharge to Lake Muskoka in the Bracebridge and Muskoka Beach region at the north end of Gravenhurst (Figure 12). Two of these facilities are water treatment plants, one is located south of the Muskoka River near Kirby's Beach/Strawberry Bay area of Lake Muskoka and the other is located near Muskoka Beach Park; both draw raw water from Lake Muskoka. The other two facilities are the Beach Road Wastewater Treatment Plant (permitted avg. daily flow = 5165 m^3/day) which discharges directly to Lake Muskoka and the Lagoon Lane Wastewater Treatment Plant (permitted avg. daily flow = 8000 m^3/day) which discharges to the Muskoka River downstream of the Town of Bracebridge via diffuser (Figure 12).

The Beach Road Wastewater Treatment Plant discharges directly to Lake Muskoka but the point of discharge is not explicitly identified in the 2022 year-end report. We recommend that the monitoring location in the Muskoka River at Lake Muskoka be analyzed for urban contaminants as well as agricultural contaminants. If concentrations of concern are noted, a monitoring location near the outlet of the Beach Road WWTP should be established.

Additional sampling sites could be included upstream of the Town at High Falls and on the South Branch of the Muskoka River upstream of the confluence with the North Branch. Assuming detectable concentrations of contaminants, additional sites may be useful in establishing the source of the contamination. We recommend that the monitoring program for urban contaminants include three sites in this region, listed in order of highest priority 1. Muskoka River at Lake Muskoka, 2. Muskoka River at High Falls, and 3. South Muskoka River at Muskoka River confluence and, however if resources do not allow monitoring at all three locations, Muskoka River at Lake Muskoka should be the initial focus with further expansion of the program to be determined by the concentrations measured at that primary site.

3.4.2.6 Port Carling Monitoring Locations

The Port Carling Wastewater Treatment Plant is permitted to treat an average daily flow of 926 m^3/day and treated effluent is discharged to the Indian River (Figure 13). The Muskoka Riverine Monitoring Program includes a recommended monitoring location upstream of the inflow of the Indian River to Lake Muskoka upstream of Mirror Lake. This site will serve as both a long-term monitoring site for water quality indicators and a contaminants site would be upstream of Mirror Lake, just downstream of the WWTP discharge (Figure 13).



Legend

- Algonquin Park
- Towns and Communities
- Lagoons
- Water and Waste Water Treatment Facilities
- District Sampling Site
- Contaminants Monitoring Location
- Roads
- Rivers
- Waterbodies
- Muskoka River Watershed

0 5 10 20 30 km

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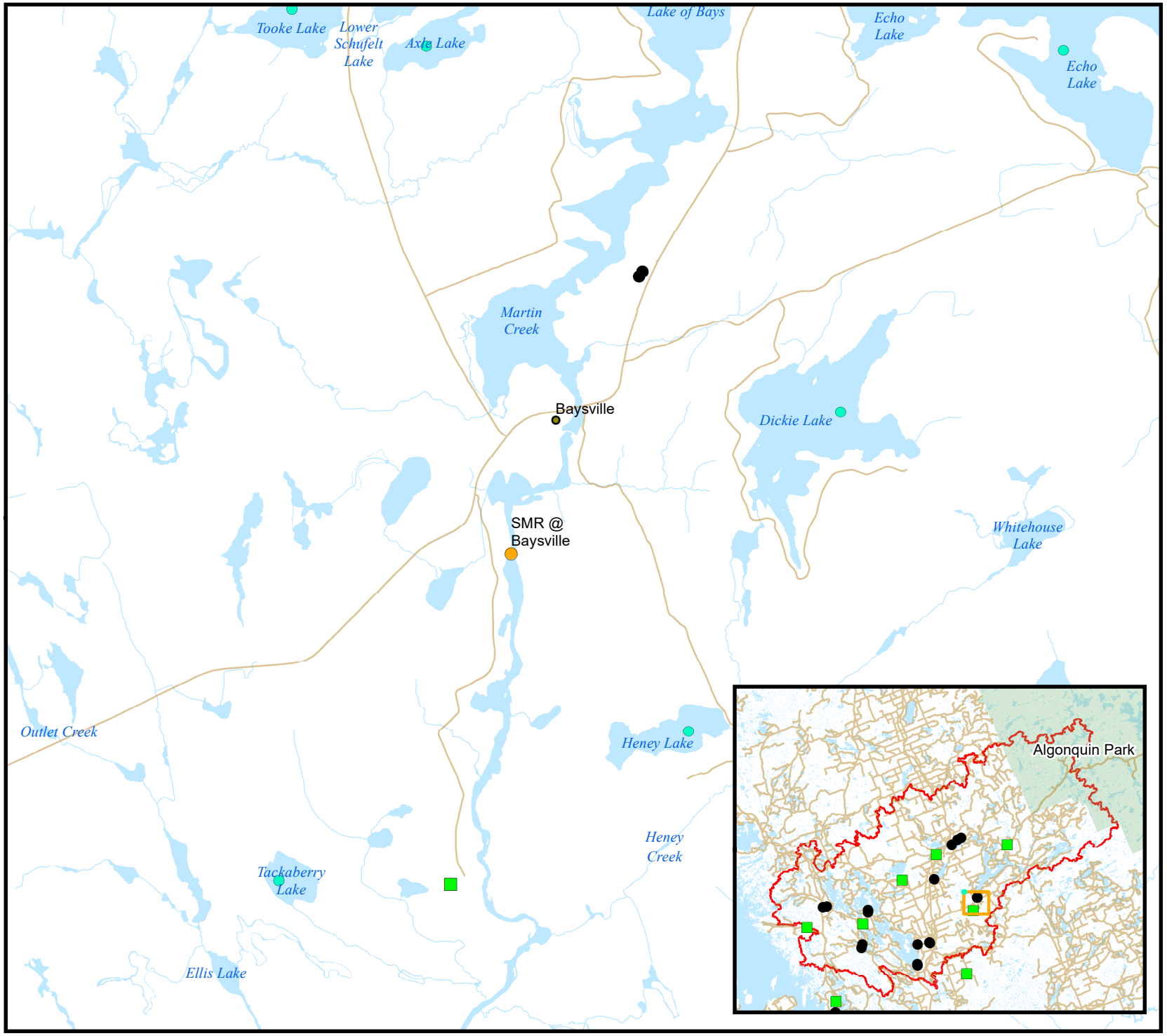
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Project #: 220010
Drafted: K. Hadley
Reviewed: B. Parsons
Projection: UTM Zone 17N
Datum: NAD 1983
Date: Nov 02, 2023

Figure 8

Huntsville/Fairy Lake Monitoring Locations



Legend

- Contaminants Monitoring Location
- Algonquin Park
- Towns and Communities
- Lagoons
- Water and Wastewater Treatment Facilities
- District Sampling Sites
- Roads
- Rivers
- Waterbodies
- Muskoka River Watershed

