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CYANOBACTERIA AND DRINKING WATER: OCCURRENCE, RISKS, MANAGEMENT AND KNOWLEDGE GAPS FOR PUBLIC HEALTH

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INTRODUCTION

With warming temperatures due to climate change and increased nutrient loads to freshwater systems, the occurrence of harmful algal blooms, largely associated with toxin-producing cyanobacteria, is expected to increase across Canada. While cyanoblooms have affected Canadian waterbodies for many years, the potential to negatively impact drinking water supplies is considered an emerging area of concern, with variations in the approaches taken to assessment and response to the risks across Canada. This evidence brief provides an overview of the scale of the issue in Canada and highlights key areas of importance for public health (PH) professionals and others involved in water management in responding to current and future risks from cyanobacteria in drinking water. This review will outline:

- Key factors affecting the proliferation of cyanoblooms
- The prevalence of cyanoblooms across Canada
- The health effects from exposure to cyanotoxins and risks to drinking water supplies
- The effectiveness of drinking water treatment for decreasing risks of exposure
- Existing approaches to management of cyanobloom risks to drinking water
- Knowledge and practice gaps for public health

BACKGROUND

Cyanobacteria (blue-green algae) are a group of naturally occurring photosynthetic bacteria found in fresh, brackish, and marine water. Cyanobacteria comprise a diverse number of species, some of which can produce toxic substances known as cyanotoxins. Under ideal growth conditions, cyanobacteria can rapidly proliferate and cause a bloom, which can be potentially harmful when cyanotoxins are produced. Cyanobacterial blooms (cyanoblooms) can be bluish-green, green, red or brownish in colour and have the appearance of pea soup or paint, forming a thick mat or scum at the water surface. Blooms most commonly occur at or near the water surface; however, some cyanobacteria can move throughout the water column.[1]

FACTORS AFFECTING THE OCCURRENCE OF CYANOBLOOMS

Cyanoblooms are difficult to predict, as the optimum conditions for growth can vary depending on the species of cyanobacteria and characteristics of the affected waterbody. Key factors affecting growth include:

- **Nutrients** – Phosphorus (P) and nitrogen (N) are the most important, with increased loading from diffuse sources such as agricultural runoff and point sources such as sewage effluent increasing the likelihood of observing a bloom.[2,3] Nutrient loading can be increased during storm events. Other elements such as iron can also be important due to effects on P-cycling in waterbodies.
- **Temperature** – Extended periods of warm temperatures favour cyanobacterial growth (e.g. above 20°C).[4] Drought events with extended periods of warm temperatures, accompanied by periods of dry, calm water provide ideal conditions for blooms to occur.[5] Warming temperatures have been associated with blooms in low nutrient lakes and bloom occurrence later in the bloom season in some provinces.[6]
- **Lake characteristics** – Blooms are more often found in eutrophic (nutrient rich) rather than oligotrophic (nutrient poor) lakes and in ones with low flushing rates and stratification where the water column separates into different layers based on temperature.[7] Warm calm zones near the surface favour bloom formation, and cool, low oxygen zones on the lake bottom can favour the release of phosphorus bound to sediments.[8] Ecological factors such as the presence of grazing zooplankton or competition for resources can also have an impact on proliferation of cyanobacteria.[3,5,9] Once a lake has experienced a bloom, the chances of recurrence increase.

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Occurrence of cyanoblooms in Canada

Bloom season in Canada usually begins in late spring and extends into fall. Most bloom events in 2018 occurred between June and November, although one bloom in B.C. extended into January 2019. The bloom season may be getting longer in some jurisdictions, as indicated by first reports of blooms occurring earlier in the season, and last reports occurring later in the season.[10] Reported and anecdotal accounts of blooms occurring in January and February suggest that cyanoblooms are a year round issue in some areas. Most of Canada's approximately two million lakes are not monitored for the presence of algal blooms, so many may go unnoticed or unreported.

There is no definitive account of the number of cyanoblooms experienced in Canada each year, but in 2018 nearly 150 incidences of waterbodies affected by cyanoblooms were found to be publicized on provincial government or health authority websites or media sites across Canada. According to these sources, the highest numbers of waterbodies affected by blooms were found in Ontario (66) and Alberta (44). Nineteen reports of waterbodies affected by blooms were found for Manitoba with some waterbodies (e.g. Lake Winnipeg) experiencing multiple and long-lasting blooms. Smaller numbers of blooms (e.g. <10) were also reported in each of B.C., Saskatchewan, Nova Scotia, New Brunswick and Newfoundland and Labrador. Prince Edward Island (P.E.I.) reported no blooms in 2018, and has only reported eight blooms since 2004. No records of reported blooms or advisories were found for Canada's three territories in the past three years.

Reporting for Quebec for 2018 was not available at the time of writing, but provincial authorities reported two blooms in 2017.[11] This follows a change in 2016 to streamline Quebec's approach to bloom monitoring to reduce surveillance of waterbodies that routinely experience blooms, as well as waterbodies not used as drinking water sources. In the decade preceding this change, an average of 107 waterbodies were reported to be affected by cyanoblooms per year in Quebec.

Surveillance strategies are not consistent across provinces, making it difficult to determine if blooms are increasing in all locations, although reports from provinces with more consistent reporting approaches seem to show an increase.[10,12] Some increases in bloom reporting may be due to more established monitoring and reporting procedures or increased awareness amongst members of the public or water stewardship groups in some areas. However, the combination of land use changes, diffuse and point source pollution and increasing temperatures present conditions likely to favour the increased occurrence of cyanoblooms. Other climate related factors such as precipitation, wind, hydrology of streams and rivers feeding lakes, and limnological factors such as lake stratification may also affect frequency of bloom occurrence in the future.[13]

CYANOBLOOMS AND HEALTH RISKS ASSOCIATED WITH EXPOSURE IN DRINKING WATER

The presence of a bloom and its relative appearance and colour are not indicators as to whether a bloom is toxic, but are the first visual indication that a risk exists from exposure through recreational contact or ingestion of contaminated drinking water or food.[1,14,15] The primary risks of harm from cyanobacteria come from the cyanotoxins produced intracellularly and released during the organism's lifespan or released when the cells die and burst. Toxins may remain in a waterbody after a bloom has disappeared, and some toxins may persist in sediments.[3]

Cyanotoxins and effects on health

Approximately 5% of the more than 2000 known species of cyanobacteria are known to produce cyanotoxins, and some cyanobacteria can produce more than one cyanotoxin.[16] Cyanotoxins can target a range of organs, such as the liver (hepatotoxins), nervous system (neurotoxins) and skin and acute exposure can result in vomiting, diarrhoea, skin irritation, rash, fever, and headache, amongst other symptoms.[17,18] The potential health effects are wide ranging, and in some cases still poorly understood, particularly chronic health impacts.[9,19-21] Most studies of health effects of cyanotoxins are based on animal studies, with limited study on humans, including epidemiological evaluation of long-term exposures.[21,22]

