1-5 Chancery Lane, Bracebridge, ON P1L 2E3 │705-645-0021
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Environmental Sciences Ltd.

Water Quality Indicators – Muskoka River Watershed

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

September 23, 2022

Final Report

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September 23, 2022 HESL Job #: J220010

Glenn Cunnington
Manager, Watershed Programs
The District Municipality of Muskoka
70 Pine Street
Bracebridge, Ontario
P1L 1N3

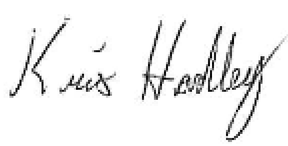
Dear Mr. Cunnington:

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

We are pleased to submit the Draft Report for the Water Quality Indicators – Muskoka River Watershed Project. The report summarizes the current water quality monitoring programs within the Muskoka River Watershed, provides a review of the current and emerging issues in water quality in the region, and identifies gaps in the current monitoring programs, while providing recommendations for the Community Round Table towards developing a 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

Report Prepared by:

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

Christine Geiger, M.Sc.
Aquatic Scientist

Emily Ham, M.Sc.
Junior Aquatic Scientist

Andrea Smith, Ph.D.
Senior Scientist

Report Reviewed by:

Brent Parsons, M.Sc.
Senior Aquatic Scientist

Executive Summary

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);
- Review the programs that are currently operating in the watershed, including information on monitoring goals, methods, and water quality parameters (Section 3); and
- Develop recommendations for a comprehensive water quality monitoring program based on known and emerging threats to aquatic ecosystem health with local relevance to the Muskoka River Watershed (Section 4)

A comprehensive literature review was completed to showcase the current understanding of emerging threats to water quality in the Muskoka River Watershed including changing climate, harmful algae blooms such as cyanobacterial blooms in oligotrophic (low-nutrient) lakes, calcium decline, invasive species, salinization, and contaminants (pharmaceuticals, microplastics and nanomaterials). The emerging issues were selected with consideration of their relevance in the Muskoka River Watershed, and local relevance is further discussed separately under each emerging issues.

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. Changing climate is expected to continue and is anticipated to exacerbate other emerging threats to water quality including invasive species, harmful algal blooms, salinization, and eutrophication.

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 the Muskoka River watershed, 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.

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. Many past invasions have been associated with ballast water releases to the Great Lakes, leading to new regulations to control invasions. E-commerce has been identified as an emerging novel vector of concern for species invasions, as 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.

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. 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. Lower calcium availability also provides a competitive advantage to *Holopedium glacialis*, which forms a jelly-capsule instead of a calcified carapace as its primary defence against predators. *Holopedium* blooms are a nuisance for water intakes, are a less efficient food source for fish (lower P 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, 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, as well as algal diversity and periphyton, and some primary consumers. Likewise, anti-inflammatories and antidepressants have be shown to negatively impact species abundance and the composition algal communities.

Microplastics became a topic of discussion in the early 2000s, when microplastic particles were found as common pollutants in marine environments (beaches and estuarine sediments). 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. It has been demonstrated in laboratory studies that microplastics can adsorb environmental contaminants on their surfaces and act as vectors for these contaminants.

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. The market for ENMs is currently dominated by health and fitness products, including active wear, sunscreens, cleaning supplies, cosmetics and sporting goods. ENMs in these products are typically surface-bound or suspended in liquid and therefore have a medium to high potential for release into water.

We reviewed relevant materials from the active monitoring programs in the Muskoka River Watershed, including specific program components (e.g., monitoring frequency, sampling staff, sampling location, parameters, laboratory used, and QA/QC procedures) so that common monitoring metrics could be compared between programs. The list of programs reviewed includes:

- MECP Dorset Environmental Science Centre Monitoring (Lake Partner Program [Water Quality], Dorset Lakes, benthic invertebrates and crayfish)
- The District of Muskoka (DMM) - Recreational Water Quality Monitoring Program
- Muskoka Lakes Association (MLA) Water Quality Initiative Program
- Lake of Bays Association (LOBA) Annual Water Quality Monitoring Program
- The Township of Seguin Annual Water Quality Monitoring Program

- Bracebridge Ministry of Natural Resources and Fisheries (fish, late-summer dissolved oxygen)
- Leech Lake Cottagers Association Water Quality Program (in cooperation with Fleming College)
- Leonard Lake Stakeholders Association Monitoring Program

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 lead to 15 recommendations to improve the current monitoring program 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 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 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 IWM data available alongside 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.

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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);
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2. Emerging Threats to Water Quality

A comprehensive literature review was completed to showcase the current understanding of emerging threats to water quality in the Muskoka River Watershed including changing climate, harmful algae blooms such as cyanobacterial blooms in oligotrophic (low-nutrient) lakes, calcium decline, invasive species, salinization, and contaminants (pharmaceuticals, microplastics and nanomaterials). The emerging issues were selected with consideration of their relevance in the Muskoka River Watershed, and local relevance is further discussed separately under each emerging issues.

2.1 Changing Climate

Climate change is impacting temperate lake systems and is expected to continue to exert an influence on limnological properties of lakes globally over the next few decades (e.g., Williamson et al. 2009, Sharma et al. 2016). A recent climate forecast report by the Muskoka Watershed Council predicted a 3-4°C increase in air temperatures in the Region by 2050 (Sale et al. 2016). Increases in air temperatures over the past several decades have led to shortened ice-cover periods (e.g., Futter 2003, Yao et al. 2013), increased water temperatures (e.g., Schindler et al. 1990, Magnuson et al. 1997, Dobiesz and Lester 2009), advanced onset of thermal stratification (e.g., Stainsby et al. 2011) and increased thermal stability in lakes (e.g., King et al. 1997, 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 in biological communities, including algae (Rühland et al. 2008; 2015), and the proliferation of nuisance cyanobacterial species that release harmful toxins (Ferris and Lehman 2007, Paerl and Huisman 2008, O'Neal et al. 2012). The ability of cyanobacteria to store phosphorus, fix nitrogen and regulate its position in the water column is particularly advantageous, as climate change brings stronger thermal stratification, sequestering nutrients outside the epilimnion where it cannot be accessed by other algal groups (see Section 2.2)

Recent research has identified lake ecosystems as important sentinels for climate change (Adrian et al. 2009). Physical lake properties, in particular, may serve as suitable indicators of lake responses to warming because of their coherence among lakes, their ease of measure, and their known relevance to ecosystem processes and function (Adrian et al. 2009). Lake water temperatures, for example, are easily monitored, and highly correlated with regional air temperature (Sharma et al. 2015). Moreover, shifts in water temperature may lead to significant changes in integrative variables such as water column stability (i.e., thermal stability; Hadley et al. 2014), and in the intensity and duration of thermal stratification (Adrian et al. 2009). Physical changes of this nature may directly or indirectly affect chemical and biological conditions in lake ecosystems (Rühland et al. 2015), for example it has been estimated that climate change may threaten 50% of global freshwater fish species (Darwall and Freyhof 2015; Reid et al. 2018), while increases in water temperature in freshwaters has been linked to changes in species distribution, disease and decreased survival (Parmesan 2006; Hermoso 2017; Bassar et al. 2016).

2.2 Harmful Algal Blooms

Cyanobacterial blooms are a significant management challenge in freshwater lakes in the Muskoka River Watershed. Considerable research has been completed to characterize cyanobacterial bloom dynamics in eutrophic systems but much less is known about cyanobacterial dynamics in oligotrophic systems and what options are available in lieu of traditional nutrient management.

2.2.1 Oligotrophic (Low-Nutrient) Lake Cyanobacterial Blooms

Aphanizomenon, Dolichospermum, Microcystis, and *Gloeotrichia* are the most common genera of cyanobacteria found in oligotrophic lake blooms in south-central Ontario over the past decade (Winter et al. 2011; HESL 2020). These genera of cyanobacteria have several key adaptations that make them prone to blooming in oligotrophic lakes and particularly difficult to manage through typical lake management strategies. *Aphanizomenon, Dolichospermum, Microcystis,* and *Gloeotrichia* contain gas vesicles which allow them to control their buoyancy in the water column. These gas vacuoles allow rapid migration through the water column, for example, moving from the sediment to the surface through 2 m of water in ~10 minutes. This vertical migration can allow colonies to out-compete other species by maximizing habitat preferences related to temperature, CO_2, nutrient, and light conditions, as well as avoiding and minimizing grazing pressure (Hansson, 1996; Carey et al., 2008; Reinl et al. 2022).

Aphanizomenon, Dolichospermum, Microcystis, and *Gloeotrichia* have life-cycle strategies that include the ability to remain dormant under unfavourable conditions. *Aphanizomenon, Dolichospermum,* and *Gloeotrichia* can form dormant resting stages, called akinetes, on the surface of lake sediments. Akinete resting stage production may be beneficial in increasingly variable conditions including intermittent nutrient availability; nutrient limitation has been identified as a trigger of akinete formation in oligotrophic systems (Callieri et al., 2014; Kaplan-Levy et al., 2010).

The life cycle of akinete forming cyanobacteria consists of multiple phases, summarized briefly as: 1) germination on the sediment, 2) growth on the sediment, 3) gas vesicle formation and migration into the water column, 4) growth and division in the water column, 5) formation of resting stages, called akinetes, 6) sinking of akinetes out of the water column to the sediment, and 7) resting and maturation of the akinetes on the sediment. Together, the first three of these phases (germination to migration) are commonly referred to as recruitment. Population dynamics of many cyanobacterial species can depend critically on recruitment from sediment resting stages (e.g., Trimbee and Harris, 1984; Barbiero and Welch, 1992), particularly in ice-covered, north temperate lakes (Carey et al., 2014). Research suggests that up to 50% of *Gloeotrichia echinulata* populations in the water column are comprised of cells recruited from the sediments and thus factors which affect its life cycle at various stages will facilitate bloom events in both eutrophic and oligotrophic lake environments (Barbiero and Welch, 1992; Karlsson-Elfgren et al., 2005; Carey et al., 2008).