0 5 10 20 30 km

N

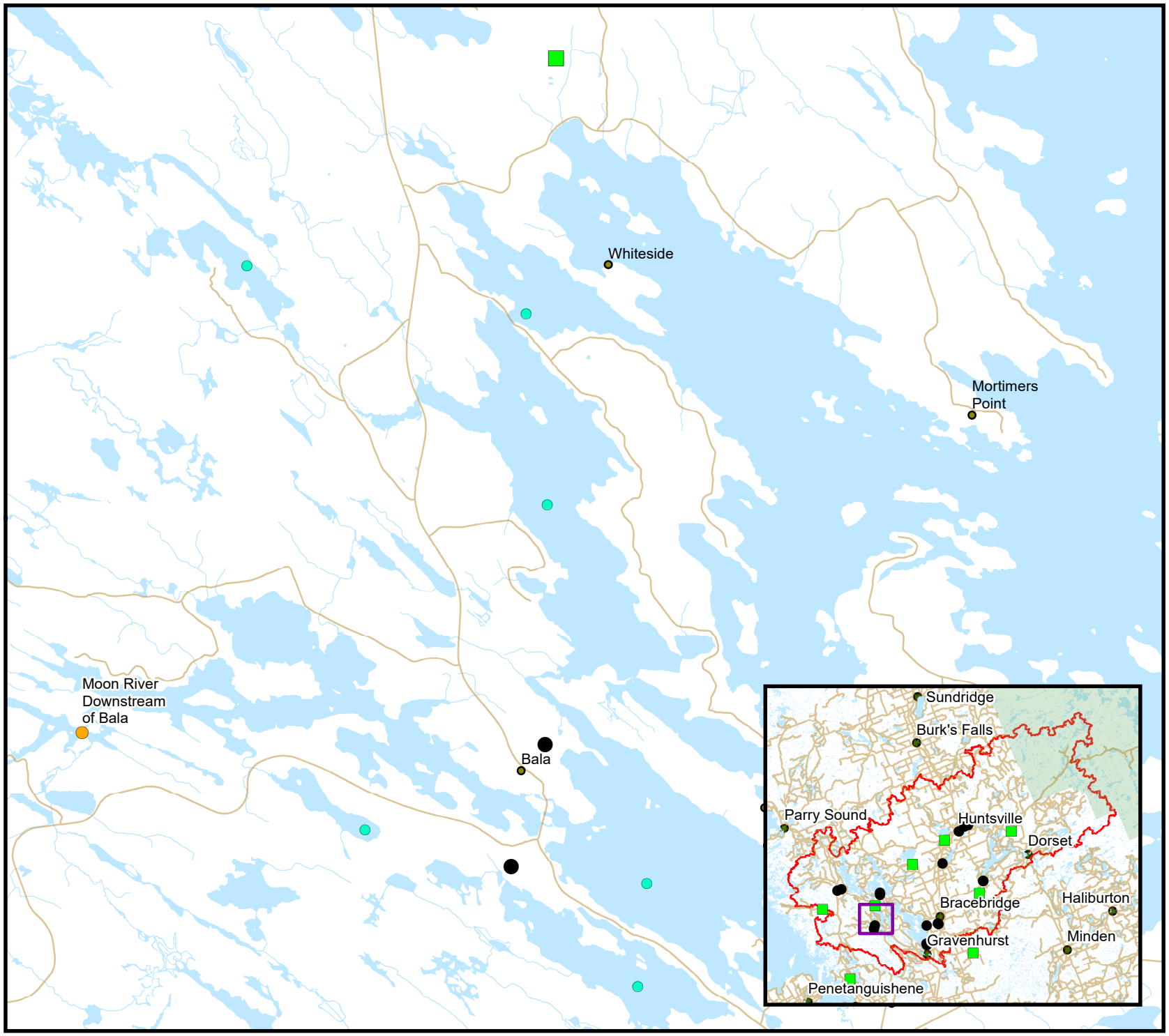
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Drafted: K. Hadley
Reviewed: B. Parsons
Projection: UTM Zone 17N
Datum: NAD 1983
Date: Nov 02, 2023

Figure 9

South Muskoka River at Baysville Monitoring Locations



Legend

- Contaminant Monitoring Location
- Lagoons
- Water and Wastewater Treatment Facilities
- District Sampling Sites
- Roads
- Rivers
- Waterbodies
- Muskoka River Watershed
- Towns and Communities

0 10 20 40 60 km

Scale = 1:1,931,701

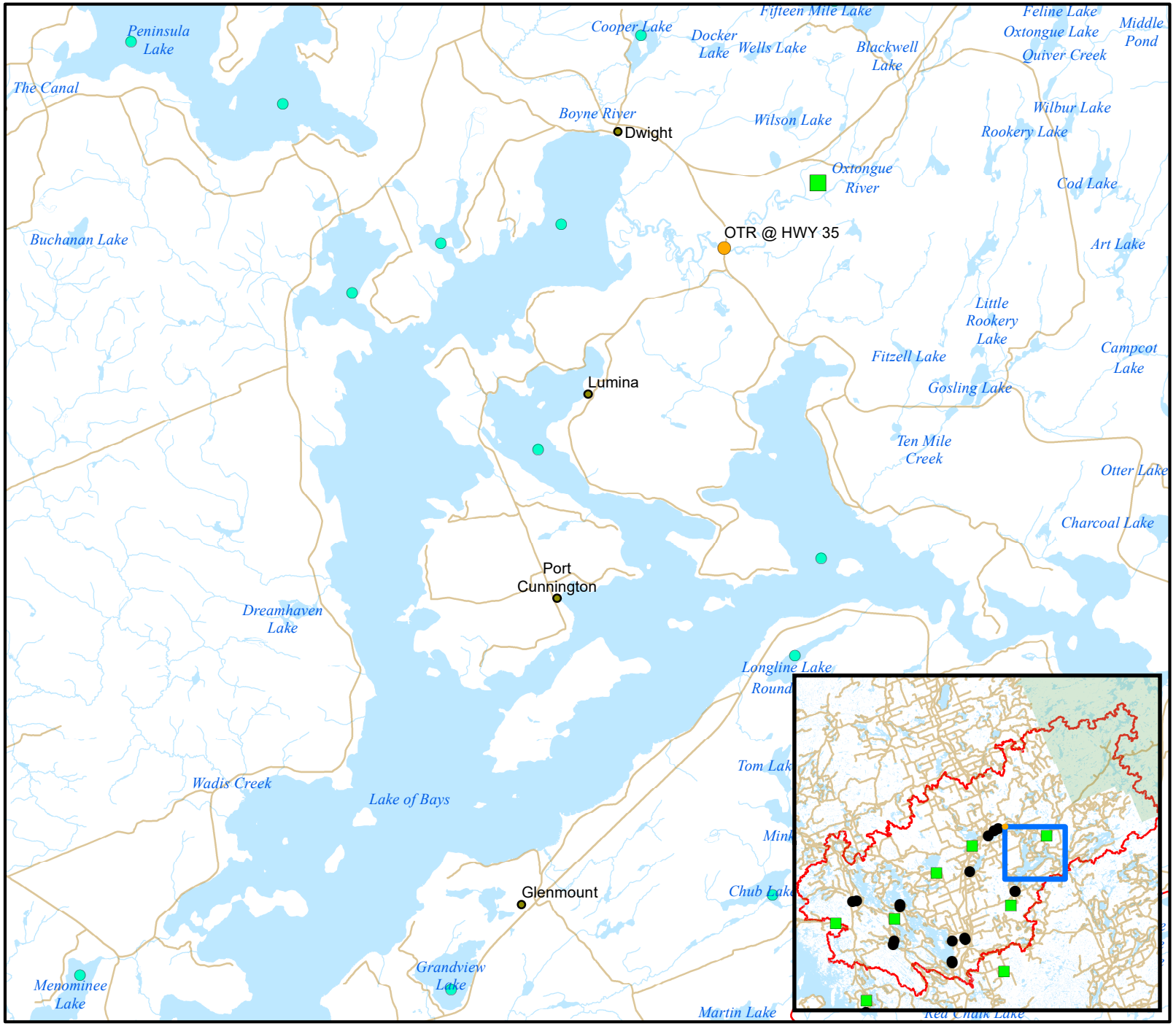
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Reviewed:	B. Parsons
Projection:	UTM Zone 17N
Datum:	NAD 1983
Date:	Nov 02, 2023

Figure 10

Bala
Monitoring Locations



Legend

- Contaminant Monitoring Location
- Towns and Communities
- Lagoons
- Water and Wastewater Treatment Facilities
- District Sampling Sites
- Roads
- Rivers
- Algonquin Park
- Waterbodies
- Muskoka River Watershed

