

Managing cyanobacterial toxin risks to recreational users: a case study of inland lakes in South East Queensland

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ABSTRACT

The management of inland waterways to protect recreational users from cyanotoxin exposure is complicated by the common management practice of using proxy indicators of cyanotoxin production (cell counts and biovolumes of potentially toxin species), rather than the cyanotoxin itself. This widely accepted practice is further complicated by a lack of advisory guidelines for non-microcystin-producing cyanotoxins. This study has investigated the effectiveness of this management approach over five and a half years, monitoring 65 different sites in South East Queensland using phycollogical and toxin-analysis. This study concluded that cell counts of *Cylindrospermopsis raciborskii*, the most common potentially toxin producing species of cyanobacteria in South East Queensland's inland lakes, was a poor proxy indicator for cylindrospermopsin toxin production. Seqwater, the local water authority responsible for the management of recreational access to drinking water storage lakes, initiated an alternative management approach for recreational cyanobacterial water quality management in December 2016. This new approach is based on cyanobacterial toxin guideline values for five different cyanotoxins, with closures and warning notices issued based on the actual cyanotoxin concentration, not the proxy indicator. We encourage other recreational water management authorities consider this approach to manage recreational access in the future.

Key words | cyanobacteria, cyanotoxin triggers, management, monitoring, recreation

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INTRODUCTION

Seqwater delivers a safe, secure and reliable water supply to 3.1 million people in South East Queensland (SEQ), as well as providing essential flood mitigation services and water for irrigation and managing catchment health. Seqwater has further government-driven obligations that include the provision of and managing Seqwater's land and lakes in ways that benefit the community, including for recreational purposes with 2.6 million annual visitors. The use of drinking water lakes for recreational activities can adversely affect source water quality. This is further complicated by Seqwater owning <5% of the catchment land from which it sources raw water for drinking water production, making

catchment and source water quality management challenging. Any negative impacts on water quality from Seqwater-approved recreational activities must be weighed against the public health benefits and wellbeing of the community and local economies resultant from recreation in and around natural surface waters (Fewtrell & Kay 2015). As part of this recreational commitment to the people of SEQ, on-water recreational access is permitted on 17 Seqwater lakes for primary and secondary contact recreation. It is well established that exposure to poor quality recreational waters can result in negative human health outcomes (Fewtrell & Kay 2015), therefore Seqwater strives

to maximise recreational access while minimising the impact on drinking water sources and exposure of recreational users to hazards. The two most common recreational water quality hazards in SEQ are microbial contamination and cyanobacterial cyanotoxins, of which the latter has the most common impact on recreational water access in SEQ.

Cyanobacteria, also known as blue-green algae, are a diverse group of prokaryotes that occupy a broad range of ecological niches. They are found in fresh, brackish and marine water environments (Wood 2016), however in recent times they have been more commonly associated with the eutrophication of water resources and subsequent toxin-producing cyanobacterial blooms (Merel *et al.* 2013). Eutrophication of shallow monomictic lakes, which are common in SEQ, occurs due to a range of anthropogenic and climatic factors, including but not limited to: strong thermocline formation, high catchment nutrient loads, low turbidity and relatively deep euphotic zones which enable cyanobacteria to quickly multiply (Corbel *et al.* 2014). Under normal seasonal conditions, extensive blooms can form that may impact on drinking water treatability and recreational amenity and suitability. Human activities, population growth and climate change are likely to have an increasing impact on the severity and duration of blooms into the future with it being suggested that cyanobacteria, including toxin-producing taxa, are increasing in abundance. A multiple lake study undertaken by Rigosi *et al.* (2015) of cyanobacterial blooms under future climate change scenarios indicated that increasing water temperatures of 0.8 °C (from a 24 °C initial condition) and/or an increase in total phosphorus from 0.01 mg/L to 0.02 mg/L would result in a 5% increase in cyanobacterial bloom severity conditions. As water resources are being continually pressured for multiple uses and the number of recreators and drinking water consumers continues to increase, this change in toxic species dominance under favourable growth conditions is an emerging human and environmental health concern (Corbel *et al.* 2014).