Akinete germination appears to be regulated by one or more lake-wide variables (e.g., increasing light, temperatures, nutrients, dissolved oxygen or a combination of these factors; Kaplan-Levy et al., 2010). For example, in Lake Sunapee, an oligotrophic lake in New Hampshire, Carey et al. (2008; 2009) found that a pulse of sediment phosphorus occurred prior to a significant increase in recruitment rate of *Gloeotrichia echinulata* in 2005 and 2006. The cause of the pulse could not be ascertained, however, and it is not known if *Gloeotrichia echinulata* germination was accelerated by a discrete pulse of phosphorus, or because phosphorus exceeded a certain threshold concentration. Carey et al. (2014) suggest that the rate and timing of recruitment is also modified by local, microhabitat characteristics including water depth (Karlsson-Elfgren et al., 2004), sediment chemistry and substrate type (Carey et al., 2008, 2009), the size of the akinete bank (Forsell, 1998), bioturbation (Pierson et al., 1992; Karlsson-Elfgren et al., 2004), and grazing (Rengefors et al., 1998). Lake level fluctuations resulting from extreme climate patterns may also play an important role in cyanobacterial blooms in oligotrophic lakes. For example, recent research has linked phosphorus pulses resulting from lake level fluctuations in an oligotrophic lake to the summer appearance of a *Dolichospermum lemmermannii* bloom (Callieri et al., 2014), suggesting that both climate change and/or excessive water withdrawals resulting in lake level fluctuations could increase the threat of harmful algal blooms. The most recent research on bloom formation in oligotrophic lakes notes that conditions favourable for germination and recruitment are not yet fully understood and vary among systems suggesting more research still needs to be done to understand an attempt to manage these blooms (Reinl et al. 2021).

Oligotrophic cyanobacterial blooms therefore present a serious management challenge as a) they are unlikely to respond to common Harmful Algal Bloom (HAB) management practices which address nutrient concentrations in the water column (e.g. alum) or in the watershed (e.g. vegetative buffers) and b) they can have an immediate and significant impact on its surrounding ecosystem, progressing from low relative abundance in the plankton community to complete dominance the following year (Jacobson, 1994). Once established in low-nutrient lakes, Dolichospermum and Gloeotrichia may become a consistent part of the phytoplankton assemblage as seed banks of its akinetes can continue to draw phosphorus from sediments providing them with considerable advantages over other algal groups. Nutrients such as nitrogen and iron, in addition to phosphorus, are also thought to be important to the life cycle and blooms of Gloeotrichia echinulate and other cyanobacteria species. Section 2.2.1.1 outlines the importance of these nutrients in additional detail.

2.2.1.1 Other Nutrients

Phytoplankton compete for finite resources beyond just phosphorus, which has historically been referred to as the limiting nutrient for algae growth, and so other key nutrients may contribute to the success of cyanobacteria in oligotrophic lakes. Cyanobacteria can take up and store both phosphorus and nitrogen (Cottingham et al., 2015; Reinl et al. 2021). The ability of *Aphanizomenon, Dolichospermum,* and *Gloeotrichia* to fix atmospheric nitrogen provides them access to a pool of nitrogen not available to other algae, while previous research indicates that cyanobacteria preferentially use nitrate, nitrite, or ammonium from the water column when they are available, leaving little for other phytoplankton (Szasz and Pettersson, 2000; King and Laliberte, 2005). Once these biologically available nitrogen sources have been depleted, other non-nitrogen fixing phytoplankton often die out, while cyanobacteria can continue to meet its nitrogen demands by fixing atmospheric nitrogen.

Cyanobacterial species may also thrive when they have access to reduced iron (Molot et al., 2014; Sorichetti et al., 2014a, b; Verschoor et al., 2017; Reinl et al. 2021). Iron sources in lakes and rivers include catchment runoff and internal loading from sediments during periods of low oxygen. Models dealing with phytoplankton competition are often based on macronutrient use efficiency and the consequences of adding more phosphorus and nitrogen into a lake ecosystem. Phytoplankton, however, require other micronutrients to compete. For example, cyanobacteria require ferric iron ($Fe3+$) for nitrogen-fixation (Murphy et al., 1976) and nitrogen-assimilation (Lin and Stewart, 1998). Iron is required for chlorophyll synthesis, the production of photosynthetic electron transport proteins and during the photosynthetic production of organic compounds. Cyanobacteria are the only group of phytoplankton that possess a specialized iron uptake system providing a competitive advantage over eukaryotic phytoplankton in iron-limited conditions (Wilhelm and Trick, 1994). Cyanobacteria can use siderophores (i.e., iron-binding compounds) to scavenge iron thus facilitating their uptake and dictating the relative bioavailability of ferric iron to other phytoplankton.

Recent research has found that cyanobacterial biomass was highest at low iron concentration and suggests that the rise in cyanobacteria in oligotrophic lakes necessitates a better understanding of the mobilization of iron to lakes and/or lake controls on the fate of iron (Sorichetti et al., 2016). This specialized research involves highly detailed investigations at the time of bloom occurrence to determine if micronutrients were a factor but is not yet advanced enough to inform management of cyanobacterial blooms.

The literature review does present some important conclusions for the ongoing management effort in the Muskoka River Watershed. Most importantly, the existing scientific body of literature suggests that the conventional understanding and management of algal blooms that is based on monitoring and controlling phosphorus concentrations in the water column, especially in nutrient-enriched lakes, is not likely to explain the development of oligotrophic cyanobacterial blooms. Phosphorus remains an important concern in managing lakes in the watershed, however, to understand, predict and manage cyanobacterial blooms in low nutrient lakes, new monitoring methods and a greater depth of interpretation must be employed.

2.3 Calcium Decline

Numerous lakes in south-central Ontario were acidified during the latter half of the 20^{th} century by regional acid deposition from industrial smelting (Hall and Smol 1996; Jeffries et al. 2003). A long-term consequence of acidification is that calcium concentrations in softwater lakes on the Precambrian Shield have declined (Stoddard et al. 1999, Watmough et al. 2003). Thin soils, underlain by weather-resistant granite, result in leaching rates of calcium that typically exceed the replenishment rate from weathering and atmospheric deposition (Watmough et al. 2005). This shrinking of the terrestrial calcium pool, combined with decreased precipitation, has resulted in a reduced export of calcium to lakes. A variety of site-specific mechanisms can also contribute to declining concentrations of calcium 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 calcium in lakes. For example, crayfish, like other crustaceans, depend on lake-water calcium, 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), while at ambient calcium concentrations <5 mg/L, European crayfish (*Astacus astacus*) showed decreased survival and reduced growth (Rukke 2002). In Algonquin Park, regional calcium 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. 2014). 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).

Calcium decline has also resulted in a shift in microscopic herbivore communities in softwater lakes across eastern North America. Lower calcium availability provides a competitive advantage to *Holopedium glacialis. Holopedium* has a low calcium requirement as a result of it having a jelly-capsule instead of a calcified carapace as its primary defence against predators (e.g., fish). *Holopedium* blooms are a nuisance for water intakes, are a less efficient food source for fish (lower phosphorus content), and more difficult for invertebrate predators to catch which may alter the food web within a lake and put additional stress of fish populations. Furthermore, calcium decline results in reduced growth rates for daphniids, bosminids, and copepods (Arnott et al. 2017) with potential impacts at both higher and lower trophic levels (i.e., less food for fish, and less grazing to control algae).

2.4 Invasive Species

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). Many past invasions have been associated with ballast water releases to the Great Lakes, leading to new regulations to control invasions. Freshwater ecosystems are particularly vulnerable to the effects of invasive species (Sala et al. 2000). Canada has approximately 60% of the world's lakes and 20% of the world's freshwater supply, and there is a lot of human development and activity along and within our southern waterways, putting them at increased risk of biological invasions (CCFAM 2004). Aquatic Invasive Species (AIS) are a leading cause of native freshwater species, like fish and molluscs, becoming threatened or endangered in the country (Dextrase and Mandrak 2006). Historically, ballast water in ships arriving from abroad has represented the single largest source of AIS to Canada, but there are many other ways in which AIS reach new areas, including through live bait, live food fish, canals and water diversions, irrigation systems, and aquarium and water garden pathways (CCFAM 2004). 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. One of the main agents of secondary spread once AIS have established is through transient boaters, who move their boats from waterway to waterway for recreational purposes (Dalrymple et al. 2013; Shaw et al. 2014).

The Muskoka Watershed Council (2010) summarized invasive species in or near Muskoka, 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.

Prevention is the best option when dealing with AIS, since management efficiency decreases, and management costs increase as the invasion process progresses (Leung et al. 2002; Simberloff et al. 2013). While prevention should be the priority, it is inevitable that some AIS will still be introduced and spread. Consequently, a comprehensive management approach will require early detection, rapid response, and eradication, containment and control components (Pyšek and Richardson 2010). Public awareness and stakeholder engagement are critical at all stages of a strategic approach because they can promote behavioural change that prevents the introduction and spread of AIS and can build public support for prevention and management initiatives (Waldner 2008; Eiswerth et al. 2011).

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*)		

Starry stonewort (*Nitellopsis obtusa*) is an invasive macroalgae which has invaded numerous lakes in the Kawarthas represents a potential threat to lakes within the Muskoka River Watershed, however the severity of that risk is not yet clear. Starry stonewort has demonstrated a preference for calcareous waters (Larkin et al. 2018) which may offer some protection for the soft water lakes of the Muskoka River Watershed, which are typically below the 28.8 - 107.1 mg/L (mean = 50.8 mg/L) of calcium reported for starry stonewort in North America. However, the native habitat range for starry stonewort is significantly broader ([Ca] = 5 – 172 mg/L) suggesting that potential for invasion may exist. Starry stonewort forms large, dense mats which once established are difficult to manage and nearly impossible to eradicate. It is highly effective at outcompeting native macrophytes and can even outcompete other invasive macrophyte species (e.g., Eurasian milfoil).

2.5 Salinization

Salinization of freshwaters in Ontario has been an ongoing area of research and remains one of the most pressing environmental issues in the Muskoka River Watershed. Freshwater salinization is a global threat to freshwater resources with contributions from many industrial, agricultural, and other anthropogenic stressors (Dugan et al. 2020; Likens et al. 2010; Kaushal et al. 2005). Analysis of spatial patterns in Muskoka from long-term Lake Partner Program and Broad-scale Monitoring Program data, collected by the MECP, has shown that proximity to urban centres and major roadways is a substantial factor in determining chloride concentrations of freshwaters suggesting that winter road maintenance and urban land use are the primary drivers of chloride concentrations in Ontario (Sorichetti et al. 2022). The threat to freshwater resources posed by salinization is predicted to intensify with climate change, as the frequency and duration of extreme weather events such as droughts, heatwaves increase resulting in higher evaporation which concentrations salts in freshwaters (IPCC 2014; Jeppesen et al. 2020).

