

Chapter 9: Cyanobacterial compliance

Contents

9.1	Introduction	2
9.1.1	Algal bloom development	4
9.1.2	Health significance of cyanotoxins	9
9.1.3	Taste and odour caused by cyanobacteria	11
9.1.4	Occurrence of toxic cyanobacteria internationally and in New Zealand	12
9.2	Risk management	15
9.2.1	Assessment of risk	15
9.3	Monitoring	18
9.4	Compliance	21
9.5	Sampling and testing	24
9.5.1	Sample testing	24
9.5.2	Sample collection	25
9.6	Transgressions	32
9.7	Risk reduction	33
9.7.1	Alert levels	33
9.7.2	Preventive and remedial measures	36
9.8	Recommended Reading	48
Appendix 1: Chlorine C.t values for reducing microcystin-LR concentration to 1 µg/L in a batch or plug-flow reactor		49

Appendix 2: Detailed Case Study for the Use of the WHO/IPCS Framework to Assess Risk to Human Health from Exposure to Microcystins in Drinking-water 49

References 51

List of tables

Table 9.1: Example assessment of the potential for high biomass of planktonic cyanobacteria based on environmental conditions ^a	5
Table 9.3: Information that may help in situation assessment and management	16
Table 9.5: Summary of performance for water treatment processes capable of removing cell-bound microcystins by removing whole cells	45
Table 9.6: Efficiency of dissolved toxin removal by oxidants/disinfectants and activated carbons	47

List of figures

Figure 9.1: Rapid assessment of the level of risk posed by toxic cyanobacteria in a drinking water source	17
Figure 9.2: Procedure for use of the integrated hose-pipe sampler for planktonic cyanobacteria and cyanotoxins	28
Figure 9.3: Benthic cyanobacteria monitoring and sampling schematic of layout of transects and survey areas	30
Figure 9.4: Benthic cyanobacteria monitoring and sampling schematic of transect cross-section showing arrangement of sampling points	31
Figure 9.5: Alert levels framework for the management of cyanobacteria in water supplies	34

9.1 Introduction

This chapter provides information on cyanobacteria and cyanotoxins because of the increasing number of supplies that encounter difficulties with these micro-organisms, and because many water suppliers may have little understanding of how to manage them. Although prepared primarily for use in relation to drinking-water supplies, the information should also be of use to those managing recreational waters.

The purpose of this chapter is to provide:

- general information on cyanobacteria, the factors that control bloom formation, and their toxins and health significance
- advice on how the risk they present to consumers can be evaluated
- discussion on meeting the cyanotoxin compliance requirements of the DWSNZ

- guidance on how the public health risk associated with cyanotoxins can be managed.

For those who do not wish to read the full text in this chapter, but are concerned with information to support the requirements of the DWSNZ, the following sections are those of greatest importance:

- Compliance with the DWSNZ: see section 9.4
- Sampling: see section 9.5
- Transgressions: see section 9.6
- Risk management: see section 9.7
- Refer to the datasheets for cyanobacteria and for the individual cyanotoxins, in Volume 3 of the *Guidelines*.

Over recent years, water supplies in some parts of New Zealand have experienced an increase in the number of cyanobacterial blooms. These events have the potential to introduce toxins that can have acute and, if their concentrations are high enough, fatal consequences for consumers. Experience of such events in New Zealand is still relatively limited, and consequently this section provides substantial detail to assist water suppliers in dealing with cyanobacteria.

Cyanobacteria, which belong to the group of organisms called prokaryotes, are primarily aquatic organisms with many characteristics of bacteria. Unlike eukaryotes (which includes the algae), they are characterised by the lack of a true cell nucleus and other membrane-bound cell compartments such as mitochondria and chloroplasts. As their metabolism is based on photosynthesis and due to the blue and green pigments many cyanobacteria produce, they have also been termed blue-green algae. They may grow as filaments or colonies readily visible, or single-celled causing discolouration of water. They include planktonic (free-floating) and benthic (attached) species. Being microscopic (several micrometres wide or less), a microscope is required to identify cyanobacteria to the genus level.

Cyanobacteria are not, of themselves, a health hazard, but the toxins they produce (called cyanotoxins) are. For this reason it is recommended that public health management be focussed on the cyanotoxins, and that cyanobacteria in drinking-water be managed as a chemical problem (Chorus and Bartram, 1999). The presence of cyanobacteria can be regarded as a trigger for monitoring for cyanotoxins. Cyanobacteria can also cause taste and odour problems, see Chapter 18, and geosmin, 2-methyl isoborneol and β -cyclocitral in the organic chemicals datasheets. Cyanobacteria inhabit all natural waters and generally only become a problem only when they increase to excessive numbers (water blooms). Why population densities reach bloom proportions is a subject for much discussion and research (eg, Smith and Lester 2006; Oliver et al 2012).

Concern about the effects of cyanobacteria on human health has grown in many countries in recent years for a variety of reasons. These include cases of poisoning attributed to toxic cyanobacteria and awareness of contamination of water sources (especially lakes) resulting in increased cyanobacterial growth. Cyanobacteria also continue to attract attention in part because of well-publicised incidents of animal poisoning. Outbreaks of human poisoning attributed to toxic cyanobacteria have been reported in several countries including Australia, following exposure of individuals to

contaminated drinking water, and the UK, where army recruits were exposed while swimming and canoeing. However, the only proven human fatalities associated with cyanobacteria and their toxins have occurred in Brazil (see section 9.1.2).

9.1.1 Algal bloom development

Cyanobacteria are members of the community of phytoplankton (which means small free floating plants; however cyanobacteria are actually bacteria) and the bottom-dwelling organisms living on the surface of the sediments and stones in most water-bodies. The right combination of environmental conditions, particularly elevated nutrient concentrations, may cause their excessive growth (bloom formation), leading to blue, brown or greenish discolouration of water through the high population density of suspended cells, and to the formation of surface scums. Such accumulations of cells may lead to high toxin concentrations. Because the conditions that lead to excessive growth of planktonic cyanobacteria (free-floating in the water column) and benthic cyanobacteria (attached to the substrate of rivers, lakes and reservoirs) can be quite different, we discuss each individually in the following section.

9.1.1.1 Key Drivers of Planktonic Cyanobacteria Growth

Cyanobacteria have very low requirements for growth as they primarily produce their energy from sunlight. Planktonic cyanobacteria grow floating in the water column of lakes and reservoirs. When there are shifts in the abundance of limiting factors (light, temperature, nutrients) cyanobacteria are able to flourish and blooms occur. Because some planktonic cyanobacteria also possess strategies to overcome growth-limiting factors (eg, the ability to control buoyancy, store nitrogen and phosphorous, and fix atmospheric nitrogen into usable forms), they are often able to grow under less-ideal conditions. Under non-ideal conditions, planktonic cyanobacteria are also able to lay dormant in the sediment of lakes and reservoirs until conditions change. Whilst some cyanobacteria produce specialised cells (ie, akinetes) that are able to lay dormant for hundreds of years, other cyanobacteria will over-winter in the sediment until water conditions are more ideal for growth in the following year.

a) Eutrophication

High concentrations of nutrients, usually phosphorus and nitrogen, can cause increases in natural biological production in waterways. These conditions can result in visible cyanobacterial or algal blooms and surface scums. The concentrations of phosphorus in the water often limit the growth of planktonic cyanobacteria, but in a substantial number of lakes in New Zealand, the dissolved nitrogen concentrations are said to be the limiting factor despite some cyanobacteria being able to fix nitrogen.

Some lakes are naturally eutrophic, but in most the excess nutrient input is of anthropogenic origin, resulting from wastewater discharges or run-off from fertilisers and manure spread on agricultural areas. Where nutrient concentrations in water bodies are naturally low, or have been lowered by remedial actions to limit nutrient run-off, high cyanobacterial populations may still develop where species that are able to fix atmospheric nitrogen are present or where sediment previously introduced into

lakes provides a nutrient source that is liberated during times of stratification. The relationship between nutrient concentrations and the predominance of different microorganisms can be quite complex; for example, cyanobacteria grow in Antarctica and the high slopes of Mt Ruapehu.

Understanding the conditions that promote the growth of cyanobacteria in water bodies is useful for predicting whether cyanobacterial problems are likely to occur. A fundamental basis for the growth of planktonic cyanobacteria is the concentration of total phosphorus, as the total amount of phosphorus in the system limits the total amount of biomass that can be produced. Water temperature is also an important factor for assessing the potential for cyanobacterial growth, as shown in Table 9.1. Data on additional factors, such as chlorophyll *a*, thermal stratification, local weather conditions influencing stratification and concentrations of nitrogen, can improve the assessment.

Table 9.1: Example assessment of the potential for high biomass of planktonic cyanobacteria based on environmental conditions ^a

Indicator	Very low	Potential for high biomass of planktonic cyanobacteria (blooms)			Very high
Total phosphorus (µg/L)	<10	12–25	>25–50	>50–100	>100
Water residence time	River, visible current	<1 month	<1 month	<1 month	≥1 month
pH	<5–6	<6–7	<6–7	<6–7	>7
Temperature (°C)	<10	10–<15	15–<20	20–<25	≥25
Secchi disc during cyanobacteria season (m)	≥2	<2–1	<1–0.5	<1–0.5	<0.5

^a The higher the number of these conditions that are fulfilled, the greater the potential for high biomass. This table has been taken from WHO (2015), which was adapted from Umweltbundesamt (2014).

b) Temperature

Provided nutrient and light levels do not limit planktonic cyanobacteria growth, blooms will persist in waters with temperatures between 15 and 30°C (and pH levels between 6 and 9), with maximum growth rates occurring at temperatures in excess of 25°C.

d) Light

The intensity of daylight needed for optimal growth depends on the species of cyanobacteria. Extended exposure to moderate to high light intensities is lethal for many species, although species that form surface blooms are tolerant of these conditions. Maximum growth results from intermittent exposure to high light intensities. Cyanobacteria require little energy to function. As a consequence, they are able to grow at faster rates than other phytoplanktonic organisms at low light intensities.

e) Alkalinity and pH

Alkalinity and pH determine the chemical speciation of inorganic carbon, such as carbonate, bicarbonate and carbon dioxide. Low carbon dioxide concentrations favour the growth of several cyanobacterial species. Hence, water conditions such as low alkalinity and hardness and the consumption of carbon dioxide by algae during

photosynthesis, increasing the pH, give cyanobacteria a competitive advantage (Health Canada 2000, edited 2002).

f) Atmospheric CO₂

Analysis of cyanobacterial pigments in sediment cores from over 100 northern hemisphere temperate and sub-arctic lakes revealed that the abundance of cyanobacteria had increased in nearly 60 percent of lakes over the last 200 years, possibly due to increased industrialisation. This increase was disproportionate compared to other phytoplankton, and the rate of cyanobacterial increase became more rapid after about 1945, coinciding with an increase in rates of fertiliser application and the introduction of phosphorus-containing detergents, and possibly the growth in coal and gas power stations. Increasing atmospheric concentrations of CO₂ and increased diffusion of CO₂ into water bodies was initially thought to be disadvantageous to cyanobacteria. However, recent research has shown that the genetic diversity of CO₂ concentrating mechanisms among cyanobacterial strains and species, and the physiological flexibility of these systems allows rapid adaptation of cyanobacterial populations to increases in atmospheric CO₂ concentrations. Mathematical models and laboratory experiments both support the view that rising atmospheric CO₂ concentrations are likely to intensify cyanobacterial blooms in eutrophic and hypertrophic waters. From Health Stream, accessed July 2018)

g) Gas vesicles

Many planktonic cyanobacteria contain gas vesicles that can be used to control buoyancy. Through the filling and collapse of gas vesicles, and the fixation of carbohydrates from photosynthesis some cyanobacteria can control their movement to optimum depths in the water column. For example, filling the vesicles with gas allows cyanobacteria to rise towards the surface where light is more abundant, and the collapse of gas vesicles and storage of heavy carbohydrates allows the organism to sink down through thermal gradients to reach nutrients in the cooler layers.

h) Growth rates

Cyanobacteria have slow growth rates compared with other phytoplankton, which means they require long retention times in still water bodies for blooms to form. Turbulence and high flows are unfavourable to the growth of cyanobacteria, as they interfere with their ability to maintain optimum depths in the water column.

9.1.1.2 Key Drivers of Benthic Cyanobacteria Growth

Blooms of benthic (attached or mat-forming) cyanobacteria can occur in rivers and in lakes and reservoirs where light can penetrate to the substrate. In rivers, benthic cyanobacterial mats are usually observed during periods of stable (but not necessarily) low flow. Benthic cyanobacteria are widespread throughout New Zealand rivers and are found in a wide range of water quality conditions, including oligotrophic waters (waters with low nutrients). The potential for these cyanobacteria to develop in waters with low nutrients requires vigilance from drinking-water operators using river water. The most common mat-forming benthic cyanobacterial genus in New Zealand is *Microcoleus* (previously *Phormidium*). During stable flow conditions *Microcoleus* mats can

proliferate, at times forming expansive black/brown leathery mats across large expanses of river substrate. Flow conditions, substrate, water chemistry and species composition can influence the macroscopic appearance of benthic cyanobacterial mats and at times they may be confused easily with other algal groups; eg, diatoms, green algae. Microscopic confirmation should be undertaken to confirm whether cyanobacteria are the dominant component of attached communities. These mats also commonly detach from river/ lake substrates and float on the water surface, forming floating rafts in rivers, lakes and reservoirs. This is because under certain environmental conditions, or as mats become thicker (and bubbles of oxygen gas become entrapped within them), they will detach from the substrate and may accumulate along river edges. During these events the risk to human and animal health is higher due to accessibility of toxins to river users and bankside abstractions. Additionally, during these periods the cells are likely to be lysing and releasing toxins.

a) Nutrient availability

The majority of data on nutrient drivers for benthic cyanobacteria growth is from *Microcoleus* and *Phormidium*. These cyanobacteria generally follow an accrual cycle consisting of mat initiation through colonisation or regrowth of relic populations, its subsequent growth via lateral expansion (which could be driven by cell motility, cell division, and biomass accrual) and lastly, physical or natural detachment of mats (McAllister et al. 2016). After colonisation, the balance of growth- and loss-promoting factors determines the length of the accrual cycle, the size and persistence of the accrual. Because the mats become complex micro-environments once established, nutrients from the water column are not necessarily limiting for these benthic cyanobacteria following the colonisation phase and establishment of the benthic mat.

The nutrient conditions under which *Microcoleus autumnalis* and closely-related *Phormidium* species, reach high percentage cover are broad. For example, McAllister et al. (2018a) and Wood et al. (2017) found that proliferations occurred at nitrogen concentrations ranging from 0.02 and 0.9 mg/L. Dissolved reactive phosphorous (DRP) concentrations below 0.01 mg/L were initially thought to favour *Microcoleus autumnalis* to proliferate. However, recent research suggests a slightly higher upper limit of 0.05 mg/L (McAllister et al. 2018a).

Wood et al. (2015) showed that conditions within *Microcoleus autumnalis* mats differ significantly from the overlying water column, including the development of high pH (> 9) during the day (due to photosynthetic depletion of bicarbonate) and low dissolved oxygen (< 4 mg/L) concentrations at night (due to respiration). These conditions facilitate the release of DRP bound to sediment which partially explains the propensity of proliferations to form under low DRP conditions. For this reason, sediment inputs into freshwater systems may promote the growth of *Microcoleus* blooms.

