Management of cyanobacteria in drinking-water supplies

Information for regulators and water suppliers

Second edition

World Health Organization

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Contents

Acknowledgements . . . iv

Abbreviations . . . v

Glossary . . . vi

1. The purpose of this technical brief . . . 1

2. What are cyanobacteria? . . . 2

3. How can cyanobacteria affect drinking-water supplies and human health? . . . 3
   - 3.1 Toxins . . . 3
   - 3.2 Off-flavours and odours . . . 4
   - 3.3 Effects of blooms on water treatment . . . 4

4. Where are cyanobacteria likely to be found, and what causes their growth? . . . 5
   - 4.1 Occurrence of cyanobacteria in water . . . 5
   - 4.2 Environmental conditions that favour cyanobacterial blooms . . . 5

5. How can the risk associated with cyanobacteria in the water supply be assessed and effectively managed? . . . 7
   - 5.1 Developing a monitoring programme . . . 8
   - 5.2 Monitoring to assess the potential of a water source to support blooms . . . 8
   - 5.3 Monitoring of cyanobacteria, cyanotoxins and taste- and odour-causing compounds . . . 9
   - 5.4 Developing a short-term response strategy to bloom events . . . 10
   - 5.5 Developing a longer-term nutrient load and cyanobacterial control strategy . . . 12
   - 5.6 Avoiding intake of cyanobacterial cells through optimizing the site of water abstraction . . . 13
   - 5.7 Removal via water treatment . . . 14

6. Overall conclusions . . . 17

References . . . 18

Figures

Fig. 1. Cyanobacterial bloom (left); *Microcystis* sp. (middle; magnified 200-fold); *Anabaena* sp. (right; magnified 400-fold)

Fig. 2. Components of water safety planning as they relate to the assessment and management of toxic cyanobacteria

Fig. 3. ALF decision tree for monitoring and managing potentially toxic cyanobacteria in drinking-water supplies (as template to be adapted to local conditions)

Tables

Table 1. WHO health-based values for selected cyanotoxins and exposure scenarios

Table 2. Conditions affecting and indicating the likelihood of cyanobacterial blooms

Table 3. Alert levels for cyanobacterial biomass indicators that should trigger management responses

Table 4. Overview of measures to suppress P release from sediments and/or cyanobacterial growth by influencing internal water body processes

Table 5. Treatment performance (percentage removal) for cyanobacterial cells, intracellular/extracellular cyanotoxins, geosmin and MIB

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Abbreviations

ALF	alert levels framework
ATXs	anatoxin-a variants
CYNs	cylindrospermopsins
DIN	dissolved inorganic nitrogen
DIP	dissolved inorganic phosphorus
MAR	managed aquifer recharge
MCs	microcystins
MIB	2-methylisoborneol
N	nitrogen
P	phosphorus
STXs	saxitoxins
TN	total nitrogen (includes the dissolved fraction and that bound in biomass)
TP	total phosphorus (includes the dissolved fraction and that bound in biomass)
WSP	water safety plan

Glossary

Benthic	Living on the bottom of a water body
Biovolume	The volume of cells per unit amount of water; usually quoted in cubic millimetres (mm^3) per litre
Bloom	A massive amount of cyanobacterial biomass on the surface and within the water body, often dominating the phytoplankton of a water body
Congener	Variation of the basic structure of a chemical substance, e.g. a cyanotoxin, often with consequence for its toxicity
Eutrophication	Enrichment with nutrients (P and N), leading to elevated amounts of biomass (often of cyanobacteria) and thus of organic matter
Metalimnion	Water layer (usually <1 m thick) between the warm, frequently mixing upper water layer (the epilimnion) and the cold, deep bottom water (the hypolimnion)
Periphyton	Cyanobacteria and algae living on submerged water plants
Phytoplankton	Planktonic organisms capable of photosynthesis, i.e. algae and cyanobacteria
Planktonic	Living suspended in the water; planktonic organisms include zooplankton, phytoplankton and bacteria
Scum	Cyanobacterial biomass accumulating on the surface of a water body
WSP	A water safety plan is a proactive risk assessment and risk management approach to help ensure drinking-water safety; encompasses the entire drinking-water supply, from catchment to consumer

1. The purpose of this technical brief

This technical brief provides general information on the management of cyanobacteria in drinking-water supplies to help regulators and water suppliers safeguard public health.

This document is an update of the technical brief, originally published in 2015. It has been updated based on the information contained within the publication *Toxic cyanobacteria in water – a guide to their public health consequences, monitoring and management (1)*. Additional references are cited as needed.

This technical brief describes measures to prevent the formation of cyanobacterial blooms and options to manage such blooms and their toxins when they occur. Although some of the measures are specific to cyanobacteria, many are equally useful for the management of other hazards. Risks from toxic cyanobacteria should be assessed along with the other hazards that may be encountered in a water supply (e.g. microbial, chemical or acceptability-related hazards, or hazards associated with a lack of sufficient water quantity). This can be effectively achieved by developing and sustainably implementing a water safety plan for the water supply system.

2. What are cyanobacteria?

Cyanobacteria, also known as blue-green algae, are of relevance to public health because of the toxins they may contain (see section 3.1). From a drinking-water supply perspective, the presence of cyanobacteria may also indirectly impact public health by reducing the efficacy of water treatment and disinfection processes, or decreasing user acceptance if they produce taste and odour compounds.

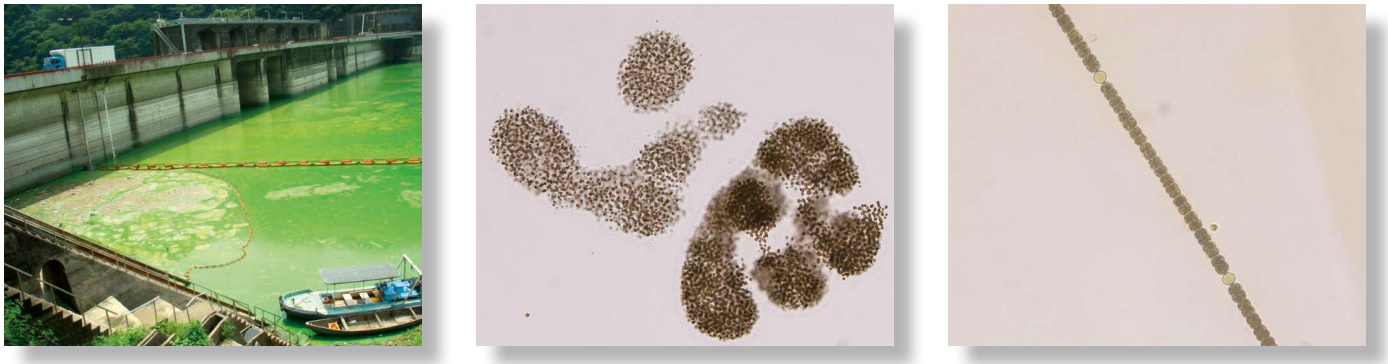
These photosynthetic bacteria share some properties with algae: they possess chlorophyll a and liberate oxygen during photosynthesis. They also contain a blue pigment specific to cyanobacteria that can give some species a bluish-green appearance which is why blue-green algae is a common term for these organisms. However, because they produce different pigments, many cyanobacteria do not appear blue-green. They can range in colour from blue-green to yellow-brown to red. Although cyanobacteria are naturally present in surface waters in low or moderate numbers, very high amounts of biomass (known as blooms) are usually caused by human activity enriching the water with phosphorus (P) and nitrogen (N). Some cyanobacteria produce toxins, called cyanotoxins.

Cyanobacteria can occur as single cells or in groups, as colonies or as filaments. They can be found in fresh, marine and brackish waters. Frequently occurring genera in drinking-water sources include *Anabaena, Aphanizomenon, Chrysosporum, Cuspidothrix, Dolichospermum, Microcystis, Moorea, Oscillatoria, Phormidium, Planktothrix* and *Raphidiopsis.*[1]

Some cyanobacteria can control their buoyancy and seek water depths that provide optimal growth conditions. This ability to move vertically gives cyanobacteria an advantage over other phytoplankton species with which they compete for nutrients and light. Buoyant cyanobacteria, such as *Dolichospermum* (*Anabaena*) and *Microcystis*, may float upward when mixing is weak and accumulate in dense surface scums (Fig. 1). Other cyanobacteria, such as *Raphidiopsis* and *Planktothrix*, largely stay dispersed, but can reach very high cell densities, causing pronounced turbidity. Species of some genera (including *Planktothrix rubescens* and *Raphidiopsis raciborskii*) can accumulate at the metalimnion (the interface between the warm surface water layer and the cold deep layer above the sediment) of thermally stratified lakes and reservoirs, forming rather thin layers of high cell density at depths at which drinking-water offtakes may be located. Still others, termed benthic or periphytic, such as *Moorea*, *Oscillatoria* and *Phormidium*, form mats on surfaces such as sediment or attach to other underwater surfaces, such as submersed vegetation, piers and rocks.