The most commonly reported cyanotoxins are microcystins (MC) with more than 90 variants.[23] Microcystins are a hepatotoxin and can be produced by many species of cyanobacteria including *Microcystis* spp., *Anabaena* spp. and *Planktothrix* spp.[19] The International Agency for Research on Cancer (IARC) has classified one MC variant, microcystin-LR (MC-LR), as Group 2B, possibly carcinogenic to humans after chronic exposure.[24] MCs are one of the most widespread cyanotoxins and usually the only one measured in Canadian waterbodies.[4,21]

Microcystis wesenbergii.
Photo credit: FWC Research

Other common groupings of cyanotoxins include anatoxins (neurotoxin), saxitoxins (neurotoxin), and cylindrospermopsins (hepatotoxin) although there is little routine monitoring of these compounds in Canada. Other than MC, anatoxin-a is the only other cyanotoxin for which drinking water limits exist in Canada (Quebec only). Little data is available on distribution and concentrations of other toxins, but blooms have been found to contain mixtures of cyanotoxins.[25] One cyanotoxin for which interest is growing is β-N-methylamino-L-alanine (BMAA), a neurotoxin that can be produced by multiple genera of cyanobacteria. BMAA has been found to have potential links to neurodegenerative diseases such as amyotrophic lateral sclerosis (ALS), Parkinson's disease and dementia, but correlation is not yet well understood. This toxin has been detected in brain tissues of Canadian Alzheimer patients, and has been found in Canadian waterbodies, but does not appear to be widespread in the environment, and there is currently no evidence of adverse health effects due to exposure from drinking water.[22,25,26]

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Evidence of health Impacts from cyanotoxin exposure in drinking water

Records of human mortality or morbidity resulting from cyanotoxin exposure via drinking water are relatively scarce. A literature review of global cyanotoxin poisoning events identified 115 incidents in humans between 1800 to 2010, of which just 27 were related to drinking water exposure, and three to haemodialysis treatment with contaminated water.[27] The remaining incidents were largely related to recreational exposure. Each incident may represent one or more individuals affected and although drinking water incidents are rare, they have the potential to affect large numbers when they occur. One of the most significant and catastrophic incidents of cyanotoxin poisoning in treated water occurred at a haemodialysis clinic in Caruaru, Brazil, in 1996. Over 100 patients became ill following haemodialysis treatment, with over 50 dying due to acute liver failure, later attributed to cyanotoxin poisoning in the source water.[7,20,21] In this case MCs were identified as the cause, and acute poisoning was thought to be exacerbated by intravenous exposure. In the same clinic, drinking water was consumed; however, no incidents of acute poisoning were reported amongst those consuming drinking water only.

Acute exposure

Five incidents of morbidity related to cyanotoxin exposure in Canada were recorded between 1800 and 2010, all of which were related to recreational exposure in the years up to 1970, with no incidents attributable to drinking water.[27] There is likely under-reporting of acute illness, which may be associated with generic and relatively mild symptoms. For example, a study of 267 families (466 individuals) carried out in southern Quebec found that residents of three resort lakes affected by cyanoblooms recorded significantly higher incidence of some symptoms (gastrointestinal illness, muscle pain, skin symptoms, ear symptoms) amongst participants whose water supply came from one of the lakes contaminated with cyanobacteria.[28] In this study, none of the individuals experiencing symptoms visited a health provider as a result, and it was not possible to attribute these symptoms directly with exposure levels. Non-specific health effects such as gastrointestinal illness may be less likely to be attributed to cyanotoxin poisoning as compared to more common causes such as enteric bacteria in consumed food or drinking water. Those affected may experience only mild symptoms and may not choose to report these to a health provider.

Chronic exposure

While current levels of exposure and experienced symptoms appear to be limited, more waterbodies may experience increased frequency and duration of blooms and potential exposure periods.[21] The literature on the effects of chronic exposure to low levels of cyanotoxins in drinking water is scarce. One Canadian study attempted to assess whether an association between liver cancer and surrogate markers for cyanobacterial exposure could be identified in various locations across Canada.[29] The study found no correlation between incidence of liver cancer and surrogate markers of potential cyanobacterial exposure, which included agricultural activity and cattle and swine densities. The study, however, had many limitations with regards to the use of national level data that did not provide scope for assessing correlations at finer units of geography or population. Also, the surrogate markers of potential cyanobacterial exposure provided a broad generalization of when and where blooms occur, but were not tied to actual bloom events or affected drinking water sources. Around the world there have been a few studies of chronic impacts on human populations exposed to drinking water affected by cyanotoxins. A study from China suggested that chronic exposure to cyanotoxins in drinking water from the Three Gorges Reservoir may be associated with liver damage amongst exposed children.[21] A study in Ohio looking at the risk of cancer and exposure to cyanobacteria affected drinking water was inconclusive, and while there is evidence of carcinogenicity there is inadequate data on long-term effects in humans and animals.[21]

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Occurrence of cyanotoxins in Canadian drinking water sources

Exposure to cyanotoxins in drinking water can occur when drinking water is extracted from an affected waterbody, and inadequate treatments are implemented to remove cells or toxins. The presence of a bloom does not always result in the presence of cyanotoxins, but there is also potential for cyanotoxins to accumulate over periods of low-level cyanobacteria growth that do not result in a bloom.[25]

Which drinking water sources are most affected?

Cyanoblooms are more likely to form in surface waters such as lakes and reservoirs; therefore, water supplies taken from these sources are susceptible to cyanotoxin contamination if cyanoblooms occur near water collection or intake points. Most intake points are deep in a lake or reservoir, and can avoid bloom affected areas near the surface, but depth of intake is not always fully protective as some cyanobacteria can move vertically in the water column and water levels can fluctuate (e.g. following dry summer spells or drought).

Groundwater that is under the direct influence of surface water (GUDI) may be at a lower risk than surface water, although shallow GUDI wells close to affected waterbodies can still be exposed to infiltration from surface waters. In rare cases, low levels of cyanotoxins have been detected in groundwater; however, protected groundwater sources are perceived to be at a very low risk of cyanotoxin contamination.[30,31] Surface water sources from fast-flowing rivers are also suggested to be at a low risk of cyanotoxin contamination, as cyanoblooms are unlikely to become established in these types of waterbodies.