What has also become clear over the last decade of research into benthic *Microcoleus*, is that site specific differences are very apparent. This has been demonstrated in studies conducted in the Manawatu catchment (Wood et al 2014), the Wellington region (GRWC 2016) and in the international studies described above. Cawthron Institute is developing a model which provides relatively realistic real-time estimates of *Microcoleus* cover, however, because of the site-specific differences mentioned above the models need to be calibrated using site-specific data (Cawthron 2018).

b) Temperature

There is general agreement in the literature that high temperatures are correlated with increased *Microcoleus autumnalis* and *Phormidium* cover (Heath et al. 2011, Schneider 2015, Wood et al. 2017, Echenique-Subiabre et al. 2018a). Heath et al. (2011) showed that temperatures >14 °C were correlated with increased cover and Echenique-Subiabre et al. (2018a) found that cover was highest under temperatures exceeding 16 °C. During summer when water temperatures are warmer, there may also be fewer occasions of higher flow flushing away any build-up of benthic micro-organisms (eg, as discussed in the following subsection and in Heath and Wood, 2010). Global warming will extend the duration of 'summer temperatures' and cause longer periods with the absence of 'flushing flows'.

c) Flows and Flushing

High velocity has been identified in many different studies as having a positive influence on *Microcoleus autumnalis* and *Phormidium* growth (Hart et al. 2013, Heath et al. 2015, McAllister et al. 2019). Heath et al. (2015) and Hart et al. (2013) highlighted that *Microcoleus autumnalis* was dominant at velocities greater than 0.4 m/s in the Hutt and Waipara Rivers (New Zealand), respectively. Similarly, in experimental stream mesocosms McAllister et al. (2018b) found that an increase of 0.1 m/s in velocity resulted in higher biomass accrual and McAllister et al. (2019) found that expansion and biomass accrual was greatest in run habitats (near-bed velocities of 0.25–0.45 m/s). Velocity is likely to influence growth in complex ways, including through influencing the effectiveness of grazers and through reducing the boundary layer, thus allowing greater diffusion of solutes in and out of the mat matrix.

Flushing flows were identified as the key variable regulating *Microcoleus* abundance (GRWR, 2016). However, it remains unclear how the length of the accrual (growth) period between flushing flows affects *Microcoleus* growth. Longer accrual periods between large flushes (>9x median flow events) were associated with a greater magnitude of *Microcoleus* growth. However, there was no relationship between *Microcoleus* growth and accrual period length for smaller (and more generically used) >3x median flushing flow events. It is likely that the magnitude of flushing flow required to remove *Microcoleus* proliferations from the riverbed varies greatly depending on the physical characteristics of each river, making it difficult to assess the relationship between flushing flow frequency and *Microcoleus* growth. In the Hutt River, analysis of GWRC's long-term flow record at Taita Gorge (from 1979 to 2013) revealed that there has been no significant change in the annual frequency of flushing flows and average accrual period. While flushing flow frequency is likely to be an important driver of *Microcoleus* growth in rivers where it occurs, it did not explain why some rivers in the Wellington Region experience *Microcoleus* blooms and others do not.

d) Light

As benthic cyanobacteria require light in order to grow, light penetration limits the depth they can grow in lakes and reservoirs. Because cyanobacteria are very efficient at harvesting light, this may be at depths greater than what can be visually observed from the surface.

9.1.2 Health significance of cyanotoxins

Cyanobacteria do not multiply within the human body and are therefore not infectious. Many cyanobacteria, however, produce potent toxins. Exposure to these toxins, either in the cells or the water, through ingestion, inhalation or through contact with the skin, is therefore the primary health concern associated with cyanobacteria.

Cyanotoxins belong to a diverse group of chemical substances, each of which shows specific toxic mechanisms in vertebrates. Some cyanotoxins are strong neurotoxins (anatoxin-a, anatoxin-a(S), saxitoxins), others are primarily toxic to the liver (microcystins, nodularin and cylindrospermopsin) and yet others (such as the endotoxins) appear to cause health impairments (such as gastroenteritis), which are poorly understood. Assignment of health effects to specific species or toxins is often difficult because several cyanobacterial species may co-exist in a water body. Global data show that hepatotoxins (those causing liver damage) occur most frequently, although there have been blooms producing neurotoxins that have led to animal deaths. The effect of different neurotoxins or hepatotoxins occurring simultaneously is highly likely to be additive. WHO (2017a) discusses the effects of chemical mixtures and includes a microcystin case study – some of which has been added to this chapter as Appendix 2.

Not all strains of cyanobacteria carry the genes required for toxin production, and the factors which trigger toxin production in toxin-capable strains are not well understood. Cyanobacterial blooms often contain a mixture of toxin producing and non-producing strains, and their relative proportions may vary over the duration of a bloom. Currently, it is not possible to reliably predict whether a bloom that includes toxin-capable strains will produce toxin or how much may be produced as multiple cyanobacterial species may also be present in a bloom, with their proportions varying over time. In addition to toxic metabolites, many cyanobacterial species also produce other problematic metabolites that may adversely affect the taste and odour of water even at very low concentrations (Health Stream, accessed July 2018).

Generally, toxicity is not a trait specific for certain species; rather, most species comprise toxic and non-toxic strains. For *Microcystis* (and other microcystin-producing cyanobacteria), it has been shown that toxicity for a strain depends on whether or not it contains the gene for microcystin production (Rouhiainen et al 1995; Dittmann et al 1996) and that field populations are a mixture of both genotypes with and without this gene (Kurmayer et al 2002). Experience with cyanobacterial cultures also shows that microcystin production is a fairly constant trait of a given strain or genotype, only somewhat modified by environmental conditions (see various contributions in Chorus 2001). While conditions leading to cyanobacterial proliferation are well understood (the physiological or biochemical function of toxins for the cyanobacteria is the subject of many hypotheses: Chorus and Bartram 1999), the factors leading to the dominance of toxic strains over non-toxic ones are not. See WHO (2003) for reference details.

Table 2.3 of the DWSNZ lists provisional maximum acceptable values (PMAVs) for some cyanotoxins. Refer to Chapter 1: Introduction, section 1.6.2 for information about MAVs. Chorus (2012) collated cyanotoxin standards and regulations from several countries around the world. USEPA (2015a) provides a link to the Drinking Water Health Advisory for the Cyanobacterial Toxin Cylindrospermopsin; Drinking Water Health Advisory for the Cyanobacterial Microcystin Toxins; and the Health Effects Support Documents for Anatoxin-A, Cylindrospermopsin and Microcystins. See individual datasheets.

The effects of cyanotoxins can be both acute and chronic, and protection against both long-term exposure, and short-term exposure, is required. While some short-term exposure can lead to health effects from which recovery is complete, it can also result in long-term damage to target organs.

Acute effects:

- dermal exposure, particularly if cells are accumulated under swimsuits and wet suits, may lead to skin irritations and allergic reactions (Pilotto et al 1997)
- symptoms involving irritation of internal and external mucous membranes; ie, gastro-intestinal or respiratory organs, eyes, ears, mouth and throat are also reported
- exposure to cell material of any cyanobacteria can cause illness such as fever, probably evoked by lipopolysaccharides contained in the cell wall of cyanobacteria (Keleti et al 1979; Lippy and Erb 1976)
- neurotoxins administered in mouse studies led to rapid respiratory arrest
- extensive kidney and liver damage following exposure to cyanotoxins has been reported (eg, Hawkins et al 1985)
- severe acute effects on human health appear to be rare, the only fatalities associated with cyanobacteria or their toxins having been reported in Brazil. In 1988 a new impoundment in Brazil developed an immense cyanobacterial bloom and there followed approximately 2,000 gastroenteritis cases, 88 of which resulted in death. Cyanobacterial toxins were the likely cause (Teixera et al 1993), with contamination by heavy metals and pathogens ruled out. In 1996 (Jochimsen et al 1998; Carmichael et al 2001; Azavedo et al 2002), over 100 kidney patients developed liver disease and over 50 deaths were attributed to dialysis with water containing cyanobacterial toxins (Jochimsen et al).

Chronic effects:

- the key concerns of chronic effects associated with cyanotoxins are liver and kidney damage as well as tumour promotion, but there is a lack of clinical studies relating to chronic exposure (such as tumour promotion, eg, Ueno et al 1996, and liver damage), and this hinders the determination of safe concentrations for long-term exposure
- animal experiments have shown chronic liver injury from continuing oral exposure to cyanotoxins.

Members of the population at greatest risk when exposed to cyanotoxins are children (because their water intake:bodyweight ratio is higher than that of adults), and those who already have damaged organs that may be the target of the toxins. Recreational exposure is the most probable pathway for ingestion of a high dose of microcystins or nodularins. Any water sport that involves immersion of the head invariably leads to some oral uptake or aspiration (IARC 2010).

The health risks associated with cyanotoxins are greatest when cyanobacterial cell concentrations are high due to excessive growth (ie, bloom events). The highest cyanotoxin concentrations are usually contained within the cells (intracellular), and toxin concentrations dissolved in the water (extracellular toxins) are rarely reported above a few µg/L (Chorus and Bartram 1999). While the risks associated with cyanobacteria may rise and fall with the development and decay of bloom events, in some countries cyanobacteria may be present in water bodies over extended periods of time which results in continued exposure to subacute concentrations (Ressom et al 1994; Hitzfeld et al 2000), and the possibility of chronic health effects.

When a cyanobacterial bloom develops in a water body, exposure of those using the water for recreational purposes to hazardously high cyanotoxin concentrations will be most likely where cell densities are high, particularly in surface scums. Wind-driven accumulations of surface scums can result in toxin concentrations increasing by a factor of 1,000 or more. Such situations can change within very short time periods (within hours). Children playing in shallow zones along the shore where scums accumulate are particularly at a risk.

The death of cyanobacterial cells, through the organism reaching the end of its lifecycle or through measures taken to control blooms, can result in higher than normal concentrations of extracellular toxin. Episodes of acute sickness have been reported after treatment of cyanobacterial blooms with copper sulphate to control the bloom, which then resulted in release of cyanotoxins into the water and breakthrough of dissolved toxins into drinking-water supplies.

It is preferable to control the health hazards associated with cyanotoxins by reducing the likelihood of bloom formation, rather than having to remove the cyanobacteria and any extracellular toxin present from the water. Monitoring of source water for evidence of the start of bloom development, or the potential for bloom formation, overcomes difficulties such as inadequate analytical methods associated with the measurement of cyanotoxins themselves.

9.1.3 Taste and odour caused by cyanobacteria

Cyanobacteria have, for a long time, been recognised as a nuisance in the drinking-water industry because of the ability of several taxa to produce earthy and musty smelling compounds, notably geosmin and 2-methyl isoborneol (2-MIB), for which the odour detection thresholds of less than 10 ng/L are remarkably low amongst sensitive individuals. β-Cyclocitral is formed by cyanobacteria in reservoirs and rivers as well.

The cyanobacterial genera that are known to produce geosmin are *Dolichospermum* (previously *Anabaena*), *Aphanizomenon*, *Lyngbya*, *Microcystis*, *Oscillatoria*,

Phormidium/Microcoleus, *Schizothrix* and *Symploca* (Perrson 1983, cited in Chorus and Bartram 1999). All of these (except *Symploca*) are also known to include toxin-forming species and strains. Because of this, the possibility of using odour compounds as an early warning for the development of toxin-producing cyanobacterial blooms has been considered. However, there is no evidence of a correlation between toxin production and the production of taste- and odour-producing compounds that would provide a warning of toxicity. It is very unlikely that the production of taste and odour compounds is biochemically connected to the production of cyanotoxins (Chorus and Bartram 1999).

9.1.4 Occurrence of toxic cyanobacteria internationally and in New Zealand

Not all cyanobacteria that have been found to produce toxins have been identified in New Zealand. Table 9.2 lists, in alphabetical order, some of the species found internationally to produce toxins and the nature of the toxin produced. This list is continually increasing, and should not be regarded as definitive. It is provided as a guide to those trying to determine whether a cyanobacterial species found in a waterbody may be a toxin producer. Cyanotoxins that have been shown to be produced by certain cyanobacteria in New Zealand are indicated in bold type.

Table 9.2: Summary of known toxin-producing cyanobacteria identified internationally by isolation of cultured strains. Species in **bold type** are known to produce the associated toxin (also in bold type) in New Zealand.

Cyanobacteria Genus/Species	Cyanotoxin/s
<i>Anabaena</i> sp.	Microcystins
<i>Anabaenopsis millenii</i>	Microcystins
<i>Annamia toxica</i>	Microcystins
<i>Aphanizomenon flos-aquae</i>	Anatoxin-a, Cylindrospermopsins, Saxitoxins
<i>Aphanizomenon gracile</i>	Anatoxin-a, Cylindrospermopsins, Saxitoxins
<i>Chrysoosporum ovalisporum</i>	Cylindrospermopsins
<i>Aphanizomenon</i> sp.	Anatoxin-a, Cylindrospermopsins, Saxitoxins
<i>Aphanocapsa cumulus</i>	Microcystins
<i>Arthrospira fusiformis</i>	Anatoxin-a,
<i>Chrysoosporum ovalisporum</i>	Cylindrospermopsins
<i>Coelosphaerium kuetzingianum</i>	Microcystins
<i>Cuspidothrix issatchenkoi</i>	Anatoxin-a
<i>Cylindrospermum stagnale</i>	Saxitoxins
<i>Cylindrospermum</i> sp.	Anatoxin-a, Saxitoxins
<i>Dolichospermum circinale</i>	Anatoxin-a
<i>Dolichospermum flos-aquae</i>	Anatoxin-a, Anatoxin-a(S), Microcystins
<i>Dolichospermum lapponica</i>	Cylindrospermopsins

Cyanobacteria Genus/Species	Cyanotoxin/s
<i>Dolichospermum lemmermannii</i>	Anatoxin-a, Anatoxin-a(S), Microcystins
<i>Dolichospermum</i> sp.	Anatoxin-a, Anatoxin-a(S), Cylindrospermopsins, Microcystins
<i>Dolichospermum spiroides</i>	Anatoxin-a(S)
<i>Dolichospermum subcylindrica</i>	Microcystins
<i>Dolichospermum ucrainica</i>	Microcystins
<i>Dolichospermum variabilis</i>	Microcystins
<i>Fischerella</i> sp.	Microcystins
<i>Geitlerinema amphibium</i>	Saxitoxins
<i>Geitlerinema carotinum</i>	Anatoxin-a, Microcystins
<i>Geitlerinema lemmermannii</i>	Saxitoxins
<i>Geitlerinema splendidum</i>	Anatoxin-a, Microcystins
<i>Gloeotrichia natans</i>	Microcystins
<i>Hapalosiphon hibernicus</i>	Microcystins
<i>Heteroleibleinia kuetzingii</i>	Microcystins
<i>Iningainema pulvinus</i>	Nodularin
<i>Leptolyngbya</i> sp.	Microcystins
<i>Limnothrix mirabilis</i>	Microcystins
<i>Microcoleus autumnalis</i>	Anatoxins
<i>Microcoleus</i> sp.	Anatoxins, Microcystins,
<i>Microcystis aeruginosa</i>	Microcystins, Saxitoxins
<i>Microcystis botrys</i>	Microcystins
<i>Microcystis flos-aquae</i>	Microcystins
<i>Microcystis ichthyoblabe</i>	Microcystins
<i>Microcystis novacekii</i>	Microcystins
<i>Microcystis panniformis</i>	Microcystins
<i>Microcystis</i> sp.	Anatoxin-a, Microcystins, Saxitoxins
<i>Microcystis viridis</i>	Microcystins
<i>Microcystis wesenbergii</i>	Microcystins
<i>Microseria wollei</i>	Cylindrospermopsins, Saxitoxins
<i>Nodularia spumigena</i>	Nodularin
<i>Nodularia sphaerocarpa</i>	Nodularin
<i>Nostoc commune</i>	Microcystins
<i>Nostoc linckia</i>	Microcystins
<i>Nostoc muscurum</i>	Microcystins
<i>Nostoc</i> sp.	Microcystins, Nodularin
<i>Nostoc spongiaeforme</i>	Microcystins