Winter de-icing salts inevitably wash into adjacent surface and ground waters during snowmelt and rainfall resulting in marked increases in chloride concentrations. High chloride concentrations can be toxic to aquatic life and impact freshwater biota at multiple trophic levels (Hintz et al. 2019). A Canadian Water Quality Guideline (CWQG) for the protection of aquatic life has been established for chloride (120 mg/L), however many lakes, and streams near roadways or in urbanized areas in Ontario, have been shown to meet or exceed this guideline (Sorichetti et al. 2022). Furthermore, recent research has shown that the CWQG is not sufficient to protect lake food webs and should be reassessed (Hintz et al. 2022).

2.6 Contaminants

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 District of Muskoka operates 9 drinking water systems, 8 wastewater facilities, and 9 septage lagoons. WWTPs are considered both sinks and secondary sources of Engineered Nanomaterials (ENMs) to the aquatic environment (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.

2.6.1 Pharmaceuticals

Pharmaceuticals are ubiquitous being found in influent and effluent of 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. In rural environments leaching from domestic septic tanks has been found to be a significant source of pharmaceuticals. 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 (*L. minor*) and 93.26 mg/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 µg/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 mg/L for both *R. subcapitata* and *L. minor*. They also noted growth inhibition at 3 mg/L for *L. minor* and 5 mg/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.

2.6.2 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.

2.6.3 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 categorised 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 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.

3. Review of Current Water Quality Monitoring Programs

We reviewed relevant materials from the active monitoring programs in the Muskoka River Watershed, including specific program components (e.g., monitoring frequency, sampling staff, sampling location, parameters, laboratory used, and QA/QC procedures) so that common monitoring metrics could be compared between programs. The list of programs reviewed includes:

- MECP Dorset Environmental Science Centre Monitoring (Lake Partner Program [Water Quality], Dorset Lakes, benthic invertebrates and crayfish)
- The District of Muskoka (DMM) - Recreational Water Quality Monitoring Program
- Muskoka Lakes Association (MLA) Water Quality Initiative Program
- Lake of Bays Association (LOBA) Annual Water Quality Monitoring Program
- The Township of Seguin Annual Water Quality Monitoring Program
- Bracebridge Ministry of Natural Resources and Fisheries (fish, late-summer dissolved oxygen)
- Leech Lake Cottagers Association Water Quality Program (in cooperation with Fleming College)
- Leonard Lake Stakeholders Association Monitoring Program

3.1 Ministry of the Environment, Conservation and Parks

3.1.1 Lake Partner Program

The Lake Partner Program (LPP) is a volunteer-based water-quality monitoring program which collects total phosphorus, calcium and chloride samples, and water clarity (Secchi disk depth) observations on lakes across Ontario (Figure 2; Table 2). The goal of the LPP is to provide early detection of changes in the phosphorus concentrations and/or the water clarity due to the impacts of shoreline development, climate change or other environmental stressors and more recently to track the impact of two key emerging threats to water quality: 1) declining calcium as a long-term consequence of acidification, and 2) increased chloride concentrations as a consequence of winter road maintenance.

In lakes on the Canadian Shield such as those in the Muskoka River Watershed, LPP volunteers collect a single spring (May) water sample for total phosphorus, while off Shield Lakes are sampled each month (May-Oct). Samples are analyzed at the Dorset Environmental Science Centre. The sampling protocol also recommends a minimum of 6 (monthly) water clarity observations using a Secchi disk.

The LPP provides an ideal entry point into water quality monitoring and lake management for individuals and small lake associations whose financial and logistical resources are limited, a single volunteer is often sufficient to collect data from a small lake. The MECP staff who manage the program provide sampling containers and guidance on how to properly sample to help ensure consistency in methods and compatibility of results from across the program. Laboratory analysis is handled at Dorset Environmental Science Centre (DESC) at no cost to participants, which provides the lowest detection limits for phosphorus analysis available in Ontario (0.32 μg/L, A. DeSellas, pers. Comm.). Method Detection Limits at commercial laboratories is typically 2-3 μg/L.

Table 2. Lake Partner Program Summary

Monitoring Frequency	Spring Annual or Monthly
Sampling Staff	600 Volunteers; Citizen Science
Sampling Locations	1260 sites in 2018; 1206 in 2019; 454 in 2020*
Parameters (Period of Record)	Secchi Depth (1980 – Ongoing); Phosphorus (2002 – Ongoing); Calcium (2008 – Ongoing); Chloride (2015 – Ongoing)
Laboratory	Dorset Environmental Science Centre
QA/QC	Duplicate samples

*Sampling impacted by Covid-19 Pandemic

3.1.2 Dorset Lakes Monitoring Program

DESC has tracked the effects of anthropogenic stressors on the aquatic and terrestrial ecosystems in the Muskoka area since the mid-1970s, using data from intensively studied lakes near Dorset, Ontario (i.e., the Dorset A lakes; Table 3). Since collection of data at the Dorset A lakes began, hundreds of studies have been completed and over 400 peer-reviewed papers on emerging issues in water quality have been made including influence of shoreline development on lake water quality (eutrophication), acidification, metal contamination, climate change, and the impacts of invasive species and native predator introductions (Yan

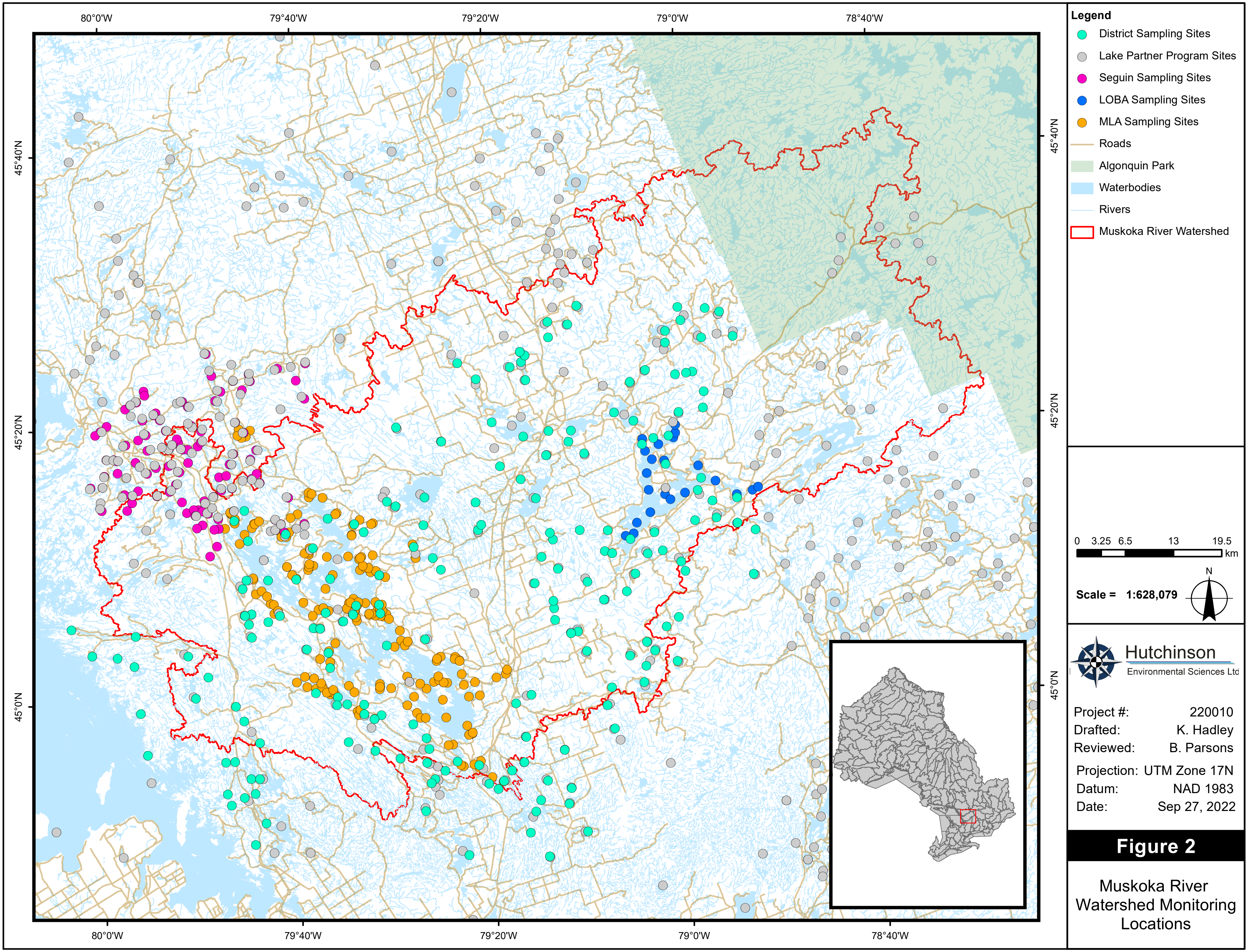


Figure 2

Muskoka River Watershed Monitoring Locations et al. 2008). The Dorset Lakes were selected to be representative of a large number of small lakes that define the Muskoka River Watershed, and the DESC dataset, while not publicly available represents the most robust long-term water quality data in the watershed.

Table 3. Dorset Lakes Monitoring Program Summary

Monitoring Frequency	Bi-weekly during ice-free season (May-November)
Sampling Staff	DESC Staff
Sampling Locations	9 Main "A" Lakes sites Blue Chalk Lake Chub Lake Crosson Lake Dickie Lake Harp Lake Heney Lake Plastic Lake Red Chalk Lake – Main Red Chalk Lake – East
Parameters (Period of Record)	Secchi Depth (1976 – Ongoing); Phosphorus (1976 – Ongoing); pH (1976 – Ongoing) Major ions (1976 – Ongoing) Temperature profiles (1976 – Ongoing) Dissolved Oxygen profiles (1976 – Ongoing) Metals (1976 – Ongoing) Ice formation and break-up
Laboratory	Dorset Environmental Science Centre
QA/QC	Field duplicates

3.1.3 Ontario Benthos Biomonitoring Network

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 DMM is a partner organization of the OBBN and provides the necessary training to lake associations interested in undertaking benthic invertebrate monitoring programs.