Surface water is the dominant drinking water source for most Canadian provinces and territories apart from the Yukon and P.E.I. where no municipal drinking water treatment plants are supplied by surface water.[32,33] In all provinces except for P.E.I., cyanoblooms have been reported to have occurred on waterbodies providing drinking water and between 4-5% of Canadian treatment plants have identified cyanoblooms as a potential source water issue.[34] As an example of the scale of the issue, in the province of Alberta, 133 lakes and reservoirs have a record of cyanobacteria or cyanotoxin detection with 21 of these used as drinking water sources.[35] No drinking water sources in the territories have been reported to be affected by cyanoblooms.[22]

Capilano reservoir. Photo credit: SqueakyMarmot via PhotoPin

Cyanobloom Lake Erie July 2015. Photo credit: earthobservatory.nasa.gov

What are the Canadian drinking water guidelines for cyanotoxins?

Microcystins are the only cyanotoxins for which Health Canada has issued guideline maximum acceptable concentrations (MAC) for drinking water. Canada's first drinking water guideline for a single cyanotoxin (1.5 µg/L MC-LR) came into effect in 2002, based on the World Health Organization (WHO) guideline of 1.0 µg/L MC-LR, but adapted for Canadian average body mass and daily water consumption. In 2018, a new guideline for drinking water of 1.5 µg/L for Total MCs was adopted. Health Canada also recommends that when the Total MC concentration exceeds 0.4 µg/L, an alternative source of drinking water (e.g. bottled water) should be used for mixing infant formula. Insufficient data on the health effects of other cyanotoxins is a barrier to assessing the risk they may pose through drinking water exposure and establishing safe guideline levels; however, this may change as more data becomes available. The U.S. Environmental Protection Agency (EPA) has now set Drinking Water Health Advisory (DWHA) limits for both MCs and cylindrospermopsin, and has also set limits for more vulnerable groups (e.g. children under six).[36]

Are drinking water treatment systems effective?

Previous studies of cyanotoxins in Canadian waterbodies affected by cyanoblooms have found that MCs are detected in most raw water samples, but the majority do not exceed the Canadian Drinking Water Guideline for MCs in treated water, although exceedances have been found in all provinces.[2,37] This has resulted in interruptions to public water supplies and DNC advisories in some cases. For example, between 2006 and 2012, 31 DNC notifications were issued on water supplies in the province of Quebec.[38]

The province of Manitoba reports that a 1995 survey of rural and municipal water supplies found cyanotoxins in 93% of raw water samples at levels of <0.1 to 0.6 µg/L. After treatment, levels ranged from <0.1 to 0.4 µg/L, below the Health Canada guideline for seasonal exposure.[39] An additional survey in Manitoba in 2015 found no cyanotoxins in treated water supplies, despite about 20 source waters affected by cyanoblooms.[40]

Municipal drinking water treatment plants

The majority of Canadian households (88%) are supplied by drinking water from large municipal drinking water treatment plants although this ranges across Canada, with only about half of the population in P.E.I. and New Brunswick supplied by municipal supplies.[32] Most large drinking water treatment plants are equipped to deal with a measure of cyanotoxin risk, with multiple treatment steps in place to address chemical and biological contaminants. Very few treatment systems may have been risk assessed specifically against high, medium or low toxin scenarios, and few may have standard operating procedures specifically designed for a major bloom event. Studies of treatment effectiveness demonstrate that large municipal plants can, in most cases, reduce microcystins in raw water to acceptable levels in treated water; however, events of breakthrough of both toxins and cyanobacterial cells have occurred in Canada.[25,41-43]

Most treatment plants use a multi-barrier approach that addresses risks from both intracellular and extracellular (free) toxins (e.g. removal of cells and toxins). The approach includes avoidance measures such as choosing appropriate intake locations to avoid areas where blooms are more likely (e.g. near surfaces or shorelines), followed by physical treatment to remove cells (e.g. filters, adsorption) and additional treatments to degrade or adsorb toxins.[44,45] Removal of cells at an early stage, prior to disinfection, is crucial to preventing the release of large doses of cyanotoxins, as treatments such as algaecides (e.g. copper sulphate) or chlorine can cause cyanobacterial cells to burst, releasing high concentrations of free toxins, which are much more difficult to remove. Pre-chlorination is used in many treatment plants as part of normal treatment operations, but during a bloom, best practice may be to stop pre-chlorination to prevent toxin releases from cells. Burst cells and organic compounds can also result in

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harmful disinfection by-products forming when chlorine is being used for disinfection and can consume chlorine residual in the treated water distribution system, reducing effectiveness of disinfection.

Once cells are removed, advanced treatments including powdered activated carbon (PAC), granular activated carbon (GAC) and/or ozone treatment have been found to be very effective in reducing remaining microcystins to below acceptable concentrations, even for source waters with >100 µg/l MC.[18,46] Advanced treatment, however, adds additional costs to water treatment systems. Filters and adsorption media such as PAC/GAC can become saturated over time, requiring greater attention to plant maintenance during bloom season to maintain treatment effectiveness.[25] Not all cyanotoxins respond to various treatments in the same way, and systems may need to be adapted to respond to specific toxins.[19,41]

Small Drinking Water Systems (SDWS) and Private Water Supplies (PWS)

Twelve percent of Canadians do not receive their water from large municipal treatment plants but are instead supplied by small drinking water systems (SDWS) or private water supplies (PWS). Users of these types of systems drawing water from cyanobloom affected lakes or reservoirs may be at higher risk of exposure to cyanotoxins than those supplied by large municipal systems. This could include seasonal properties (e.g. summer cottages) and rural homes or business. Compared to large municipal systems, SDWS have not been designed specifically for cyanotoxin removal and less study has been carried out on the effectiveness of SDWS for removal of cyanotoxins compared to larger public supplies. No studies were found that have quantified the number of unregulated drinking water supplies across Canada that may be affected by cyanotoxins during bloom season.

The Walkerton Clean Water Center (WCWC) has reviewed the effectiveness of treatment technologies for removal of cyanotoxins in small systems. The review finds that very few studies have tested small system drinking water technologies and have only reviewed extracellular MCs, rather than cyanobacteria cell removal. Of the few studies that were completed, carbon-based filters and reverse osmosis (RO) are potentially effective for extracellular MCs, but other types of household filter media and UV treatment at a typical disinfection dose are generally ineffective for complete removal.[47] A short-term pilot plant study by the WCWC on the effectiveness of various treatment technologies for both cell removal and MC-LR removal found that all treatment combinations removed cells to a high degree, all removed MC-LR by at least 81% and RO, nano-filtration, carbon-block filters, and slow-sand filters removed toxins by up to >95%. Small systems that apply disinfection only, without pre-filtration, are more susceptible to toxin exposure as chlorination can cause cell lysis and release of dissolved toxins. Health Canada states that no systems have been certified for removal of cyanobacterial cells and dissolved MCs in PWS.[22] The National Sanitation Foundation (NSF) has certified a small number of products for reducing microcystins to below the U.S. EPA DWHA level (NSF 477). However, this certification only applies to use on public water supplies and not raw source water.