For further information, see *Toxic cyanobacteria in water,* including chapter 3 *(1, 2)*.

Fig. 1. Cyanobacterial bloom (left); *Microcystis* sp. (middle; magnified 200-fold); *Anabaena* sp. (right; magnified 400-fold)



© Daiki Fujise *(photo left)*; Kazuaki Tanaka *(photo centre and right)*

[1] Insights from molecular methods have led to substantial changes in the taxonomic classification of cyanobacteria. Thus, some species formerly allocated to the genus *Aphanizomenon* have been reclassified as *Chrysosporum* or *Cuspidothrix*; some former *Anabaena* have been reclassified as *Dolichospermum*, some former *Lyngbya* have been reclassified as *Moorea*, and the genus *Cylindrospermopsis* has been renamed *Raphidiopsis*. As the revision of taxonomy is ongoing, further changes are likely.

3. How can cyanobacteria affect drinking-water supplies and human health?

Cyanobacteria affect both the safety of drinking-water – by producing toxins – and the palatability – by affecting the flavour and odour. Cyanobacteria can also affect drinking-water treatment processes.

3.1 Toxins

Cyanobacteria produce many bioactive substances, some of which have not been characterized. Some are toxic to humans – the cyanotoxins – and they have various modes of toxicity.

3.1.1 General information

The four key cyanobacterial toxin groups are microcystins (MCs), cylindrospermopsins (CYNs), anatoxin-a variants (ATXs) and saxitoxins (STXs). Each of these groups includes variants (also termed congeners) with slight differences in their structures, some of which cause substantial differences in their toxicities. In healthy cyanobacteria, most cyanotoxins are chiefly contained within the cell (intracellular cyanotoxins), whereas one group – CYNs – are also released from the cell into the surrounding water (extracellular or dissolved cyanotoxins). Intracellular cyanotoxins can be released when cyanobacteria die and cells lyse (break down), which may occur when conditions in the water body change. This also is relevant for drinking-water treatment, where processes that exert physical or chemical stress upon cells may release intracellular toxins.

Most bloom-forming cyanobacterial species (up to 75%) can produce toxins. Each type of cyanotoxin can be produced by different genera of cyanobacteria: MCs, for example, are produced by strains of *Microcystis*, *Planktothrix* and *Dolichospermum*, whereas CYNs have chiefly been found with strains of *Raphidiopsis*, *Chrysosporum* and *Aphanizomenon*. In addition, each genus of cyanobacteria encompasses species and strains that can produce more than one cyanotoxin. Some strains of *Dolichospermum*, for example, can produce MCs, CYNs, STXs or ATXs. Some benthic (bottom-dwelling) cyanobacteria, such as the genera *Moorea*, *Oscillatoria* and *Phormidium*, can also produce cyanotoxins.

3.1.2 Potential health effects of cyanotoxins

Cyanotoxins can have a variety of effects on human health. The groups of currently known cyanotoxins occurring in freshwater are either neurotoxic (ATXs and STXs) or primarily cause liver damage but can also affect other organs (MCs and CYNs); furthermore, chronic long-term effects of the latter include tumour promotion (MCs) and possibly carcinogenicity (CYNs) *(3-6)*. Acute symptoms reported from recreational contact with cyanobacterial blooms often include gastroenteritis, fever and irritation of the skin, eyes, throat and respiratory tract. However, such general symptoms are rare, usually mild and do not align with the effects of the known cyanotoxins. Most likely, they indicate that other hazards co-occurred with the cyanobacteria (e.g. pathogenic viruses or bacteria) or that the cyanobacteria contain other, as yet unknown, bioactive metabolites. Cyanobacteria need light to grow and so do not multiply in the human body and hence are not infectious.

A range of incidents with toxin-specific symptoms has been reported in which exposure to cyanobacteria in drinking-water supplies or at recreational sites was the likely cause. Although death due to cyanotoxin exposure is known for wild and domestic animals,[2] for humans lethal intoxication clearly attributable to cyanotoxins is known only from contamination during renal dialysis. For example, in Brazil, more than 50 people died when water contaminated by cyanotoxins (MCs and probably also CYNs) was used for dialysis after insufficient treatment. Drinking-water should not be used for dialysis or other intravenous applications without treatment specific for this purpose.

3.1.3 World Health Organization guideline values for cyanotoxins

The WHO *Guidelines for drinking-water quality (7)* provide the scientific point of departure for the establishment of national drinking-water regulations and standards. They include short-term and lifetime provisional guideline values for MCs and CYNs in drinking-water (Table 1), and allow that in most cases human health concerns from drinking-water pertain to seasonal or chronic exposure. These guidelines are provisional because the database is limited and new data on the toxicity of cyanobacterial toxins are still being generated. For STXs, the guidelines provide only an acute guideline value (which is not provisional), which is based on human data for acute poisoning. There is no indication of chronic toxicity following acute poisoning and available data are inadequate for establishing short-term or lifetime values. For ATXs, the experimental data available do not allow derivation of a formal guideline value for inclusion in national regulations and standards, because the studies did not identify a nonlethal dose that caused lasting adverse effects. However, if highly conservative assumptions are applied, the data do allow derivation of a provisional short-term health-based reference value to guide actions if needed (Table 1).

The WHO health-based values are intended to be applied to the sum of cell-bound and extracellular (dissolved) toxins and of all congeners.[3]

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[2] Ingestion of dislodged mats of benthic cyanobacteria or underwater plants covered with cyanobacteria with high concentrations of ATXs and/or STXs has led to a number of cases of dog and other animal deaths. However, toxins released from such materials are quickly diluted in the large water volume around them and therefore exposure through adequately treated drinking-water is not a likely scenario for human health risks.

[3] Where credible new evidence becomes available regarding the toxicity of specific cyanotoxin congeners, this may call for re-evaluating their individual contributions to the sum.

Table 1. WHO health-based values for selected cyanotoxins and exposure scenarios

Toxin	Lifetime exposure	Short-term exposure[a]	Acute exposure	Value type
MCs	1 µg/L	12 µg/L	n.d.	Provisional guideline value
CYNs	0.7 µg/L	3 µg/L	n.d.	Provisional guideline value
ATXs	n.d.	30 µg/L (also applicable for acute exposure)	n.d.	Health-based reference value
STXs	n.d.	n.d.	3 µg/L	Guideline value

n.d. = not developed.

[a] Note that short-term guideline values for MCs and CYNs are intended not to be exceeded for periods longer than about 2 weeks, during which time effective treatment should be implemented to reduce cyanotoxin concentrations to the lifetime guideline value or below; it is not intended for repeated seasonal exceedances. Because ATXs are acutely toxic, avoiding any exposure above the reference value is recommended.

Source: WHO *(3-6).*

It is recommended, as a precautionary measure, that bottle-fed infants and small children be provided with an alternative safe drinking-water source (e.g. bottled water that is certified by the responsible authorities) if concentrations are greater than 6 µg/L for ATXs, 0.7 µg/L for CYNs, and 3 µg/L for MCs or STXs,[4] even for short periods.

See Fig. 3 about the alert levels framework (ALF) on how these values can be applied (including in drinking-water sources) for early warning and to inform short-term management responses.

The *Guidelines for drinking-water quality (7)* do not include guideline values for geosmin or 2-methylisoborneol, which – as discussed below – are aesthetic concerns, not direct public health issues.

3.2 Off-flavours and odours

Cyanobacteria can produce compounds that, although not toxic, give water unpleasant odours or flavours.

3.2.1 General information

Some genera of cyanobacteria, such as *Dolichospermum*, *Phormidium* and *Planktothrix*, can produce compounds with unpleasant odours and tastes (called off-flavours). The two most common compounds causing these are geosmin and 2-methylisoborneol (commonly referred to as MIB). They impart a musty-earthy odour to drinking-water, which, although unpleasant, is harmless. Although other microorganisms, such as actinomycetes, also produce geosmin and MIB, in surface waters cyanobacteria appear to be the major source of these compounds. Although their occurrence can be a sign that toxic cyanobacteria may be present, the production of cyanotoxins is not related to taste and odour, so geosmin and MIB are not reliable indicators of the presence or absence of a toxin-producing bloom. For further information, see *Toxic cyanobacteria in water,* section 2.9 *(8)*.

3.2.2 Customer complaints and undermining consumer confidence

People can perceive taste- and odour-causing compounds at very low concentrations in water (e.g. a few nanograms per litre), much lower than the concentrations of cyanotoxins that are associated with adverse health effects. These tastes and odours can lead to customer complaints or result in consumers using an aesthetically more acceptable, but potentially less-safe, drinking-water source.