0 5 10 20 30 km

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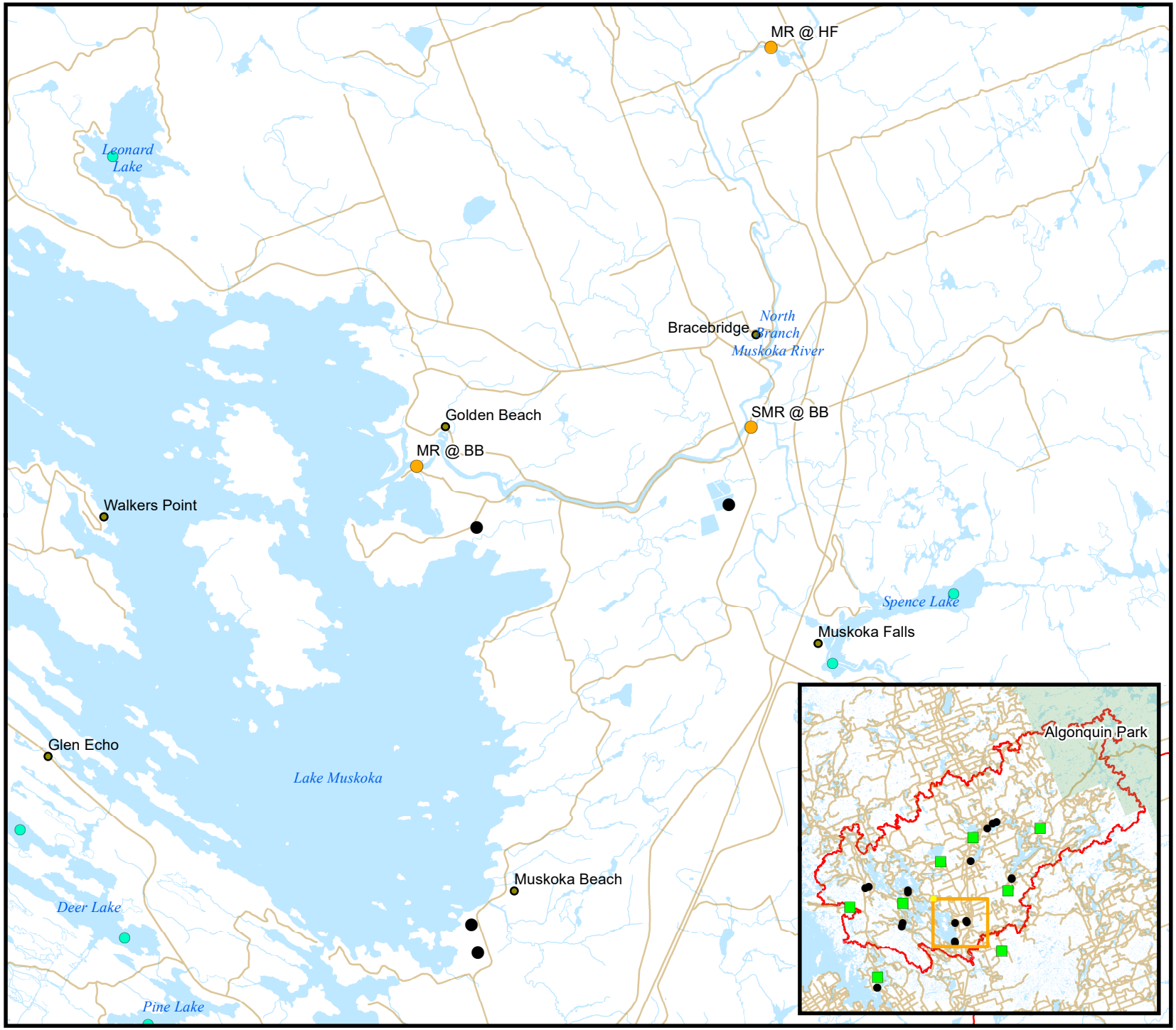
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Figure 11

Oxtongue River Monitoring Locations



Legend

- Contaminant Monitoring Location
- Towns and Communities
- Water and Wastewater Treatment Facilities
- District Sampling Sites
- Roads
- Rivers
- Waterbodies
- Muskoka River Watershed
- Algonquin Park

0 10 20 40 60 km

N

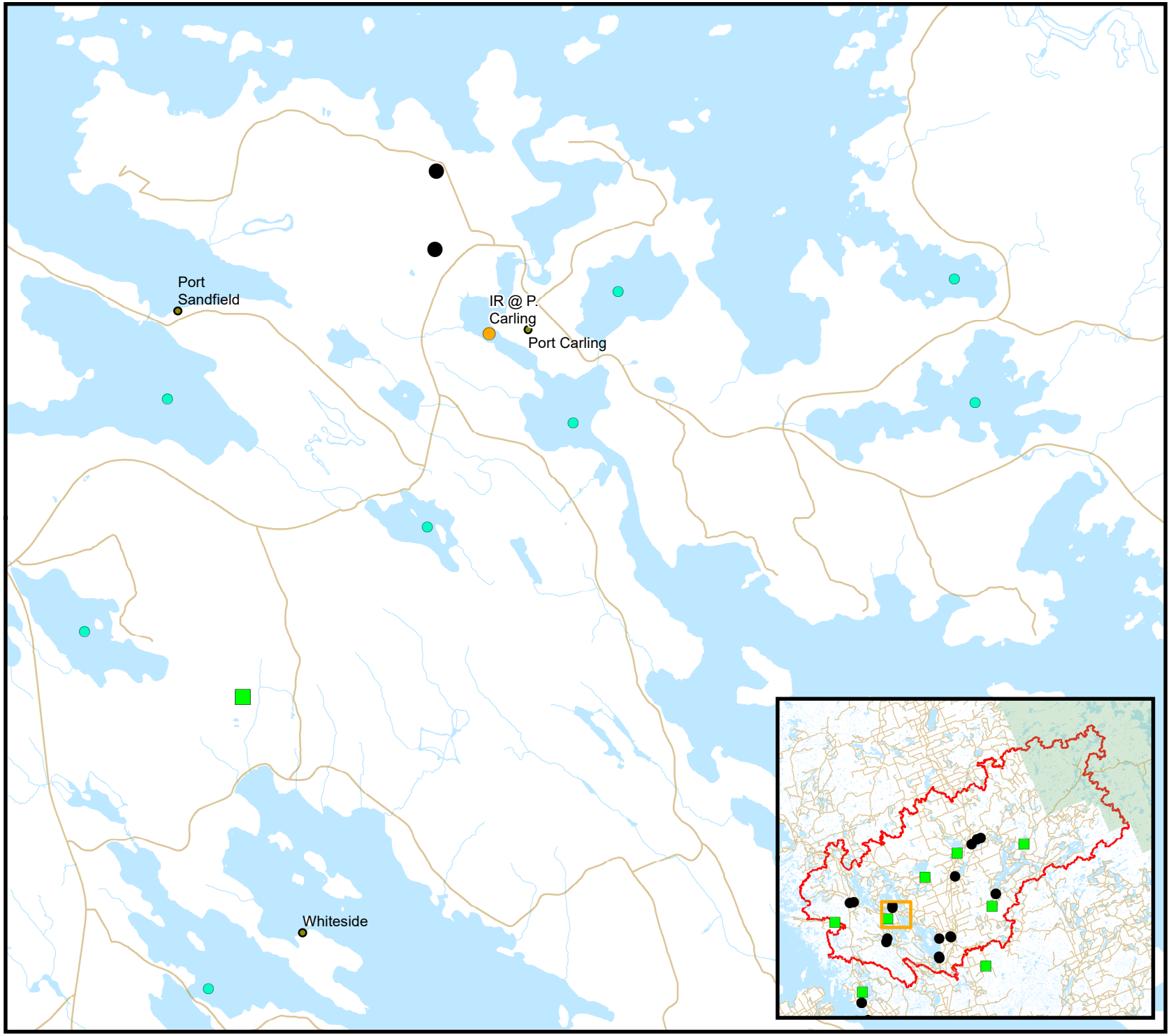
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Figure 12

Lagoon Lane and Muskoka Beach Monitoring Locations



Legend

- Contaminant Monitoring Location
- Lagoons
- Water and Wastewater Treatment Facilities
- District Sampling Sites
- Roads
- Rivers
- Waterbodies
- Muskoka River Watershed
- Towns and Communities

0 10 20 40 60 km

Scale = 1:1,931,701

N

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Drafted: K. Hadley
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Projection: UTM Zone 17N
Datum: NAD 1983
Date: Nov 02, 2023

Figure 13

Port Carling (Medora) Pollution Control Monitoring Locations

4. Reporting Framework

4.1 Annual Report

Ongoing review and refinement of the monitoring program is essential for ensuring that it is effectively characterizing contaminants in a scientifically defensible manner. To ensure quality control and quality assurance, we recommend that at the end of each monitoring season (i.e., annually) an in-depth analysis of contaminants data (e.g., summary statistics) be performed alongside analysis from the Muskoka Riverine Monitoring Program including:

- a summary of monitoring activities conducted under the Contaminants Monitoring Program.
- tabular summaries of all the data and information generated in an electronic format (i.e., Excel spreadsheet)
- statistical summaries and interpretation of all data in the report text,
- comparison of environmental conditions with federal and/or provincial guideline values where available
- Recommendations for a) follow up to any metrics exceeding trigger values, b) revisions to the monitoring programs based on any critical flaws or concerns identified in the previous year, including the addition or subtraction of monitoring locations based on results and amount of data found to be less than the laboratory's minimum detection limit.