Addressing potential public health risks for SDWS and PWS remains a key challenge, particularly where monitoring and advanced treatment technologies are unlikely to be readily available. Private water supplies affected by a cyanobloom may represent the water sources that are most at risk; however, there are no reliable sources of data documenting the presence of cyanotoxins in SDWS or PWS in Canada; therefore, the level of risk is unknown. In most cases, the recommendation for these types of water systems is to seek an alternative source during the affected bloom period. Therefore, public health responses will typically focus on awareness raising of potential risks to water supply and advice on avoidance measures for affected users.

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MANAGING RISKS TO DRINKING WATER FROM CYANOBLOOMS

Recommended approaches to managing risks to drinking water from cyanobacteria are typically structured around a situational assessment that can identify the most vulnerable water supplies and user groups, an assessment of readiness to remove or reduce health risks arising from a cyanobloom, and planning for a response.[48-50] This usually involves multiple stakeholders including environmental and public health departments, regional or provincial environmental regulators, and water utility operators.

Assessing the situation

A situational assessment can help to identify vulnerable drinking water supplies and prioritizing waterbodies for further observation during the bloom season. Assessment of vulnerable systems may include consideration of historical occurrence of blooms, source water characteristics such as high nutrient concentrations, stratification and low flushing rates, recent changes to land use or nutrient loading, and weather (frequency and timing of hot, dry and calm periods). Consideration of who is served by the water supply (e.g. PWS, SDWS, municipal systems, dialysis clinics) and critical sampling points are important to help protect the most vulnerable users. Health Canada guidance states that drinking water supplies known or suspected to be susceptible to blooms should be monitored routinely for the presence of cyanobacteria by visual inspection and other observational indicators such as increased turbidity, poor taste or odour.[22] A situational assessment may be needed to identify these supplies, and to determine the readiness of key stakeholders including public health departments or water utilities to respond to blooms. One approach is incorporating cyanobloom risks into drinking water safety plans, as is being done in Alberta (Box A).

BOX A: DRINKING WATER SAFETY PLANS – ALBERTA

Alberta was the first province to have adopted drinking water safety plans (DWSP) that consider means of protecting drinking water at all points in the journey from water source, through treatment, to distribution and end user. DWSPs are now incorporating consideration of cyanobacteria in some cases. DWSPs are usually developed by drinking water treatment plant operators, whose level of experience dealing with cyanoblooms can be important to effectively planning for cyanotoxins risks in source water.[35] Factors most commonly found to increase the risk rating to drinking water from cyanoblooms include a lack of ability to change the intake location or source water, the use of pre-treatments such as copper sulphate that cause cells to burst and release toxins, and operational limitations (monitoring capacity, lack of a response plan, limited training in optimization techniques). Improvements could include greater training and support for operators including consideration of dangers of some pre-treatment technologies, incorporating cyanobloom management in the design of systems, continued source protection measures, advice for private operators, and improvements in training and support for operators, who may not have encountered cyanoblooms in source waters. Alberta Health Services is working with Alberta Environment and utility providers to develop standard operating procedures (SOPs) for drinking water operators to manage bloom risk assessment and response.

Planning for response

Responses to blooms vary across the country and in most cases visual confirmation of a bloom is the trigger for further action.[3] Most provinces apply decision protocols for responding to a bloom based on the Health Canada guidance (Fig 1) with some variations.[22] For example, the B.C. Decision Protocol issued in 2018 uses slightly different trigger levels, including nutrient concentrations, for further action.[51]

A challenge to coordinating an effective response plan includes the coordination of multi-agency stakeholders with various responsibilities.[34] Overlapping roles in provincial ministries, health authorities and municipalities necessitate a clear response plan with responsibilities clearly allocated. Having a clear communication and action plan in place can help to ensure that those affected are informed as soon as possible of potential risks, and treatment plant operators can adjust monitoring or treatment activities as necessary. The types of action may be: no further action, additional monitoring, action to advise the public, actions to address additional treatment needs with treatment operators and other stakeholders, actions to disperse the bloom, and actions to mitigate future blooms. Action plans or protocols for responding to cyanoblooms can vary in their level of detail.

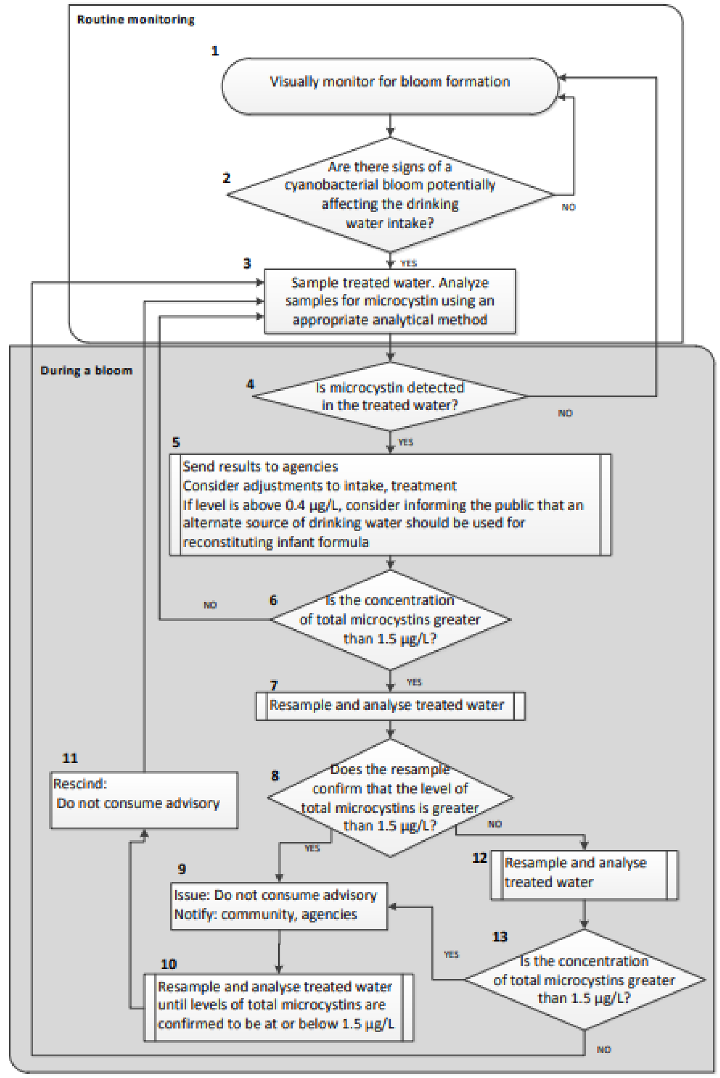

Figure 1 Health Canada flow chart for routine monitoring and bloom response.[22]

Monitoring

Once a waterbody has been identified as vulnerable, the extent of monitoring of raw and treated water will depend on the extent of the risk and available resources. Each province has their own approach to algal bloom surveillance and cyanotoxin monitoring and there is no standard approach to sample collection or analysis.[21] In many cases, provinces carry out only visual monitoring or minimal sampling, and waterbodies may only be visited in response to public reporting or complaints about algal blooms. This may be due to lack of perceived risk, lack of resources or other drinking water issues taking immediate priority.