Australia has a long history of cyanobacteria and cyanotoxins, with the first documented case of livestock poisoning and death linked to a large scum of *Nodularia spumigena* on the shores of Lake Alexandrina, South Australia in 1878 (Francis 1878). Since this observation there have been

many reports of stock and human injury and death linked to a variety of cyanobacterial species and their associated toxins. The primary toxic cyanobacteria and associated cyanotoxins of concern in freshwater Australian lakes are: *Microcystis aeruginosa* (microcystin), *Nodularia spumigena* (nodularin), *Dolichospermum circinale* (saxitoxins) and *Cylindrospermopsis raciborskii* (cylindrospermopsin) (Merel *et al.* 2013; Antunes *et al.* 2015); of which *C. raciborskii* and its cylindrospermopsin toxin is the most prevalent in SEQ. *Cylindrospermopsis raciborskii* has gained considerable attention due to its worldwide distribution and strong toxic bloom-forming potential (Antunes *et al.* 2015). Able to tolerate and thrive under a wide range of temperature and light regimes, the organism's high phenotypic plasticity, coupled with significant intraspecific variability, has facilitated its invasion and dominance in both temperate and tropical lakes globally (Antunes *et al.* 2015). In SEQ it has been suggested that higher phosphorus availability is preferentially favouring the toxic strain dominance of *Cylindrospermopsis raciborskii* (Burford *et al.* 2014), with work by Willis *et al.* (2017) indicating that two toxic strains of *C. raciborskii* sampled from SEQ lakes are highly adaptable, and able to grow even under relatively low phosphorus conditions. Willis *et al.* (2017) also discovered significant variability in cell count and cylindrospermopsin toxin production capability from *C. raciborskii* sampled from SEQ lakes, further underscoring the need to look beyond cyanobacterial cell counts as an indicator for cyanotoxin risk. The primary risk to recreational users from cyanobacterial blooms comes from exposure to cyanotoxins. Cyanotoxins are secondary metabolites contained in the cyanobacterial cells which can be present extracellularly in healthy cells but are most noticeable when released in the water following cellular lysis (Corbel *et al.* 2014). Cyanotoxins are known to be capable of negatively impacting human health with a multitude of papers being published on recreational and drinking water quality impacts from cyanotoxins (Merel *et al.* 2013; Korevienié *et al.* 2014). There are five classes of compounds which are widely recognised cyanotoxins: microcystin (hepatotoxin), nodularin (hepatotoxin), cylindrospermopsin (cytotoxin/hepatotoxin), anatoxin-a (neurotoxin), and saxitoxin (neurotoxin) (Otten & Paerl 2015). These toxins target different human organs with a range of potential acute and chronic impacts of exposure. Efficient management of recreation areas and

protection of recreational users from harmful cyanobacterial blooms is of critical importance to protect human health and is a priority for Seqwater.

Recreational users can be exposed to cyanotoxins through ingestion, immersion and/or inhalation of waters which contain cyanotoxins (Koreiviené *et al.* 2014). Symptoms associated with exposure may include: skin rashes, asthma, hay fever, pneumonia, dry sporadic cough with vomiting and other gastrointestinal symptoms (such as vomiting, diarrhoea, fever and headache), conjunctivitis, ear and eye irritation, allergic reactions, and acute illnesses with symptoms such as severe headache, myalgia, vertigo, and blistering in the mouth (Drobac *et al.* 2014). The toxins produced by cyanobacteria may also affect the liver, kidneys or brain. Research by Pilotto *et al.* (2004) investigated the dermal irritation associated with exposure to cyanobacterial cells and found that only 14–20% of patients tested were afflicted with a mild self-limiting skin irritation. Therefore, for the purpose of this paper, we will focus on the more severe health outcomes associated with ingestion and inhalation exposure.