Once sufficient data is available and depending on the rate of non-detects, more robust analysis (e.g., trend assessment) of contaminants data could be included in 2 to 5-year reporting including assessment of trends throughout the watershed.

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Hutchinson

Environmental Sciences Ltd.

District of Muskoka Water Quality Indicators
Citizen Science Cyanobacterial Bloom Monitoring Program

Prepared for: District of Muskoka
Job #: J220010

October 31, 2023

Final Report

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October 31, 2023 HESL Job #: J220010

Glenn Cunnington
District of Muskoka

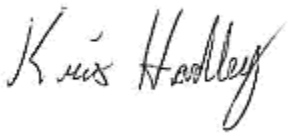
Dear Mr. Cunnington:

Re: Draft Report for the District of Muskoka - Citizen Science Cyanobacterial Bloom Monitoring Program

We are pleased to submit the Draft Report for the District of Muskoka – Citizen Science Cyanobacterial Bloom Monitoring Program Project. This report outlines the metrics necessary to document the spatial and temporal occurrence of a perceived bloom across a large spatial scale allowing data to be useful in lake management, summarizes of the current technology-based options for recording data in the field, and assesses the cost and applicability of digital Application options to the Muskoka River Watershed.

We thank you for the opportunity to undertake this assignment and look forward to receiving your comments.

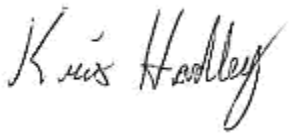
Sincerely,
Per. Hutchinson Environmental Sciences Ltd.



Kris Hadley, Ph. D.
Senior Aquatic Scientist

Signatures

Report Prepared by:



Kristopher R. Hadley, Ph.D.
Senior Aquatic Scientist

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1. Introduction

Based on the recommendations provided by Hutchinson Environmental Sciences Ltd. (HESL) to the the District Municipality of Muskoka (DMM) in the final report for the Water Quality Indicators Project to inform ongoing Integrated Watershed Management in the Muskoka River Watershed, the DMM requested that HESL develop a watershed-wide Citizen science-based bloom watch program to collect and archive detailed data on cyanobacteria and other nuisance algal blooms.

Recent confirmation of blue-green algal blooms in Muskoka lakes, and a public perception that algae are more abundant than they used to be, have resulted in substantial concern about the current and future impacts of algal blooms in Muskoka. Under the current DMM Official Plan (March 2023), lakes which experience a harmful algal bloom are registered as Schedule E2 and considered vulnerable, triggering a causation study. During the pilot program (Peninsula Lake) and several of the ongoing Causation Studies (i.e., Echo Lake, Stewart Lake) under the current official plan one of the key data gaps identified was the lack of information recorded on blooms (HESL, 2020, 2022a, b). Outcomes from the causation study program recommended the development of a citizen scientist program for bloom monitoring, recording the onset, extent, and severity of cyanobacterial blooms across the watershed.

Currently suspected cyanobacterial blooms are reported to the Ministry of the Environment, Conservation and Parks (MECP). The MECP then gathers information, conduct field visits, and performs testing to confirm if a blue-green algae bloom is present. The Muskoka Watershed Council (MWC)'s Algae Subcommittee has developed a citizen-science algae monitoring program to build an understanding of algae and algal blooms in Muskoka which was modelled on the Cyanobacteria Monitoring Collaborative's (CMC) algae monitoring program.

The CMC algae monitoring program included a tiered approach to citizen engagement and harmful algal bloom monitoring (HAB) monitoring (Table 1). The MWC program has adopted aspects of Tier III from the CMC with slight modifications to the methodology based on expert opinion to account for the properties and needs of monitoring in the Muskoka River watershed. The stated objective of the "cyanomonitoring" component of the CMC program, which builds upon Tier I and II is to:

1. track development and dynamics of cyanobacterial populations,

2. assist in tracking trends due to climate changes and current and emerging land use practices, and assess waterbody/human health vulnerability to toxic cyanobacteria.

Organizations interested in participating in the MWC program purchase or borrow equipment (i.e., sampling equipment and a fluorometer) and pay an annual fee to participate in the program. Briefly, the ad-hoc bloom sampling and analysis as a part of the program consists of:

1. recording information about the extent and duration of the bloom, whether it moves over time, and the weather conditions at the time it occurred;

2. collecting samples for fluorometric analysis over its course; and

3. submission the data online to MWC using the online forms.

Following successful completion of the pilot project (2019, 2021 and 2022), the MWC Annual Report concluded that a simple relationship between cyanobacterial algal blooms and patterns of abundance in lakes or through the season was not apparent and that additional years of data and a greater number of lakes in the program to build a dataset were required (MWC, 2023). They identified a path forward for the ongoing development of the MWC Algae Monitoring Program as:

- • Expand phytoplankton monitoring to interested lake associations across Muskoka as an addition to their existing water quality efforts;
- • Develop information materials and presentations on algae for delivery to lake associations and others;
- • Continue to collaborate with select lake associations on additional algal sampling to address specific issues of prevalence and/or causation of algal nuisance blooms;
- • Evaluate the program in 2026 and decide whether to continue beyond that date; and
- • Communicate these efforts to other lake associations across Muskoka.

The current MWC program is focused on collecting detailed information from a relatively small number of lakes to gain a greater understanding of the distribution, abundance, and seasonal cycles of phytoplankton across Muskoka area lakes and thereby identify conditions favouring harmful algae blooms.

The goal of this project was to review and highlight options for the IWM program to employ for watershed scale monitoring of perceived HABs in the Muskoka River Watershed. This information would provide an entry level option for users interested in HAB management but who may be overwhelmed by the technical scope of the MWC Algal Monitoring Program and support the growth of the MWC Program while collecting valuable data on the spatial and temporal occurrence of blooms across the watershed.

The primary focus of this project was to produce a report that:

- Outlines the metrics necessary to document the spatial and temporal occurrence of a perceived bloom across a large spatial scale allowing data to be useful in lake management.
- Summarizes the current technology-based options for recording data in the field.
    - Assesses the cost and applicability of App options to the Muskoka River Watershed.

The proposed Citizen science cyanobacteria monitoring program is not intended to replace formal reporting of the blooms to the MECP nor as a regulatory tool.

Table 1. Overview of the CMC Tiered Approach to Monitoring Harmful Algae Blooms

	Potential Program Use	Purpose	Sample Location	Sample Frequency	Sample Type	Parameters
TIER I Bloom Watch	All State & Federal water programs, general public at large, Citizen Scientitsts, beach monitors, educational institutions, lay monitoring programs	Determine high probability that a cyanobacteria bloom is occurring (ie. vs pollen), utilize as an educational tool, document frequency of occurrence, possible hotspots, report occurrence to state	wherever a bloom appears to be occurring. This could be in open water and widespread, or a distinct scum line located at the shoreline. Any surface water body, anywhere	Whenever a suspected bloom occurs; anywhere, anyplace, anytime	Smartphone image & data submittal via the bloomWatch App (see Cyanos.org)	Waterbody name, weather conditions, water surface conditions, public access, smartphone images, locational Lat/Lon
TIER II CyanoScope	All State & Federal water programs, local and state boards of health, public surface drinking water suppliers, concerned citizens, Citizen Scientists, academia & educators	To track and document the locations and occurrence of potentially toxic cyanobacteria genera	Any surface water bodies	Anytime, anywhere, any frequency	Concentrated 53 Micron Plankton Net sample	Locational data (waterbody name, town, Lat/Lon), digital microscope image submittal
TIER III Cyanomonitoring	All State and Federal water monitoring programs, public drinking water supplies, lake & river associations, various stakeholders, researchers	track spatial and temporal distribution of cyanobacteria pigments, frequency of occurrence, long term trends, concentration levels, and potential toxicity	Minimum of one site per waterbody from the deep hole area or a specific shoreside location	Minimum baseline of one sample collected every other week from June 1 through September 30. Additional samples may be collected from other waterbodies, other sites, other depths, and other frequencies, as long as the minimum baseline is completed. Long term monitoring	Integrated tube sample from the surface to a depth of 3 meters, or a one meter integrated tube sample if collected from the shoreline	Chlorophyll a concentration, Phycocyanin concentration, possible toxin analysis