Cyanobacteria Genus/Species	Cyanotoxin/s
<i>Oscillatoria agardhii</i>	Microcystins
<i>Oscillatoria limnetica</i>	Anatoxin-a
<i>Oscillatoria limosa</i>	Microcystins
<i>Oscillatoria margaritifera</i>	Microcystins
Oscillatoria sp.	Anatoxin-a, Microcystins
<i>Phormidium ambiguum</i>	Cylindrospermopsins
<i>Phormidium corium</i>	Microcystins
<i>Phormidium favosum</i>	Anatoxin-a
<i>Phormidium sp.</i>	Anatoxin-a, Microcystins
<i>Phormidium splendidum</i> (Syn. <i>Geitlerinema splendidum</i>)	Microcystins
<i>Phormidium uncinatum</i>	Anatoxin-a, Microcystins, Saxitoxins
<i>Planktothrix agardhii</i>	Microcystins
<i>Planktothrix formosa</i>	Anatoxins
<i>Planktothrix rubescens</i>	Microcystins
Planktothrix sp.	Anatoxins, Microcystins , Saxitoxins
<i>Plectonema boryanum</i>	Microcystins
<i>Pseudoanabaena frigida</i>	Microcystins
<i>Pseudocapsa dubia</i>	Microcystins
<i>Radiocystis fernandoi</i>	Microcystins
<i>Raphidiopsis brookii</i>	Saxitoxins
<i>Raphidiopsis curvata</i>	Cylindrospermopsins
<i>Raphidiopsis mediterranea</i>	Anatoxins, Cylindrospermopsins
Raphidiopsis raciborskii	Cylindrospermopsins, Saxitoxins, Microcystins
<i>Rivularia biasoletiana</i>	Microcystins
<i>Rivularia haematites</i>	Microcystins
<i>Schizothrix rivularianum</i>	Microcystins
Scytonema cf. crispum	Saxitoxins
<i>Scytonema drilosiphon</i>	Microcystins
<i>Snowella sp.</i>	Microcystins
<i>Synechococcus lividus</i>	Microcystins
<i>Synechocystis sp.</i>	Microcystins
<i>Tolypothrix distorta</i>	Microcystins
<i>Tychonema bourrellyi</i>	Anatoxins
<i>Umezakia natans</i>	Cylindrospermopsins
<i>Woronichinia sp.</i>	Microcystins

Cyanobacteria Genus/Species	Cyanotoxin/s
Notes: This is a compilation of worldwide information. New toxic species continue to be identified, and all cyanobacteria should be regarded as potentially toxic until proven otherwise.	

Most environmental benthic samples or mats consist of multiple species. A recent report (Cawthron 2015) lists the six known toxin-producing benthic cyanobacterial species in New Zealand, and their cyanotoxins:

- *Nostoc commune* microcystins
- *Oscillatoria* sp. anatoxin-a, microcystins, homoanatoxin-a
- *Microcoleus* sp. dihydroanatoxin-a, dihydrohomoanatoxin-a
- *Planktothrix* sp. microcystins
- *Scytonema* cf. *crispum* saxitoxins
- Unknown species nodularin

Two reports of cyanobacterial data collected from New Zealand waterways; Podivinsky and Williamson (2009), Nokes (2010), demonstrate that there is the potential for cyanotoxins to pose a risk. A key finding (Nokes 2010) was:

Where substantial blooms develop, toxin concentrations readily exceed provisional maximum acceptable values (PMAV) by a factor of 10, and in some instances by four-to-five orders of magnitude. Cyanobacteria are an extremely dangerous hazard in drinking and recreational waters because of the speed at which cyanobacterial toxin producers multiply, the concentrations toxins can reach, the difficulty in removing toxins from the water, and the severity of the health effects that can be associated with them. The most effective strategy for defence against them is to take measures to stop blooms developing.

9.2 Risk management

9.2.1 Assessment of risk

Assessing the risk posed by cyanobacterial toxins, or the potential for development of cyanobacterial blooms, and linking this to effective measures for the protection of public health within available resources, is complex.

Ideally, situation assessments would be proactive (ie, carried out with the intention of preventing the bloom from developing) enabling water managers to:

- determine whether contingency planning is required and
- initiate long-term action, such as pollution control to minimise bloom formation.

However, at times it may be reactive (ie, carried out as a response to the development of the bloom), such as assisting in interpretation of specific local events or conditions to provide information on which to base emergency or incident responses. In this

context, Water Research Foundation (WRF, 2018) developed a toolkit for effective cyanotoxin communications as part of a risk management plan.

The type of information that could be used to assess the risk due to cyanobacteria is summarised in Table 9.3.

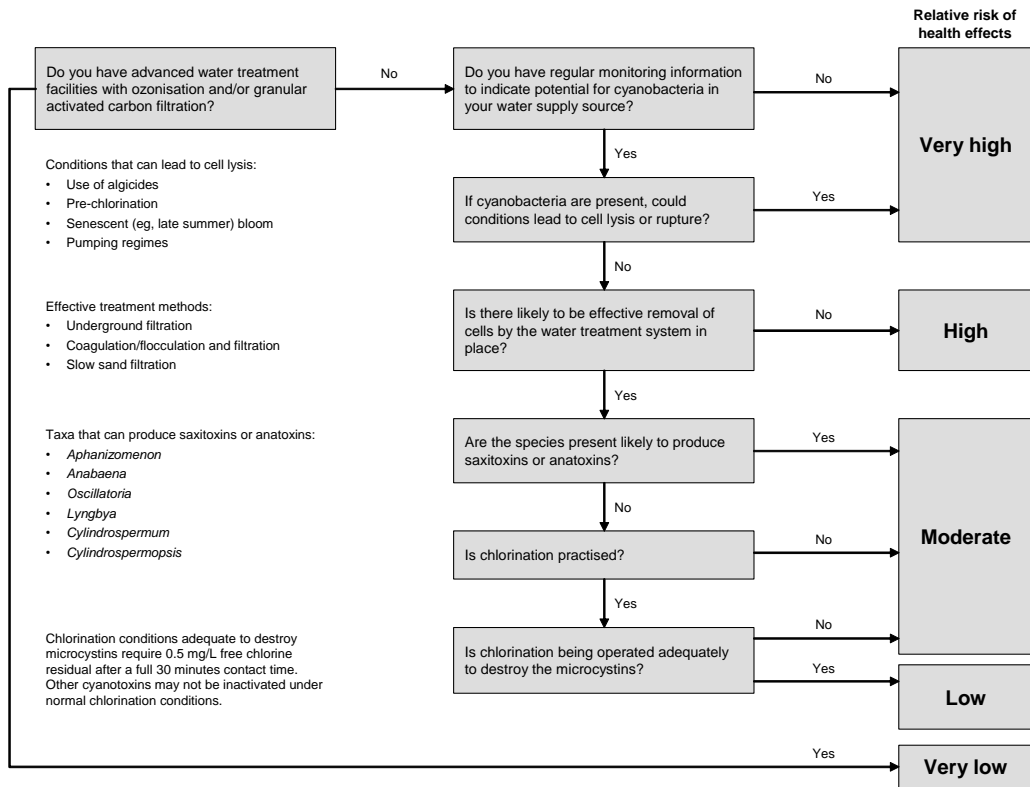
Table 9.3: Information that may help in situation assessment and management

Observation	Sources of information	Management options
Potential for bloom formation	Water quality monitoring data (nutrients, temperature, etc)	Basis for proactive management (ie, actions to stop conditions developing that will allow bloom formation)
History of bloom formation	Cyanobacterial blooms may follow marked seasonal and annual patterns	Can inform proactive management
Monitoring of cyanobacteria and/or cyanotoxins	Turbidity, discolouration, odour, cell microscopic identification, cell counts and toxin analysis provide increasingly reliable information	Possible basis for proactive management provided cell counts are monitored regularly
Scum scouting	In areas of high public interest the general public and untrained agency staff may play a role in identifying and reporting obvious hazards such as scums	Possible only during event and enables only reactive management (ie, taking actions after the bloom has developed)
Reporting of animal deaths and human illness	Requires both the willingness of the community to assist in providing the data and a mechanism for data collection which may not exist	Possible only during event and informs only reactive management
Epidemiological detection of disease patterns in the human population	Requires both effective reporting and large-scale effects before detection likely	Normally well after an event; can inform future management strategies

From Chorus and Bartram 1999.

A diagram to rapidly assess the level of risk to health presented by a cyanobacterial bloom, by considering the treatment processes in place, is given in Figure 9.1, which assumes that treatment processes are working properly, and that they are capable of treating the concentrations of toxin or cell concentrations in the raw water. If either of these assumptions is invalid, the absolute levels of risk may be markedly different.

Figure 9.1: Rapid assessment of the level of risk posed by toxic cyanobacteria in a drinking water source



Modified from WHO 1997, and Chorus and Bartram 1999.

USEPA (2015) is intended to assist water suppliers that choose to develop system-specific plans for evaluating their source waters for vulnerability to contamination by microcystins and cylindrospermopsin. It could also serve as a model for addressing potential concerns from other cyanotoxins in the future. The document provides a stepwise approach to inform their decisions on whether and how to monitor and (or) treat for microcystins and cylindrospermopsin and when and how to communicate with stakeholders. The approach includes the following steps:

1. Step 1 involves conducting a system-specific evaluation for vulnerability to blooms.
2. Step 2 suggests activities for preparing and observing for potential blooms.
3. Step 3 describes monitoring activities to determine whether cyanotoxins are present in the raw water, and recommended communication and treatment activities if cyanotoxins are found in the raw water.
4. Step 4 describes monitoring activities to determine whether cyanotoxins are present in finished water and recommended communication and treatment activities if cyanotoxins are found.
5. Step 5 describes continued finished water monitoring (confirming the initial finished water sample in Step 4), treatment and communication activities if cyanotoxins are found in the finished water above acceptable concentrations.

Chorus (2005) and Burch (2008) have summarised current approaches to cyanotoxin risk assessment, risk management and regulations in different countries. The approach taken by different countries varies from informal arrangements where information is gathered by different organisations and collated by one group for non-specific

publication, to formal guidelines and regulations. Most countries with specified values use the WHO tolerable daily intake (TDI) for microcystin-LR with slight variation (from 0.84 to 1.5 µg per L). Monitoring and trigger points for cyanotoxin testing (rather than cyanobacteria testing) and for actions to neutralise cyanotoxins varies considerably between countries. For example, Brazil has an upper tolerance of 10,000 cells per mL or 1.0 mm³ biovolume, whereas Australia has an upper limit of 6,500 cells per mL, with cyanotoxin testing coming in below these levels.

An attempt to predict the vulnerability of reservoirs in Australia to cyanobacterial blooms has resulted in a vulnerability index (Leigh 2010). The analysis suggests that strong links exist between the physical environmental of dammed river systems, their physicochemical characteristics and algal ecology. The vulnerability index used parameters which satisfied the following four conditions:

- 1 correlation with water quality was well established in the literature
- 2 parameters were easily calculated from readily available data on reservoir or catchment characteristics
- 3 parameters were not strongly correlated with each other
- 4 parameters were relatively static or predictable though time so that the index was unaffected by substantial spatial and temporal variation.

The resources mentioned above may be useful for strategies for assessing the risk posed by cyanobacteria in a specific water supply and developing a cyanobacteria management plan.

9.3 Monitoring

The design of monitoring programmes for cyanobacteria and their toxins is more challenging than programmes for other pathogens or chemical determinands. Factors that contribute to the added complexity are their ability to grow in open waters, not necessarily near a particular source; scums of cyanobacteria may be shifted and concentrated by wind; toxins may be contained in their cells, or dissolved in the water, be absent, or develop very quickly.

Monitoring programmes for these organisms need to be tailored to the characteristics of each body of water. They also need to be flexible to take account of changes in the risk the toxins present with time and location. Collection of historical information regarding blooms and growth conditions, and identification of patterns of cyanobacterial growth can be used to help focus the monitoring programme on critical periods and locations in the water body of interest.

WRF (2016) discusses methods for monitoring cyanobacterial development, including:

- Chlorophyll *a* is common parameter that can be measured and used to indicate the presence of algae. It measures algal biomass fairly accurately and can be analysed using probes or relatively simple laboratory equipment. One shortcoming of chlorophyll *a* as an indicator of cyanobacteria growth is that it is found in all algae, not just cyanobacteria.

- Buoy monitors are becoming an increasingly popular way to collect real-time water quality data. Sensors are available that measure phycocyanin (a pigment which is largely unique to cyanobacteria) and chlorophyll *a*. Real-time chlorophyll *a* and phycocyanin measurements are probably most helpful if the water utility considers them in terms of relative changes, rather than considers them as stand-alone measurements.
- Satellite photographs of water bodies and visible algae blooms are being used as an early warning tool in some regions in the United States. Ohio Environmental Protection Agency (OEPA) routinely reviews satellite data to see if any drinking water sources seem to be having algae blooms. If the agency determines a bloom may be present, the water utility is contacted and asked to provide information, including how close the bloom is to the intake. Based on that information, OEPA decides if cyanobacteria counts and cyanotoxin screening should take place. The sensitivity of this method is unlikely to be high enough for monitoring drinking water supplies.

Operational monitoring (monitoring to assist in the operation of a supply) includes both regular inspections and testing. In small and remote systems, close attention should be paid to checking that the preventive measures used to protect water supplies are functioning.

The frequency of catchment assessments will depend on the characteristics of each site, the source of raw water, the time the water remains in storage, and the subsequent treatment that is provided. As well as regular inspections in the immediate vicinity of the intake area, every catchment where there is habitation or free public access should be comprehensively inspected at least once a year for potential sources of pollution.

A structured strategy for planktonic cyanobacteria monitoring programmes is recommended and might include:

Level 1 Visual inspection for transparency, discolouration:

- move to Level 2 if poor transparency and discolouration are observed.

Visual inspection for scums, detached, accumulated cyanobacterial and mats:

- move to Level 3, if visual inspection indicates that cyanobacteria are present.

Measurement of temperature and assessment of structure of the water column:

- move to Level 3, if the temperature is more than 18°C, or there is persistent stratification of the water body.

These inspections should be made weekly or fortnightly.