In 2011, Seqwater developed and implemented its Recreational Water Quality Management Plan (RWQMP), which outlined the water quality criteria for opening and closing recreational water bodies to protect recreational users from exposure to a range of hazards, the most common of which, by prevalence, is cyanobacteria and their associated cyanotoxins. A number of alert-level frameworks have been developed for managing recreational risks from cyanobacterial exposure. Building on the learnings from Kuiper-Goodman *et al.* (1999), the World Health Organization (WHO) further reviewed the health significance of algae and cyanobacteria in fresh water to develop a guideline for recreational water environments (WHO 2003).

An Australian guideline for managing risks, including cyanobacteria, in recreational waters has been developed by the National Health and Medical Research Council (NHMRC) (2008) and incorporates the principles from the previous framework documents. These guidelines provide a risk-based practical approach aimed at helping authorities who manage recreational water quality. Seqwater had adopted these guidelines for managing risks in recreational waters as part of the overarching RWQMP, however, at the time, there were minimal cyanobacterial guidelines

and advisory documents for non-microcystin-producing species and their toxins. Due to the absence of available standard triggers for other cyanotoxins and potentially toxin-producing (PTPs) species, Seqwater developed a recreational monitoring program based on phycological analysis, investigating both combined cyanobacterial biovolume triggers and PTP species cell count as proxy indicators for toxin levels. Targeted toxin analysis was only triggered when the precursory indicators specified an elevated level of risk might be present. Extensive monthly water quality monitoring (increasing in frequency with each alert level) at multiple locations on each Seqwater recreational lake ensured the waterways were fit for the approved recreational activity with the RWQMP following a four-level cyanobacterial escalation/de-escalation system.

Seqwater's RWQMP has been designed and operated for the last five and a half years to protect recreators from poor water quality conditions associated with cyanobacteria. On review, it became apparent that the use of proxy indicators (cyanobacterial biovolume and cell counts of PTPs) for cyanotoxin production had some significant limitations and a new approach to recreational cyanotoxin exposure management might be required (Willis *et al.* 2015, 2016). This was supported by monitoring data and input from Seqwater's research partners and the broader academic community. The objectives of this paper are to discuss how Seqwater has approached the issue of recreational cyanobacterial water quality management and how Seqwater developed a new set of cyanotoxin-specific guidelines for the fiscally and socially responsible management of recreational access to its lakes.

MATERIAL AND METHODS

Monitoring program data and analysis

The previous Seqwater RWQMP collected monthly data from July 2011 to December 2016 at 65 monitoring sites on 17 recreational lakes, using a 5 metre integrated sampling tube to represent the algal population in the top 5 metres of the water column representative of the euphotic zone. Algal biovolume and cell counts were undertaken at

National Association of Testing Authorities Australia (NATA) certified laboratories by manual phycollogical analysis (NATA Method QWI-MIC/MW024) and cyanotoxin (NATA Method QWI-ORG/EP248 by liquid chromatography tandem mass spectrometry (LC-MS-MS) for cylindrospermopsin and QWI-ORG/EP248 in accordance with QWI-EN/02 for other algal toxins). The sampling frequency of these recreational sites would increase as biovolume triggers exceeded 4 mm³/L (fortnightly sampling triggers) and 10 mm³/L (weekly sampling triggers) respectively, in the presence of a secondary indicator (cell counts of PTP species). Data collected from this five and a half year period for cyanobacterial biovolume, PTP cell counts and cyanotoxin production were assessed for each recreational lake to determine how effectively the proxy indicators were predicting the cyanotoxin risk. This statistical analysis was performed on SSPS Statistics 20 for Windows (SPSS Inc., Chicago, IL, USA) using non-parametric Spearman's rank order.