Note: Reproduced from Quality Assurance Program Plan (QAPP) for the Cyanobacteria Monitoring Collaborative Program (CMC, 2022)

2. Watershed-wide Cyanobacterial Bloom Monitoring Metrics

Monitoring cyanobacteria as part of a watershed wide initiative is a significant logistical undertaking due to the variability in the occurrence (i.e., timing and location) of HABs. Cyanobacteria may bloom for a few hours or less, be spatially limited to specific locations within a particular waterbody (e.g., a single bay) and may also move rapidly depending on local conditions. The use of citizen-science provides local knowledge of where and when blooms may be occurring and a response time to gathering information that cannot be achieved by other means. When blooms are reported to a the Ministry of Environment, Conservation and Parks (MECP) or Health Ministry through spills action, limited resources are available to respond and sample those perceived blooms, particularly given the recent uptick in reporting by property owners and other stakeholders. Taking advantage of the observations of local citizens provides valuable information on bloom formations which is needed to better understand and document the onset, extent, and severity of cyanobacterial blooms.

Once a suspected bloom has been discovered it is important to collect all the necessary site data to accompany water quality samples and profiles. Metadata ("data about the data") is crucially important and must accompany the primary data for it to be interpretable (i.e., useful). The following types of metadata should accompany a bloom report:

- At time of reporting.
    - water body name
    - site description
    - site latitude & longitude
    - name(s) of observer
    - current water surface conditions
    - anecdotal notes on recent local conditions
    - images of blooms (standardized)
- Follow up information.
    - any additional information from laboratory or MECP
    - any additional information from water quality or other analyses (if part of a water quality monitoring program)

The following portions of the report are focused on smartphone-based app solutions for recording and reporting suspected blooms as opposed to field sheets or other methods. Citizen encounters with HABs often occur while individuals are out walking their dogs, jogging, or getting ready work and therefore benefits from a monitoring solution that can be easily and rapidly deployed. Before considering the cost of developing a proprietary application for this purpose, we explored four options for recording HABs from other jurisdictions to assess their functionality and applicability in the Muskoka River Watershed.

3. Technology-based Options for Cyanobacterial Monitoring

Potential options for collecting and storing data on blooms are numerous, for example the EPA and UK Centre for Ecology and Hydrology currently employ smartphone applications (i.e., bloomWatch and Bloomin' Algae) to allow citizens to document harmful algae blooms including location, photos and other metadata. In Australia a recently developed application adds the use of a dichotomous key to help with identifying the algal types prior to reporting via the application, while BloomOptix employes an AI model to automatically identify and count cyanobacterial cells belonging to six of the most common HAB producing genera: *Microcystis*, *Dolichospermum*, *Aphanizomenon*, *Woronichinia*, *Limnoraphis*, and *Gloeotrichia*. In Section 3.1 to 3.4 we have outlined the utility of each of these solutions in the Muskoka River Watershed and highlighted their strengths and weaknesses before providing our recommendation for the best option for deployment by the IWM project for watershed wide HAB tracking. All Apps are free to download, however BloomOptix AI requires an annual subscription to use.

3.1 Bloomin' Algae

Bloomin' Algae is a citizen science app for reporting the presence of harmful algal blooms of blue-green algae which includes expert verification by the UK Centre for Ecology & Hydrology (UKCEH). The app provides guidance on what blooms look like using a limited number of simple pictures to differentiate between green algae, floating macrophytes and harmful cyanobacteria blooms (Figure 1). A global map interface allows bloom reports to be seen in real time from across the globe, and each report is colour coded based on confirmation by professionals (i.e., Confirmed, Rejected, Pending Review; Figure 1).

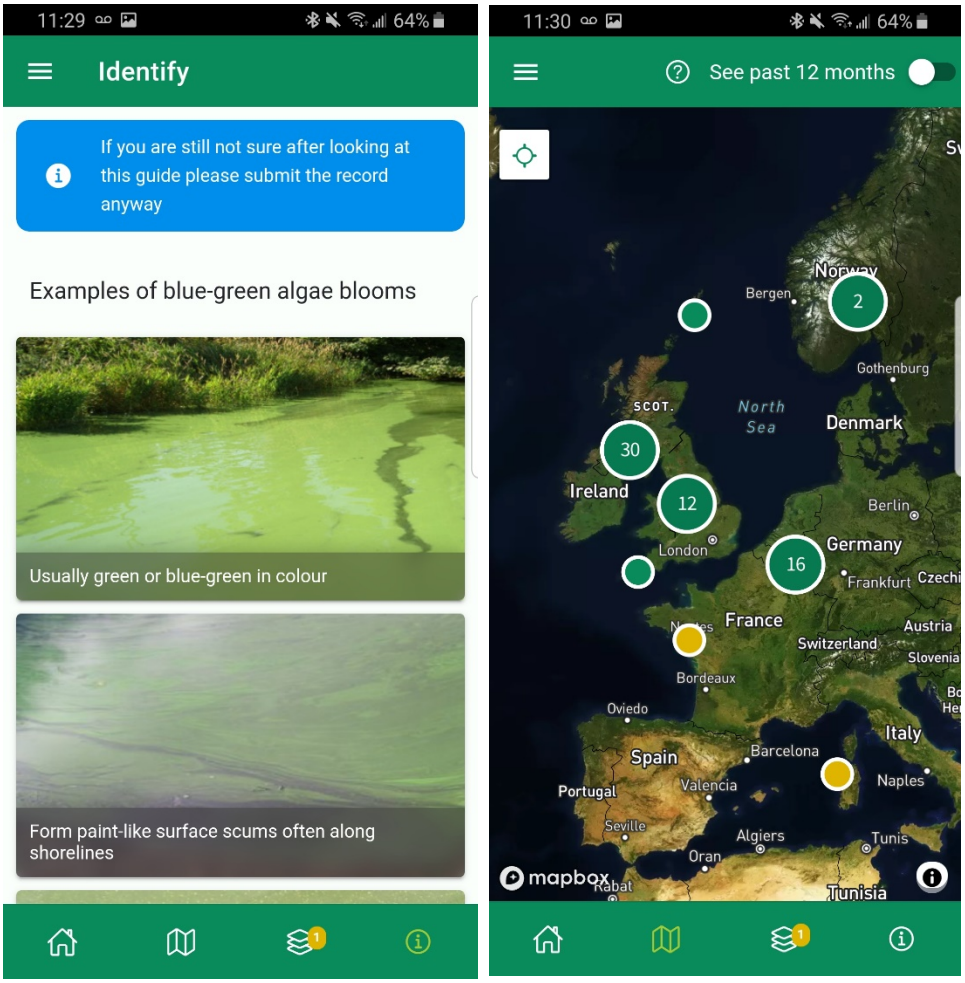


Figure 1. Photos of the Algal Identification and Global Map Interfaces of the Bloomin' Algae App.

The user interface is simple, with submissions being managed through a single screen that includes photos and limited metadata (Figure 2). Metadata categories available are location (based on phone's GPS), bloom size based on 4 categories (doormat, parking space, tennis court, and even bigger), user activity (what were you doing and what activities are done at this location?) and a text comment field for additional information.