Level 2 Measurement of nutrient concentrations:

- dissolved nitrogen and total phosphorus should be measured. Phosphorus can be the nutrient that limits cyanobacterial growth, but in a substantial number of New Zealand lakes, growth is nitrogen-limited.

Measurement of hydrological characteristics, which should include:

- retention times of water in lakes
- the persistence of thermal stratification of lakes
- the accrual period in rivers. The accrual period is the amount of time available for growth of periphyton (attached algae) in rivers, ie, the amount of time between flood events.

Measurement of light penetration:

- penetration of light below the warm upper mixed layer in a stratified water body will favour cyanobacterial growth.

Inspection of the catchment to identify the source of the nutrients:

Information about factors in this level, which are likely to influence bloom formation, together with cell counts, will help to develop the ability to predict bloom formation. Monthly measurement is satisfactory, at least for the first two years; more frequently if there are rapid changes in the nutrient concentrations.

Level 3 Determination of biomass of cyanobacteria (at least fortnightly; weekly or more frequently if Alert Level 1 (see section 9.7.1 and Figure 9.5) is exceeded:

- identification of cyanobacterial taxa and population densities is a good basis for assessing risk
- assessing the potential for the presence of toxins may assist with decision making (eg, determining if potential toxin-producing taxa are present, assessing samples for cyanotoxin production genes or using passive sampling devices such as SPATT samplers; (see below)
- use the Alert Levels framework (see section 9.7.1 and Figure 9.5) to determine what action should be taken
- move to Level 4 if Alert Level 1 is exceeded.

Level 4 Determination of toxicity of the water or toxin concentrations (fortnightly is sufficient, unless there is reason to believe toxin concentrations are changing rapidly and are close to 50 percent of a PMAV):

- this level of monitoring allows more accurate assessment of the concentrations of toxins present in the water
- use the Alert Levels framework (see section 9.7.1 and Figure 9.5) to determine what action should be taken.

The collation of monitoring information gathered during one bloom event, (water appearance, water temperature, preceding weather conditions, hydrology (water levels and flows), nutrient concentrations, cell counts, cyanobacterial taxa, and toxin concentrations) will provide a valuable basis for predicting when future blooms may occur and the levels of risk associated with the bloom as it develops.

Cyanotoxin concentrations change with environmental and hydrological conditions, and toxin concentrations may be low at the start of bloom events. Current sampling practices (eg, grab samples) provide only a snapshot of cyanotoxins present at one point in time and may miss areas or times of highest risk, and can fail to give early warning. These are particular issues when sampling rivers where continuous flows transport toxins rapidly. A passive *in situ* methodology known as solid phase adsorption toxin tracking technology (SPATT) has been shown to be a simple and sensitive means of warning of toxic micro-algal bloom development and associated shellfish contamination in the marine environment. Wood et al (2010 and 2018) describe trials using SPATT samplers in rivers. SPATT sampling does not allow you to measure toxin concentrations within cyanobacterial cells; but the fraction of a toxin that has been released from cells into the water. Although it is not possible to relate the concentrations of toxins measured in the SPATT sampler to the concentrations in the river water, this technique provides a useful management tool for early warning of low concentrations of toxins in a water body allowing proactive management of a cyanobacteria problem.

Because toxin-production in cyanobacteria cannot be confirmed microscopically, making decisions about the potential risk in a water supply can be difficult. Analysis for the actual toxins is the ultimate means of assessing the risk, however, analysis for cyanotoxin production genes is an emerging tool that can assist with deciding when analytical testing is deployed and what toxins to test for. This technique uses polymerase chain reaction (PCR) to detect the DNA sequences that code for cyanotoxin production in cyanobacteria. Without the genes, cyanobacteria are unable to produce the toxins. When applied in a cyanobacteria monitoring programme, this technique provides an indication of the potential for cyanotoxin production in a water supply and can be used (alongside cyanobacteria cell counts) to trigger toxin testing of water. An additional advantage of the technique is that it provides guidance on which cyanotoxins to test for analytically. Because the technique is prone to false positives (as sometimes only a portion of the entire gene cluster required to produce the toxin is present in a cyanobacterial strain) and because gene copy numbers don't necessarily correlate with toxin concentration, follow-up toxin testing is required to determine the potential risk.

9.4 Compliance

Cyanotoxins are chemical determinands, and like other chemical determinands can be given Priority 2 classification. However, the way this assignment is made, and the consequent compliance requirements, is different from those of other chemical determinands.

The factors leading to these differences are:

- cyanobacteria may appear irregularly, or annually;
- cyanotoxins may be present at potentially health-significant concentrations for only short periods, so monitoring throughout the whole year is unnecessary;
- cyanobacterial numbers, and, hence, cyanotoxin concentrations, can increase rapidly, therefore higher monitoring frequencies than for other chemical

determinands are required to ensure that the water supplier is aware of toxin concentrations reaching health significant concentrations;

- unlike most chemical determinands, the health effects of cyanotoxins are acute at low concentrations and potentially fatal, although there may also be long-term effects.

Some compliance requirements for cyanotoxins result from a toxin being assigned as a Priority 2 determinand (DWSNZ section 7.3). Other compliance requirements have also to be met to ensure that the water supplier has systems in place to determine when cyanotoxins reach potentially health significant concentrations, and to manage the risk to their consumers. These requirements are contained in section 7.2 of the DWSNZ.

Section 7.2 (DWSNZ) lists four sets of requirements, two of which specify objectives that have to be met for compliance.

- 1 Collect information about the source that will assist in determining:
 - a) whether cyanobacteria are present in the source water
 - b) when cyanotoxin concentrations (in the source water) reach or exceed potentially health-significant concentrations (greater than 50 percent of PMAV).
- 2 Develop a protocol, approved by the drinking water assessor, that:
 - a) identifies which determinands or observations are to be monitored for assessing the development of cyanobacteria
 - b) specifies the actions that will be taken in the event of any cyanotoxins reaching a potentially health-significant concentration
 - c) initiates a cyanotoxin monitoring programme in the source water when the protocol indicates that the risk of cyanotoxins being present has reached a predetermined level based on evidence from 7.2(1)(b).

The ways in which these objectives are to be met are undefined. Risk management protocols that best suit supply circumstances can therefore be developed. This approach has been taken because of the variable relationship that exists between cyanotoxin concentrations in a water and surrogate parameters, such as cell count. These should be developed as a section of the Water Safety Plan (WSP) for the water supply. An example Alert levels framework for planktonic cyanobacteria based on overseas experience and available toxin quota data is presented in section 9.7.1. Local knowledge and site-specific challenges may mean that the framework and the cyanobacteria cell concentrations used to define the Alert levels might be adapted. Some references about the conditions that alter cyanobacteria growth and distribution include: Ahern et al 2008; Baldwin et al 2008; Bayer et al 2008; Burger et al 2008; Downs et al 2008; Kobayashi et al 2008; Redden and Rukminasari 2008; Ryan et al 2008; Shaw et al 2008.

Experience of managing cyanobacterial blooms in New Zealand waters is limited. The first set of requirements in section 7.2 (DWSNZ) therefore obliges the water supplier to gather information to provide a scientifically defensible basis for the protocol that has to be prepared in the second set of objectives. Measurements or observations that could be monitored to meet the first set of requirements include:

- source appearance,
- water temperature,
- pH,
- nitrogen and phosphorus concentrations,
- water level or flow (cyanobacteria bloom events normally have happened in low flow waters),
- taste and odour complaints,
- cell counts of cyanobacteria,
- determination of the presence of stratification in the water column (lakes and reservoirs),
- direct toxin measurement.

Experience may show that other parameters correlate well with the development of cyanobacteria in source waters. Sharing information between water suppliers in the same area or drawing from the same source, will assist in making best use of what has been learnt from past algal bloom events.

The protocol required for compliance requirement 7.2(2) is developed from the information collected as a result of meeting requirement 7.2(1). Completion of this protocol is not required for compliance, if its development is waiting for the data collection of requirement 7.2(1), and this collection is underway. As part of this protocol the water supplier must specify what actions will be taken to manage the health risk when a cyanotoxin reaches a potentially health-significant (greater than 50 percent of its PMAV) concentration. Section 9.7 of this chapter provides information that will assist in identifying the actions needed in these circumstances. These actions must be incorporated in the water safety plan (WSP – formerly known as a public health risk management plan, PHRMP).

The fourth compliance requirement of section 7.2 (DWSNZ) is:

- 4 notify the DWA when the protocol shows the development of cyanobacteria and cyanotoxins in the source water has reached a stage where source water cyanotoxins are approaching 50 percent of the PMAV.

It is important to keep the DWA regularly informed of the outcome of monitoring results so that, should the results indicate greater than 50 percent PMAV, the DWA can assign Priority 2b in a timely manner to protect public health. After Priority 2b has been assigned, it necessary for the supplier to monitor the source water, raw water and the treated water for cyanotoxins (section 7.3.2).

The completion of requirements 7.2(1) and (2) is needed to meet this requirement. Priority 2 determinands are usually identified through the Priority 2 Chemical Determinands Identification Programme. This is not possible for cyanotoxins because of the large and rapid variability in their concentration. The Priority 2 classification of cyanotoxins is therefore made by the DWA using monitoring information provided by the water supplier, requirement 7.2(4).

After a cyanotoxin has been classified as a Priority 2 determinand, the requirements of section 7.3 (DWSNZ) must be met. See section 9.5.2 of this chapter for information about recognised laboratories.

Samples for cyanotoxin testing must be taken twice-weekly from the water leaving the treatment plant. Either through the success of the actions set out in the WSP, or because of a subsidence in the size of the bloom causing the high cyanotoxin concentrations, the toxin concentration will eventually drop. Once the cyanotoxin concentration in three successive samples (taken at the required frequency of twice weekly) has been found to be less than 50 percent of its PMAV, and the concentration in each sample is less than the previous, the classification of the cyanotoxin is returned to Priority 3.

For other chemical determinands, monitoring of Priority 3 determinands is generally not required. This is because sufficient evidence should have been collected to establish that there is only a low likelihood of the determinand appearing in the water again at concentrations exceeding 50 percent of its PMAV. This assumption cannot be made for cyanotoxins because of the possibility of the redevelopment of a bloom. Therefore, although a cyanotoxin may be reclassified as Priority 3 and monitoring of the toxin itself may cease, the monitoring requirements of the protocol developed in section 7.2 of the DWSNZ must continue.

9.5 Sampling and testing

9.5.1 Sample testing

As with other testing required for demonstration of compliance with the DWSNZ, a Ministry of Health recognised laboratory must be used. Methods for analysis of the cyanotoxins are given in the datasheets (Volume 3, Part 2.4). Discussions on cyanotoxin analyses appear in publications by the Cawthron Institute (2005 and 2018). Because of the intermittent need for these tests, the instrumental analysis of cyanotoxins can be expensive.

Several New Zealand laboratories have IANZ accreditation for the identification and enumeration of cyanobacteria, and for cyanotoxin analysis. A list of the New Zealand laboratories recognised by the Ministry of Health to conduct analyses for cyanobacteria and related cyanotoxins may be found on the Ministry of Health website www.health.govt.nz/water, 'Publications', located under 'Registers'. See the latest edition of the *Register of Recognised Laboratories: Drinking water supplies* (updated annually).

Whichever laboratory is used for testing, advice should be obtained from the laboratory about sampling containers for the particular determinand in question, before collecting the samples, because there is some evidence that common additives in plastics could contaminate water samples and co-elute with microcystins to give erroneously high readings (van Apeldoorn et al 2007).

Cyanotoxin field tests are being developed so water suppliers can monitor changes more rapidly than waiting for results from accredited laboratories. These include Abraxis Dipsticks, Creative Diagnostics Dipsticks, Jellet Rapid Test Kit, and Beacon MC Tube Kit. These are not currently accredited cyanotoxin test methods and can be expensive (perhaps up to \$50 per test), however, they provide a means of rapidly acquiring information on whether cyanotoxins are present in a waterbody to assist decision making. Health Canada (2011); Brylinsky (2012); Cawthron (2018).

9.5.2 Sample collection

Sampling to obtain information to help in the management of cyanobacteria may be undertaken via three routes:

- determination of nutrient concentrations (to assess the potential for cyanobacteria growth),
- assessment of the cyanobacterial population for both number and species (to assess for the organisms themselves),
- determination of cyanobacterial toxin concentrations (to assess for the determinand itself).

The following provides detailed guidance for sample collection and handling, and is based on the Queensland Harmful Algal Bloom Response Plan, 2002 (developed by the Department of Natural Resources and Mines, Environmental Protection Agency, Queensland Health, Department of Primary Industries, Local Governments and water storage operators, Australia). It is recommended that advice from the analytical laboratory carrying out the testing, or other local experts, be sought to determine whether the procedures given here need to be modified to suit the requirements of the laboratory or the conditions of the water source. Details for benthic monitoring and sampling have been adapted from the *New Zealand Guidelines for Cyanobacteria in Recreational Fresh Waters – Interim Guidelines* (2009). See also Biggs and Kilroy (2000).

9.5.2.1 Sampling for planktonic cyanobacteria

The design of monitoring programmes for cyanobacteria is challenging due to factors such as:

- their ability to grow in open waters,
- the ability of some species to regulate their buoyancy,
- the formation of surface scums that may be shifted and concentrated by wind,
- the interactions of buoyant cells with the surface drift currents created by wind,
- the ability of some species to produce toxins that may be contained in their cells or dissolved in water.

The heterogeneous (mixed) and dynamic nature of many cyanobacterial populations can make sampling site selection difficult. A flexible response to the current situation when choosing the sampling sites may, at times, be more appropriate than following a rigid programme. Alternatively, fixed sites may always be sampled within a broader monitoring programme, to provide linear time series, and supplemented with sampling

of sites currently harbouring cyanobacterial scums. Water suppliers are beginning to use drones to estimate cyanobacterial coverage. Satellite imagery is being used more frequently overseas to estimate the abundance of cyanobacteria in water bodies and to track the movement of cyanobacteria blooms in large lakes, however, its application is highly dependent on the size of the water body and the types of cyanobacteria blooms that occur in the water body.

The selection of sampling sites is a key factor in collecting representative samples. The following should be considered:

- the history, if available, of cyanobacterial population development and occurrence of toxins in the water body, or similar water bodies nearby, this information may indicate sites most likely to harbour scums/mats;
- specific incidents, such as animal deaths or human illness, may provide indications of 'high risk' sites;
- morphometric and hydrophysical characteristics of the water body (eg, exposure to wind or thermal stratification) may help identify sites which are prone to scum accumulation;
- prevailing weather conditions, particularly wind direction, which can lead to scum accumulation along certain shorelines;
- local logistical resources, accessibility and safety factors.

The nature of the information required should determine where samples are taken and how.

Two types of water sample can be taken: grab samples and composite samples. Grab samples are single samples used to provide information about a particular site at a particular time. Where there may be uneven distribution of a determinand, either in space (geographical location, water depth) or time, a composite sample may be necessary. This type of sample is designed to gather representative information about the determinand that cannot be provided by a single sample. A number of grab samples at different locations or times may be taken then mixed together, or the water may be sampled continuously while changing the location of sampler intake. The latter approach may be used in sampling at different depths, for example.