Drinking water treatment plant operators will often increase monitoring during bloom season, and may adjust operational and maintenance practices in line with the multi-barrier approach. The key considerations include avoidance, followed by cell removal, toxin degradation, and maintenance to minimize buildup of removed toxins and recontamination.[35] Standard operating procedures for dealing with various levels of risk (e.g. low, medium, or high toxin levels) are not always available, and the experience of operators is often an important factor in responding to treatment needs.

Monitoring tools

A major barrier to increasing waterbody surveillance and extending monitoring activities to stewardship groups and citizen scientists is the lack of easy-to-use, rapid, cost effective and accurate field monitoring tools. Jar or stick tests may be able to assist with identifying whether a bloom is caused by cyanobacteria, or green algae (which does not produce cyanotoxins). Current field tests typically provide rapid results, but most offer low resolution. For example, test strips are commonly used to detect the presence of MCs above 1 μg/L, and have been found to be suitable for confirming the presence of MCs. However, these tools are sometimes difficult to interpret and may produce false positive results up to 38% of the time, resulting in further laboratory testing that is not always necessary.[35,37] In B.C. other non-cyanobacterial indicators may be used in monitoring such as nutrient concentrations, N:P ratios, or temperature during bloom season.[51] Use of these indicators requires a good historical dataset to predict conditions that may trigger blooms in a particular waterbody. Fluorescence techniques that detect light emission from phycocyanin, a pigment in cyanobacteria, have been suggested as useful real-time monitoring tools to alert drinking water treatment plant operators to changes in the source water by detecting rapid increase or decay of cyanoblooms, but these are not currently used in many monitoring systems.[52,53]

Laboratory tests provide more accurate identification and quantification of cyanobacteria species or cyanotoxins but these tests are more time consuming and costly. Typical tests include:

- Enzyme linked-immunosorbent assay (ELISA): estimates MC concentrations but cannot distinguish between MC variants.
- Polymerase chain reaction (PCR): detects the presence of a toxic gene in cyanobacterial cells to indicate that toxin producing cells are present. Not all cyanobacteria carrying a toxic gene will produce toxins (about 20% may not) and environmental factors for toxin production also exist.[44,54,55] Quantitative real-time PCR (qPCR) may be promising for field monitoring in the future.[56]
- Chromatography (e.g. LC/MS): provides precise identification and quantification of cyanotoxins but requires more expensive equipment and technical expertise.

Laboratory testing may provide more accurate results, but is of little use in many cases due to the time delay between collection of samples and receipt of results. This can be several days to weeks after a bloom has been visually confirmed. Cyanoblooms are dynamic events and changes in weather or water conditions can result in blooms moving, collapsing or spreading. In contrast the use of phycocyanin monitoring tools at a drinking water plant in Quebec in 2008 and 2009 detected rapid increases in cyanobacteria in raw water that led to breakthrough and accumulation of cyanobacterial cells.[43] Sampling on a once or twice weekly basis or relying on laboratory results with long turnaround times may have missed these events and prevented rapid response from operators.

Advisories

There are mixed approaches to issuing of an advisory for cyanobloom affected waters, which may differ by the types of uses (recreational, drinking water) and the trigger or alert levels used by the relevant authority (e.g. visual confirmation, confirmation of toxic cyanobacteria, MC levels above a threshold). In waterbodies where cyanoblooms typically occur every year (e.g. Lake Champlain, Lake Ontario, Lake Erie, Lake of the Woods and Lake Winnipeg) advisories may be physically posted at various locations for the entire bloom season, whether blooms are visually present or not. These are often accompanied by a media release, and many provinces host lists of current cyanobloom advisories on their websites throughout bloom season. Reporting on events in other waterbodies across Canada is variable.[3,4] In some provinces, such as Saskatchewan, a general province-wide advisory is issued each bloom season to alert members of the public of the potential presence of blooms, and the appropriate measures to reduce health risks associated with exposure to contaminated water. Other provinces and health authorities have also taken this approach to issuing general summer advisories in recent years. Advisories may extend for the full bloom season, as is the case in Alberta, or protocols may be in place to lift an advisory when consecutive sampling results show cyanotoxin levels within acceptable limits. Due to lack of resources for continuous sampling throughout a bloom season, a precautionary approach to keep advisories in place is often adopted.

Advice offered on provincial or regional government websites to members of the public during an algal bloom is similar across Canada. For drinking water, users of unregulated supplies (e.g. SDWS and PWS) may be advised to seek alternative sources if possible, not to boil water, and use precautions when washing clothes or dishes and bathing in affected water. Users of regulated supplies are typically advised to continue to use their drinking water as normal, unless the water utility provider recommends that customers use an alternative source. If necessary, utility operators will issue DNC orders for affected supplies. The length of advisory periods can include the entire bloom season, or advisories may be rescinded once a bloom has visually cleared. Knowing when to call an end to an advisory is still an area of uncertainty, particularly for waterbodies where unregulated drinking water supplies are affected. Maximum cyanotoxin concentrations produced by cyanoblooms do not always to coincide with maximum bloom density; toxicity can persist for days or weeks after a bloom has disappeared. Sudden releases of toxins can also occur when cyanoblooms die, either at the end of a season or due to chemical treatments to kill the cyanobacteria.[57] Previous study has indicated a lag time in natural waters of about nine days before degradation of MCs commences once released to the environment.[58] Therefore precautionary approaches may see advisories extended beyond the visual confirmation that a bloom has dissipated.