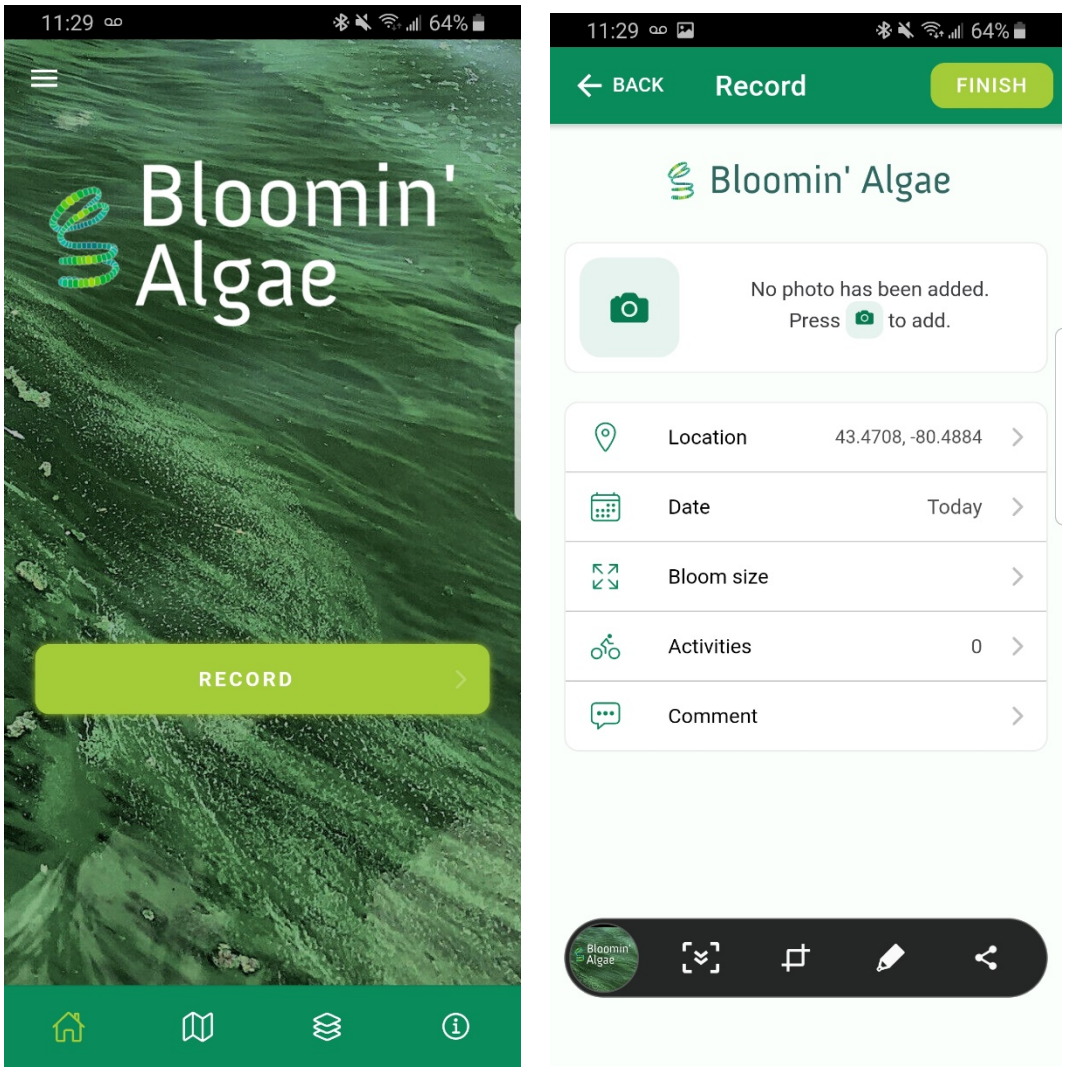


Figure 2. Photos of the Home Page and Data Entry Page of the Bloomin' Algae App.

Based on our contact with the developer, the app and background iRecord database will function in Canada, however, it would take work by the app developer and the UKCEH team who manage the app and the database to update the app and allow users and verification system to be set up for Canada. The existing verification system would not support Canada and the District would need to identify verifiers willing to check the records submitted by the public and provide expert judgement on whether it is a cyanobacterial bloom or not. This shortcoming puts the app at a disadvantage as it would need logistical and financial development by the District to be functional in Canada. Furthermore, the metadata associated with each upload is somewhat limited and therefore would rely on users to use the comment box to include the full list of desired information discussed in Section 3.

3.2 BloomOptix AI

3.2.1 Overview and Features

BloomOptix AI employs an Android and iOS app interface to automatically identify and count cyanobacterial cells belonging to six of the most common HAB producing genera: *Microcystis*, *Dolichospermum*, *Aphanizomenon*, *Woronichinia*, *Limnoraphis*, and *Gloeotrichia*.

The App is intended to be deployed alongside a mobile device compatible microscope, which to our knowledge currently includes only a single model by ioLight. The 150x microscope links wirelessly, takes advantage of the phone photo backup and storage, while the AI provides colony ID and Enumeration (density) estimates in 30 seconds. The BloomOptix app is geolocated, linked with weather data, and databased. The start up cost of this system is similar to the costs associated with the MWC Algal Monitoring Program, (i.e., a 3,000 USD start up microscope kit which includes 1-year annual subscription); however, the ongoing annual subscription fee (1,500 USD) is substantially higher than the current MWC program cost (250 CAD).



Figure 3. Photo of ioLight Microscope in use in the Field (bloomoptix.com).

Bloom samples are collected based on grab samples and homogenized before plating for the mobile microscope in the field. A presentation on the methods for analysis recommended that users plate two slides per sample and collect 5 photos per slide.

The use of the AI model once trained theoretically removes the need for confirmation by scientist and reduces analysis time by analyzing samples in the field. Real world testing of the system was provided in a webinar by the App developer and included deployment of 20 microscopes to test 170 HABs across 5 US states. A total of 5000 microscope photos were collected and used to train the AI in identification of cyanobacteria. From these 5000 photos, ~4000 photos were used in results comparisons between human taxonomic experts and the trained AI.

In 12% of the comparisons AI "outperformed" human experts which was largely attributed to human errors related to the repetitive nature of the task (e.g., skipped images and data entry errors). In 5.9% of the comparisons the AI systems was deemed inaccurate including 3.4 % false positives (AI misidentifying vegetative debris as cyanobacteria) and 0.9% false negatives.

The BloomOptix AI team is currently exploring how well results correlated with data collected by fluoroprobe (i.e., a sampling device used to measure algal composition in the water column using light) and on developing an analytics system that would turn sample collection information into warnings that identify conditions that have previously led to HABs.

BloomOptix AI provides the most robust reporting option for field observations of the Apps that we reviewed. Submissions can include a variety of metadata including known closures at the lake, sampling depth, secchi depth, water temperature, physical water body characteristics, water chemistry results (e.g., pH, conductivity), current weather, UV conditions, and toxin concentrations. Bloom extent is included as a categorical variable determine by the user based on 1-5 scale. No other app reviewed included more than a few basic categories for submitting information.

3.2.2 Challenges

Our review of the BloomOptix AI information available identified several challenges and limitations that may prohibit its deployment as part of a HAB monitoring strategy in the Muskoka River Watershed. Our target was to find applications that provide an easy path to entry into HAB monitoring for citizen scientists interested in collecting data, while simultaneously collecting watershed scale data on the occurrence of HABs. The BloomOptix AI system is similar in many ways to the Tier II solution provided by the Cyanobacterial Monitoring Collaborative (Table 1) with the addition of an AI component that aims to accelerate the collection and analysis of samples.

The current AI model only identifies and enumerates six HAB producing genera. The incorporation of addition genera to the AI model (e.g., *Planktothrix*) would require collection of samples, photos and further training of the AI model and therefore may limit the spatial applicability of the system in the Muskoka River Watershed.

Additionally, we have methodological concerns that may limit comparability between lakes across the watershed. For example, capturing 10 pictures per sample where each slide consists of only 2 drops of sample would not assess much of the sample. Clumping of cyanobacteria is likely to occur despite efforts to homogenize samples and could seriously and randomly skew cell density estimations depending on where users choose to take photos. Furthermore, where on the slide each of the 5 photos are taken is at the discretion of the user and may therefore bias results towards high estimates of total cell count and lead

to issues with comparability across a watershed scale monitoring program. Improving comparability across the watershed would require the development of a standard procedure for sample analysis in the field.