Concentrations of nutrients, cyanobacteria and cyanotoxins are unlikely to be the same throughout a water body because of stratification within it, and other factors such as wind and currents that may shift cyanobacterial masses. Unless the factors that may affect the concentration of a determinand within the water body are understood, interpretation of the data from a single grab sample is likely to be difficult.

Single grab samples are valuable when a water supplier wishes to know the cyanotoxin concentration entering the treatment plant at a particular time, or, the greatest cyanotoxin concentration that may challenge the treatment plant. When identifying the sampling location to gather worst-case information, consideration needs to be given to such factors, as the ability of some species to be blown by the wind on the surface of the water, or to accumulate at different depths in the water.

Samples should also be included from points where previous samples have revealed unsatisfactory water quality. When assessing the risk associated with cyanotoxins

entering the reticulated water, water suppliers should collect samples at locations and times likely to reveal the highest concentrations of cyanobacteria and their toxins.

Site inspection should be carried out at the time samples are taken. From this the following should be recorded:

- weather conditions, including the wind direction and velocity;
- whether the bottom of the lake/reservoir is visible at a depth of about 30 cm along the shore line;
- any distinct green, blue-green, or brown colouration of the water;
- a distinctive odour;
- signs of cyanobacteria as blue-green streaks on the surface or scum.

This information may assist in interpretation of sample analysis.

Collecting water samples for planktonic phytoplankton identification and enumeration

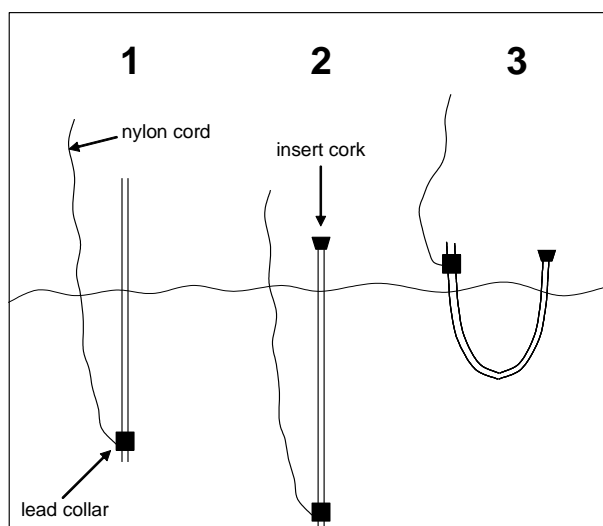
Ideally sampling should be conducted from a boat. Depth integrated samples are recommended for open water sampling where a representative sample of the water column is desired. The samples should be collected using a flexible hose-pipe sampler. A rigid pipe can be fitted with a one-way valve, which tends to simplify the operation of withdrawing the pipe and sample from the water. The length of the sample pipe should reflect the appropriate depth to which the cells are likely to be mixed. This may vary from approximately 2–10 metres depending on the degree of stratification and exposure of the water body to the influence of wind. When the mixing status is unknown, a five-metre long pipe is recommended, however a two-metre long pipe may be more appropriate in shallower areas.

The inner diameter of the pipe should be at least 2.5 cm and flexible pipes are generally more practical than rigid pipes for pipe lengths greater than two metres. The recommended method for the use of the hose-pipe sampler is show below.

The following equipment is needed in order to take samples:

- integrated hose-pipe sampler: 5 m length of 2.5 cm diameter plastic piping with a weighted collar at one end (see Figure 9.2),
- a cord attached to the hose and boat,
- a rubber cork to fit one end of the hose,
- a bucket,
- a sample bottle and lid (minimum 200 mL capacity).

Figure 9.2: Procedure for use of the integrated hose-pipe sampler for planktonic cyanobacteria and cyanotoxins



The procedure for collecting the sample is as follows:

- 1 Attach a cord to one end of the hose and the boat to prevent accidental loss of the hose.
- 2 Holding the hose at the top end, rapidly drop the weighted end of the hose-pipe into the water to a depth of about 5 m.
- 3 Return hose to the boat without inserting the rubber cork.
- 4 Rinse the hose.
- 5 Repeat the procedure, but this time insert the cork into top end of the hose (so that the end is held in the hand).
- 6 Pull the bottom end of the hose to surface using the cord, so that the tube is in a U-shape (see Figure 9.2).
- 7 Lower the weighted end of the hose into a bucket and remove the cork. Ensure that the entire contents of the hose are emptied into the bucket.
- 8 Mix the contents of the bucket and then transfer part of the contents into a sample bottle, leaving a 25 mm gap at the top of the bottle. Discard the rest of the contents of the bucket.

Note: Some species of phytoplankton can cause skin irritation. If sampling from an area that has a high concentration of phytoplankton, minimise contact with the water during sampling by wearing appropriate protective clothing, in particular gloves. Normal hygiene precautions such as washing off any splashes and washing hands before eating or drinking should be observed at all times. When not in use, the hosepipe sampler and bucket should be kept clean and stored in a dark shed or cupboard.

Where sampling from a boat is not practicable (eg, a river, bank, shoreline, bridge or valve tower) sampling should be assisted by the use of a pole-type sampler. The bottle is placed in a cradle at the end of an extendable pole to avoid contamination of shoreline-accumulated scums.

9.5.2.2 Sampling for benthic cyanobacteria

River intakes should also be inspected for benthic (attached) cyanobacterial mats. These appear as expansive, thick black or dark-brown slimy mats on the riverbed or growing on intake structures. The mats commonly detach from the substrate and float on the water surface, accumulating behind obstructions in the river channel or in lakes / reservoirs. For this reason, knowledge of cyanobacteria concentrations upstream from the intake site is also valuable. An underwater viewer is generally required to assess the extent of benthic cyanobacteria in rivers. These viewers are commercially available and allow a clear view of the stream bed with no interference from surface turbulence and reflection. They also enable definition of a more-or-less standard area of the stream bed at each survey point (ie, equivalent to a quadrat in terrestrial ecology).

Benthic cyanobacteria can also grow attached to the bottom substrate of lakes and reservoirs. This type of cyanobacteria poses a management challenge as it often grows out of sight (depending on water clarity) and can slowly accumulate even in low nutrient waters. Some signs of benthic cyanobacteria in water reservoirs can be the presence of cyanobacteria odour compounds (eg, geosmin or MIB) in the water, identified either through analytical testing or complaints from water consumers, despite an absence of cyanobacteria in planktonic cell count samples, or the observation of detached mats in the reservoir. If benthic cyanobacteria are suspected in a water reservoir, sediment samples should be collected using a Ponar grab sampler (or similar) and analysed for cyanobacteria or cyanotoxins. Multiple samples from around the water body may need to be collected to gather an idea of the extent of benthic cyanobacteria present. Alternatively, qualified divers could be used to survey the base of the reservoir for benthic cyanobacteria, however, this can be a costly exercise.

Collecting samples for benthic cyanobacteria identification and quantification

Under certain circumstances samples for benthic cyanobacteria may be required (eg, *Microcoleus autumnalis* and *Microseria wollei*; previously *Phormidium autumnale* and *Lyngbya wollei*). In most cases benthic samples are collected for qualitative analysis. Samples can be collected using a benthic sampler such as an Eckman grab or a rigid plastic corer (eg, PVC or polycarbonate pipe). Multiple samples from different locations or rocks should be taken and either analysed individually (if possible) or combined into a single container and analysed as a composite sample. If large quantities of sediment/sample are collected, this can be thoroughly mixed and a sub-sample for analysis can be stored in a smaller specimen jar.

Measuring the abundance of benthic cyanobacteria in rivers

For monitoring and sampling benthic cyanobacteria, upon arriving at a survey area, spend approximately five minutes looking along a 30–60 m section of river bed for the presence of cyanobacteria mats. Ensure that this section includes some runs and riffles. Mark out four transects in the selected area by placing marker rocks along the water's edge, approximately 10–15 m apart. Record details, including site, date, time, etc, and note the general presence/ absence of cyanobacterial mat and the presence of any detached mat along the shoreline. Assemble the underwater viewer and, starting at the downstream end, wade into the stream at right angles to the water's edge. Go out to a

depth of approximately 0.6 m (Figures 9.3 and 9.4). A standard maximum depth of 0.6 m should be used at all sites, where possible. In shallow rivers, the transects may span the entire width. Record the maximum distance and depth for transect 1. Hold the underwater viewer about 20 cm under the water more or less on the transect line. The area of view should be ahead of you, not one that has just been walked over. Holding the viewer steady and as vertical as possible, estimate to the nearest 5 percent the proportion of the area you see which is occupied by the cyanobacterial mat. Coverage should only be recorded if mats are greater than 1 mm thick. It is useful to record the presence of thin mats as well.

Figure 9.3: Benthic cyanobacteria monitoring and sampling schematic of layout of transects and survey areas

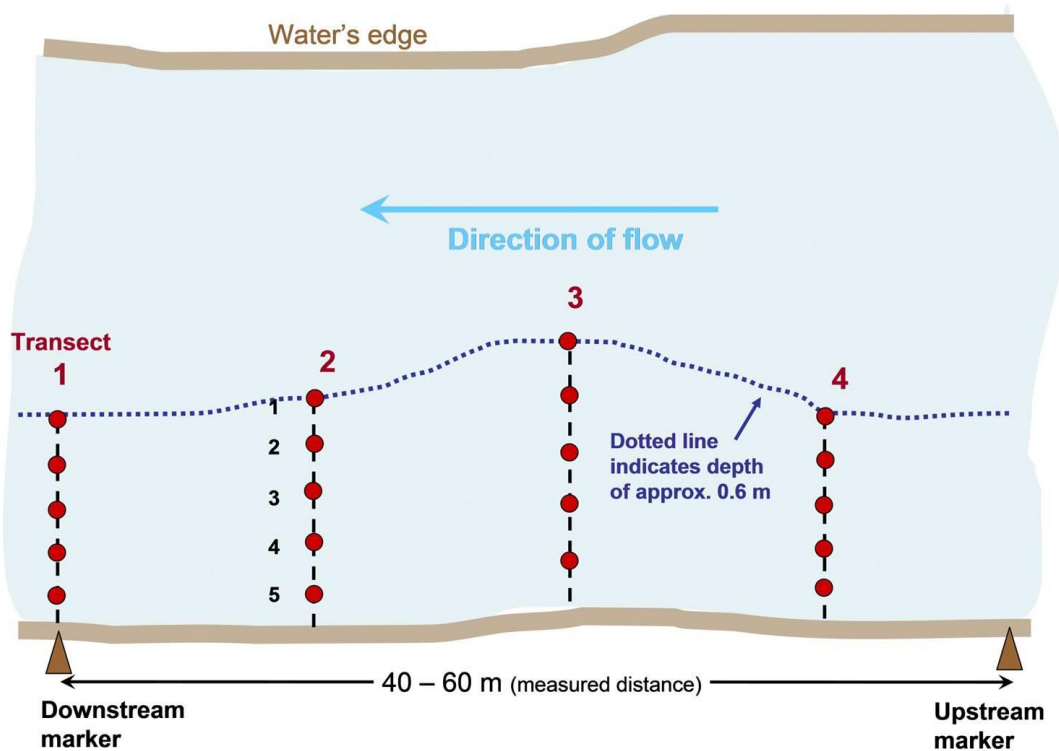
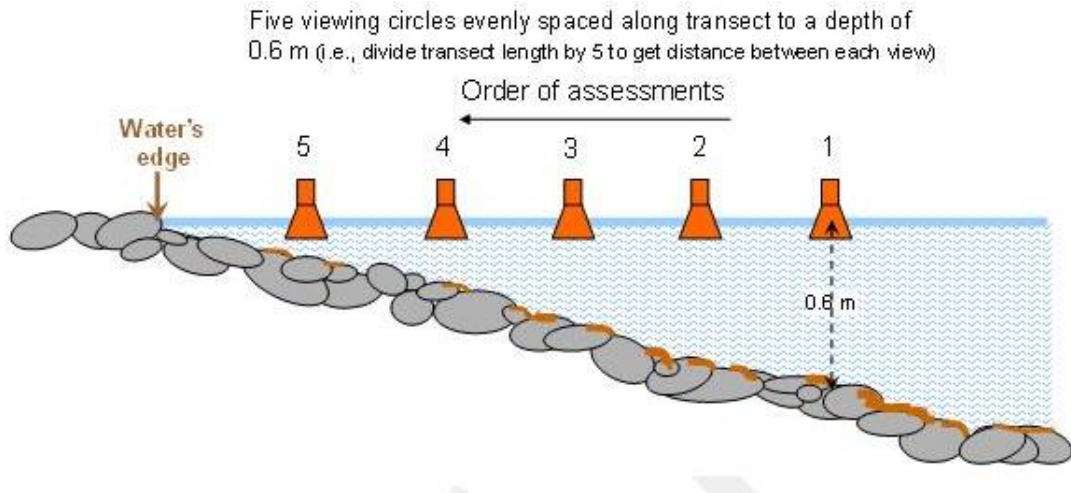


Figure 9.3 illustrates a benthic cyanobacteria monitoring and sampling schematic of layout of transects (numbered in red) and survey areas (red circles, numbered in black) at a site (not to scale). The numbering indicates the order in which assessments are made. The transects are spaced evenly along the survey reach. It may not always be possible to have five viewer results (ie, steep sided rivers), in these circumstances take as many views as practical per transect (Source: C Kilroy, NIWA).

Figure 9.4 illustrates a benthic cyanobacteria monitoring and sampling schematic of transect cross-section showing arrangement of sampling points (not to scale). Assessment 1 will cover a greater area than assessment 5 because of the greater water depth. However, this will be the case at all sites. Therefore, assessments should be comparable (from *New Zealand Guidelines for Cyanobacteria in Recreational Fresh Waters – Interim Guidelines*, source: C Kilroy, NIWA).

Figure 9.4: Benthic cyanobacteria monitoring and sampling schematic of transect cross-section showing arrangement of sampling points



9.5.2.3 Sampling for toxin analysis

- **Qualitative:** Qualitative toxin analysis is generally performed by bioassay, and is performed when either more sophisticated techniques are unavailable, or the identity of the toxin is initially unknown. Samples for qualitative analysis may be collected from concentrated scums or by trailing a phytoplankton net (10–50 µm mesh) from a boat or casting the net from the shoreline. The volume of sample required is dependent upon the concentration of the cells. Up to 2 litres may be required if cell concentrations are low. Advice should be sought from the analytical laboratory before collecting and submitting a sample for qualitative toxin analysis.
- **Quantitative:** Quantitative toxin analysis is performed using a variety of methods suited to the type of sample and the toxin present. Samples are collected in the same manner as those taken for phytoplankton identification and enumeration, however, storage conditions and the volume of sample is dependent on the type of analysis to be used (consult with the testing laboratory for specific information). In general, at least 500 mL of water should be collected.

9.5.2.4 Preservation, transport and storage of samples

- **Samples for identification and enumeration:** To ensure the sample remains in a condition suitable for identification and enumeration, Lugol's iodine preservative solution should be added to the sample as soon as possible after collection. See APHA (2005) for the recipe. Sufficient Lugol's iodine solution should be added to render the sample a colour resembling weak tea (ie, 0.5 mL Lugol's iodine per 100 mL of sample). It is sometimes useful to retain a portion of sample in a live (unpreserved) state, as some species of phytoplankton may be easier to identify in this way. The analytical laboratory can advise on whether unpreserved samples are required.