3.3 Effects of blooms on water treatment

Cyanobacterial blooms challenge drinking-water treatment due to the associated high levels of organic substances. This increases operating costs through:

- increasing the amounts of treatment chemicals needed
- increasing the energy needed for more frequent filter backwashing
- potentially increasing need for re-activation or renewal of carbon media.

Blooms also increase the concentrations of dissolved organic matter that is not readily removed by conventional treatment steps. This may not only increase the amount of disinfectant needed but may also increase the concentration of disinfection by-products formed, including some that may cause unpleasant taste and odour.

[4] Note that the acute GV of 3 µg/L for STXs is based on infants.

4. Where are cyanobacteria likely to be found, and what causes their growth?

Cyanobacteria are found in a diverse range of environments, including soils, seawater and, most notably, freshwater environments. Heavy blooms, causing human health risks due to high concentrations of cyanotoxins, are primarily found in eutrophic water bodies, that is, those having high concentrations of the nutrients P and N.

4.1 Occurrence of cyanobacteria in water

Cyanobacteria occur in fresh water in nearly all parts of the world. During recent decades, cyanobacterial abundance has increased in many surface waters around the world, with blooms resulting from increased concentrations of nutrients – that is, P and N (known as eutrophication). *Raphidiopsis raciborskii* has substantially expanded its geographical range: it was initially identified exclusively in tropical and subtropical latitudes, but its prevalence in temperate regions – including northern Europe, southern Australia, New Zealand, the northern United States of America and southern Canada – has increased. Nonetheless, in most water bodies in these regions, heavy blooms are most often formed by other cyanobacteria, especially *Microcystis*, *Planktothrix* and *Dolichospermum*.

The most common point source of nutrients is domestic wastewater – often from treatment plants with insufficient nutrient removal and sometimes from subsurface infiltration of groundwater influenced by septic systems. Diffuse sources can also introduce high nutrient loads, often from agriculture, as a result of run-off from animal feedlots and from fields to which mineral fertilizer or manure has been applied. In regions with effective P removal in wastewater treatment but intensive agriculture, the latter tends to be the main cause of eutrophication. For more information see *Toxic cyanobacteria in water*, chapter 7 *(9)*.

While bloom formation can typically take several weeks, cyanobacterial biomass can accumulate at the water body surface to form localized scums within less than an hour. Some cyanobacteria can proliferate year-round if conditions allow their survival. Where pronounced seasonal patterns strongly influence growth (e.g. winter light deficiency in temperate zones; monsoon dilution in tropical and subtropical climates), blooms typically show seasonal patterns with maxima in late summer or towards the end of the dry season. Such patterns tend to reoccur in a given water body.

4.2 Environmental conditions that favour cyanobacterial blooms

Understanding the conditions that promote the growth of cyanobacteria in water bodies is fundamental for assessing whether blooms are likely. These conditions interact and include:

- elevated nutrient concentrations
- light conditions (high turbidity can promote dominance of some species)
- stable water body stratification or, for species that cannot migrate vertically, shallow mixing
- water retention times <1 turnover per month
- for some species, higher water temperatures (>20–25 °C).

Like all phytoplankton, cyanobacteria need resources to grow – that is, nutrients and light. Nutrient concentrations, primarily P and N, determine the capacity for biomass to form. Provided the capacity for biomass formation is present, whether or not this biomass is dominated by cyanobacteria or other phytoplankton organisms strongly depends on light availability and hydrological conditions.

Limiting resources typically vary seasonally. For example, in many shallow water bodies of temperate zones, during winter, light limits the amount of biomass that can form. In contrast, during spring and early summer P is limiting (i.e. is the limiting factor). During later summer and early autumn, N may become limiting, especially in shallow water bodies. When both N and P concentrations are high enough to support a large biomass density, this renders the water so turbid that light becomes limiting. Water bodies do not attain the maximum cyanobacterial biomass potentially supported by one resource if another one is limiting.

4.2.1 Nutrient concentrations

Where nutrient concentrations are high – for example, under eutrophic conditions – and hydrophysical conditions are favourable for cyanobacteria (see section 4.2.2 for further information), heavy blooms can develop, causing biomass to chiefly consist of cyanobacteria. The cyanobacterial biomass then contains most of the nutrients,[5] leaving only a smaller fraction for planktonic algae, zooplankton and other bacteria. This is why the concentrations of total phosphorus (TP) and (to a lesser extent) total nitrogen (TN) serve as measures of the maximum amount of cyanobacteria that could occur where hydrophysical conditions promote bloom formation. Estimating this maximum amount is a basis for assessing the concentrations that cyanotoxins can attain. See section 5.2.1 for more information on TP and TN.

4.2.2 Hydrological and light conditions

The most relevant hydrological conditions affecting cyanobacterial growth are thermal stratification (which can be influenced by local weather

[5] As explained in more detail in section 5.2.1, this is especially the case for P, because cyanobacteria can store large amounts of P (but not of N), sufficient for up to four cell divisions.

conditions) and water exchange rates. Some hydrological conditions render any cyanobacterial blooms unlikely. These include high water exchange rates (>1 turnover of water body volume per month) that dilute blooms faster than cyanobacterial cells can multiply, which is why blooms are not found in rapidly flowing streams and rivers. Also, deep, vigorous mixing that entrains cells into dark layers for much of the time, reduces bloom biomass and precludes scum formation. Less extreme hydrological conditions are more likely to affect which cyanobacterial species dominate rather than to prevent their occurrence.

Higher cell densities are attainable when mixing is minimal or shallow (provided nutrient concentrations are high enough) because cells then spend less time in deep dark water layers. Shallow mixing down to 2–4 m benefits cyanobacteria that cannot migrate vertically (e.g. *Planktothrix agardhii*), while stable stratification benefits those that can adjust their depth (e.g. *Microcystis*). For some cyanobacterial species (especially *Planktothrix agardhii*), high biomass density causing high turbidity (with Secchi disc readings <0.5–1 m) creates a positive feedback loop, stabilizing their dominance over other phytoplankton. This is because they can use low light levels more effectively than other phytoplankton can.

In less-eutrophic, thermally stratified water bodies, some filamentous, usually toxic cyanobacteria (e.g. *Planktothrix rubescens* and sometimes *Raphidiopsis raciborskii*) may produce blooms at the metalimnion. Growth in this layer requires water to be sufficiently clear to allow some light to reach the metalimnion, so eutrophic water bodies tend to be too turbid for cyanobacteria to grow in this layer. Metalimnetic layers of *Planktothrix rubescens* are known to occur at TP concentrations in the range 10–25 µg/L, and they tend to disappear if concentrations below 10 µg/L can be achieved *(10)*. Benthic or periphytic cyanobacteria (e.g. *Moorea, Oscillatoria* and *Phormidium*) also develop in less-eutrophic water bodies, where light reaches the bottom of the water body, enabling their growth.

4.2.3 Climate change

Climate change can affect cyanobacterial growth through a range of mechanisms, many but not all of which render conditions more likely to support blooms. One is increased temperature. Temperatures above 20 °C enhance the growth rates of many cyanobacterial species more than those of many other phytoplankton species, providing a competitive advantage for these organisms where nutrient concentrations are high. A further mechanism, relevant in temperate climates, is that increased spring and summer water temperatures intensify and lengthen the duration of water stratification periods. This can not only increase the duration of blooms but also give them more time to build up very high amounts of biomass, provided nutrient concentrations are high enough to support that. However, higher temperatures may also have a contrasting effect where they render thermal stratification more stable, which reduces transport of nutrient-rich bottom water to surface-near layers and so limits the amount of biomass that can develop. Where ice cover was common previously but now forms only briefly or not at all, higher concentrations of cyanobacteria may survive throughout the winter and start rapid population growth as early as spring. Warmer winters have been shown to promote the development of *Planktothrix* populations. In arid climates, longer dry periods can extend the duration of blooms.

Climate change impacts on precipitation can both increase and decrease the likelihood of blooms. Intense rainfall can increase nutrient discharge into water bodies, thus promoting bloom formation, but it may also disrupt blooms by increased flushing and mixing. When drought increases the water retention time, nutrient concentrations may increase due to lack of dilution, thus potentially promoting blooms. In contrast, drought may reduce nutrient concentrations due to reduced influx of water carrying fertilizers. Intense snowfall leading to a large spring melt and flooding may also affect cyanobacterial occurrence. Furthermore, storm events can increase water body mixing, thus interrupting bloom development. For further information, see *Toxic cyanobacteria in water*, including chapter 4 *(1, 11)*.

For management, it is key that climate change can only promote blooms if nutrient concentrations are sufficiently high to support them. Thus, nutrient load reduction is the most effective measure to strengthen the resilience of the water-use system against the effects of a changing climate.