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.

3.2 Bracebridge Ministry of Natural Resources and Fisheries

3.2.1 Broad-scale fish community monitoring

The Ecological Framework for Fisheries Management (EFFM) was implemented by the Ontario Ministry of Natural Resources and Forestry (MNRF) in 2004. The EFFM changed the way recreational fisheries are managed, moving from individual lake management to a landscape approach, based on 20 fisheries management zones (FMZs; Figure 3). These FMZs form the basis of fishing regulations (i.e., catch limits and seasons). Monitoring for the EFFM began in 2008 under the broad-scale fisheries monitoring program (BsM) to inform the MNRFs understanding and management of fish assemblages, including identification of environmental stressors and trends. The Muskoka River Watershed falls within Fisheries Management Zone #15 which extends beyond the Muskoka River Watershed east to the Ottawa River (Figure 4).

A representative sample of lakes between 50 and 250,000 ha in surface area within each FMZ are randomly selected and sampled once every five years. Lakes are split into two categories:

Trend lakes - must contain brook trout, lake trout, or walleye.

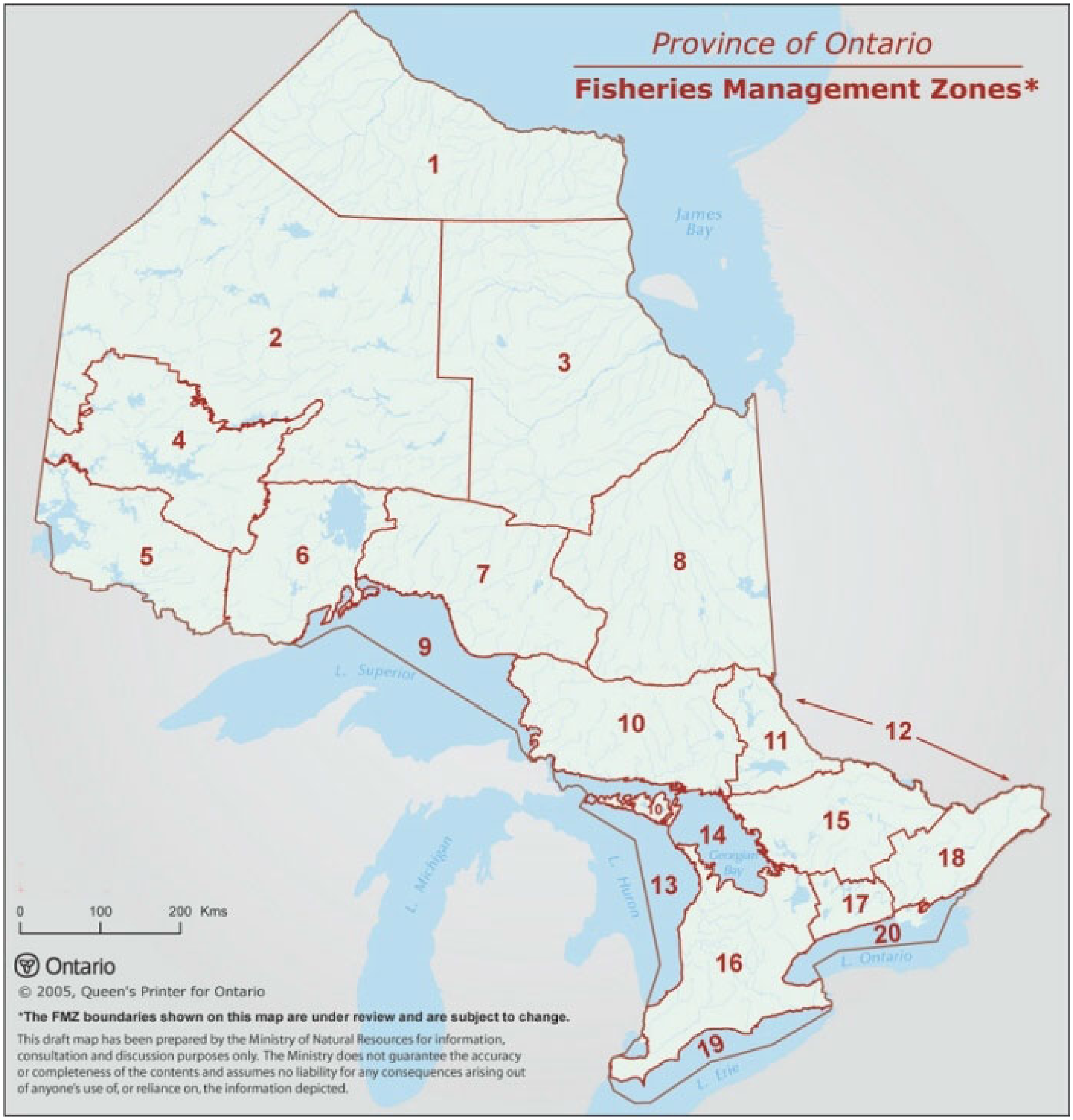
i. for detecting changes in fish populations and aquatic ecosystems over time

State lakes - any lakes greater than 50 hectares regardless of the fish species present.

i. for describing the overall status of fish populations at a point in time

The MNR states that the BsM program aims to survey 10% of all known brook trout, lake trout, and walleye lakes in Ontario.

Figure 3. Ontario Ministry of Natural Resources Fisheries Management Zones



The first five-year monitoring cycle of the BsM program ended in 2012 and included the assessment of ~630 lakes. According to MNRF, 160 lakes were to be sampled in 2015 (Year 3 of the second cycle of monitoring). Information recorded for each lake includes fish health and tissue chemistry, physical lake properties and a suite of water chemistry variables (Table 4).

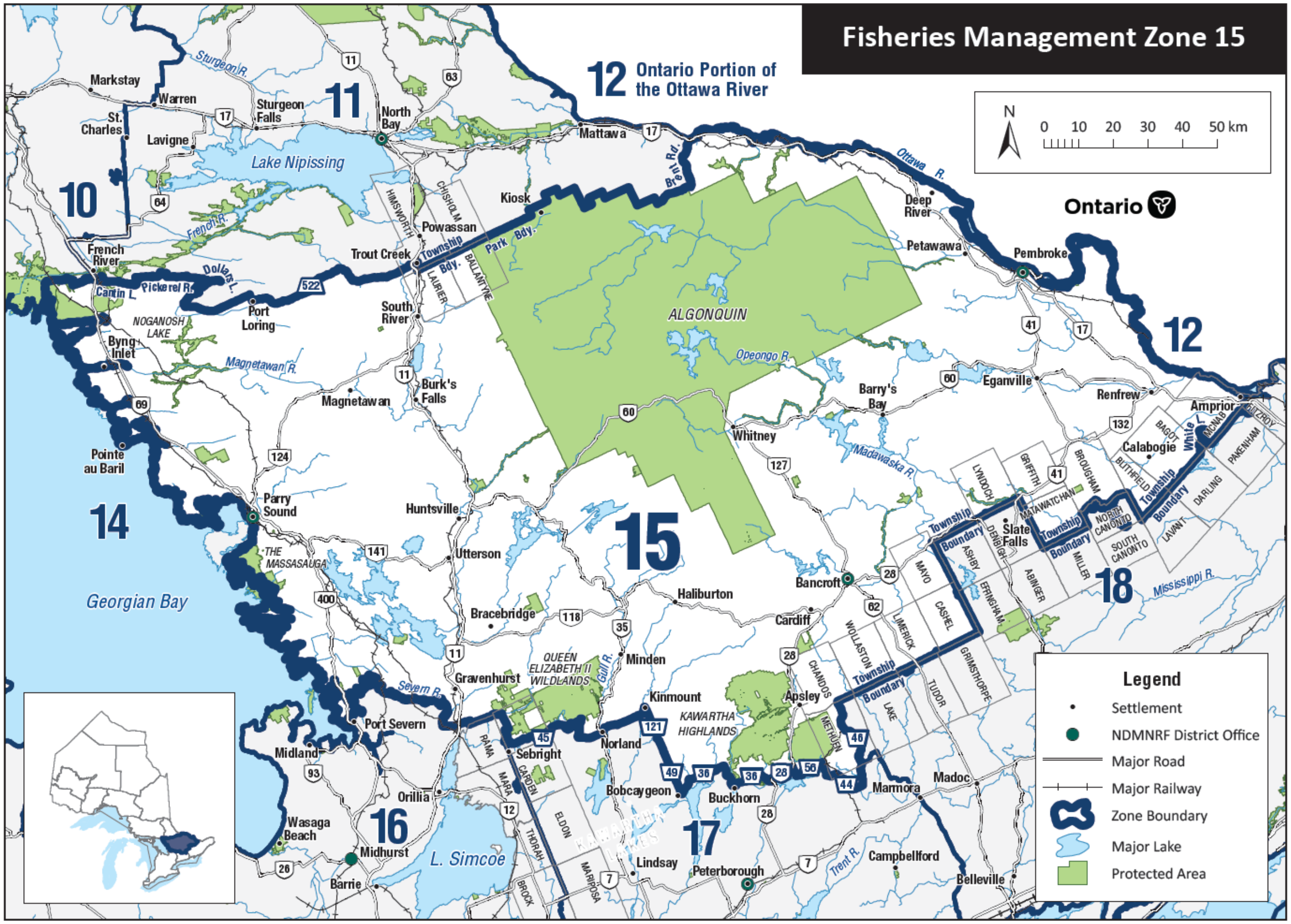
During lake surveys, MNRF staff sample fish to estimate abundance, record fish health characteristics, test for contaminants and record physical, biological (i.e., invasive species) and chemical lake data (Table 4). The Ministry of the Environment, Conservation and Parks is responsible for publishing this information. The Sportfish contaminant monitoring program publishes guidance reports on fish consumption in Ontario based on data collected during the BsM program using 12 contaminants and groups of contaminants (Table 4).