New cyanotoxin specific guidelines

The selection of new toxin guidelines for the revised cyanobacterial triggers followed a hierarchical approach, as there are no guidelines for cyanobacterial cyanotoxins other than microcystin currently available. While the NHMRC (2008) framework recommends a tiered approach to cyanobacterial monitoring based on the suitability for recreation, it was accepted that all cyanobacterial monitoring would be standardised at Seqwater recreational sites and triggered from a standard base plan. Given the quantity, variety and typically high or very high cyanobacterial risk of Seqwater storages, this approach gave the most transparent and manageable process over multiple sites.

The NHMRC (2008) provides cyanotoxin guidelines for microcystins which has been adopted as the Seqwater high-level guideline value. For the other four cyanotoxins (Table 1) without a recreational guideline value, Seqwater has chosen to address the primary recreation risks through modifying Australian Drinking Water Guidelines (ADWG) advisory limits (NHMRC 2011) and assuming a conservative ingestion rate of 200 mL, double that used in NHMRC (2008). Using this approach, a threshold concentration that is 10-fold greater than the drinking water threshold (based on 2 L consumption) can be derived.

Table 1 | New RWQMP cyanotoxin action limits

Toxin	Unit	Low Level	Medium Level	High Level	Extreme Level
Microcystin (leucine containing) (LR) mass toxicity equivalents	µg L	<3	≥3	≥10	≥25
Saxitoxin (carbamate saxitoxin group) (STX) toxicity equivalents	µg L	<9	≥9	≥30	≥75
Cylindrospermopsin	µg L	<3	≥3	≥10	≥25
Nodularin	µg L	<4	≥4	≥13	≥30
Anatoxin-a	µg L	<3	≥3	≥10	≥25

This approach is the basis for the derivation of the WHO upper-level guideline (WHO 2003). The setting of recreational ingestion rates at 200 mL is significantly greater than the findings of Dufour *et al.* (2006) of 37 mL for children per swim but is consistent with Koreiviené *et al.* (2014), who calculated that a swimmer can be expected to imbibe up to 50–200 mL of water in one recreational session. Sailboarders or water-skiers are theoretically likely to imbibe more than that again (Koreiviené *et al.* 2014). The management advantage of having high assumed ingestion rates is that it helps to take into account the unknowns around cyanotoxin ingestion rates and the effective toxicity of aerosolised cyanotoxins. Studies by Sinclair *et al.* (2016) indicated adult patients exposed to 10 minutes of aerosolised droplets at a car wash could inhale up to 3.78 mL. Recreational users on ski boats would be expected to be exposed to both inhalation and ingestion over several hours of recreational exposure and therefore a 200 mL level and subsequent triggers have been set to protect Seqwater's recreational users. Where ADWG guidelines were not available (anatoxin-a), following the hierarchy of information sources listed in the ADWG (NHMRC 2011), Drinking-water Standards for New Zealand (2008) have been used. The assessment of secondary contact recreation toxin guidelines was based on a 2.5-times multiplier of the High guideline values which was determined based on suggestions by topic area experts (pers. comm. Ian Falconer), as information on the inhalation of aerosolised cyanotoxins is

currently a theoretical hazard owing to a paucity of experimental data (Koreivienė *et al.* 2014).

RESULTS AND DISCUSSION

Statistical analysis revealed there is a positive correlation between the *C. raciborskii* cell counts and cylindrospermopsin ($r = 0.553$, $n = 963$, $p < 0.001$). However, the r^2 of the proxy indicator prediction was very poor ($r^2 = 0.066$) and therefore supports the assessment that the cell counts of *C. raciborskii* are an ineffective recreational management indicator for cylindrospermopsin toxin production. This finding is supported by Willis *et al.* (2015, 2016) who found cylindrospermopsin toxin production by *C. raciborskii* to be strain dependent, with highly variable toxin production occurring at the same cell-count levels. Without the five and a half years of data collated from monitoring under the previous RWQMP it would not have been possible for Seqwater to determine that this approach, while valid and supported by current advisory documents, was not adequately aligning the proxy indicators of the risk to the actual cyanotoxin risk, which has been supported by several recent papers (Otten & Paerl 2015; Willis *et al.* 2015). Assessment of other cyanotoxins and their proxy indicator species was not possible due to the small number of detections in Seqwater's monitoring data.