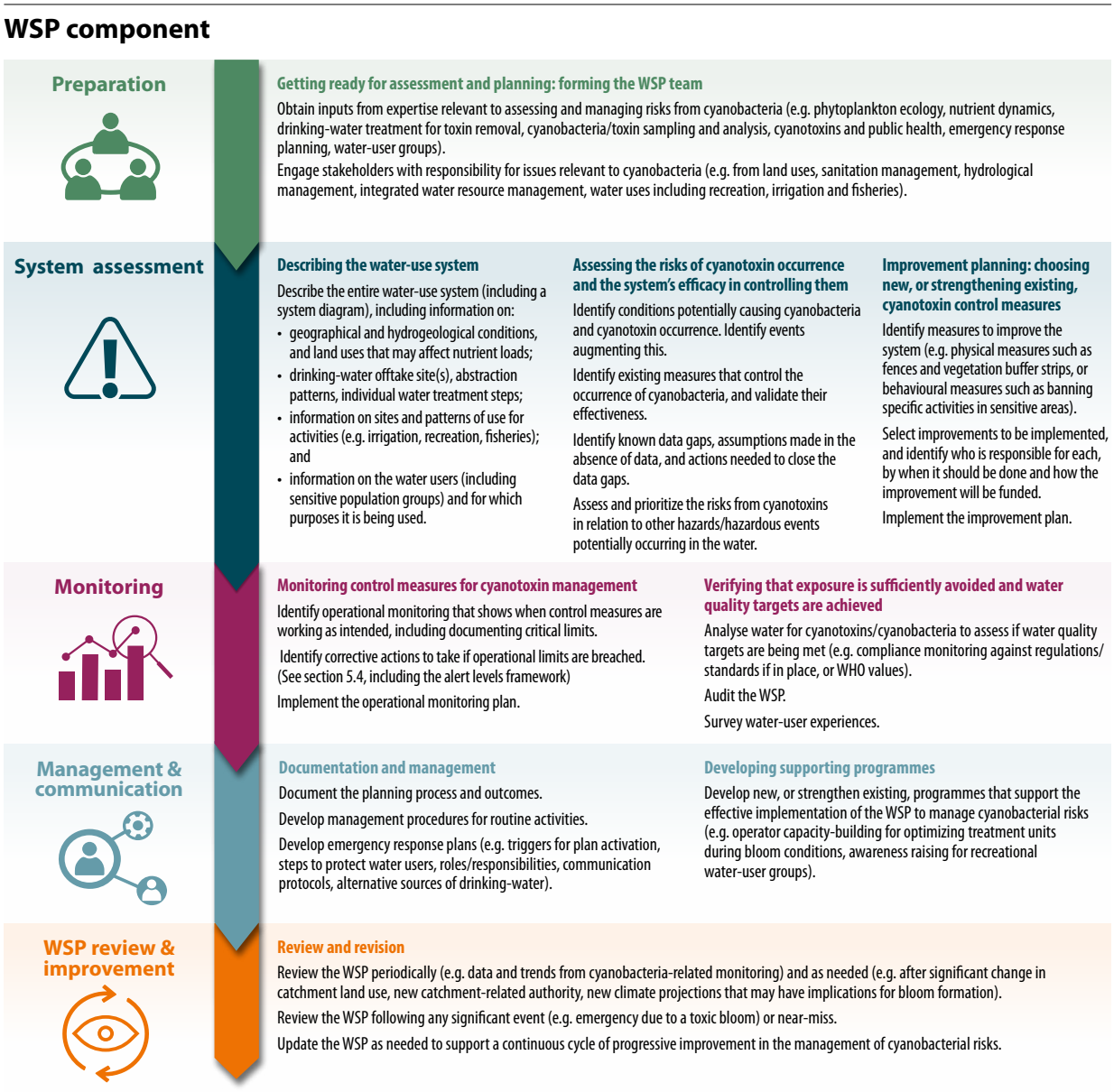
5. How can the risk associated with cyanobacteria in the water supply be assessed and effectively managed?

The most effective means of consistently ensuring the safety of a drinking-water supply is through the use of water safety planning – a comprehensive risk assessment and risk management approach that encompasses all steps in the water supply, from catchment to consumer *(7)*. The primary objective of a water safety plan (WSP) is ensuring a safe drinking-water supply through:

- identification of risks from hazards and hazardous events
- prevention or minimization of contamination of source waters
- reduction or removal of contamination through treatment processes
- prevention of recontamination during storage/distribution and at the consumer level.

For guidance on water safety planning for large and small supplies, see various WHO resources *(12-14)*. *Toxic cyanobacteria in water*, chapter 6 *(15)* gives guidance on applying the water safety planning approach to cyanobacteria in different settings, from smaller rural to larger urban water supplies. Some considerations for integrating cyanobacterial risks within the WSP framework are given in Fig. 2.

Fig. 2. Components of water safety planning as they relate to the assessment and management of toxic cyanobacteria



Source: Adapted from WHO *(1, 13)*.

A variety of source protection and source management actions are available to decrease the probability of bloom occurrence. The most sustainable and effective measure is to keep the water body's concentration of P or of N low enough so that they cannot support substantial growth of biomass. This requires a sufficiently low external nutrient load from the catchment. An increasing number of water bodies have responded to P load reduction with declines in intensity and duration of blooms.[6] However, experience with TP load reduction shows that nutrient concentrations may take years or decades to decline sufficiently. In many regions, nutrient loads are still increasing in the wake of population growth, urbanization without sufficient wastewater treatment and intensification of agriculture. Thus, many surface water sources will continue to periodically harbour substantial blooms for some time yet. When risk assessment shows blooms to be likely, management should follow a dual approach – combining a longer-term nutrient load reduction strategy with a short-term response strategy for bloom events. Monitoring data are needed to inform both short- and long-term management actions.

5.1 Developing a monitoring programme

The scope of a monitoring programme will depend on the frequency and extent of blooms as well as on the options and resources locally available. At minimum, to enable short-term responses to bloom events, monitoring must provide an indication of when elevated cyanobacterial biomass reaches the drinking-water supply. On-site visual assessment of water body turbidity and scouting for surface blooms are effective, low-cost, direct methods that can trigger increased vigilance when such events occur. A more comprehensive situation assessment is achieved by regular monitoring of cyanobacterial biomass, species composition and/or toxin concentrations (see section 5.2). Beyond this, however, an understanding of the water body's potential to support blooms is an important basis both for preparing for short-term responses as well as for developing a longer-term abatement strategy.

Several-year data sets with monthly or fortnightly sampling provide a comprehensive basis for cyanobacterial risk assessment and management. Timing, frequency and depth of sampling should consider the (sometimes rapid) variation of cyanobacterial densities between locations within the water body. Scum densities are influenced by local conditions, such as changes in wind direction. The factors influencing the appropriate frequency of sampling include the cost of monitoring and availability of analytical services, the season, previous observations of the timing and rate of cyanobacterial bloom development, and approaches employed in preventing and controlling cyanobacteria. In many water bodies, cyanobacteria occur with quite regular annual patterns. Once these patterns are understood, monitoring can be specifically targeted to critical times. If regular (e.g. monthly) monitoring is not feasible, data from a specific point in time (e.g. spring overturn or end of dry season) may serve for preliminary screening to identify those water bodies most likely at risk of blooms, possibly to be followed by a focus on these for more detailed assessment. *Toxic cyanobacteria in water*, chapters 12 and 11 *(16, 17)* provide more detailed guidance to plan for and develop monitoring programmes and targets for water body conditions, cyanobacteria and their toxins.

[6] Globally, almost no examples exist for successful mitigation of eutrophication through the reduction of N loading. In part, this is due to the cheap availability of industrially produced N fertilizers, whereas global stores of readily available P for use as fertilizer have been depleted such that availability is becoming limited.

5.2 Monitoring to assess the potential of a water source to support blooms

Table 2 summarizes parameters that can be easily monitored to assess the likelihood of cyanobacterial blooms. Each of these is discussed in more detail in subsequent sections.

5.2.1 Nutrient concentrations

The most important chemical parameters for assessing bloom potential are the nutrients P and N. A substantial body of field data shows that, per microgram of TP, phytoplankton biomass rarely exceeds a biovolume of 0.3 mm^3 or 1 µg of chlorophyll a. Moreover, for TP, evidence is accumulating that, depending on the hydromorphological conditions of the water body, persistent blooms become unlikely if concentrations are below ~20 µg/L or, in shallow or flowing water bodies, below ~50 µg/L (with the exception of *Planktothrix rubescens* residing in the metalimnion; reducing these requires <10 µg/L TP). For TN, less field data are available, but corresponding thresholds can be estimated to be 7–20-fold those for TP.