Photo credit: Conrad Kuiper via PhotoPin

Mitigation

Mitigation strategies can be proactive and seek to protect unaffected waterbodies from future blooms, but in practice, they are primarily reactive. Strategies for mitigating cyanoblooms are often coordinated by the relevant environmental agency and can be internal or external to the affected waterbody. These can include immediate strategies to disperse a bloom, such as algaecides or treatments to precipitate phosphorus out of solution, aeration to disrupt stratification and increased mixing, or introduction of other physical or biological controls such as algae grazers.[57] External strategies can include watershed management, seeking to reduce point and non-point source loads of nutrients. This can include setting maximum daily loading rates for key point sources of nutrients (e.g. wastewater treatment plants) or encouraging changes to land-based practices that reduce diffuse nutrient loading (e.g. changes to agricultural practices).[3,7,59] External measures can also include engagement of citizens, both to report cyanoblooms and to raise awareness of practices that could reduce nutrient loading into waterbodies.

Cooperative efforts may be needed where waterbodies share jurisdictional boundaries. An example is the Great Lakes Water Quality Agreement between the US and Canada, established to control nutrient loading into Lake Erie. There are still gaps in understanding of nutrient pathways, and knowledge of how climate change, land use changes, and expanding population and development will affect bloom occurrence and intensity.[49] Efforts to control future blooms are difficult given the global nature of climate change; however, factors such as nutrient remediation could offset to some degree the stimulatory effect that increasing temperature has on cyanoblooms.[43]

Public health participates in mitigation strategies to varying degrees depending on the affected waterbodies and possible impacts on health due to recreational or drinking water exposure. Without a greater understanding of how cyanoblooms are impacting health, it is difficult to design strategies that are targeted and appropriate to protect the most vulnerable users. The lack of health surveillance for cyanotoxin-associated illnesses during bloom season limits the ability to communicate the relative risk of harm to the public from cyanoblooms, and encourage citizen engagement in mitigation meaures.[49]

Cyanotoxin poisoning may go undiagnosed, and there is no reporting requirement for cyanotoxin related illness.[60] Improved information for health practitioners and the public on exposure routes and cyanotoxin-related symptoms could enable relevant authorities to develop better reporting, response and mitigation strategies. In 2016, the US Centres for Disease Control (CDC) launched a One Health Harmful Algal Bloom System (OHHABS). The system allows for voluntary state and territorial reporting of HABs, human illness and animal illness. This is linked to the National Outbreak Reporting System (NORS) and is helping to build information for public health on the extent and degree of acute illnesses related to cyanoblooms.[60] An equivalent system does not exist in Canada for cyanobacterial illnesses.

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SCAN OF PROVINCIAL AND TERRITORIAL APPROACHES TO MANAGING CYANOBACTERIAL RISKS TO DRINKING WATER

All provinces have adopted the Health Canada Guidelines for drinking water into provincial guidance, although monitoring for cyanotoxins varies from active monitoring of vulnerable waterbodies to reactive monitoring when complaints are received.[61] All provinces work with multiple agencies to manage cyanotoxin risks to drinking water. This includes municipal operators of drinking water systems, First Nation's communities, provincial and regional health authorities and other public health and environmental stakeholders (e.g. ministries responsible for the environment, or public health). Responsibility for issuing advisories and taking action may vary by waterbody (e.g. a drinking water source or recreational water). Examples of approaches used in each of Canada's provinces and territories are presented below:

British Columbia

In 2018, the B.C. Government (Health Protection Branch) issued the updated Decision Protocols for Cyanobacterial Toxins in B.C. Drinking Water and Recreational Water.[51] The protocols provide strategies and resources for local government, health authorities and operators of drinking water systems to assess and manage risks due to cyanoblooms. Stakeholder roles and responsibilities are outlined, and suggestions for preparation and communications are provided. The protocol separates out the decision tree for drinking water and recreational water and summarizes the important actions that could be taken, including a decision support tool for unregulated water systems. One of the differences between other provincial protocols is the use of nutrient concentrations (N, P, and N:P ratio) as triggers for further action, along with visual confirmation of a bloom. All other provinces use visual identification of a bloom as a trigger. The First Nation Health Authority in B.C. has adopted a similar protocol based on the B.C. Protocol and works with First Nations communities to respond to bloom events.

Alberta

Since 2005, all drinking water plants drawing surface water have been required to test for MC-LR during bloom season.[34] Alberta was the first province to have adopted drinking water safety plans (DWSP), which consider means of protecting drinking water at all points in the journey from water source, through treatment, to distribution and end user. DWSPs are now incorporating consideration of cyanobacteria in some cases, where cyanoblooms are present in source waters. A study to evaluate risk from cyanotoxins in Alberta's 404 regulated drinking water systems found that overall there is very low risk from cyanotoxins in Alberta public drinking water systems.[35] DWSPs that focus on continuous improvement and mandatory analysis for cyanotoxins contribute to high quality protection. Alberta Health Services (AHS) provides advice on safe water treatment for SDWS and PWS affected by cyanoblooms. A precautionary approach is typically recommended (e.g. switching to an alternative safe supply), but reducing risks through application of the multi-barrier approach is also suggested. The Alberta Environmental Public Health Information Network (AEPHIN) has recently launched an interactive website for reporting on cyanoblooms in Alberta Recreational Waters. This allows users to explore results by geography, lake name and test results, which could be a useful tool for users of SDWS or PWS on affected waterbodies.[62]

Saskatchewan

The Saskatchewan Ministry of Health and Water Security Agency (WSA) issue a province-wide advisory to the public each bloom season, warning about the risks of drinking or swimming in water where cyanoblooms are present. Drinking water plants regulated by the WSA must meet the drinking water standard for MC-LR by July 2020. The protocol for managing risks to drinking water from cyanoblooms recommended by the WSA includes visual monitoring for bloom formation during bloom season. If a bloom is detected, sampling for total MCs in the source water is recommended. For surface water sources supplying water to >5000 persons, monitoring is required monthly during the bloom season, and following detection of a bloom for smaller supplies.[63] A 2013 study found levels in drinking water at selective locations in the province were well below the standard or not detected.[40]

Manitoba

The issue of lake eutrophication has been a high-profile problem in Manitoba in recent decades, with Lake Winnipeg in particular affected by several blooms each year. The Province of Manitoba and Government of Canada announced the Lake Winnipeg Basin Initiative in 2007, combining efforts of various public bodies and local stewardship to achieve a reduction of P levels by 50%, and restore the lake to pre-1990 conditions to reduce harmful algal blooms.[64] Other groups are active in monitoring cyanoblooms in Manitoba, such as the Lake Winnipeg Foundation, who helped to establish the Lake Winnipeg Community-Based Monitoring Network, engaging citizens in lake monitoring. Cyanobloom and cyanotoxin monitoring and reporting in Manitoba follows protocols based on Health Canada and WHO frameworks.[34] The Government of Manitoba provides the public with access to up-to-date interactive maps that show drinking water advisories as well as beach monitoring information.[65] The beach monitoring information reports on both the location of blooms along with cell counts for cyanobacteria and concentrations of MCs, which could be a useful tool for local water users (including PWS users) to see the status of both bloom density and cyanotoxin concentration near any PWS intake points.