3.3 AlgaeScumID

The AlgaeScumID App was developed by the University of Technology Sydney (UTS) for identifying and monitoring potentially toxic freshwater algae that may be forming scums. The App employs a series of questions (i.e., a dichotomous key) to identify and determine the potential toxicity of the algal bloom. It also includes background information on algal blooms and allows reporting of suspected blooms. The AlgaeScumID App allows users to report sightings of algal blooms, upload photos and record the location of the bloom.

Based on our discussion with members of the team behind the app, one major issue which would hamper its use within the Muskoka River Watershed is the lack of functionality outside the iOS environment. Currently the app only functions on iOS devices and would require funding to be updated for Android functionality. This is a serious limitation in the App and puts it at a considerable disadvantage relative to the other available solutions which would not require this significant investment to be viable in the Muskoka River watershed.

3.4 Cyanobacteria Monitoring Collaborative – bloomWatch Application

bloomWatch app is Tier I of the three-tiered approach to cyanobacteria monitoring employed by the Cyanobacteria Monitoring Collaborative. The primary objective of app is to document the spatial and temporal occurrence of a perceived bloom for further verification and to serve as an education and outreach tool by providing an entry level option for engaging the lay person on cyanobacterial blooms. The only tool required is an IOS (version 7.1 or newer) or Android phone (version 4.0 or newer). The app provides limited guidance on what blooms look like using simple pictures to differentiate between pollen accumulations and harmful cyanobacteria blooms.

The user interface for the app includes four input screens:

- an introductory/welcome screen
    - explains the purpose of bloomWatch
    - contact information and email addresses where submissions will be sent (e.g., a District expert),
    - name of the waterbody
- general information screen (Figure 4)
    - current weather (four categories)
    - lake surface conditions (four categories)
    - bloom extent (five categories)
        - Categorical variable that utilizes common items/places (i.e., tennis court) to aid lay person in accurately quantifying the bloom area.
    - user comments and additional observations
- photo screen page (Figure 5)
    - geo-located

    - three separate and distinct images of a perceived bloom.
        - Image 1 is a large area photo to capture the extent of the bloom and part of the shoreline in the picture and a large area of the lake and some skyline.
        - Image 2 is an image from a standing position to the water surface a distance of ten to thirty feet to document if the bloom is stacking up along the shoreline, has a surface scum or matt, is limited to a very narrow band along the shoreline or a small cluster, or appears to extend from the shoreline into the majority of the lake.
        - Image 3 is a close-up photo of the bloom from three feet away or less, or if possible, a picture of the bloom material in a clear glass container held out at arm's length to help verify if the bloom may be filamentous in nature, globular or in clumps, a thin film, accumulates at the surface, etc.
- data submittal screen
    - verifies date and location information,
    - images submitted are sent to the crowdsourcing database (access available through ArcGIS Online) and immediately to the other pre-determined contacts.

The bloomWatch app includes all the metadata information that we identified in Section 3 as necessary to inform watershed wide HAB monitoring. The user interface is simple, with submissions being managed through four input screens. Data entry is quick and intuitive, and a tutorial video is available to facilitate adoption by users with a variety of technical experience. Once collected data are publicly available in a central database that is managed by the CMC (Figure 6), allowing data to be accessed by scientists, stakeholders and the District to inform annual reports, management and monitoring actions and removing the need for the District to standardize and manage data independently. A single data point on Three Mile Lake shows that the Application is functional in Canada but that use is limited (Figure 6). Supporting the widespread use of the bloomWatch app within the District would provide an entry level option for users interested in HAB management for minimal investment.

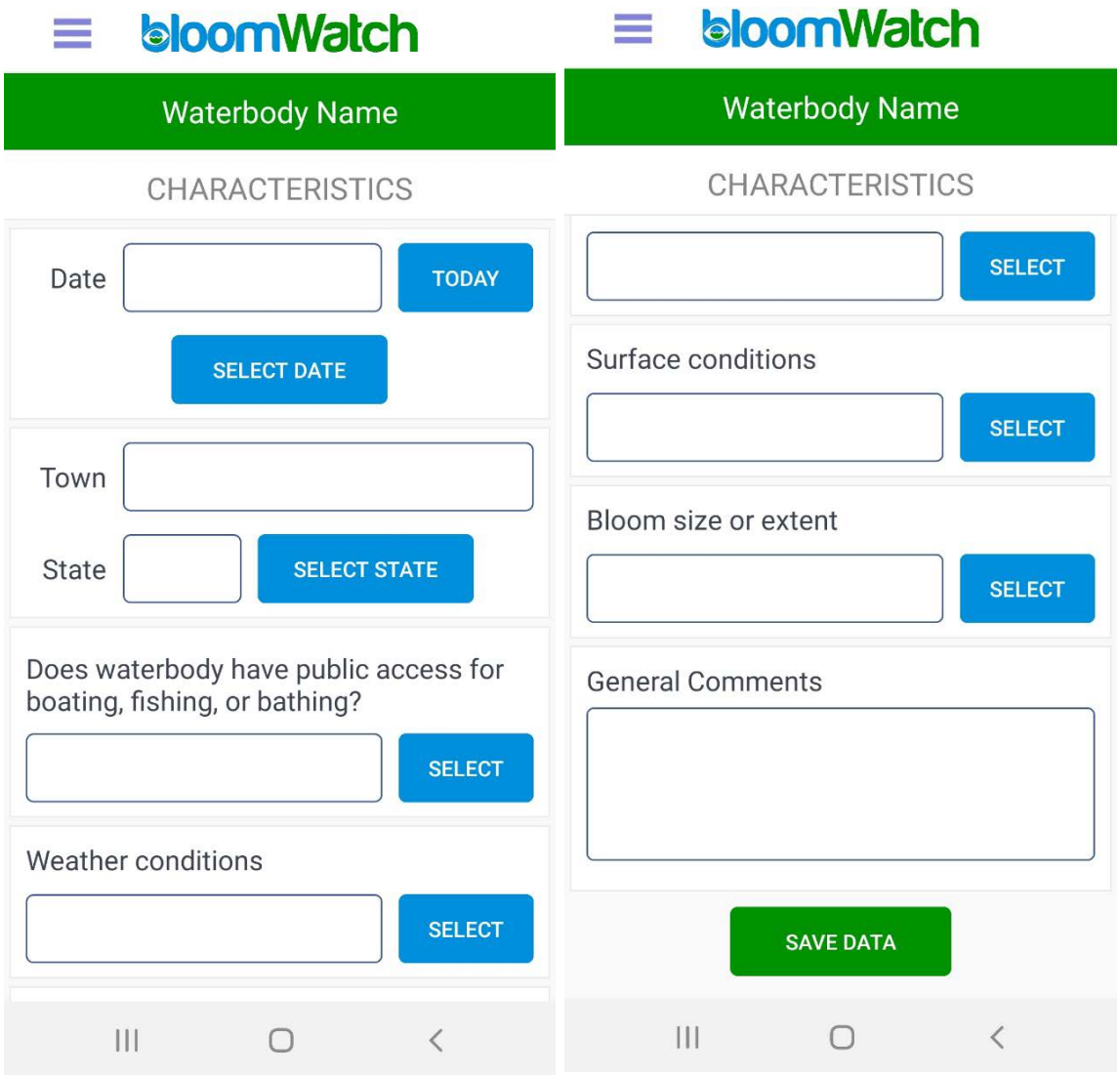


Figure 4. bloomWatch Bloom Extent and Metadata.