Table 4. Broad scale Monitoring Program Summary

Fish Health Characteristics	Lake Physical Properties	Water Chemistry Data	Fish Tissue Chemistry*
• Length • Weight • Sex • Maturity • Ageing structure: scales and/or ear bone • Contaminant sample (muscle tissue)* • Stomach contents	• Secchi Depth • Temperature Profile • Dissolved Oxygen Profile	• True colour • pH • Conductivity • Alkalinity • Calcium • Magnesium • Sodium • Potassium • Chloride • Sulphate • Silicate • Iron • Dissolved inorganic carbon • Dissolved organic carbon • Ammonia/Ammonium • Nitrate/Nitrite • Total Kjeldahl Nitrogen • Total Phosphorus	• Mercury • Mercury, PCBs, mirex/photomirex and pesticides • PCBs, mirex/photomirex and pesticides • Mercury, PCBs and mirex • Mercury, other metals, PCBs, mirex/photomirex and pesticides • Mercury and other metals • Dioxins and furans • Chlorinated phenols and chlorinated benzenes • Polycyclic aromatic hydrocarbons (PAHs) • Dioxins, furans and dioxin-like PCBs • PCB congeners • Polybrominated diphenyl ethers and Polychlorinated naphthalenes

*Some overlap exists between contaminant groups as not all contaminants are detected for each fish species tested in each lake sampled.

Figure 4. Fisheries Management Zone #15.



3.3 District of Muskoka (DMM) Programs

The DMM maintains several monitoring programs aimed at assessing and tracking lake health. Water chemistry is monitored through the Recreational Water Quality Monitoring Program (Section 3.3.1), while biological and physical lake health are assessed through the benthic monitoring program (Section 3.3.2) and Shoreline Land Use Surveys (Section 3.3.3), respectively. The DMM currently partners with numerous local organizations as part of its Lake System Health Program, the following associations and organizations participated in the 2019 Lake System Health Program:

- Ontario Stewardship Rangers
- Trillium Lakelands District School Board
- Patterson's Bay Association
- South Muldrew Lake Community Association
- Bella Rebecca Community Association
- South Muskoka Lake Community Association
- McKay Lake Association
- Tawingo College
- Loon & Turtle Lake Cottage Association
- Ril Lake Association
- Mary Lake Association
- Buck Lake Association
- Peninsula Lake Association
- Walker & Pell Lakes Association
- Fox Lake Association
- Otter Lake Association
- Lake Vernon Association
- Three Mile Lake Association
- Muskoka Discovery Centre
- Bay Lake Property Owners' Association
- Haliburton-Muskoka-Kawartha Children's Water Festival
- Stewart Lake Association
- Wood Lake Cottagers' Association

3.3.1 Recreational Water Quality Monitoring Program

The stated purpose of the recreational water quality monitoring program is to establish a long-term record of key water quality parameters to track trends over time and inform management decisions intended to protect Muskoka's recreational lake water quality. The program samples 193 sites on a rotational basis and is usually capable of sampling 80-85 sites per year (Table 5; Figure 2).

The DMM monitoring program is operated in collaboration with the Dorset Environmental Science Centre (DESC). Trained summer staff collect Secchi depth, temperature and dissolved oxygen profiles along with a suite of chemistry parameters including metals, major ions, calcium, chloride, nutrients, and pH (Table 5).

Table 5. Recreational Water Quality Monitoring Program Summary

Monitoring Frequency	Annual
Sampling Staff	Trained District Summer Staff
Sampling Locations	193 sites on 164 lakes; rotational
Parameters (Period of Record)	Secchi depth (spring and summer) Temperature profiles Dissolved Oxygen profiles Metals Major Ions Phosphorus (minimum detection limit = 0.36 μg/L)
Laboratory	Dorset Environmental Science Centre
QA/QC	Field Duplicates on all Phosphorus samples

3.3.2 Biological Monitoring Program

The District's biological monitoring program was initiated in 2003 and provides training for lake associations interested in undertaking volunteer monitoring programs including FrogWatch, PlantWatch and benthic sampling. The benthic program follows the OBBN protocols and contributes data to the Ontario Benthos Biomonitoring Network (See Section 3.1.2). FrogWatch and PlantWatch are part of the NatureWatch network of citizen science monitoring programs 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 population 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.

3.3.3 Shoreline Land Use Surveys

The shoreline land use program began in 2002 collecting data on shoreline vegetation, structures, and other information on the first 20m of land around a lake. Information on all built structures, the condition of the shoreline and general land uses adjacent to a lake is mapped and made available for municipal planning programs, lake associations, and Municipalities. The DMM maintains a database of all information collected with the goal of using the information to identify long-term trends respecting this important ecological area.

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. In 2019, shoreline survey work was partially completed for one lake (Peninsula Lake) suggesting that methods to improve the rate of data collection or to involve the community in collecting shoreline data may be valuable.

3.4 Muskoka Lakes Association (MLA) Water Quality Initiative Program

The Muskoka Lakes Association (MLA) was founded in 1894 to represent the lakeshore residents in the Muskoka Region. It has operated Water Quality Initiative (WQI), a monitoring program focused on Lakes Rosseau, Joseph and Muskoka (as well as many smaller surrounding lakes), since 2002. The MLA's water quality efforts are concentrated on:

- Protecting and promoting water quality through their monitoring program, and,
- Promoting responsible land use

The MLA Environment Committee manages over a hundred volunteers to collect annual water quality data and retains independent consultants to analyze their data and to provide recommendations and program modification/development options. Annual water quality reporting presents the most recent data collected and compares it to data collected from 2002 to the present based on trend analysis.

The MLA and their volunteers monitored 55 areas within 18 lakes and rivers for a total of 687 samples between May and October in 2021 (Figure 2). Each sampling area represents a geographic location encompassing a group of WQI monitoring sites, usually focused on a river, lake or embayment of interest to the MLA. Samples are analyzed for Total Phosphorus (TP) and bacteria (*E. coli* and total coliform), while Secchi disk depths are recorded at each site (Table 6).

Table 6. Muskoka Lakes Association Water Quality Initiative Program Summary

Monitoring Frequency	• May to August • 1 Spring sample, 2-3 additional ice-free samples
Sampling Staff	• Citizen scientist volunteers

Sampling Locations	• 195 sites across 55 areas • 2021 lakes o Lake Joseph o Lake Rosseau o Lake Muskoka o Brandy Lake o Bruce Lake o Clear Lake o Gullwing Lake o Gull Lake o Leonard Lake o Mirror Lake o Skeleton Lake o Silver Lake (Port Carling) o Silver Lake (Gravenhurst) o Star Lake • 2021 rivers o Indian River o Moon River o Joseph River o Muskoka River • 687 samples collected in 2021
Parameters	• Total Phosphorus (3 µg/L) • Bacteria – *E. coli* and total coliforms • Water temperature – surface
Laboratory	• ALS Environmental
QA/QC Protocol	• Field duplicates for phosphorus samples

3.5 Lake of Bays Association (LOBA) Annual Water Quality Monitoring Program

The Lake of Bays Association (LOBA) has championed a volunteer-based water quality monitoring program in Lake of Bays since 2001. The aim of the program is to characterize phosphorus and bacteria levels as an indication of general lake and watershed health and to compare different sites across the lake, while fostering community involvement and education.

LOBA has been monitoring spring turnover phosphorus levels as part of the Ministry of Environment, Conservation and Park's Lake Partner Program but the independent monitoring program began in 1970 to monitor bacteria levels in the lake during the ice-free season. In 1972, LOBA became a Ministry of Environment Self-Help Program participant collecting Secchi depth measurements and water samples for Chlorophyll *a* analysis. In 1978, the program transitioned to analyzing total phosphorus and LOBA expanded the area of study in the summer of 2001 to include near-shore sites adjacent to developed and undeveloped properties, and areas influenced by wetlands and rivers. In 2002, the program was again expanded to include monitoring of total phosphorus concentrations in near-shore areas and in the Hollow and Oxtongue rivers and river deltas. Site selection has changed as the understanding of water quality conditions in Lake of Bays has increased and, since 2009, sampling has focused on deep water sites, nearshore disturbed and undisturbed locations, and inflowing rivers. In 2020, the Covid-19 pandemic suspended the data collection program, however the program was able to return to operation in 2021.

Water samples for bacteria and total phosphorus were collected at 23 sites in Lake of Bays in 2021 which included deep, open water locations (‘Deep Water’ sites, n=9), nearshore sites adjacent to developed areas (‘Disturbed’ sites, n=5), undeveloped shorelines (‘Nearshore Undisturbed’ sites, n=5), and both river (Oxtongue and Hollow rivers) and river-influenced (Oxtongue Delta) sites (‘River’ sites, n=4; Table 7; Figure 2).

Table 7. Lake of Bays Association Annual Water Quality Monitoring Program Summary

Monitoring Frequency	Annual; Three summer samples
Sampling Staff	Citizen Science volunteers coordinated by the Lake of Bays Association
Sampling Locations	23 sites on Lake of Bays
Parameters (Period of Record)	• Total Phosphorus (3 µg/L) • Bacteria – *E. coli* and total coliforms • Water temperature – surface
Laboratory	ALS Environmental
QA/QC	Field Duplicates; targeting 10% of total sample size

3.6 The Township of Seguin Annual Water Quality Monitoring Program

In 2022, Seguin Township completed year 14 of the Water Quality Monitoring Program. This program collects total phosphorus (TP) concentration data, Secchi disk depth, temperature and dissolved oxygen concentration profiles, lake depth, dissolved organic carbon, calcium and chloride concentrations (Table 8). The program began in support of the water quality model developed to predict phosphorus concentrations in the Township[1] and has continued to allow the Township to identify any changes in lake water quality as they emerge.

Monitoring is conducted by summer students employed by Seguin Township. Independent consulting staff provide sampling guidance and training, which consists of two half day training sessions (i.e., spring and fall) and ongoing technical guidance. Independent consultants also assist with coordination with the laboratory at the Dorset Environmental Science Centre (DESC) and provide data analysis and annual reporting. Duplicate water samples are collected from ~40 sites per year on a rotational basis for analysis of spring overturn TP concentration and in August, sites are revisited to measure dissolved oxygen and temperature profiles, Secchi depth and lake depth.

Spring total phosphorus data are also collected by volunteers for several of the lakes in the Township under the province's Lake Partner Program (LPP) using the same sampling protocols as Seguin's program and analyzed at DESC. Available LPP total phosphorus data collected since 2002 are compiled, reviewed and added to the Seguin data set annually to increase the monitoring dataset. However, LPP data availability often lags behind data collected and analyzed for the Township program.