Preserved samples are reasonably stable as long as they are stored in the dark. If samples are unlikely to be examined for some time, they should be stored in amber glass bottles or PET plastic bottles with an airtight seal. Polyethylene bottles tend to absorb iodine very quickly into the plastic and should not be used for long-term

storage. Live samples will begin to degrade quickly especially if there are high concentrations of cells present. These samples should be refrigerated and examined as soon as possible after collection.

- **Samples for toxin analysis:** Careful handling of samples is extremely important to ensure an accurate determination of toxin concentration. Some toxins are readily degraded both photochemically (ie, by exposure to light) and microbially. Samples should be transported in dark cold conditions and kept refrigerated and in the dark prior to analysis.

9.5.2.5 Training and quality

It is essential that staff involved in the collection of field samples be trained in all facets of collecting, transporting and delivering samples. Samplers should be aware of sample requirements including sample sites, types and numbers at each water body.

They should also be fully trained in the process of visual inspections and the need to collect samples of cyanobacterial scums if present. Samplers should undergo continual training to ensure new procedures are learned and existing skills are refreshed.

9.6 Transgressions

A transgression results from an exceedance of a cyanotoxin PMAV. This requires remedial actions to reduce the risk to consumers. Section 9.7 provides guidance material that can be used for planning the remedial actions to be taken following a transgression.

Remedial actions should not be left until a transgression has occurred; preventative measures should be put in place as a potential risk becomes apparent. When the routine monitoring undertaken as a requirement of section 7.2 of the DWSNZ shows the likelihood of algal bloom development or the growth of cyanobacteria to a level at which toxin concentrations may be a concern, remedial actions should be taken to reduce the likelihood of a transgression occurring.

Section 7.3.3 of the DWSNZ lists actions that must be taken in the event of a cyanotoxin transgressing its PMAV. These must be incorporated into the WSP when it is prepared. The WSP should also include any other actions the water supplier considers important for their particular supply. These may have become apparent during the collection of information undertaken to meet the requirements of section 7.2.

9.7 Risk reduction

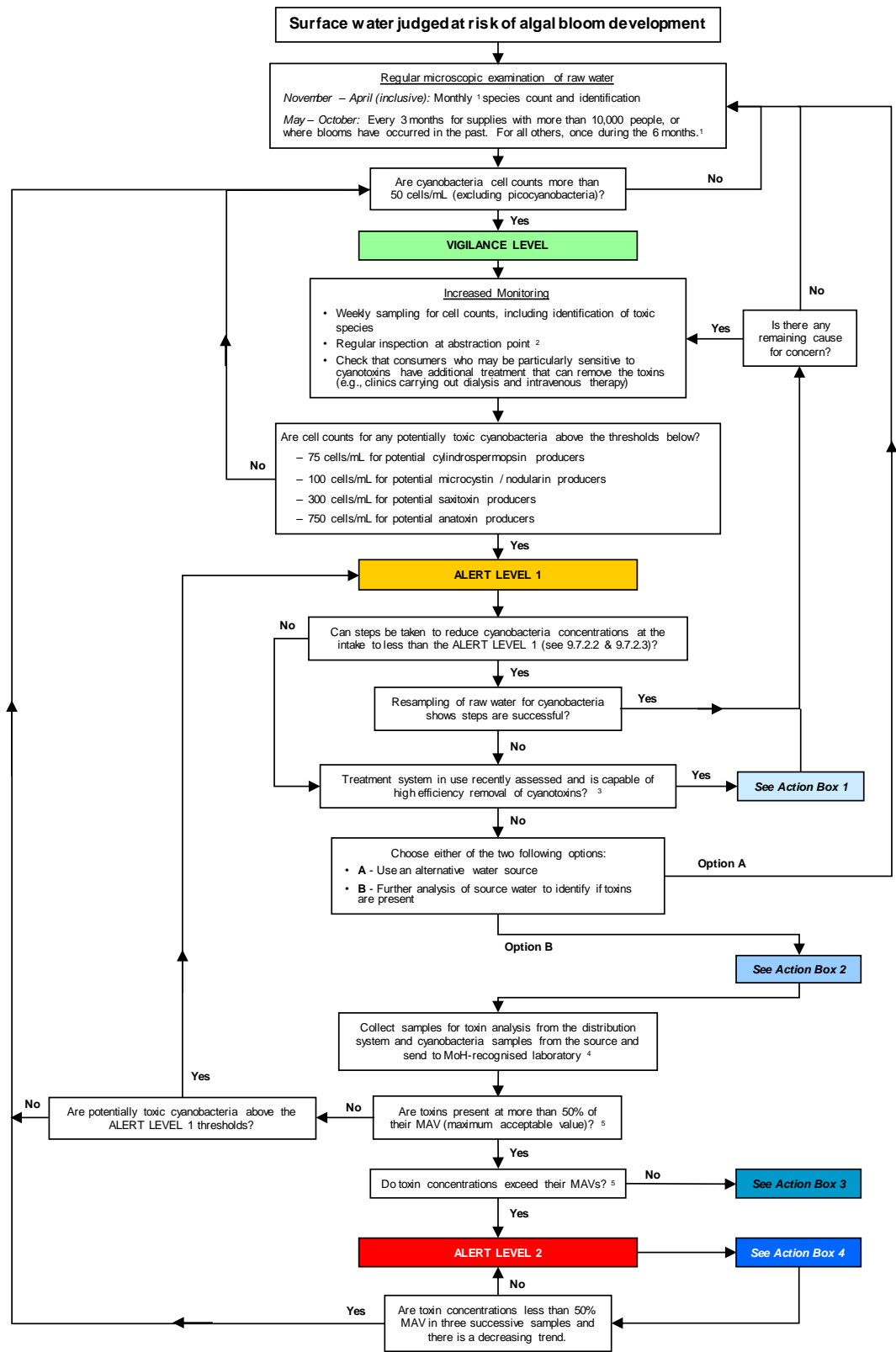
9.7.1 Alert levels

An Alert Levels framework is a monitoring and management action sequence that water treatment plant operators and managers can use to provide a graduated response to the onset and progress of a cyanobacterial bloom. The decision tree provided in Figure 9.5 should be seen as a general framework to assist with developing a site-specific framework. It is based on local and overseas experience and data, but may require adaptation of specific alert levels and actions to suit local conditions. Individual water suppliers may wish to augment the minimum monitoring requirements set out in Figure 9.5, making use of their own data, knowledge and experience; this should be documented in the WSP. Where possible, water managers should gather information about cyanobacteria abundance (cell concentrations for planktonic cyanobacteria or percentage coverage for benthic cyanobacteria in rivers) and their relationship with cyanotoxin concentrations in their source waters. Site specific data may mean that the cell concentration thresholds used in a WSP may differ from the those in the alert levels framework in Figure 9.5. Monitoring of the type noted in Level 1 of section 9.3 could be used before the Vigilance Level in Figure 9.5 is reached to supplement the low frequency microscopic examination of the water.

Note that there are difficulties in identifying the risk arising from benthic cyanobacteria attached to riverbeds, the substrate of lakes and reservoirs or supply intakes by the microscopic examination of the raw water (ie, by determining cell concentrations in the water) required in Figure 9.5. Section 9.5.2 provides advice on sampling in these situations and an alert level framework for a site afflicted with benthic cyanobacteria may differ substantially from the example framework for planktonic cyanobacteria in Figure 9.5.

Cyanotoxins are currently measured in three suites: the microcystin / nodularin, the anatoxin / cylindrospermopsin, and the PSP (saxitoxin) suite, with each suite costing \$200–500. Because the cost of analysing cyanotoxins is high, water suppliers with source waters that have a history of cyanobacterial blooms will have a real incentive to manage their catchment and raw water quality. They will need to develop a contingency plan that can be implemented at short notice, see section 9.7.2.3.

Figure 9.5: Alert levels framework for the management of planktonic cyanobacteria in water supplies



Notes:

- 1 Treatment plant staff must be able to recognise cyanobacterial blooms and know what action to take, if they develop between samplings.
- 2 Make sure intakes are not located where scum may be blown by the prevailing winds.
- 3 Treatment capable of removing more than 99 percent of cells without their lysis, or removing more than 90 percent of extracellular toxins (see Tables 9.4 and 9.5).

- 4 LC-FLD (liquid chromatography with fluorescence detection) will be needed to quantify saxitoxins. LC-MS (liquid chromatography – mass spectrometry) is suitable for all other toxins in the DWSNZ. ELISA (enzyme linked immunosorbent assay) is a research tool for saxitoxin analysis with potential for routine use. Where a calibration standard for a toxin is unavailable, bioassay should be undertaken to determine whether toxins present are a potential risk to health.
- 5 When multiple toxins are present in a water supply, the cumulative effects from toxins with similar modes of action should be accounted for (ie, cylindrospermopsins, microcystins and nodularins as hepatotoxins; anatoxins and saxitoxins as neurotoxins) using the ratio of each toxin concentration to the relevant MAV and summing the ratios (see s 8.2.1.1 of DWSNZ). Should this sum exceed 0.5 for 50% of the MAV, or 1 for 100% of the MAV, then proceed through the Alert Levels Framework.
- For example, if 1.5 µg/L of saxitoxins and 3.5 µg/L of anatoxin-a were detected in a drinking water, the ratio for these neurotoxins would be:
- saxitoxin, $1.5 \mu\text{g/L} \div 3 \mu\text{g/L} = 0.5$
 anatoxin-a, $3.5 \mu\text{g/L} \div 6 \mu\text{g/L} = 0.58$,
 giving a combined ratio of, $0.5 + 0.58 = 1.08$.
- This value exceeds 1 (the MAV) and consequently the Alert Level 2 threshold is breached.

Source: Modified from Chorus and Bartram 1999. Cell counts based on Australian Drinking-water Guideline 6 (2004). Other data sources: Jones et al 1993, NHMRC/ARMCANZ 1996.

Action Box notes

Action Box 1

- Continue regular monitoring of raw water (and treated water if necessary) to ensure adequate system performance, particularly if the cyanobacteria cell concentrations remain above the Alert Level 1 thresholds.
- Consider analysis of the treated water to confirm the absence of toxins.

Action Box 2

- Consult with health authorities and other appropriate agencies.
- Investigate options for reducing the nutrient load.
- Ensure that the local authority places signs at the water source, warning people not to swim, fish or practise any other sport within the contaminated areas.
- Prepare to:
 - implement water supply contingency plan
 - use an alternative source of water, or
 - use water treatment processes capable of removing cells or toxins (see section 9.7.2.3 and Tables 9.4 and 9.5), or
 - provide drinking-water by tanker or bottles.

Action Box 3

- Continue monitoring as required by section 7.3.2 (DWSNZ). Ideally, samples of raw water should be composite collected over 24 hours.
- If possible, use an intake that has not been affected.

- Assess level of health risk using Figure 9.1.

Action Box 4

- Continue monitoring as required by section 7.3.2 (DWSNZ), but preferably increase the monitoring frequency to daily, if toxin concentrations are near, or exceed their MAV.
- Close the water body temporarily.
- Assess level of health risk using Figure 9.1.
- If not already done, have water analyses carried out to determine which toxin is present, and its concentration.
- Activate contingency plan (which should include):
 - use of alternative water source, OR
 - provision of drinking water by tanker or in bottles, OR
 - use of advanced treatment processes (powdered activated carbon and/or DAF (dissolved air flotation) and/or ozonation)
 - provision of safe water from an alternative source (eg, tanker) to consumers particularly sensitive to toxins (eg, clinics carrying out dialysis or intravenous therapy)
 - increase sampling for cell counts (or biovolume) to assess bloom growth/decay, and help in management of raw water abstraction
 - use of aeration of the reservoir to reduce cell growth.
- Contact the DHB so they can coordinate with their dialysis patients directly.
- Routine supervision of dialysis clinic water treatment system.
- Consider whether there is a need to replace the water treatment plant sedimentation step with a DAF system.
- Do not use water source for drinking again until four weeks after testing shows that the toxin concentrations are consistently less than 50 percent of their MAV, cell counts have returned to less than the Vigilance Level Threshold (50 cells/mL, excluding picocyanobacteria), or cell counts are less than the Alert Level 1 Threshold when potential toxin-producing cyanobacteria are present:
 - 75 cells/mL for potential cylindrospermopsin-producing cyanobacteria
 - 100 cells/mL for potential microcystin-producing cyanobacteria
 - 300 cells/mL for potential saxitoxin-producing cyanobacteria
 - 800 cells/mL for potential anatoxin-producing cyanobacteria

9.7.2 Preventive and remedial measures

Providing safe drinking-water from cyanobacteria-infested surface waters requires consideration of the system as a whole, and the use of different combinations of

resource management and treatment tailored to the specific locality. There also needs to be local assessment of performance and local optimisation of resource management and treatment strategies.

A drinking-water safe from cyanotoxins will either draw from a resource that is unlikely to harbour cyanotoxins (eg, groundwater or surface water that does not support cyanobacterial growth), or have treatment in place that is likely to remove cyanobacterial cells (without causing their rupture) as well as removing cyanotoxins. When cyanobacterial blooms occur in New Zealand, alternative water sources are often unavailable, and water treatment plants may not have the capacity to remove all cyanobacterial cells or related toxins that are the prime health hazard. However, in many circumstances a potential cyanotoxin hazard can be managed effectively without the necessity of advanced treatment processes, through good water resource management.

There are three levels of management, consisting of preventive and remedial measures that can be used to control cyanobacteria and their toxins. In decreasing order of preference, these are:

- measures to reduce nutrient inputs into the water,
- management of the source water or reservoir,
- treatment to remove cyanobacteria or their toxins.

An important aspect of managing cyanotoxins, as with any risk management planning, is to ensure an emergency incident plan has been developed in advance in the WSP to deal with situations in which preventive measures have failed and rapid cyanobacterial growth has led to acutely dangerous toxin concentrations. These plans need to take into consideration, as far as possible, the capacity of water supply and laboratory personnel to react to emergency situations.

9.7.2.1 Measures to reduce nutrient inputs

Cyanobacterial bloom formation can be avoided by reducing the (controllable) factors allowing the cyanobacteria to grow; ie, nutrients and light.

A water supply's WSP should identify activities and situations within the catchment that may adversely affect water quality. Activities leading to the direct input of human or animal waste into water or indirect input through processes such as run-off from pastures, or fertiliser use, should be identified as a concern. To reduce the effects of these activities on the nutrient concentrations in the water, steps need to be taken to limit animal access to water sources, and to encourage agricultural practices that minimise the loss of nutrients in manure and fertiliser into water sources through run-off. Treatment of sewage to reduce its nutrient content, before disposal into water or on to land, may also be needed.

Land use and land practices are often outside the direct control of water suppliers. In these circumstances, assistance from the regional council should be sought to work with the affected community to determine what actions to reduce nutrient input are practicable.