While TP and TN concentrations serve to assess overall bloom potential, it is useful to also determine the dissolved inorganic nutrient fractions for P and N (DIP and DIN, respectively) to inform potential nutrient management strategies. Information on DIP and DIN concentrations can indicate if these nutrients are limiting cellular uptake rates, with DIP <3–10 µg/L or DIN <30–100 µg/L indicating that these nutrients are limiting uptake rates at the time of sampling. This information can support decisions on strengthening mitigation measures that target N loading, especially if those targeting P loading are not sufficiently effective. For example, a typical pattern, especially in shallow lakes, is that in spite of P-load reduction, internal cycling of P stored in sediments allows the concentration of DIP to exceed 3–10 µg/L during the bloom season while DIN concentrations decline towards the range 30–100 µg/L. In such situations, focusing further measures on N loading may be more effective. As one option, Shatwell & Köhler *(19)* propose that management measures in the catchment should begin such periods of N limitation earlier, thus preventing summer blooms, for example by timing fertilizer application differently to avoid N loads specifically during early summer. Concentrations of P and N are determined with standard laboratory methods, using unfiltered samples for TP and TN and filtered samples for DIP and DIN.

5.2.2 Hydrological and light conditions

For assessing water exchange rates (or their inverse – water retention time) data on water flows of main tributaries are often available and if the water volume of a lake or reservoir is known, exchange rates can be calculated. Assessing mixing and stratification requires data showing temperature profiles over depths. These can be measured at intervals during sampling campaigns or continuously by thermistor chains deployed below a buoy.

Table 2. Conditions affecting and indicating the likelihood of cyanobacterial blooms

	Very low		Potential for cyanobacterial biomass (blooms)		Very high
Total phosphorus	≤10 µg/L	10–20 µg/L	20–50 µg/L	>50 µg/L	
Hydrological conditions[a]	Mountain stream or brook	River with rapid flow	Stratified, >10 m depth: potential for *Planktothrix rubescens* accumulating at the metalimnion	Stratified, 5–10 m depth favours scum-forming taxa, i.e. *Microcystis, Dolichospermum, Aphanizomenon*; sufficiently deep and vigorous mixing hindering scum formation can suppress their growth	Shallow and well mixed: favours non-scum-forming taxa, i.e. *Planktothrix agardhii* and other fine filamentous forms, e.g. *Limnothrix*
Transparency[b]	Very clear: Secchi depth often >7 m	High: Secchi depth ~3–7 m	Moderate: Secchi depth ~1–3 m	Low: Secchi depth often <1 m	
pH	pH <6	pH 6–7	pH ≥7	pH >7, often >8 or >9 due to high rates of photosynthesis caused by high biomass	

[a] Note that hydrological conditions and nutrients act together to promote cyanobacterial growth whereas transparency and pH are both consequences of – and conditions for – their proliferation.
[b] Determined as the depth at which a white or black-and-white disc of 20 cm lowered into the water is no longer visible.
Source: Adapted from *Toxic cyanobacteria in water,* chapter 8 *(18)*.

Transparency is most commonly and inexpensively measured by determining the depth at which a white (or black-and-white) disc of 20 cm diameter (a Secchi disc) just barely ceases to be visible when lowered into the water.

5.2.3 pH

Blooms are unlikely if pH <6–7. This is because the compounds in which carbon is available in water depend on pH, and cyanobacteria lack the specific uptake mechanisms necessary for the carbon compounds that occur at pH <6. Higher pH (i.e. pH >7) typically is a consequence of high rates of photosynthesis caused by high biomass of phytoplankton, often dominated by cyanobacteria, and thus can serve as indicator of possible bloom occurrence.

While Table 2 and the explanatory text in this section give a broad overview of criteria for assessing the likelihood of cyanobacterial bloom formation, the interplay of nutrients with other growth conditions that determine if blooms occur is complex. Expertise in phytoplankton ecology should therefore be sought when assessing bloom likelihood, and planning monitoring programmes and remediation measures. See *Toxic cyanobacteria in water*, chapters 4 and 8 *(11, 18)* for more detailed information and guidance.

5.3 Monitoring of cyanobacteria, cyanotoxins and taste- and odour-causing compounds

Monitoring of cyanobacteria ranges from visual observation at the site – looking for signs such as scums, greenish streaks, films or discolouration – to detailed pigment analyses and microscopy. To determine whether cyanobacteria are present in source waters and how concentrated they are, direct visual inspection for discolouration, significant turbidity or surface scums of cyanobacteria in water sources is an effective first check. A typical bloom colour is green with an olive hue; however, the colours can range from grey or tan to blue-green or reddish. During short periods of cell lysis, the water may also be bright turquoise or blue. If cyanobacteria are suspected, species identification, cell count and biomass determination by microscopic observation are recommended. For staff with some experience in microscopy, identification of cyanobacteria at the genus level is not difficult, and this can be sufficient to detect a potential cyanotoxin hazard, especially from the common genera *Dolichospermum*, *Cuspidothrix, Chrysosporum, Aphanizomenon, Microcystis, Raphidiopsis* and *Planktothrix*.

A commonly used measure of the biomass of phytoplankton, including cyanobacteria, is biovolume (i.e. cell number per litre, multiplied by the mean cell volume of the respective species). Measuring the concentration of a key pigment, chlorophyll a, can provide a further estimate of cyanobacterial biomass if performed in combination with a brief qualitative check under the microscope as to whether cyanobacteria are dominant and thus the chief source of chlorophyll a. Phycocyanin, the pigment specific to cyanobacteria, provides a more specific measure. Pigment concentrations can be analysed in the laboratory, on site with hand-held fluoroprobes, or by remote sensing, which may use drones, aeroplanes to satellite imaging. For more information see *Toxic cyanobacteria in water*, chapters 11 and 13 *(17, 20)*.

Quantifying cyanobacterial biomass allows estimation of the maximum cyanotoxin concentrations that may be present. In field samples, ratios of toxin to biovolume rarely exceed 0.3 µg/mm^3 and ratios of toxin to chlorophyll a rarely exceed 1 µg/mm^3. In most cases, both ratios are several times lower than these values.

For most groups of cyanotoxins, sensitive test kits are available (often based on immunoassays). Although some test kits can be applied directly in the field, major fractions of all cyanotoxins are typically cell-bound, requiring extraction before analysis (e.g. through freeze–thaw cycles). This is more readily done in the laboratory. Differentiation between cell-bound and dissolved toxin requires separation of cells from water by filtration before extraction. Instrumental analysis allows more precise quantification, and highly sensitive liquid chromatography – tandem mass spectrometry techniques are increasingly being used. However, besides specifically trained staff, mass spectrometry detection requires quantitative reference standards for each congener, and these are not available for all congeners of a toxin group. This is a problem, especially for MCs, which have many congeners. A solution to this problem is to include detection via photodiode array, as this provides similar signals for all MC congeners. *Toxic cyanobacteria in water*, chapter 14 *(21)* give an overview of analytical methods for the specific groups of cyanotoxins and guidance on choosing analytical methods.

Molecular tests that identify the presence of gene fragments involved in toxin production are increasingly available for frequently occurring cyanobacterial taxa. Although these do not provide information on toxin concentrations or biomass, they can indicate whether a bloom consists of toxin-producing strains.

The presumptive presence of geosmin and MIB can be assessed by the earthy, musty smell of the water. Analytical confirmation and quantification require specific equipment (gas chromatography–mass spectrometry) and skills. For more information, see Kozisek et al. *(22)* and TCIW *(8)*.

5.4 Developing a short-term response strategy to bloom events

Short-term responses to prevent exposure to cyanotoxins in drinking-water should be based on monitoring parameters that allow rapid recognition of situations with increasing risk. The response strategy then needs to include further monitoring, increased sampling frequency, and analysis to trigger management measures that prevent exposure before concentrations reach levels of potential health concern. Measures to be taken where a risk has been identified can include timely informing of the public and relevant authorities, optimizing existing water treatment processes, adding further treatment steps, or providing an alternative supply until the bloom event is over or the system is under control.

Early warning and short-term management responses are most effectively organized within an ALF, (Fig. 3) which should be adapted to local circumstances. Adaptation is best based on an assessment of the source water body's potential to harbour blooms, as discussed in section 5.2. The ALF proposed here then primarily uses levels of cyanobacterial biomass to trigger responses when biomass reaches levels at which concentrations exceeding cyanotoxin alert values can no longer be excluded. This is useful where monitoring of cyanobacterial biomass is quicker than analysing cyanotoxin concentrations, enabling more rapid responses. Monitoring only specific cyanotoxins (rather than cyanobacterial biomass) would miss any toxins not specifically addressed in the analyses. Moreover, establishing an understanding of which cyanobacterial taxa dominate contributes valuable information about possible patterns of scum formation and helps with planning longer-term measures to reduce their occurrence.