Table 8. Township of Seguin Water Quality Monitoring Program Summary

Monitoring Frequency	Annual; spring overturn and late-summer
Sampling Staff	Trained summer students
Sampling Locations	40-45 per year; rotational from ~120 lakes
Parameters (Period of Record)	Total Phosphorus Calcium Chloride Temperature and Dissolved Oxygen profiles
Laboratory	Dorset Environmental Science Centre
QA/QC	Field duplicates

3.7 Individual Lake Independent Monitoring Programs

During project initiation District staff provided HESL with a list of 74 cottage, ratepayer, and road associations within the Muskoka River Watershed. We contacted these organizations to determine if they operated an independent monitoring program or participated in the Lake Partner Program. We received replies from 13 of the associations that were contacted. Several of the associations contacted expressed an interest in water quality monitoring and requested information on how they can become involved which

[1] *Hutchinson Environmental Sciences, Ltd., 2016.* Review, Update and Refinement of Seguin Township's Water Quality Model (SWQM) and Phosphorus Management Approach. *Final report prepared for Seguin Township. January 2016. 67pp*

suggests that guidance and education for small independent lake association would be valuable. Two of the organizations contacted, Leech Lake and Leonard Lake, replied to indicate that they organized and operated independent monitoring programs.

3.7.1 Leech Lake Cottagers Association Water Quality Program

The Leech Lake Cottagers Association (LLCA) maintains a long-term water quality monitoring program, which has operated continuously since 2010. The Leech Lake Cottagers Association (LLCA) has partnered with Fleming College's Ecosystem Management Technology students to monitor and assess the lake, with laboratory analysis being carried out at the Centre for Advancement of Water and Wastewater Technologies (CAWT). The goal of the LLCA program is to analyze water chemistry, benthic macroinvertebrates, zooplankton, bacteria, and shoreline development as indicators of lake health (Table 9; Figure 5).

Total phosphorus detection limits for the Leech Lake monitoring program are not clear as all values in the report were reported as below detection, despite values as high as 0.036 mg/L (Table 10). Assuming values above 0.01 mg/L were assigned "<" symbols incorrectly, the data may still be of little utility in a larger data set because the assumed detection limit of 0.010 mg/L is considerably higher than most other monitoring programs and above the current 10-year average phosphorus concentration for Leech Lake (0.0067 mg/L). Additional guidance on developing and maintaining a water quality program may benefit individual lake associations interested in participating in data collection beyond the Lake Partner Program and ensure that data gathered are useful to both the lake association and the larger effort to monitor the Muskoka River Watershed.

Table 9. Leech Lake Cottagers Association Water Quality Program Summary

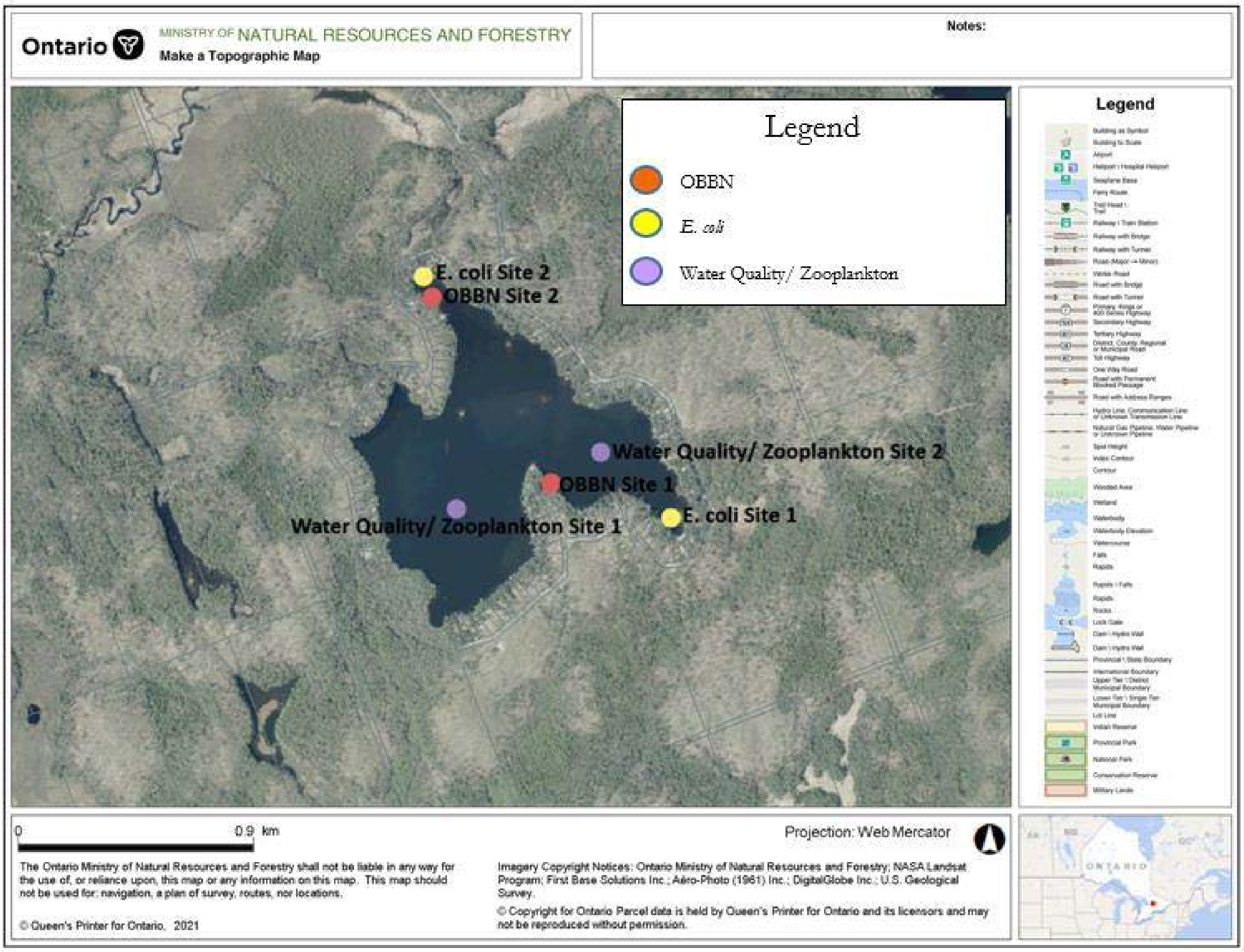
Monitoring Frequency	Annual; late summer sampling
Sampling Staff	Fleming College Students
Sampling Locations	2 water quality, 2 OBBN and 2 nearshore bacteria
Parameters (Period of Record)	Total Phosphorus* pH, Conductivity, Alkalinity, Total Suspended Solids, Turbidity, Total Kjeldahl Nitrogen, Total Phosphorus, Calcium, Total Organic Carbon Secchi Depth Temperature and Oxygen Profiles
Laboratory	Centre for Advancement of Water and Wastewater Technologies (CAWT)
QA/QC Protocol	

*Total phosphorus concentrations in Leech Lake were reported at various detection limits.

Table 10. Total phosphorous concentrations found in Leech Lake, Bracebridge, ON from 2017-2021.

	Units	2017	2018	2019	2020	2021
Site 1	mg/L	< 0.021	< 0.011	< 0.011	< 0.010	< 0.022
Site 2	mg/L	< 0.010	< 0.010	< 0.010	< 0.011	< 0.036

Figure 5. Leech Lake Sampling Locations (LLCA, 2021).



3.7.2 Leonard Lake Stakeholders Association Monitoring Program

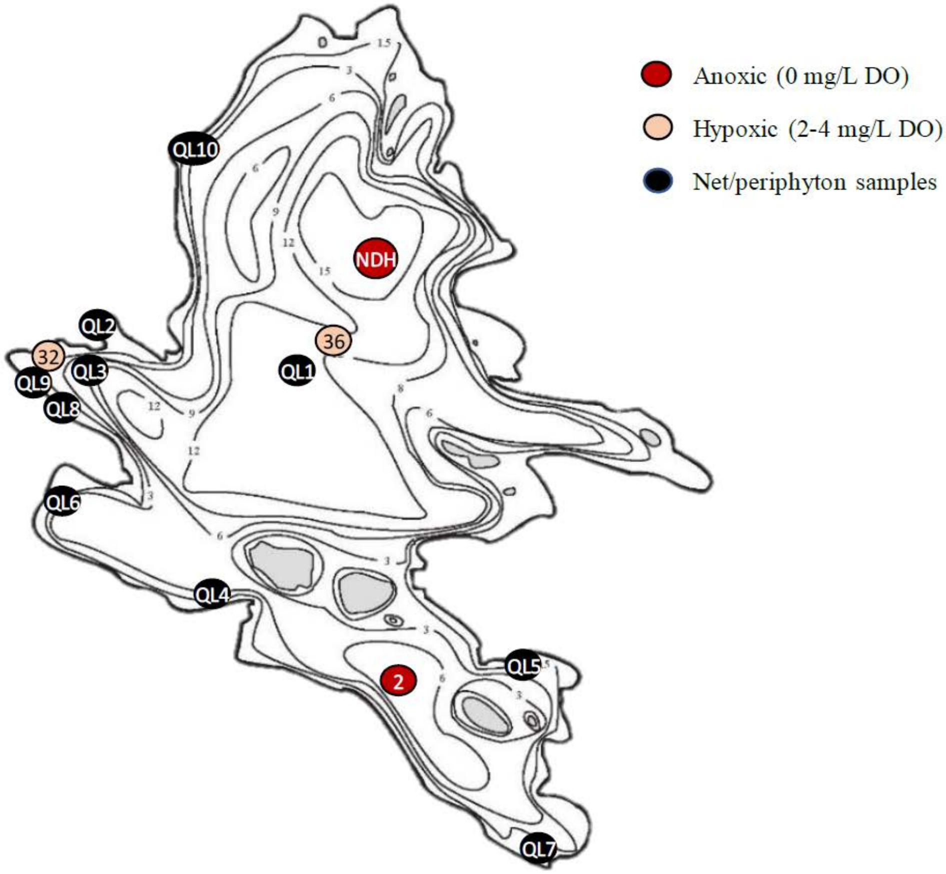
In 2017, the Leonard Lake Stakeholders Association (LLSA) engaged a small team of private consultants to analyze and report on limnological data collected as part of their stewardship program. Leonard Lake: Water Quality and Algal Blooms: Status, Monitoring and Management (LLSA, 2017) summarized previous information on Leonard Lake, including lake morphometry, background information and historical monitoring data, in addition to assessing data collected between May and October 2017 (Table 11; Figure 6). Samples were collected for nutrients, metals, and trophic status (i.e., chlorophyll *a*), in addition to water clarity and profiles of dissolved oxygen and temperature.