There may be a substantial delay (many years) between the introduction of steps to reduce nutrient input and nutrient concentrations dropping below levels expected to sustain an algal bloom. This is because feedback mechanisms within the ecosystem, such as the release of nutrients that have been stored in sediments, will continue to release nutrients into the water during periods of thermal stratification. Artificial mixing of a reservoir, to limit thermal stratification and the release of sediment-bound nutrients, is another means for reducing bio-available nutrients in a water reservoir, however, this strategy generally has high costs associated with it. Sediment capping is a water quality restoration technique, where nutrient-rich sediment is covered by a capping agent that blocks the release of nutrients during periods of stratification. However, before sediment capping is considered, the introduction of nutrient-rich sediment into the reservoir should be addressed otherwise new sediment will be deposited on top of the capping agent and internal nutrient cycling processes will restart.

Nutrient concentrations should be monitored following the introduction of nutrient reduction measures, so that trends in these concentrations can be identified.

9.7.2.2 Management of the source water or reservoir for planktonic cyanobacteria

Management of the source water or reservoir to reduce the concentrations of cyanobacteria and their toxins being taken into the water supply include:

- engineering techniques to alter the hydrophysical conditions to reduce cyanobacterial growth,
- positioning of abstraction points,
- selection of intake depth,
- abstraction through an infiltration gallery,
- barriers to restrict scum movement,
- use of algicides, which should be used with extreme caution because of their ability to cause cell lysis and the release of toxins into the water.

Natural microbial populations in water bodies can degrade cyanotoxins.

Measures addressing light availability directly (eg, artificial mixing or shading) or controlling nutrients by manipulating the types and numbers of organisms (eg, aquatic plants or non-toxic microalgae that compete for nutrients with the cyanobacteria) is an area that has been used successfully; primarily in less eutrophic situations. For highly eutrophic waters under restoration by a reduction of nutrient loading, such measures may accelerate and enhance success.

A commercial product, Phoslock™, has been developed in Australia that is designed to remove phosphorus from water. Phoslock™ is a reaction product of bentonite clay and lanthanum chloride in which the proportion of exchangeable cations (mainly sodium) is replaced by lanthanum cations through electrostatic binding. Phoslock™ is designed to adsorb oxyanions, predominantly phosphate, from a variety of natural aquatic environments notably in order to reduce the incidence of algal blooms. The

recommended dosage is 100:1 Phoslock™ to filterable reactive phosphorus (FRP). NICNAS (2014) has assessed the use of Phoslock™.

Proactive reduction in nutrient concentrations using riparian strips and control of land use, etc. is a preferred action compared to the persistent control of cyanobacteria using algicides such as copper sulphate. Algicides have difficulty in removing a bloom; they are more effective at preventing a bloom if dosed early enough. Risk management issues relating to algicides are discussed in the MoH Water Safety Plan Guide Ref. P4.1: Pretreatment Processes – Algicide Application. See also CRCWQT (2002). The use of copper sulphate to control cyanobacterial growth can release toxins through cell lysis, and either destroy the natural micro-organisms that degrade toxins, or inhibit the action of the enzymes that carry out the degradation (Heresztyn and Nicholson 1997). Copper sulphate may prevent formation of phytoplankton blooms if dosed early enough, preferably in the morning when cyanobacteria are likely to be close to the surface and the water is generally calm, but algicides are unlikely to eliminate a bloom, once it is underway.

A study by Water Quality Research Australia (WQRA 2012) assessed the performance of copper sulphate, chelated copper sulphate, stabilised hydrogen peroxide,¹ sediment capping, surface mixing, and ultrasound treatment for control of algae and cyanobacteria. Performance of the algicides depended on water quality and the type of organism; all needed a higher dose than claimed by the supplier.

Control of cyanobacteria blooms using ultrasonics have not been shown to be particularly effective to-date.

9.7.2.3 Treatment options to remove cyanobacteria and cyanotoxins

The final step in controlling cyanobacteria and their toxins is the water treatment process. The water treatment train needs to be able to remove suspended material (bacterial cells) as well as water soluble toxins (eg, microcystins, nodularins, saxitoxins, cylindrospermopsins and anatoxins), which are the primary health hazard. The effectiveness of a water treatment system in doing this is determined by many factors. The brief analysis below, based on a comparative assessment of experiments in countries affected by cyanobacterial contamination, identifies the main factors and also the capacity of established and novel treatment processes for the removal of cells and dissolved toxins. As a general observation, conventional surface water treatment plants using coagulation, clarification and filtration are effective in removing cyanobacterial cells, but they are only partially successful in removing cyanobacterial toxins.

Much of the work on cyanotoxin removal has focused on single treatment steps, but a multi-barrier approach is more effective.

Until a bloom collapses or is otherwise affected by some treatment practice, the majority of toxins will be retained within the cells, making removal of intact cells a high treatment priority. Cylindrospermopsin and deoxycylindrospermopsin may be exceptions, as these toxins can be released by actively growing cells into the

¹ This can be sodium carbonate peroxyhydrate which releases sodium carbonate and hydrogen peroxide.

surrounding water. Under bloom conditions, a substantial proportion of toxin may be released to the water column, making removal of soluble toxin an unavoidable concern.

Table 9.4 summarises the toxin-removal performance of treatment processes capable of removing cell-bound microcystins by removing whole cells. The effectiveness of processes that can remove extra-cellular toxins (ie, oxidation/disinfection processes and activated carbon processes) are presented separately in Table 9.5. Table 9.5 sets out removal data for a range of toxin groups.

A number of factors concerning good practice and the effective design and operation of treatment plants should be considered in conjunction with the information in Tables 9.4 and 9.5. These include:

General

- Chemical preparation and dosing facilities must be of adequate size, have appropriate retention times, and chemical doses and treatment conditions (eg, pH level) should be optimised.
- Frequent monitoring of treatment performance is crucial to ensure safety, particularly with respect to cyanotoxin removal. The performance of different treatment steps is variable, for reasons that are not understood, and there is no suitable surrogate that can be used to assess cyanotoxin removal. Variable and often high loads of dissolved organic carbon (DOC) during cyanobacterial blooms may rapidly compromise treatment procedures that were initially successful. This is because non-toxic natural organic matter, which is present at much higher concentrations than the cyanotoxins, may saturate the capacity of the treatment process.
- Best results are achieved by combinations of treatment steps, and by the separate evaluation of cell removal and the removal of dissolved toxin (eg, combinations of pre-oxidation to enhance cell removal with effective post-oxidation to ensure destruction of liberated toxin, or combinations of cell removal and slow sand filtration).
- The complexity of managing cyanobacterial contamination necessitates consultation with the relevant health authority.

Raw water treatment and pre-oxidation

- Raw water sources and abstraction should be managed to minimise the cyanobacterial concentrations in the raw water delivered for treatment, but such steps as adjusting the abstraction depth.
- An earlier process used in New Zealand was microstraining, see Chapter 12. A microstrainer would be particularly effective at removing filamentous algae and cyanobacteria.
- Pre-oxidation should be avoided because it often results in cell lysis and resulting release of cyanotoxins into the water. Physical removal of cells should be undertaken before high concentrations of pre-oxidant are added to the water. Separation of steps into a low pre-oxidation dose to enhance flocculation, and a higher dose after cell removal to oxidise dissolved toxins is a safer approach. Pre-

oxidation should not be used, if it cannot be shown that the process results in an overall improvement in the removal of cyanotoxins.

- Pre-ozonation is preferable to pre-chlorination, especially in conjunction with primary disinfection by ozone further down the treatment line, eg, between clarification and filtration (usually dosed at a minimum of 1 mg/L).
- Algicides, such as copper sulphate, as well as pre-oxidants, can cause cell lysis and the release of cyanotoxins.

Coagulation/flocculation/clarification

- Conventional treatment plants without ozone or granular activated carbon (GAC) might satisfactorily remove cyanobacterial cells and dissolved toxins if coagulation, clarification, filtration and superchlorination – dechlorination (with a C.t value of more than 15 mg/min/L) or ozonation are carried out effectively.
- At optimum turbidity and UV absorbance removal rates, coagulants such as aluminium sulphate, PAC and ferric chloride are able to remove most cyanobacterial cells without physical damage and the release of toxins, eg, *Microcystis aeruginosa* and *Anabaena circinalis* cells (Drikas et al 2001). Lysis will be more predominant if coagulation occurs at pH <6.
- However, under normal bloom conditions it is highly likely that the cells are in various stages of their growth cycle, with some already dying and releasing toxins. A further treatment step may therefore be required to remove extracellular toxins.
- Under normal operating conditions, very little additional toxin is released from settled cells if sludge is rapidly removed from sedimentation basins. However, cells that are held up in the sludge blanket can remain viable and multiply for at least 2–3 weeks, so increasing the sludge blanket discharge volumes or frequency will probably be required.
- Recycling to the head of the plant of supernatant from sludge thickening or drying should not be done until the bloom is over or all toxins in the sludge have degraded.
- Dissolved air flotation (DAF), in which the clarification (sedimentation) process is replaced by the release of compressed air into the water to float flocs to the surface, has often been found more effective than clarification in removing cells from cyanobacteria-rich waters.

Some other observations reported by Newcombe et al (2015) are:

- Do not use prechlorination.
- While turbidity cannot be used as an indicator of the presence of cyanobacteria or cell concentration, use the decrease in settled water turbidity with coagulant dose as a surrogate for, or indicator of, cell removal if the initial turbidity is greater than 10 NTU.
- If the presence of cyanobacteria results in increased coagulant demand to achieve improved settled water turbidity, the application of a particulate settling aid, or even powdered activated carbon, may lead to improvements.
- In most conditions, *Cylindrospermopsis raciborskii* was the least readily removed cyanobacterium by coagulation, maybe <90 percent.

Although removal of cyanobacteria through conventional coagulation can be very effective, 100 percent cell removal is unlikely in normal full scale operations; in general 90–95 percent removal was the optimum. In the event of high cell numbers entering the plant, monitor for cell carryover and accumulation in clarifiers. This can lead to serious water quality problems if not rectified.

Chlorination

USEPA (2015 and 2016) states that the effectiveness of chlorine in microcystin and cylindrospermopsin oxidation is highly dependent on pH, temperature, water quality and the initial toxin concentration. Oxidation of extracellular cyanotoxins is most effective when the pH is below 8. This is especially the case for microcystins. Cylindrospermopsin can be effectively oxidised by chlorine when the pH ranges from 6 to 9. Chloramines and chlorine dioxide are not effective for microcystins or cylindrospermopsin oxidation at typical contact times used in drinking water application. USEPA (2015) includes a table showing chlorine C.t values (explained in Chapter 15) for reducing microcystin-LR to 1 µg/L in a batch or plug flow reactor. This table has been copied to Appendix 1 of this chapter. See section 3.3 of the USEPA (2015) report for how to calculate C.t values to achieve a lower concentration of microcystin-LR or use the Cyanotoxin Tool for Oxidation Kinetics (CyanoTOX, a spreadsheet tool for estimating the removal of extracellular cyanotoxins under various conditions; Stanford et al, 2016).

Monochloramine and chlorine dioxide are not effective.

Ozonation (WQRA 2010)

Microcystins and cylindrospermopsin: at pH > 7 maintain an ozone residual >0.3 mg/L for at least 5 minutes contact. C.t values in the order of 1.0 mg min L⁻¹ have been shown to be effective.

Saxitoxins: ozonation is not recommended as a major treatment barrier, at this stage, more research is required.

Supernatant return

WRF (2016a) suggests:

Sludge treatment facilities offer a suitable environment for the persistence and proliferation of cyanobacteria, and confinement in the sludge may not result in rapid cell death as previously believed. In supernatant sampled from a full-scale treatment plant, cultured and environmental cyanobacteria remained viable, and in some cases multiplied, over a period of up to 35 days. This suggests that the supernatant itself may offer a suitable environment for cyanobacteria to thrive. This is particularly a risk in sludge lagoons, which are shallow and often have detention times of several weeks, allowing accumulation and proliferation of cyanobacteria not captured in the sludge.

In batch reactors in the laboratory, it was shown that cyanobacteria can survive and produce metabolites for at least 10 days in alum sludge, suggesting that in the dynamic environment of a full-scale sludge treatment facility cell survival may be even more prolonged. Mass balance evaluations suggest that metabolite concentrations may increase to up to five times the initial concentrations within the sludge blanket. This indicates a much greater risk associated with recycling

sludge supernatant than can be estimated from the raw water quality. This potential increased risk should be taken into consideration when operational decisions regarding recycling are required. In light of these results, a qualitative assessment based on the inlet metabolite mass balance may prove to be a significant underestimation of the actual risk to drinking water quality. The very wide range of biological, chemical, and physical parameters that may influence the concentration of metabolites in sludge supernatant severely restricts the ability of water quality managers to estimate risks associated with supernatant recycling.

Some general conclusions were drawn based on the research. Due to its rapid release and degradation in most environments, geosmin exhibits the lowest risk to water quality. In contrast, MIB, microcystins, saxitoxins and cylindrospermopsins pose a significant risk to water quality and safety if the practice of supernatant recycling is continued. The findings of this research and previous literature show that, in a static (batch) system:

- cyanobacteria, once captured in the sludge, will generally begin to lyse between 0–2 days;
- some cells will remain viable in the sludge, and the maximum release (indicative of total cell death and lysis) may take up to several weeks;
- the metabolites released may represent up to five times the initial mass in the closed system;
- the time taken for the biodegradation of the metabolites to half the observed maximum concentration may be a week or longer, depending on the metabolite and the environmental conditions.

It is probable that during an ongoing cyanobacteria challenge, in the dynamic system of a sludge lagoon or other treatment facility, these timeframes will be significantly longer as cells and metabolites are replenished in the system.

The supernatant return should remain offline for 3–4 weeks after the challenge has abated, to allow the cyanobacteria numbers to decrease and the metabolites to degrade. Before bringing the supernatant return back on line the cell numbers and metabolite concentrations should be determined to be at an appropriate concentration for the treatment barriers. This is particularly important in the presence of saxitoxins, which are recalcitrant to biological degradation.

Sand filtration

- Slow sand filter plants remove phytoplankton cells effectively, although pre-treatment steps are generally applied to maximise filter runs and efficiency. Because of the biological activity in slow sand filters and long contact times, some removal of dissolved toxin should be expected, but this capability is unclear. Slow sand filter plants with pre-ozonation and/or sand-GAC sandwiching would be expected to be effective for dissolved toxin removal (but this has not been confirmed). Slow sand filtration is not a common treatment process in New Zealand.

Membrane filtration

- Cells can be removed by membrane filtration systems. However, care is needed when selecting microfiltration membranes because the characteristics of the membrane will affect the extent to which cells trapped in the membrane cannot be removed during backwash. Death and lysis of these cells will then result in toxin release into the water.
- Care is needed in the use of direct filtration, as long filter runs will trap more cells in the filter bed than short runs, leading to release of greater amounts of cyanotoxins following cell death and lysis.
- Recent studies by Water Research Australia (WRA) indicate that a nanofiltration (NF) membrane as the final stage of an integrated membrane system (IMS) may be the best method for maximising removal of extracellular cyanobacterial metabolites. Selection of the correct NF membrane was essential. The most efficient removal of cyanobacterial metabolites was achieved with using a polyamide NF membrane with a molecular weight cut-off (MWCO) of about 100 Da. This membrane should also be hydrophilic for the best retention of flux. A ultrafiltration membrane incorporating coagulation and powdered activated carbon addition is also a practical treatment. Aluminium chlorohydrate (ACH) is the best readily available coagulant for removal of intracellular cyanobacterial metabolites. ACH may also be a better coagulant for UFIMS in remote locations as lower doses are required for flux retention (WRA 2012).