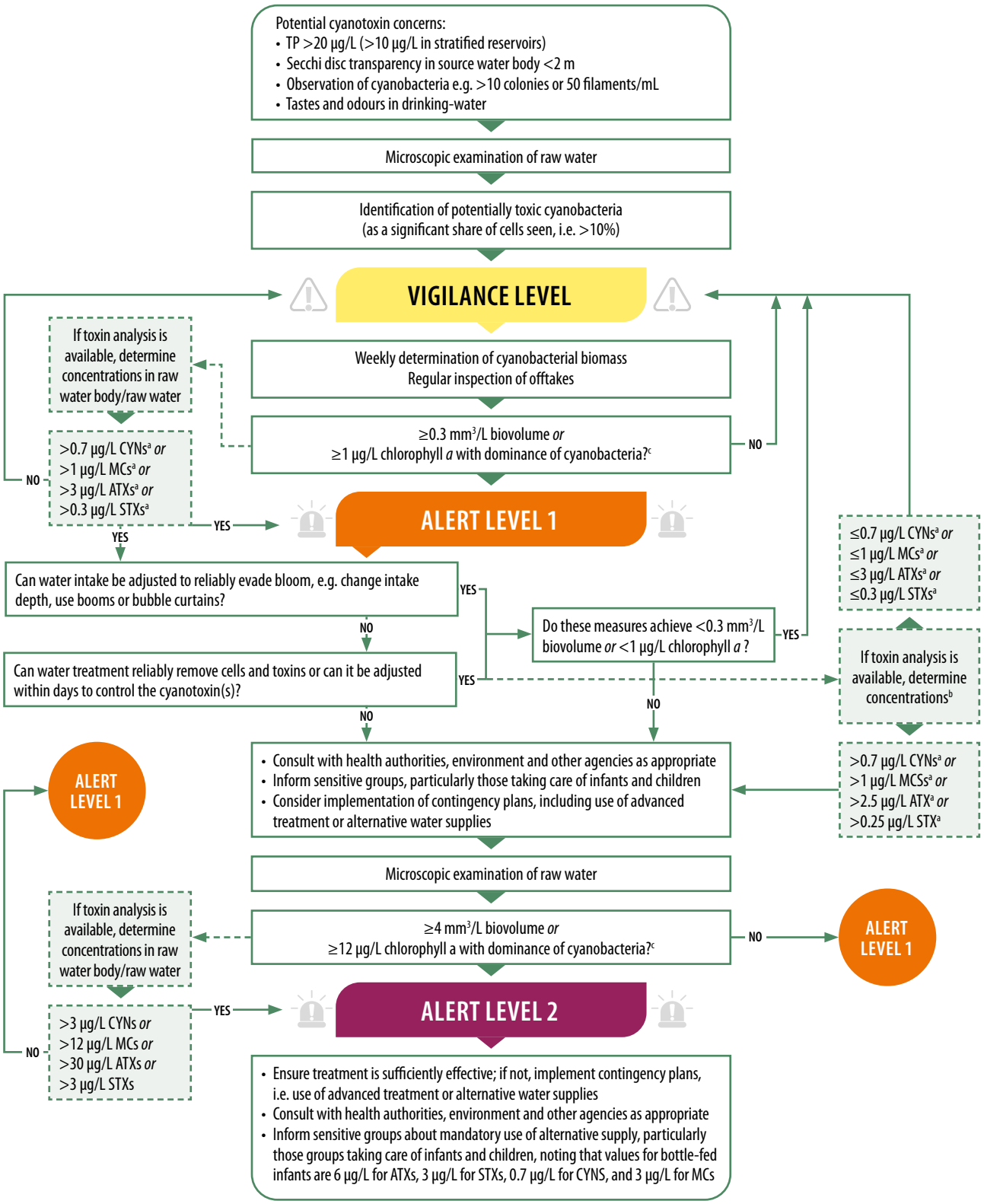
Although the measures of biomass used in *Toxic cyanobacteria in water (1)* and the *Guidelines for drinking-water quality (7)* are biovolume or chlorophyll a (see Table 3 for alert levels associated with these indicators), any other indicator of biomass that is locally more useful may be used as well (e.g. on-site fluorometry, cell counts, satellite imaging or even turbidity recorded online). Any such measure should be periodically calibrated to ensure it adequately indicates cyanotoxin concentrations. Wherever possible, periodic toxin analysis should be performed when blooms occur in the source water, especially when biomass indicators approach alert level 2.

Toxin concentrations in blooms can vary substantially, and if monitoring includes periodic toxin analysis, local toxin:biomass ratios can be established, improving hazard analysis. Since the alert values for these biomass indicators reflect the upper range of MCs:biomass ratios found in field samples, toxin content in many blooms is much lower and calibrating toxin:biomass ratios through occasional toxin analysis from the local blooms may allow higher biomass thresholds to be used. Also, specifically for CYNs, the fraction dissolved in water may persist well after the CYN-producing cyanobacteria have disappeared, and thus alert levels based on cyanobacterial biomass may not reflect the hazard from this toxin.

The ALF template differentiates three levels of trigger responses:

- the observation of (yet) low levels of cyanobacteria (vigilance level), which should trigger intensified monitoring;
- bloom biomass that renders the exceedance of lifetime values likely (alert level 1), which should trigger the dissemination of information, implementation of remedial measures and in some cases the implementation of contingency plans, including additional technical measures such as advanced treatment or provision of alternative water supplies; and
- heavy blooms possibly causing even short-term values to be exceeded (alert level 2), which should trigger the implementation of contingency plans more likely.

Fig. 3. ALF decision tree for monitoring and managing potentially toxic cyanobacteria in drinking-water supplies (as template to be adapted to local conditions)



Notes:
As dissolved CYNs may be persistent, regular microscopy is particularly important to detect possible producer organisms and then to trigger chemical analysis of CYNs; alternatively, monitor CYNs.
[a] See Table 1 footnotes for information on how these values should be interpreted.
[b] Analyse in raw water for checking effect of measures to avoid bloom intake and in treated water for checking the efficacy of treatment.
[c] If CYN or STX producers are dominant, analysing CYNs/STXs is recommended to determine whether alert levels for biovolume/chlorophyll a are sufficiently protective.

Source: Adapted from *Toxic cyanobacteria in water*, chapter 9 *(23)*.

Table 3. Alert levels for cyanobacterial biomass indicators that should trigger management responses

Alert level thresholds	Alert values for indicators of cyanobacterial biomass		Cyanotoxin alert values[a]			
	Biovolume (mm^3/L)	Chlorophyll *a* (with cyanobacteria dominant) (µg/L)	MCs (µg/L)	CYNs (µg/L)	ATXs (µg/L)	STXs (µg/L)
AL 1	0.3	1	1 [a] (lifetime pGV)	0.7 [a] (lifetime pGV)	(3 [b]) (1/10 of AL 2)	(0.3 [b]) (1/10 of AL 2)
AL 2	4	12	12 (short-term pGV)	3 (short-term pGV)	30 (short-term provisional reference value; also applicable for acute exposure)	3 (acute GV)

AL = alert level; GV = guideline value; pGV = provisional guideline value.

[a] Short-term GVs for MCs and CYNs are intended not to be exceeded for periods longer than about 2 weeks, during which time effective treatment should be implemented to reduce cyanotoxin concentrations to the lifetime GV or below; they are not intended for repeated seasonal exceedances. See Table 1 footnotes for additional information on how these values should be interpreted.

[b] Note that the AL 1 thresholds for ATXs and STXs are not formal WHO GVs for lifetime exposure, but merely concentrations 10 times smaller than those for acute exposure.

5.5 Developing a longer-term nutrient load and cyanobacterial control strategy

The short-term response strategies discussed in section 5.4 are specific to cyanobacteria and should be based on conditions promoting bloom formation and/or on the observation of cyanobacterial occurrence. This information is also necessary for developing a longer-term response to sustainably control cyanobacterial blooms. Such an approach requires developing a nutrient load reduction strategy, considering the time it takes for the nutrient concentrations within the water body to respond to load reduction. Such a strategy is best integrated into a more comprehensive approach because elevated loads of P and N originate from wastewater and agriculture and thus usually co-occur with other hazards, such as pathogens and chemicals. This reinforces the need for application of a WSP approach.

Preventive programmes to manage cyanobacteria in water should be developed in coordination with agencies responsible for managing water resources, including environmental, agricultural and health authorities.

5.5.1 Management measures to reduce nutrient loads into the water body

Nutrient load control can be achieved through good watershed management practices. Limiting the input of nutrients from wastewater effluent has shown some substantial success, especially for P. Where P was removed from household detergents, this typically halved the P concentration in domestic wastewater. Precipitating P in wastewater treatment further reduces concentrations by 80–90% and is required in many countries for larger treatment plants. Removing N requires treatment first to nitrify (i.e. oxidizing urea and ammonia to nitrate via aeration) and then denitrify (turning nitrate to atmospheric N_2) and has not been implemented as widely as P precipitation. An advantage of also reducing N is that denitrification also occurs within the water body, releasing N_2 to the atmosphere where it is no longer available for re-release into the water. In contrast, P is only lost to the sediment, from which some of it may be released back into the water. Dispersing effluent from sewage treatment or septic tanks on land has the advantage of promoting denitrification, but planning should consider risks of groundwater contamination with nitrate and/or pathogens. Where septic tanks are in use, these should be properly sealed to prevent contamination of groundwater.