The Leonard Lake monitoring program is an example of an expanded monitoring approach, putting past long-term data and a comprehensive sampling year together to assess the state of the lake. While the data collected during the 2017 program can be incorporated into a larger watershed scale dataset, parameters collected exclusively in 2017 will only provide a snapshot of water quality in the lake and highlight the need for expanded monitoring of water quality parameters as part of a revised comprehensive monitoring program.

Table 11. Leonard Lakes Stakeholders Association Monitoring Program Summary

Monitoring Frequency	Isolated program; 2017
Sampling Staff	Leonard Lake Association, Citizen Science
Sampling Locations	Four Water Quality Sites (2, 32, 36 and NDH) Ten "Qualitative" Sampling Stations (QL1-10)
Parameters (Period of Record)	Total Phosphorus Secchi Depth Nitrate Dissolved Metals Dissolved Oxygen profiles Temperature profiles Chlorophyll a Plankton

Figure 6. Leonard Lake Sampling Sites during 2017 Sampling (LLSA 2017)



3.8 PWQMN Monitoring

The Provincial Water Quality Monitoring Network (PWQMN) collects and analyzes water quality samples from streams and rivers across southern and northern Ontario. The PWQMN dataset includes data to assess a number of emerging issues in water quality in the province including total and dissolved nutrients, metals, and chloride. Historical data from 20-30 stations, sampled within the Muskoka River watershed, are available (Figure 7). However, most of the data collected in the watershed began in the 1960s and no data has been collected since 1995, limiting its usefulness to the IWM program. Water quality programs within the watershed are focused on lake monitoring stations and therefore additional river data may be valuable in identifying and tracking emerging issues and should be considered as part of the expanded water quality monitoring initiative in the Muskoka River Watershed.

4. Developing a Comprehensive Water Quality Monitoring Program

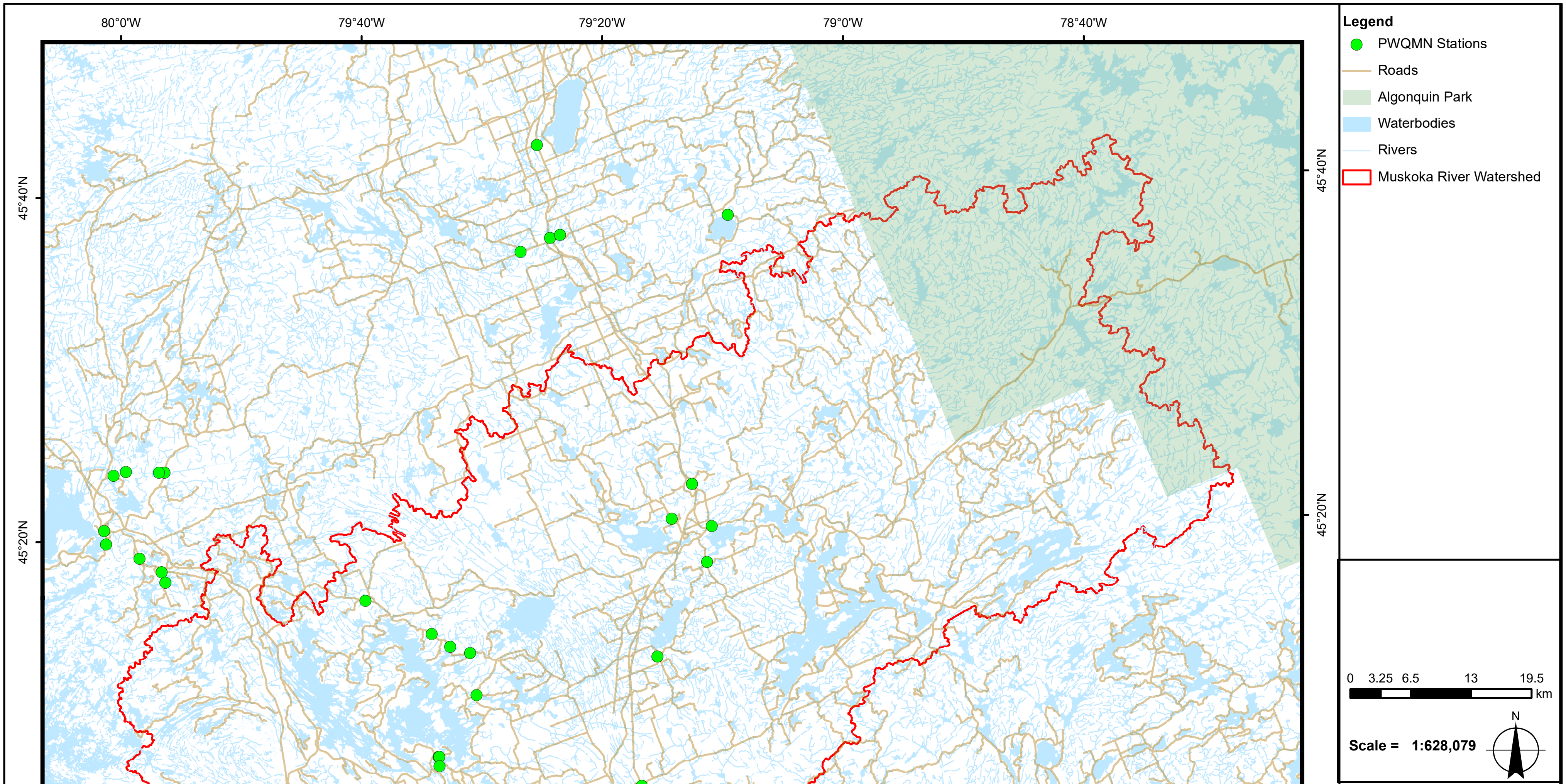
Findings from the literature review of emerging threats to water quality and the review of current water quality monitoring programs are discussed in the following paragraphs to inform general recommendations for program development and specific recommendations related to the identification and selection of specific water quality indicators.

4.1 Program Development

Building on existing water quality monitoring programs to develop a coordinated, science-based water monitoring program which encompasses lakes, wetlands, and streams to track climate-driven changes in water quality and aquatic biota is a significant undertaking and will require an adaptive approach to assess and adjust program features as monitoring and research needs change over time. For example, the Government of the Northwest Territories facilitates and supports a community-based water quality monitoring program across the Mackenzie River Basin which includes an independent program review, including assessment of the full data set every five years. Developing and maintaining a watershed-wide monitoring program will require significant long-term financial and staffing resource commitment.

Recommendation #1 - Agencies need to coordinate their efforts and where possible resources to address emerging issues.

Water quality monitoring in the Muskoka River Watershed is comprised of numerous programs working independently towards similar goals, most commonly tracking long-term changes in phosphorus concentrations as a means to assess and manage the impact of lakeshore development on recreational water quality and aquatic biota. Data collection and analysis protocols is consistent between many of these programs and therefore the potential to combine these datasets in high. Based on our assessment of the active water quality programs and current and emerging water quality issues, it is clear that the current monitoring programs and related data are valuable but substantial changes are required to ensure these monitoring programs can better assess emerging water quality issues. Emerging water quality issues are complex and, in some cases, poorly understood and will therefore require not only monitoring but research to understand the impact of multiple stressors more fully in a local context and inform the development of



Hutchinson Environmental Sciences Ltd.

Project #: 220010
Drafted: K. Hadley
Reviewed: B. Parsons

Projection: UTM Zone 17N
Datum: NAD 1983
Date: Sep 22, 2022

Figure 7

PWQMN Stations in the Muskoka River Watershed

watershed-wide goals and the determination of appropriate planning policies, stewardship and best management practices. A collaborative strategy between the District of Muskoka, the Dorset Environmental Science Centre, Muskoka Watershed Council, Friends of the Muskoka Watershed, Muskoka Lakes Association, Township of Seguin and additional partners will be necessary.

Recommendation #2 - Include consideration of beneficial long-term research projects and the resources required at the DESC to facilitate that research

The Dorset Environmental Science Centre is a significant asset to coordination, monitoring and assessment of environmental data in the region. Many scientists at DESC have researched water quality and aquatic science issues in the Muskoka River Watershed for their entire careers. Understanding and managing emerging issues in water quality requires long-term investment on focused research projects, in addition to long-term comprehensive monitoring. DESC is the ideal resource to undertake expanded research on emerging water quality issues, however funding and staffing requirements of such research must be supported. We recommend that the development of a comprehensive monitoring strategy include a consideration of appropriate long-term research projects and related resources required at the DESC to facilitate that research.

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

Sampling equipment is a key component of monitoring and may be the most significant obstacle to expanding water quality sampling other than perhaps funding limitations. In Section 4.2, we propose changes to the spatial and temporal scale of data collection of the existing programs which includes recommendations for expanded temperature and dissolved oxygen profiles and continuous monitoring using data loggers. Expanding the spatial coverage required for watershed scale monitoring necessitates citizen-science involvement. Purchase or rental and training in the use of this equipment will be a key step in expanding data collection in the Muskoka River Watershed.

Recommendation #4 - Develop guidance for lake associations and other coalitions participating in monitoring

During our review of the current monitoring programs in the Muskoka River Watershed, we noted that numerous organizations were interested in participating in water quality monitoring programs but lacked information. Furthermore, our review of the Leech Lake Cottagers Association Monitoring Program found that total phosphorus samples were not being analyzed in a way that was meaningful to the program. We recommend that guidance on participating in monitoring in the watershed be developed to encourage greater citizen science participation and to ensure data are collected in a consistent and comparable manner.

Recommendation #5 – Develop PWQMN partnership or re-implementation to establish long-term monitoring stations on rivers in the watershed.

Current monitoring programs in the Muskoka River Watershed tend to focus on sampling sites in deep water and nearshore locations on lakes. Stream and river sampling is generally underrepresented in the watershed. Long-term PWQMN data is often the foundation of Wastewater Treatment Plant studies (e.g., Assimilative Capacity Studies) that are required to service growing populations and these data are lacking in the Muskoka River Watershed which may prove to be a hindrance for future servicing and limit in-depth understanding of watercourses in the Muskoka River Watershed.