Ontario

In Ontario, cyanotoxin response is focused on reactive monitoring when complaints are received. The Ministry of Environment Conservation and Parks (MECP) has created a provincial level protocol (12-point response plan) for responding to bloom events, with roles and responsibilities assigned to various agencies and local public health units.[34] Bloom reports can be received by either the MECP or public health units, resulting in a site visit to confirm bloom occurrence and analysis of bloom samples for presence of cyanotoxin producing species. The turnaround time for laboratory testing is typically three weeks. The absence of toxin-producing species ends the formal response, whereas presence initiates further steps such as additional testing, alerting relevant stakeholder or issuing of advisories.10 Surface water sourced municipal drinking water systems are routinely tested for cyanotoxins. Testing is not required for SDWS, and PWS are rarely tested. An example of the approach taken in one of Ontario's 35 public health units is shown in Box B.

BOX B: CYANOBLOOM RESPONSE BY PUBLIC HEALTH SUDBURY & DISTRICTS (PHSD)

PHSD has a cyanobloom response approach developed in partnership with Public Health Ontario. In addition to issuing a general annual media release to warn the public about the health risks of cyanoblooms, PHSD will take actions in response to blooms as they are reported. On visual confirmation of a bloom, samples are analyzed by the MECP, who confirm the presence or absence of a toxin producing species. Confirmation triggers further actions. For locations experiencing a bloom for the first time in more than five years, door-to-door information is provided to the public in the vicinity of the cyanobloom on the possible health risks in addition to media releases. For areas with blooms occurring in the past five years, a general media release is issued. All locations affected are listed on the PHSD website, and the public can also access historical information on waterways affected by cyanobacteria in the PHSD area. Access to both current and historic data allows the public and PH professionals the opportunity to see where and when blooms have occurred in the past and be alert for future bloom events.[66]

Quebec

With a large number of lakes affected by cyanoblooms each year (100+), Quebec has experienced impacts on drinking water supplies that have resulted in Do Not Consume orders in the past. Quebec has had an active cyanobloom monitoring approach for many years and was one of the early adopters of drinking water guidelines for cyanotoxins (MC and anatoxin-a).[34] The approach to responding to cyanoblooms in Quebec has involved partnership working between the Ministry of Sustainable Development, Environment and Fight Against Climate Change (MDDELCC) and the Ministry of Health and Social Services (MSSS). The MDDELCC will carry out visual inspection, collect samples if required and enact procedures for the affected waterbody if results exceed limits. Operators of drinking water systems are required to record observations of cyanoblooms. Trigger levels include cyanobacterial cell counts (≥20,000 cells/mL), as well as proximity to a drinking water intake, or identification of cyanobacteria within a treatment plant. Monitoring of affected drinking water systems (about 15 per year) indicates that treatment is sufficient to achieve the guideline MAC for total microcystins.[40] Quebec has been leading in many areas of cyanobacteria research in Canada. A large research project—Algal Blooms, Treatment, Risk Assessment, Prediction and Prevention Through Genomics (ATRAPP)—is hosted at Université de Montréal, funded by Genome Canada and Génome Québec (2016 to 2020).[67] The research mission is to predict, prevent and treat the proliferation of cyanoblooms and the risks associated with cyanotoxins.

New Brunswick

New Brunswick has an Algae Bloom Response Protocol that involves cooperation between the Department of Environment and Local Government (DELG) and the Department of Health (DH). The DELG responds to reports of blooms and carries out sampling and analysis. The DELG will screen bloom reports and determine if an inspection is necessary and communicate findings with DH if a bloom is confirmed, triggering the regional Medical Officer of Health (MOH) to assess risks and determine if an advisory is required. Where a drinking water supply is affected, DH follows Health Canada guidance. The affected municipality or Office of the Chief MOH (CMOH) will issue any necessary public health advisories, posted on government websites, onsite signage and in the media. A record of current and past cyanobloom advisories is posted online by the Office of the CMOH. The Watershed Protection Program in New Brunswick seeks to prevent pollution of designated watersheds and protected zones. No records of impacts to drinking water quality in New Brunswick due to cyanoblooms were found.

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Nova Scotia

A protocol for responding to cyanoblooms in Nova Scotia includes surveillance, notification, sampling, lab analysis, and risk communication (including drinking water advisories).[40] Response to blooms may be by provincial departments or municipalities. For example, Halifax Regional Municipality monitors 23 beaches and may follow up with sampling of suspected blooms and beach closures. The municipality also provides advice on affected drinking water sources. Provincial environmental health functions, including cyanobloom monitoring for recreational waters, fall under the remit of Nova Scotia Environment. Water treatment operators are required to ensure appropriate location and frequency of sampling for cyanotoxins is undertaken (e.g. sampled in late summer or early fall) and recommend changes to monitoring if sampling is inappropriate for cyanotoxins or the location should be changed.[68]

Prince Edward Island

All drinking water supplied by municipal treatment works is sourced from ground water, so no routine monitoring for cyanotoxins on drinking water sources is undertaken. The Department of Communities, Land and Environment handle reports of blooms in cooperation with Public Health for affected waterbodies where PWS may be affected.

Newfoundland and Labrador

Since 2007, the Department of Environment and Climate Change has monitored occurrence of algal blooms on a case-by-case basis, with the Department of Municipal Affairs and Environment Water Resources Management Division reporting on annual bloom occurrences each year. No incidents of cyanoblooms affecting drinking water supplies were identified, although blooms occur occasionally on other waterbodies. A source water protection program helps to limit the potential impacts of agricultural activity on nutrient concentrations in waterbodies used for drinking water.[40] The province follows Health Canada guidance when drinking water sources are at risk.

Yukon, Northwest Territories, Nunavut

Canada's territories have a low occurrence of cyanoblooms with no reports of impacts on drinking water sources identified. The consultation on changes to the Canadian Drinking Water Guidelines for cyanotoxins received responses from the three territories indicating no expected impact from any changes. This is due to low occurrence of cyanoblooms in general and many drinking water source waters being fast flowing water sources unlikely to be affected by blooms.[40] No specific approaches to manage cyanoblooms on drinking water sources in the Canadian territories were identified.