Where agriculture is an important source of nutrient loads to water bodies, minimizing the use of mineral fertilizers and manure are key to controlling eutrophication. For P, which adsorbs to soil particles, further important measures include reducing surface run-off and controlling erosion through improved techniques of ploughing, as well as maintaining a densely vegetated buffer strip a few metres wide around the water body and its tributaries to intercept particles carried in surface run-off. For N, which is chiefly dissolved in water, drainage is a key pathway from land to water that requires control. Developing the most effective strategy requires an understanding of the hydrophysical characteristics of the catchment (including seasonal patterns of land use, nutrient sources and their pathways to the water body), as well as of the social and economic situation that determines how realistically and how quickly the targeted load reduction can be achieved – see guidance in *Toxic cyanobacteria in water*, chapter 7 *(9)*.

While nutrient load reduction is the sustainable approach to bloom control, it takes time to dilute nutrients out of a system, especially after decades of overloading both water bodies and soils in catchments with nutrients. This is exacerbated if the amounts within the water body and its sediments are high and water exchange rates are low. The speed at which

nutrient concentrations in the water body decline once the targeted load reduction is achieved depends on water exchange rates, and the time span needed may be decades rather than years. Especially in shallow water bodies and those with a long water residence time (i.e. low rate of water exchange), management measures within the water body (Table 4) may prove necessary to curb internal loading and thus achieve the target P concentration within the desired time frame.

5.5.2 *Management measures within the water body to reduce P release from the sediment or to suppress cyanobacterial dominance*

If external nutrient loads cannot be sufficiently reduced or concentrations within the water body take long periods to decline, a number of approaches and techniques are available to prevent P release from sediments or suppress the growth of cyanobacteria. Their drawback is that as long as nutrient loads continue to fertilize the water body, such measures tend to require continuous operation or at least periodic repetition. Table 4 gives an overview of these approaches, and more detailed guidance is given in *Toxic cyanobacteria in water*, chapter 8 *(18)*.

The appropriate technique(s) will depend on various factors, including local environmental conditions, cost, target periods, ecological condition of the water body, possible downstream impacts and effects on other water uses (e.g. agricultural and recreational uses). Importantly, many of these techniques may fail or even risk exacerbating the situation if they are not adequate for the specific situation. For example, if artificial mixing is applied in a water body that is not sufficiently deep, it can cause other cyanobacteria – adapted to mixing – to replace the previously prevalent species. If P release from the sediments is not from the fraction that is redox-sensitively bound to iron but rather largely from the mineralization of recently sedimented organic matter, aeration can enhance rather than suppress mineralization and thus P release (by adding oxygen and often also elevating the temperature of water above the sediment). Algicide application causing the sudden death of many cells can result in substantial release of cyanotoxins, and although drinking-water treatment would remove the toxins with the cells, dissolved cyanotoxins as well as taste- and odour-causing compounds are more likely to break through. Therefore it is crucial that if algicides are applied, this is done while cell numbers are low. In addition, impacts on agricultural use of water and on downstream ecosystems should be considered.

Interventions within the water body require careful planning, based on a comprehensive assessment of its specific conditions in collaboration with experts (especially experts in hydrology, sediment chemistry and phytoplankton ecology) as well as with stakeholders that know the water body well. Detailed guidance for system assessment and planning of interventions is given in *Toxic cyanobacteria in water*, chapter 8 *(18)*.

5.6 Avoiding intake of cyanobacterial cells through optimizing the site of water abstraction

As concentrations of cyanobacteria can accumulate on the surface of water bodies or in specific depths, variable abstraction depths may be useful for decreasing concentrations of cyanobacterial cells and their toxins in the raw water for drinking-water production. This especially pertains to stratified reservoirs in which *Planktothrix rubescens* accumulates at the metalimnion (section 4.2.2). Where scums tend to accumulate at a specific shoreline of the water body owing to a prevailing wind, choosing the offtake site away from this area can be useful. When cells accumulate at various sites of a reservoir (e.g. in different bays, depending on the wind

Table 4. Overview of measures to suppress P release from sediments and/or cyanobacterial growth by influencing internal water body processes

Intervention target	Intervention type	Technique
Suppress dominance of cyanobacteria, potentially in favour of other phytoplankton	Hydrophysical control of growth conditions	• Mixing – artificial destratification • Decreasing water retention time • Maintaining sufficient flow and thus a rapid change of hydrophysical conditions (i.e. avoiding or removing impoundments)
Suppress internal P load released from the sediment (this is only likely to be successful if sediments are a major P source relative to the external P load)	Internal P control	• Sediment removal • Withdrawal of water from the hypolimnion • Sediment treatment with P-binding agents (e.g. lime, alum, modified clay, zeolite) • Removal of fish that cause sediment resuspension • Suppression of redox-sensitive P release by oxidizing the sediment surface (through hypolimnetic aeration or oxygenation)
Enhance loss rates of phytoplankton, including of cyanobacteria	Biological control	• Biomanipulation through fish management • Supporting growth of macrophytes (i.e. aquatic plants)
Induce rapid lysis of cyanobacterial cells or inhibition of their growth	Chemical control	• Application of algicides, algistats

Source: Adapted from *Toxic cyanobacteria in water*, chapter 8 *(18)*.

direction), then if technically feasible it may also be useful to shift offtake sites, extend offtake pipes to less bloom-ridden sites in the reservoir, or to deploy surface booms or curtains that keep scums out of the abstraction site, similar to those used for oil-spill containment. For more information, see *Toxic cyanobacteria in water*, chapter 9 *(23)*.

5.7 Removal via water treatment

Where concentrations in the raw water require removal, the most effective control is the removal of the intact cells, as under most circumstances this removes 90% or more of the toxin. Where cells do enter drinking-water treatment plants it is important that pumping and treatment avoid cell damage, as this may lead to toxin release and increased concentrations of dissolved toxin entering the distribution system. For CYNs, it is important to be aware of the higher proportions of these toxins occurring extracellularly (dissolved in the water), requiring effective degradation or removal. Treatment performance for cyanobacterial cells, extracellular cyanotoxins, geosmin and MIB is summarized in Table 5, with more detailed information provided in the subsequent sections.

The appropriate treatment approach depends on a number of factors, including the hydrological situation, current treatment processes, cost of the technique and types of cyanobacteria, cyanotoxins and taste- and odour-causing compounds, as well as further microbial, chemical and physical hazards in the water supply that also require removal by treatment. Periodically repeated validation of the treatment train is important, especially during a bloom and associated local conditions because efficacy is highly dependent on water quality and other conditions in treatment systems. Validation should be conducted by analysing cyanotoxin concentrations at the plant intake and after distinct treatment steps to assess the efficacy of treatment processes and provide information for their optimization. It is also important for verifying compliance with guideline values or standards.

After effective treatment, it is important to ensure that drinking-water remains free from cyanobacterial regrowth. This can be accomplished by ensuring that any channels and storages are covered and dark, so that cyanobacteria lack the light necessary for growth.

5.7.1 Removal of cells

Slow sand filtration, riverbank filtration and managed aquifer recharge (MAR) are effective not only for cyanobacterial cells, but also for extracellular cyanotoxins, geosmin and MIB, as these undergo biodegradation during such processes. Effectiveness of biodegradation depends on the types and conditions of sediments and media, with biofilms on the surface of particles being able to effectively contribute to the biodegradation of dissolved cyanotoxins. For slow sand filters, frequent scraping of the surface layer may be necessary if filter media clog rapidly due to the high load of organic matter (note that care must be taken so that water leaching from used filter media does not reach the treatment train). If sand filter clogging occurs frequently, it is effective to couple the sand with anthracite with a diameter larger than that of sand. Efficacy may be

Table 5. Treatment performance (percentage removal) for cyanobacterial cells, intracellular/extracellular cyanotoxins, geosmin and MIB

Treatment processes	Cyanobacterial cells, intracellular cyanotoxins, geosmin and MIB	Extracellular (free) cyanotoxins	Extracellular (free) geosmin and MIB
Preoxidation[a]	–	–	–
Coagulation/sedimentation	+	–	–
Dissolved air flotation	+	–	–
Sediment passage[b]	+	+	+
Membrane filtration	+	–[c]	–[c]
Activated carbon	–	+	+
Chlorination (free chlorine)[d]	–	+	–
Chloramination and chlorine dioxide	–	–	–
Ozonation[e]	–	+	+
Advanced oxidation[f]	–	+	+

+ = 80% or more removal, although efficacy depends on treatment conditions and types of cyanobacteria and toxins; – = limited removal.