A further advantage of a cyanotoxin-based monitoring program is that it takes into account both the free-floating and benthic cyanotoxin production. This may have been overlooked under the previous program, as benthic cyanobacteria can produce different cyanotoxins that would not have triggered targeted toxin testing in the absence of a free-floating PTP indicator. The new RWQMP covers the majority of currently known cyanotoxins, with a requirement to be aware of research advances to ensure if there is a need to include new cyanotoxins in the future. Since the new program commenced on 1 December 2016, Seqwater has already recorded a low-level recreational saxitoxin detection in the absence of cell count and biovolume indicators of saxitoxin PTPs, which is postulated to be related to benthic cyanobacteria, quite possibly *Scytonema crispum*. Further research is required to assess the impact of benthic cyanobacteria and their associated

toxins on Seqwater's lakes and their management implications.

The financial benefit of this improvement has been realised through both a reduction in laboratory analysis and sampling effort (less escalated sampling requirements). Analytically, the use of an automated GC-MS/LC-MS cyanotoxin quantification, compared with human-determined identification and enumeration of cyanobacterial samples, has realised significant benefits through reduced human intervention and specialist time. This has also resulted in improved turn-around times from sample collection to confirmed result. From a sampling perspective, Seqwater manages one of the most geographically broad metropolitan water supplies in Australia and resampling of lakes at escalated frequencies can require up to 6 hours road driving and more than 2 hours boating to collect one resample. By escalating based on actual toxin risk under the new program, the amount of resampling has reduced significantly and therefore resulted in reduced resampling resource allocations and costs.

The setting of cyanotoxin recreational management guideline values in the absence of an Australian recreational advisory for all monitored cyanotoxins has followed well-accepted methods and is designed to protect the most sensitive recreational population of children, an approach which is supported by Australian and international health advisory groups. Children are especially at risk of cyanotoxin exposure due to their lower bodyweight, inherent risky behaviour around recreational waters and the toxic effects on development (Weirich & Miller 2014). Compared with adults, children also spend more time in recreational waters and swallow more water per bodyweight than adults. Children and youths may also ignore posted warnings or may be unaware of the hazards posed by waters containing cyanotoxins (Weirich & Miller 2014). Based on these collective findings, Seqwater has taken the decision to shift from using proxy indicators of risk to the measurement of the actual cyanotoxin risk, which will assist Seqwater to balance access to its recreational lakes with water quality.

Table 1 presented the action limits of the five cyanotoxins under the new RWQMP, with the actions for each step outlined in the flowchart presented in Figure 1. When toxins reach Medium Level, sampling frequency is increased to fortnightly. When levels reach High, the recreational site