CHALLENGES AND KNOWLEDGE GAPS FOR PUBLIC HEALTH

The review of grey and academic literature, reports and websites of public health and relevant provincial and territorial partners, and communication with key informants in B.C., Alberta, Saskatchewan and Ontario have identified a number of challenges, including some knowledge and practice gaps for public health in managing cyanobacterial risks to drinking water. These include areas for further study, or development of new tools or approaches:

- There is a lack of **universal indicators** for monitoring and predictive modelling such as details of bloom occurrence, cell volume, toxin concentration, and other environmental data (e.g. temperature, precipitation, wind speeds, nutrient concentrations, etc.).[4,7] A lack of **standard methods** for sampling, analysis, and frequency of monitoring makes comparison of studies difficult.[1,3,49,54,69] A consistent approach to surveillance would help to quantify the risk of exposure and the health effects of cyanotoxins, and to develop threat assessment tools for public health professionals.

- The lack of **rapid and reliable field tests** limits the swiftness of response to cyanobloom events. Laboratory testing has been observed to be of limited use in some cases due to time delays and costs which limit the number of samples that can be tested and the frequency of testing. Rapid and cost-effective field tests or real-time monitoring tools could enhance the ability of relevant authorities to carry out enhanced surveillance.[54,70] This could improve **timely detection and quantification** of risk and help PH professionals better communicate risk to the public, including providing more information on when a bloom advisory can be lifted, a key area of uncertainty in many health units.

- **SDWS and PWS** drawing water from affected waterbodies with only basic treatment (e.g. disinfection only) may be at greater risk of exposure than users supplied by large treatment plants. However, in some regions, the scale of this issue and the number of users potentially affected is unknown. Quantifying the number of affected users is an area for further study.

- **Practical advice and solutions** tailored to specific user groups, such as municipal or private SDWS, PWS and vulnerable groups are needed during bloom events. Typical advice for these water users is to seek alternative supplies, which may not always be practical in extended bloom seasons, particularly in rural areas. Bottled water can be an alternative drinking water source, although this may not be readily accessible for some people and not practical for non-drinking uses such as washing or bathing.

- Knowledge gaps may exist for some system operators who have little **experience of managing cyanotoxin risks** in drinking water treatment plants. SOPs may improve risk assessment approaches and the ability to respond to various risk levels.

- Managing risks of cyanoblooms is a process that requires the **involvement of multiple stakeholders,** with varying levels of resources and competing priorities. **Local champions and organizational leadership** could help develop a more coordinated and consistent response across regions or provinces. Sharing good practice between provinces could assist in developing the most effective approaches to bloom management and response. A **national best practice forum** on cyanobacteria could facilitate this exchange of knowledge.

- There is currently a lack of **readily accessible monitoring data** for waterbodies affected by cyanoblooms. Some provinces are increasing access to information by providing web-based interactive maps (e.g. PHSD, Government of Manitoba); however, long-term data could improve predictive models for future bloom events and assist relevant authorities **in efficiently targeting monitoring and surveillance efforts.** Linking environmental data to health impacts could improve understanding of the links between exposure and health.

- There is little known about the effects of **low-level chronic exposure** to cyanotoxins in Canada. Studies are needed on the dynamics of MCs including behaviour in the environment, toxicity mechanisms, bioaccumulation and additive, synergistic or antagonistic effects.[52,70]

- There are **research gaps** in the mechanisms and level of toxicity to human systems via various exposure routes, for a range of cyanotoxins including effects of cyanotoxins on other human systems (e.g. reproduction, kidneys), **health risks from exposure** to mixtures of cyanotoxins and other chemical stressors in water supplies, and information on the most sensitive populations via various exposure routes (considering rates of ingestion, age, underlying conditions).[4,49]

CONCLUSION

This review has identified that occurrence of cyanoblooms is prevalent in some provinces during the summer months (e.g. The Prairies, Ontario and Quebec) and that warmer temperatures related to climate change may increase the frequency and duration of blooms and extend the bloom season.

Incidents of ill-health related to cyanotoxin exposure in Canada are low and none have been recorded that are directly attributed to drinking water exposure, although this is an area of some uncertainty due to lack of data on exposure levels and reporting of mild or generic symptoms. Also, the health effects of cyanotoxins other than MC, and toxin mixtures, have not been fully assessed.

Current approaches to drinking water treatment in regulated systems across Canada appear to be sufficient to minimize cyanotoxin concentrations in waters supplied by large water treatment plants equipped with multi-barrier approaches to remove both intracellular and extracellular cyanotoxins. However, the lack of situational assessment of vulnerable supplies and populations, SOPs for operators, and access to rapid and cost-effective monitoring tools all limit the ability to respond effectively.

Small drinking water systems with limited treatment capability and private water systems drawing water from affected surface waterbodies may be at a greater risk of exposure than other drinking-water users. Approaches to managing risks to drinking water vary across the country, with examples of good practice in assessing risk, reporting on blooms, and communicating with the public identified. Sharing of best practice across Canada could enhance regional capabilities to address some of the key knowledge gaps identified.

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APPENDIX 1: REPORT METHODS

We approached this report through:

- A rapid academic literature search on cyanobloom incidents, treatment and management in general, and specific examples related to Canada;
- An internet search for provincial and territorial documents and resources reporting on cyanobloom events, responses and management protocols as they relate to drinking water;
- Consultation with public health and drinking water professionals in a selection of jurisdictions with experience in cyanobloom management for the protection of drinking water supplies for confirmation of key knowledge and practice gaps for cyanobacteria risks in water.

The rapid literature search was conducted using databases including UBC EbscoHost (with access to Medline, CINAHL, and Biomedical Reference Collection), Web of Science, and Google Scholar using the following terms:

(Cyanobacteri OR Cyanophyta OR “blue-green bacteria” OR cyanoHAB OR “harmful algal bloom” OR cyanotoxin OR microcystin OR “Anatoxin-a producing Tychonema”)

(Cyanobacteria OR “blue-green” OR HAB OR “harmful algal bloom” OR cyanotoxin OR microcystin) AND (drinking water) AND Canada

(drinking water)

(event OR outbreak)

(canad* OR “british columbia” OR coast OR atlantic [more provincial/regional terms used].

Citation mining and cross referencing of initial sources was used to identify additional literature. An internet search was carried out for regional, provincial, territorial and national government and health agency websites with content relevant to reporting of cyanobloom incidents and management and response to cyanoblooms, as well as external sources reporting on cyanoblooms.

Public health and drinking water treatment partners in the provinces of B.C., Alberta, Saskatchewan and Ontario provided valuable input and feedback to this report. This included confirmation of extent of cyanobloom occurrence, current practice with regards to cyanobloom response and management and key knowledge and practice gaps in different areas of the country, and identifying common practice with regards to risk assessment, communication, treatment and bloom advisory management.

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