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

A substantial part of any monitoring program development involves planning for the future to prepare for unforeseen management challenges. Forward thinking sample management is an important part of planning for the future and recent research examples have demonstrated the value of maintaining an archive of samples (N. Yan, Pers. Comm). Preserving samples of water, algae, and zooplankton can provide archives for the future if novel stressors need to be assessed or analytical methods improve.

4.2 Data Management and Analysis

Recommendations:

7. Make IWM data available alongside 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

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 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 an offline database of water quality data regardless of if the DataStream option is considered for added security. Lake Partner Program data is currently available on DataStream and adding data from the other monitoring programs in the area would provide

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 and are currently used by the DMM program during Lake Health Review Reports, however including additional parameters in these assessments as a measure of emerging issues is advised.

Data analysis options 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 the District's monitoring program assessment of water quality data to answer management questions relied on summary statistics (10-year average) and comparison to provincial and/or federal water quality guidelines. However, as the program has evolved, and the dataset has grown expanded data analyses in annual reporting do not appear to have been included. Time series analysis should be performed in all monitored lakes once a sufficient period of record (>=10 years) is available to assess trends in water quality.

Developing and maintaining a watershed-wide monitoring program will require significant long-term commitment. An adaptive approach, i.e., where data is assessed and the program is adjusted in response to changing monitoring and research needs, should be reviewed every 5 years to ensure that program resource allocation meets research and monitoring needs.

4.3 Identification of Water Quality Indicators

Our review of the existing water quality monitoring programs in the watershed suggests that several key emerging threats to water quality are not currently monitored. These emerging concerns are discussed in Sections 4.2.1 to 4.2.4 and used to develop a longlist of water quality parameters, which is presented in Section 4.2.5. For example, the impacts of climate change on lake health and harmful algae blooms, particularly in low nutrient lakes must be better understood if meaningful management action is to be taken (Section 4.2.1). Lakes and rivers in the watershed are sensitive to salinization because of reduced calcium concentrations and increasing chloride concentrations (Section 4.2.2). Also, pharmaceuticals, pesticides and other emerging contaminants represent a significant threat to lake heath but are not currently monitored in the watershed (Section 4.2.3).

4.3.1 Climate Change and Harmful Algal Blooms

Recommendations:

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.

Monitoring the effects of climate change on freshwater resources in the Muskoka River Watershed could be improved. The monitoring programs in the watershed that measure water temperature and dissolved oxygen profiles collect data throughout the water column primarily in the late-summer (typically mid to late August) or, in programs that lack a handheld water quality meter 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.

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 Muskoka lakes has pushed the timing of thermal maxima later in the year. Profile sampling in several programs (i.e., DMM, Seguin) is currently executed by trained summer staff with contracts ending in late August causing logistical issues with later sampling. 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 help solve both these problems and provide high resolution data for the management of cyanobacterial blooms in low nutrient lakes where wind and bottom water anoxia are thought to be major contributing factors.

Measurements of dissolved oxygen concentrations is not currently included in most programs. The District's Recreational Water Quality Program, The Township of Seguin's Long-term Water Quality Monitoring Program and Leech Lake Cottagers Association Water Quality Monitoring Program collect dissolved oxygen profiles as part of their field sampling protocols, however these profiles suffer from the same issues as those discussed for temperature above (i.e., they are collected earlier in the year than is ideal to capture the full impact of thermal stratification on bottom water oxygen concentrations), and are often insufficient to inform investigations of cyanobacteria blooms. High frequency monitoring of dissolved oxygen is considerably more logistically challenging as dissolved oxygen loggers can be prohibitively expensive and therefore, we recommend targeted dissolved oxygen logger deployment to inform lakes with frequent recurring cyanobacteria blooms.

Management of cyanobacteria blooms in Ontario lakes has historically focused on monitoring and reducing phosphorus concentrations through agricultural best management practices, and development and land use policy. However, cyanobacterial blooms in low nutrient lakes and lakes that have shown no change in nutrient concentrations over time has become increasing common. Addressing low nutrient algae blooms requires a better understanding of meteorological conditions in the watershed to link high resolution data with documented blooms. High air temperature and low wind speed pre-dated a cyanobacteria bloom in Peninsula Lake by several weeks (HESL, 2018). High resolution monitoring of meteorological data may therefore provide data on the drives of cyanobacterial blooms in Muskoka Lakes, but in some circumstances may provide an early warning indicator of potential bloom conditions. Monitoring climate data on a sub-watershed scale (i.e., the 3 sub-watersheds of the Muskoka River) may be a valuable starting point which can be scaled up in the future depending on the results and review of the program. A variety of options are available for collecting climate data, for example, Davis Instruments personal and professional weather stations range in cost from ~$1000-2000 and could be set-up and managed by the DMM or lake association partners.

Under the current DMM Official Plan, lakes which experience a harmful algal bloom are registered as Schedule E1 and considered vulnerable, triggering a causation study. During the pilot program of these causation studies on Peninsula Lake one of the key data gaps identified was the lack of information recorded on blooms (HESL, 2018). We recommend development of a citizen scientist program for bloom monitoring to compliment high frequency data on climate and dissolved oxygen. Recording the onset, extent and severity of cyanobacterial blooms for comparison against these data to inform on the conditions contributing to blooms is invaluable in the effort to manage recreational water quality. Potential options for collecting and storing data on blooms are numerous, 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.

4.3.2 Salinization

Recommendations:

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

As discussed in Section 2.5, the established Canadian Water Quality Guideline (CWQG) for chloride is not sufficient to protect lake food webs and researchers have called for reassessment of the current CWQG (Hintz et al. 2022). This suggests that alternative methods for tracking the impact of winter road maintenance activities on Muskoka lakes is warranted. Diatoms are ubiquitous in freshwater lakes and are sensitive to road salt applications, however monitoring them is labour intensive and requires taxonomic expertise. Engaging with university partners to investigate the feasibility of using diatoms (either from periphyton or surface sediment samples) as a road salt indicator should be considered.

Wide-spread issues with road salt application have been explored in the Muskoka Watershed by both the Muskoka Watershed Council (MWC, 2010), and The District of Muskoka (GHD, 2018); as well as in the Adirondack Mountains in New York State resulting in a comprehensive report (Kelting and Laxson 2010) on the effects, cost and best management practices for winter road management. Balance between safe winter road conditions and environmental protection is difficult but effort within the District is clearly already underway to manage chloride inputs.

4.3.3 Contaminants

Recommendations:

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

We recommend that the Comprehensive Monitoring Program investigate emerging contaminants relevant to the Muskoka River Watershed (e.g., active pharmaceuticals, personal care product additives, pesticides, engineered nanomaterials, and microplastics). Ecotoxicology data are severely lacking for active pharmaceutical ingredients (API) and mixtures of APIs, making the determination of a biological indicator for these compounds difficult, thus individual metrics are likely the best current approach. In remote locations the risks associated with these compounds may be minimal, and sampling may not be necessary. However, 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 WWTP outfalls, and the highest population densities in the watershed, would allow some assessment of potential impacts. 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 may include:

- Develop a list of priority APIs requiring further investigation
- Identify high risk areas in the Muskoka River Watershed
- 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

4.3.4 Longlist of Water Quality Indicators

We recommend the following longlist of water quality indicators (Table 12) as a basis for comprehensive water quality monitoring in the Muskoka River Watershed based on the assessment of emerging issues and review of existing datasets. Many of these parameters are monitored by some of the programs within the watershed, however, expanded frequency and spatial distribution of monitoring locations would improve local comprehension of water quality issues and trends. Taking advantage of the existing programs in the watershed provides an avenue for the spatial expansion of the program as the methods, detection limits and parameters being sampled complement the District's recreation water quality initiative.

Table 12. Recommended longlist of water quality indicators.

Indicator	Rationale	Monitoring Approach
Total phosphorus	**Reflects impacts from a variety of natural and human sources. Primary limiting nutrient for the growth of algae and aquatic plants.** Increases over time or in specific areas reflect population growth and human activity	Throughout watershed
Dissolved organic carbon	**Influences phosphorus concentrations from natural sources (i.e. helps to differentiate between natural and anthropogenic sources) and water clarity** Reflects changes to wetland dynamics and hydrology	Throughout watershed
Calcium	**Reflects changes to aquatic health (via legacy of acid rain)** Lakes in Muskoka are experiencing calcium decline affecting aquatic biota	Throughout watershed

Chloride	**Reflects increases from road salting for de-icing** Represents a proxy for urban development (watershed hardening and alteration) Lakes in Muskoka are reaching harmful levels for aquatic biota	Throughout watershed in surface water, groundwater, and wetlands close to selected key roads (e.g., Highways 11, 60, 118, 141)
Total suspended solids	**Reflects input from runoff or erosion** Can indicate sources of high bacterial and phosphorus levels	Throughout watershed
Water temperature	**Reflects climate change** Provides context for other indicators	High frequency automated monitoring
Dissolved oxygen	**Reflects climate change** Indicates potential danger to fish, increased risk of harmful algae blooms	High frequency automated monitoring
Escherichia coli	**Can indicate contamination due to human activity** Due to difficulties in interpretation (caused by patchy distributions and uncertain sources), targeted sampling (at limited number of sites) for general trends recommended	Targeted sampling
Benthic macroinvertebrates	**Integrate long-term ecological conditions** Composition varies with habitat, which may confound any stressor signal	Targeted sampling at specific outfalls or sources (e.g., near development) and more widespread sampling once reference conditions determined and habitat influences controlled
Cyanobacterial blooms	**Reflects nutrient enrichment and impacts of climate change** A concern for water quality and human health. Nuisance algal blooms may be increasing in Muskoka	High frequency automated monitoring and remote sensing for early detection from August – October (when blooms most commonly reported) Monitoring at downwind sites and beaches (where greatest interaction of people with water)
Fish species richness (especially sensitive cold-water species)	Fish integrate all water quality indicators and may indicate organic contamination (i.e., from road runoff)	eDNA to determine presence/absence (e.g. invasive species of concern) or netting
Emerging Contaminants e.g., Pharmaceuticals, pesticides	**Potential impacts to biological diversity and health at all trophic levels**	Targeted sampling Assess trends based on frequency of detections for compounds that are frequently below detection

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