AWWA/WRF (2015) states that RO effectively removes extracellular cyanotoxins. Typically, NF has a molecular weight cut off of 200 to 2,000 Da, which is larger than some cyanotoxins. Individual membranes must be piloted to verify toxin removal.

Activated carbon

- Granular activated carbon plants with a high empty bed contact time (EBCT) and ozone-GAC facilities can remove toxins effectively, especially if the GAC supports substantial biological activity.
- The effectiveness of treatment plants without ozone, but with GAC, will depend on the GAC EBCT value, on the degree of biological activity on the GAC, on the extent of exhaustion of the GAC and of the magnitude and duration of toxin occurrence.

Water treatment plants with rare or occasional cyanobacterial blooms are not likely to have GAC filters. Without these, powdered activated carbon (PAC) will be needed. Water supplies likely to experience cyanobacterial problems should make provisions for dealing with them. It will be necessary to find out how to purchase activated carbon for prompt delivery, and there needs to be a process in place for dosing it; these should be noted in the section of the WSP dealing with cyanobacteria and cyanotoxins.

Generally, a conventional treatment train, including the combinations of coagulation, flocculation, settling or flotation, and filtration, is preferred to treat cyanobacteria-rich waters. Picoplanktonic cyanobacteria (cyanobacteria less than 2 µm in diameter), however, are not easily removed by most filtration systems.

Boiling water typically does not destroy cyanotoxins, and cell destruction can lead to the toxins becoming more bioavailable. If boiling of water is used as a means of

destroying other micro-organisms (ie, pathogens), further water treatment must be undertaken to deal with the cyanotoxins.

In addition to the possible natural degradation of toxins by other microbes in the water, sunlight has been found to reduce the toxicity of anatoxin-a (Stevens and Krieger 1991).

WQRA (2010) includes a full discussion on the effectiveness of different grades of activated carbon, and the selection of dose rates.

Alternative source of drinking water

If contingency treatment options are unrealistic, water suppliers may need to consider treating an alternative raw water, or delivering safe drinking-water while the normal supply remains suspect.

Table 9.4: Summary of performance of water treatment processes capable of removing cell-bound microcystins by removing whole cells

Treatment process	Expected removal ¹		Comments
	Cell bound	Extra-cellular	
Copper sulphate dosing of impounded water	Very high	Causes lysis and release of dissolved metabolites	Usual effective dose 1–2 mg/L, but has been found toxic to some cyanobacterial species at concentrations less than 1 mg/L. Limited significance to human health at the doses commonly used. Accumulation in sediment can cause environmental problems, and fish find it toxic at concentrations well below the doses effective for cyanobacterial control. Toxins in the water column must be removed by some other treatment method.
Pre-ozonation	Very effective in enhancing coagulation	Potential increase	Useful in low doses to assist coagulation of cells; risk of toxin release requires careful monitoring and possibly subsequent treatment steps.
Pre-chlorination	Effective in enhancing coagulation	Causes lysis and release of dissolved metabolites	Useful to assist coagulation of cells but applicable for toxic cyanobacteria only if subsequent treatment steps will remove dissolved toxins and other released metabolites.
Combined coagulation/ sedimentation/ filtration	High	Low	Removal only achievable for toxins in cells, provided cells are not damaged. Cells of some species may be more susceptible to damage than others.
Coagulation/ dissolved air flotation	High	Not assessed, probably low	Removal only achievable for toxins in cells, provided cells are not damaged. Cells of some species may be more susceptible to damage than others.
Precipitation (for hardness reduction)/ sedimentation	High	Low	Removal only achievable for toxins in cells, provided cells are not damaged. Cells of some species may be more susceptible to damage than others.
Direct filtration	Moderate	Low	Removal only achievable for toxins in cells, provided cells are not damaged.
Slow sand filtration	Very high	Probably significant	Removal effective for toxins in cells; efficiency for dissolved microcystin is likely to depend on biofilm formation and thus on filter run length.

Membrane processes	Likely to be very high	Uncertain	Depends on membrane type, further research required to characterise performance. Some ultra-filtration membranes are able to remove dissolved microcystins, and nanofiltration and RO membranes are also expected to be able to achieve this.
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Based on data from Chorus and Bartram 1999 and Drikas et al 2001.

- 1 Likely efficiency of removal when continuously applied at optimal doses and pH and under proper operating conditions.

The processes in Table 9.5 are ineffective at removing whole cells, although some oxidants are able to lyse cells and destroy the intracellular toxins they contain.

Table 9.5: Efficiency of dissolved toxin removal by oxidants/disinfectants and activated carbons

Oxidant/disinfectant or activated carbon	Dissolved toxin removal					Comments
	Microcystins	Nodularin	Anatoxin-a	Saxitoxin	Cylindrospermopsin	
Chloramine	Ineffective	Ineffective	Ineffective	–	Ineffective	Free chlorine application will yield ineffective chloramines in waters enriched with nitrogenous compounds.
Chlorine	High (pH < 8)	Very high (pH < 8)	Low (pH 6-7)	High (pH ≈ 9)	Very high (pH 6 –9)	Toxin destruction is pH-dependent, and pH control is necessary. Conditions for removals noted are for free chlorine >0.5 mg/L and contact time > 30 minutes. Effectiveness reduced with increased dissolved organic carbon (DOC). The cells of some cyanobacteria can be lysed and the toxins they contain destroyed by chlorine.
Chlorine dioxide	Ineffective	–	Ineffective	–	Ineffective	Ineffective for the doses used in drinking-water treatment. Limited data.
Hydrogen peroxide	Ineffective	–	–	–	–	Ineffective on its own. Limited data.
Ozone	High	High	High	Low – moderate Variable effectiveness – dependent on toxin variant	High	Level of removal influenced by water chemistry (ozone demand). Cell lysis followed by intracellular toxin destruction has been observed for microcystins. In general, the ozone dose should be sufficient to provide an ozone residual after five minutes contact time. Effectiveness reduced at lower temperatures.
Potassium permanganate	High	–	High	Ineffective	Low – moderate, more data required	Contact time 30 minutes. Effective on soluble toxin but only in absence of whole cells.
UV irradiation	Ineffective	–	Ineffective	–	Ineffective	Toxins can be destroyed by UV light, but not at the doses used in water treatment. Titanium dioxide has been found to catalyse the destruction of some toxins. Advanced oxidation, combining hydrogen peroxide and UV treatment, appears effective for the removal of anatoxin-a and cylindrospermopsin, and microcystins when using high UV doses.
Powdered activated carbon (PAC)	High	Some removal, limited data	Some removal, limited data	Poor to very high Depends on carbon and toxin variant	Moderate More data required for reliable evaluation	Effectiveness depends on the type of activated carbon, and water quality conditions. Carbons with a large number of large pores provide best removal. Wood-based carbons usually provide best removal. Large differences in levels of removal are seen between different microcystin variants. Doses of effective PACs are generally greater than 20 mg/L.
Granular activated carbon (GAC)	High	–	Removal probable, more data required	Moderate removal of toxicity in saxitoxin equivalents Depends on toxin variant, carbon, and period in use	Removal probable, more data required	Carbons with a large number of large pores provide best removal. Biodegradation influences the extent of toxin removal. Removal efficiency decreases with time. Natural organic matter will reduce effectiveness by occupying adsorption sites.
Biological granular activated carbon	High					See GAC, biological activity enhances removal efficiency and bed life.

9.7.2.4 Drinking-water treatment for households and small communities

Domestic treatment of drinking-water has been a recent issue of concern in New Zealand. Many reticulated supplies provide excellent quality drinking-water and additional household treatment may actually cause deterioration rather than improvement. However, domestic treatment may have a role in regions supplied with poor quality drinking-water. Such treatment, using filtration, activated carbon and oxidation has shown a good removal of health hazards associated with cyanobacteria.

New (previously unused) point-of-use filter cartridges can achieve a removal of microcystin variants in the range 30–60 percent, and this degree of removal could be increased to about 90 percent by the passage of the water through three such filters. The removal may drop to 15 percent, however, by the time the filter is halfway through its expected life. The form of the cyanobacteria also has an influence on the efficiency of removal. A filter consisting of activated carbon and ion exchange resins may remove about 60 percent of the filamentous cyanobacteria, while up to 90 percent of the single cells pass through (eg, *Microcystis*). As with other filter systems, the death and lysis of cells retained on the filter creates a potential concern.

9.8 Recommended Reading

The Ministry for the Environment and the Ministry of Health published in 2009 the *New Zealand Guidelines for Cyanobacteria in Recreational Fresh Waters – Interim Guidelines*. This document contains material that is also relevant to managing and sampling drinking-water sources and is recommended to be consulted for additional scope.

In addition, Water Research Australia (WaterRA; formally the CRC for Water Quality) produces many reports and technical notes relevant to managing cyanobacteria in both recreational waters and drinking-water sources and is recommended to be consulted for additional scope. These reports can be found at: <https://www.waterra.com.au/publications/>. A readable fact sheet produced for the public and water managers was produced by WaterRA in 2015: <https://www.waterra.com.au/publications/document-search/?download=1172>.

Lopez et al (2008) produced one of the technical reports for the US Congress required by the Harmful Algal Bloom and Hypoxia Amendments Act of 2004, acknowledging that harmful algal blooms are one of the most scientifically complex and economically damaging issues challenging our ability to safeguard the health of the nation's aquatic and marine ecosystems.

A thorough Guidance Manual was published in 2009 for the Global Water Research Coalition (GWRC) by Water Quality Research Australia and SA Water – see references. This is recommended reading, as is WQRA (2010) which is probably easier to access.

WHO (2015) published a report on the management of cyanobacteria in water supplies. Also, in 2015 the AWWA/WRF published *A Water Utility Manager's Guide to Cyanotoxins*. Other useful documents include *Toxic Cyanobacteria in Water: A guide to*

their public health consequences, monitoring and management Chorus and Bartram (editors), published on behalf of the World Health Organization 1999. A publication in 2008 provides holistic coverage of cyanobacteria (Hudnell 2008), with a chapter on cyanotoxin removal during drinking-water treatment (Westrick 2008).

Greater Wellington Regional Council reported on the findings of a decade of monitoring and research on cyanobacterial blooms in regional rivers (GWRC 2016).

Scientific reviews specific to New Zealand toxic cyanobacteria have been published on benthic cyanobacteria that can grow in many New Zealand rivers (previously called *Phormidium autumnale* but now called *Microcoleus autumnalis*; McAllister et al 2016) and the cyanotoxin microcystins that frequently occurs in New Zealand lakes (Puddick et al 2019).

Appendix 1: Chlorine C.t values for reducing microcystin-LR concentration to 1 µg/L in a batch or plug-flow reactor

pH	Initial microcystin-LR concentration (µg/L)	C.t value (mg/L-min)			
		10°C	15°C	20°C	25°C
6	50	46.6	40.2	34.8	30.3
	10	27.4	23.6	20.5	17.8
7	50	67.7	58.4	50.6	44.0
	10	39.8	34.4	29.8	25.9
8	50	187	161	140	122
	10	110	94.9	82.3	71.7
9	50	617	526	459	399
	10	363	310	270	235

From USEPA (2015). Note that a C.t value of 50.6 is met if the FAC is 1.0 mg/L after 50.6 minutes; or 0.84 mg/L after 1 hour.

Appendix 2: Detailed Case Study for the Use of the WHO/IPCS Framework to Assess Risk to Human

Health from Exposure to Microcystins in Drinking-water

Excerpts from WHO (2017a).

Microcystins are a group of hepatotoxins produced by the cyanobacterium *Microcystis* and a range of other species. The basic structure consists of seven amino acids in a ring (cyclic heptapeptide) with molecular weights in the range 800–1100. Within this structure there can be modifications of all seven amino acids resulting in over 80 structural variants with a common mode of action. Microcystin-LR is the best characterised and among the most toxic of the congeners.

Blooms of microcystin-producing cyanobacteria in water bodies can contain more than one cyanobacterial strain or species and multiple variants of toxins. **What concentration of microcystins might consumers of drinking-water be exposed to?**

Concentrations of microcystins in drinking-water can be predicted from those found in untreated sources of drinking-water by applying expected reductions achieved by treatment processes and manipulation of water intakes. In some circumstances the depths of intakes into treatment plants or distribution systems can be varied to reduce toxin concentrations. This can be effective for species such as *Microcystis* and *Dolichospermum* (*Anabaena*) which produce surface blooms but less so for *Planktothrix* which can be more evenly spread in the water. Coagulation and filtration are effective in removing cyanobacterial cells and intracellular toxins while chlorine and other oxidising disinfectants are effective in reducing concentrations of extracellular toxins.

The concentration in drinking-water PEC_{dw} can be calculated using the following formula:

$$PEC_{dw} = \frac{RW \times (100 - DR) \times (100 - TR1) \times (100 - TR2)}{100 \times 100 \times 100}$$

Where:

PEC_{dw} is the predicted concentration in drinking-water ($\mu\text{g/L}$)

RW is the concentration in untreated water

DR is the reduction in concentration as a percentage by manipulating the intake depth

TR1 is the reduction in concentration as a percentage by treatment process 1 (eg, filtration)

TR2 is the reduction in concentration as a percentage by treatment process 2 (eg, chlorination).

To reflect a worst-case situation, conservative assumptions are made to determine maximum risk without variable depth intakes and inadequate or poorly managed treatment. In this example, a concentration of 55 $\mu\text{g/L}$ of microcystin-LR has been used which is at the upper end of concentrations detected in Lake Taihu in China (which has been subject to severe cyanobacterial blooms).

As there is a provisional WHO drinking water guideline value available for microcystin-LR, this can be used for risk characterisation. The estimated concentration of

microcystin-LR assuming no removal by treatment processes, 55 µg/L. This is clearly in excess of the provisional WHO guideline value for microcystin-LR of 1 µg/L. Therefore, further evaluation considering impacts of treatment on exposure assessment should be undertaken.

The case study used the following removal values:

- the reduction achieved by manipulation of the intake depth is 90 percent
- the reduction achieved by coagulation and filtration is 99.5 percent of whole cells
- in healthy blooms 90–95 percent of toxin is intracellular; based on this filtration can remove 90 percent of toxins
- in the latter stages of a bloom 50 percent of the toxin may be intracellular; based on this filtration can remove 50 percent of toxins
- providing that a chlorine contact time of at least 30 mg.min/L is achieved, chlorination can remove at least 98 percent of toxins remaining after filtration.

Using a deterministic approach and based on a conservative estimate of 50 percent of the toxin being intracellular the predicted concentration PEC_{dw} can be calculated as:

$$PEC_{dw} = \frac{55 \times (100-90) \times (100-50) \times (100-98)}{100 \times 100 \times 100} = 0.06 \mu\text{g/L}$$

The estimated drinking-water concentration of 0.06 µg/L in this scenario is well below the provisional WHO guideline value. Even if intake depth data was not available, further assessment would not be necessary as the estimated concentration of microcystins-LR in that case would be 0.6 µg/L, which is still below the WHO provisional guideline value.

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