[a] Preoxidation enhances coagulation performance and can degrade some dissolved toxins (see text); however, it may result in release of cyanotoxins or geosmin and MIB from cells without their sufficient degradation.
[b] Sediment passage includes slow sand filtration, bank filtration and managed aquifer recharge.
[c] Effectiveness depends on pore size of membranes. Nanofiltration and reverse osmosis are effective.
[d] Chlorination may release cyanotoxins from cells which may not be sufficiently degraded and it is not effective for ATXs.
[e] Ozonation may release cyanotoxins from cells which may not be sufficiently degraded. Effectiveness for STXs is uncertain.
[f] Experience with the various advanced oxidation methods in real-scale drinking-water treatment is limited.

reduced if the water temperature is low or the filtration rate is high. These methods are not costly and are fairly easy to apply, even where resources are limited. Abstraction through riverbank filtration is possible where the underground is not rocky but consists of sufficiently permeable sediment. Detailed guidance is given in *Toxic cyanobacteria in water*, chapter 9 *(24)*.

Dissolved air flotation is especially effective for removal of buoyant species containing gas vesicles, which typically form surface scums. Waters of high colour and low turbidity are best suited for flotation processes.

Coagulation/sedimentation/filtration is effective to remove many species of cyanobacteria and cell-bound cyanotoxins, especially MCs, depending on pH, coagulant type and dose. It may not be sufficiently effective in removing CYNs, which may largely occur extracellularly and thus be present even after the producing cyanobacteria have disappeared from the water body. Sediments (sludge) should be rapidly removed from the treatment system (e.g. from the clarifier) to avoid the release of cyanotoxins and taste- and odour-causing compounds. Backwashing should be done frequently to reduce the release of dissolved toxins to the filtered water, taking care to prevent backwash water from reaching the treatment train. Post-coagulation (the addition of coagulants after sedimentation) is effective for some small and light cyanobacteria – such as *Synechococcus* spp. – that may be difficult to remove using normal coagulation/sedimentation.

Preoxidation (chlorination or ozonation before coagulation/sedimentation/filtration) increases coagulation performance; however, it carries a risk of cyanobacterial cell disruption releasing dissolved organic carbon from plankton and particulate organic matter, including cyanotoxins or taste- and odour-causing compounds. Preoxidation can degrade most released cyanotoxins (with the exception of ATXs when chlorine is applied) if the required residual and contact time can be achieved. With other oxidants, such as potassium permanganate, preoxidation can be effective against MCs and ATXs, but limited or no data are available for other cyanotoxins. Where toxin release by preoxidation cannot be excluded, effective oxidation at the end of the treatment train is especially important (see section 5.7.2).

Membrane filtration (microfiltration, ultrafiltration, nanofiltration and reverse osmosis), although expensive, is effective for removing cyanobacterial cells, and nanofiltration as well as reverse osmosis are also effective in removing extracellular toxins. Efficacy depends on the pore size of the membranes – usually less than 1 µm – and on the membrane materials. Frequent backwashing and removal of backwash water from the plant are recommended for avoiding the release of cyanotoxins and taste- and odour-causing compounds. Pretreatment of the raw water is also recommended to prevent fouling and optimize membrane performance.

5.7.2 Removal of cyanotoxins and of geosmin and MIB dissolved in water

Long travel times through suitable types of sediment (in the range of weeks), which may occur in riverbank and slow sand filtration, as well as MAR, can achieve effective biodegradation of dissolved cyanotoxins – see detailed guidance in *Toxic cyanobacteria in water*, chapter 9 *(24)*. Slow sand filtration, riverbank filtration and MAR are also effective at removing the taste- and odour-causing compounds geosmin and MIB *(25, 26)*.

Although expensive, powdered activated carbon and granular activated carbon are effective at removing extracellular cyanotoxins. Effectiveness of activated carbon depends on the carbon dose, the type of carbon (wood-based powdered activated carbon for MC and CYN) and the contact time (>30 minutes recommended for powdered activated carbon). For granular activated carbon, effectiveness depends on flow rates and on operational lifetime (with breakthrough being typical after several months unless established biofilms significantly degrade the toxins). The carbon must be regenerated or replaced at routine intervals, the timing of which is often based on the breakthrough of total organic carbon. However, toxin breakthrough may occur before significant total organic carbon breakthrough is detected. Activated carbon is also effective at removing geosmin and MIB.

Chlorination can be effective against many cyanotoxins, including CYNs, MCs and STXs, but is ineffective in degrading ATXs. Conditions for efficacy include a pH <8, a sufficiently high free chlorine concentration, and contact time. Chloramine and chlorine dioxide are not effective. As noted in section 3.3, blooms introduce substantial amounts of organic matter into the raw water, and thus in addition to substantially increasing disinfectant demand, will result in many different by-products being formed unless treatment removes them effectively. This applies in specifically to preoxidation (section 5.7.1). Chlorination can be followed by activated carbon treatment to remove disinfection by-products as well as, to some extent, taste- and odour-causing compounds. However, due to the extremely low odour thresholds of geosmin and MIB (<10 ng/L), chlorination on its own may not be sufficiently effective in reducing the concentrations of these compounds.

Ozonation may degrade most dissolved cyanotoxins very effectively –up to 100 % when conditions are optimized (e.g. pH 7–8 and at sufficiently high dose and long contact time). Efficacy is less certain for STXs, for which research is limited. Moreover, coupling ozonation with activated carbon is an effective way to remove both cyanotoxins and taste and odour compounds. Activated carbon following ozone treatment can also be used to remove ozonation by-products.

Other options include advanced oxidation processes. As they are less commonly used for this purpose, less experience is available regarding their dependency on the chemical characteristics of the water and the type of toxin. Required doses and contact times are not well established. In consequence, advanced oxidation processes in particular require site-specific design, optimization and validation.

As noted in section 5.7.1, nanofiltration and reverse osmosis are also effective in removing extracellular toxins.

For more detailed guidance on the removal of cell-bound as well as dissolved cyanotoxins in water treatment, see *Toxic cyanobacteria in water*, chapter 10 *(27)*. See *Toxic cyanobacteria in water,* section 2.9 *(8)* for more guidance on removal of geosmin and MIB by selected water treatment options.

5.7.3 Important issues in treating raw water that contains cyanobacteria

Inhibition of coagulation

Some cyanobacteria, such as the genus *Microcystis*, produce proteins that can inhibit coagulation, which cause a decrease in removal efficiencies of particulates (including cyanobacterial cells) and dissolved organic matter, such as disinfection by-product precursors.

Filter clogging and breakthrough

Larger-sized cyanobacteria can clog filters when present in high numbers, increasing the need for washing or exchanging filters. These processes potentially damage cells, thus leading to the release of cyanotoxins and taste- and odour-causing compounds from trapped cyanobacterial cells. Small cyanobacteria, such as *Synechococcus*, and filamentous cyanobacteria, such as *Aphanizomenon* and *Planktothrix*, may be poorly retained on filters and, when present in high numbers, can break through, increasing turbidity and colour in treated water. Sometimes filaments visible with the naked eye may break through.

Impact on disinfection

In addition to the issue of release of cell-bound cyanotoxins, disinfectant demand and disinfection by-product formation increase when cyanobacterial cells are present in high numbers.

6. Overall conclusions

Management of cyanobacteria is most effective when focusing on bloom prevention through catchment and water source management as part of a WSP approach to managing risks to a water supply system (Fig. 2). The adoption of the WSP approach includes establishing a cross-sectoral team to analyse the local situation, assessing the health risks and developing management plans. WSPs provide a valuable platform to facilitate communication between stakeholders in the catchment, who may be subject to different legislation (e.g. agriculture, wastewater, water management, health).

As part of water safety planning, it is important to determine bloom potential or track bloom development through nutrient monitoring and biomass determination at regular intervals. Differentiation of biomass by cyanobacterial taxa (with the genus level providing a sufficiently precise identification in most cases) improves the basis for predicting toxicity and understanding conditions driving cyanobacteria occurrence.

Preventive approaches may not always be effective in the short term, especially where nutrient loads are high and where implementation of measures to reduce nutrient loads sufficiently for effective control of cyanobacterial biomass takes time. In such situations, treatment processes and other barriers in place should be validated and monitored on an ongoing basis to ensure they are working as intended (operational monitoring), especially during bloom situations. This must take into consideration the types of cyanobacteria, cyanotoxins and taste- and odour-causing compounds, as well as other microbial, chemical and physical hazards in the water supply. Site-specific verification, including toxin analyses, is recommended to assess the overall effectiveness of the management practices in place.

Developing and implementing an ALF for early warning and to guide monitoring and management responses is recommended. The template given in Fig. 3 can be a useful starting point and, where resources allow, it is recommended this be adapted to local circumstances.

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