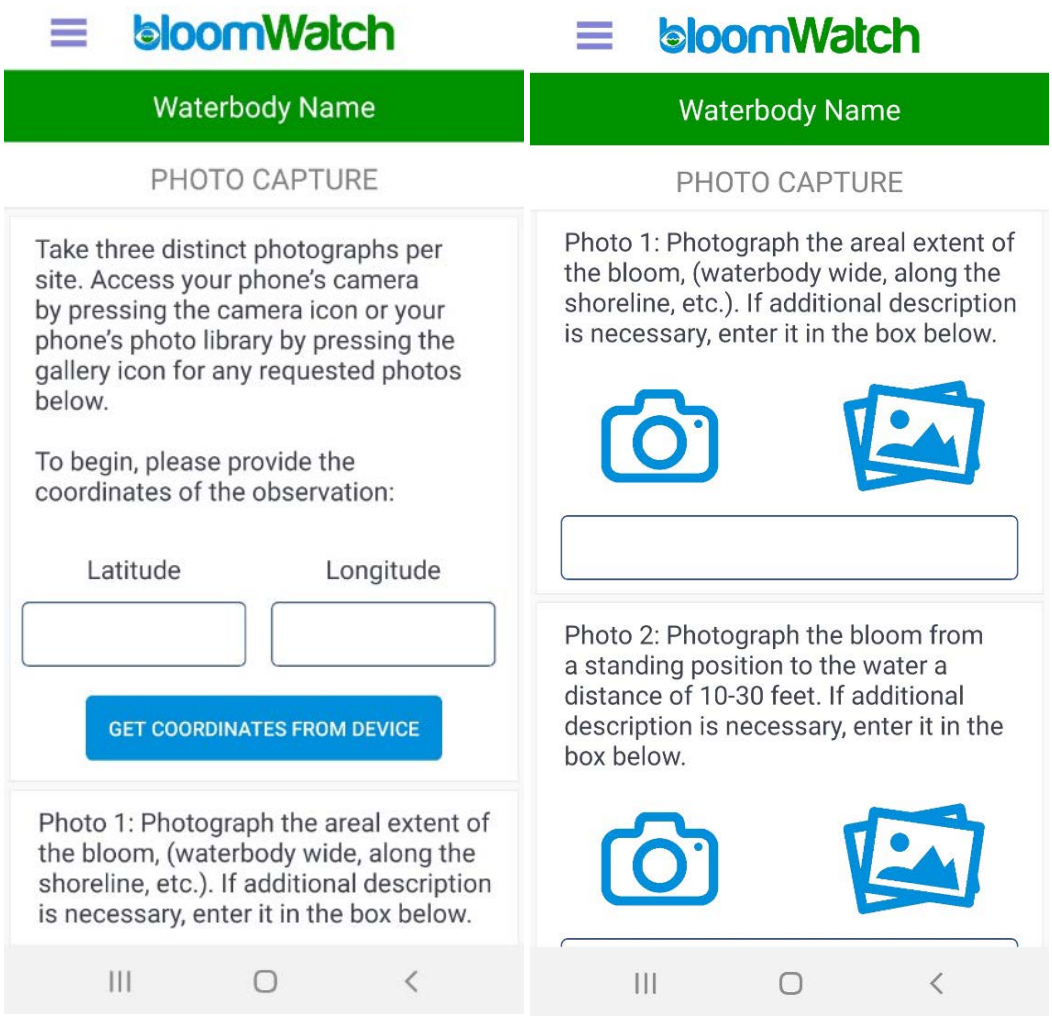


Figure 5. bloomWatch Photo Capture Screen with Guidance on Capturing Photos.

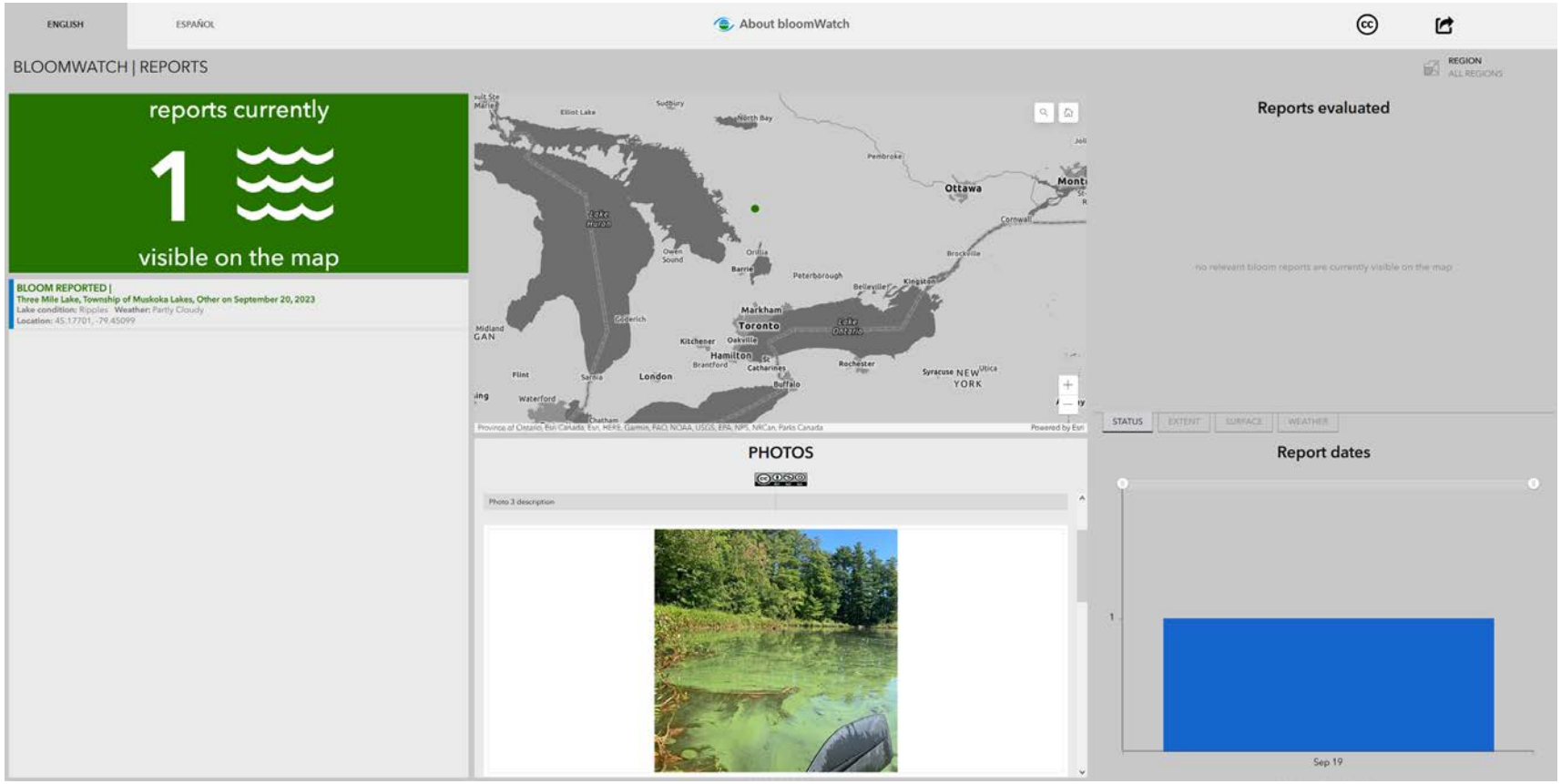


Figure 6. Web Interface of the CMC bloomWatch Database.

4. Summary and Conclusions

The goal of this project was to review and highlight options for the IWM program to employ for watershed scale monitoring of perceived HABs in the Muskoka River Watershed. Prior to exploring the cost and requirements of developing a proprietary application to serve the IWM program, we reviewed four potential existing applications. Based on our review we determined that the existing options provided the necessary features needed to document the extent and properties of blooms across the Muskoka River Watershed.

Based on our review the bloomWatch application provides the best option for deployment as part of the ongoing Integrated Watershed Management Project in the Muskoka River Watershed. The app was readily available for use on a wide range of devices. In addition to allowing the collection of spatial data on harmful algal blooms the app provides an avenue for engagement and outreach that could facilitate the growth of the MWC Algal Monitoring Program. The current MWC Algae Monitoring Program draws substantially on Tier III of the Cyanobacteria Monitoring Collaborative. Supporting the widespread use of the bloomWatch app within the District would provide an entry level option for users interested in HAB management but who may be overwhelmed by the technical scope of the MWC Algal Monitoring Program. Furthermore, integrating bloomWatch into the current Algae Monitoring strategy at the District would have little to no meaningful upfront cost and could be promoted through existing avenues at the District including the Waterweb and Engage Muskoka platforms.

5. References

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