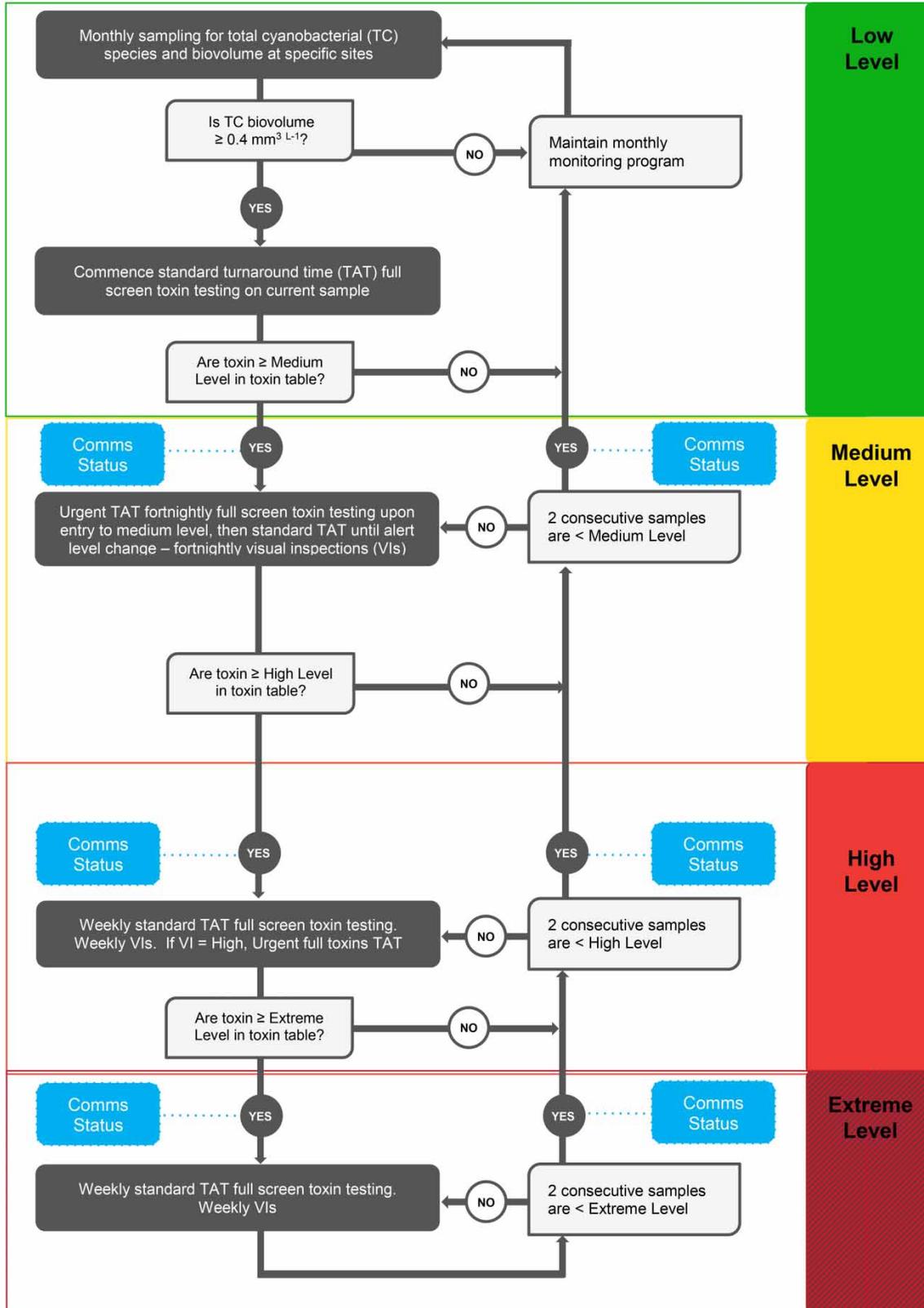


Figure 1 | New RWQMP flowchart for sampling escalation and de-escalation based on toxin concentrations presented in Table 1.

will be closed to primary contact recreation. Communication of this closure occurs through multiple communication methods including: signage at the site, emails to registered email groups, updated website and recreational notices. Monitoring will be maintained at a weekly frequency. If levels reach Extreme, primary recreation will remain closed and an advisory notice will be issued recommending against secondary contact recreational activities. De-escalation requires two consecutive water samples below any of the specific guideline levels to reduce the sampling frequency and reopen sites or remove advisory notices.

CONCLUSIONS

Recreational lakes in SEQ are subject to frequent and prolonged algal blooms, most commonly of the cylindrospermopsin toxin-producing species *C. raciborskii*, which is not currently covered by Australian recreational advisory limits. The use of biovolume and cell counts for the prediction of cylindrospermopsin production by *C. raciborskii* was ineffective, as it significantly over-predicted toxin production. In order to facilitate safe recreational access to Seqwater's lakes, there was a requirement to generate a range of recreationally specific toxin triggers to cover the five major types of cyanotoxins observed in Australia to protect recreators from free-floating and benthic cyanotoxin exposure risks. We encourage other recreational water management authorities consider this approach to maximise recreational access in a fiscally and socially responsible manner.

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