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Addressing Public Health Risks for Cyanobacteria in Recreational Freshwaters: The Oregon and Vermont Framework

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ABSTRACT

Toxigenic cyanobacteria, commonly known as blue green algae, are an emerging public health issue. The toxins produced by cyanobacteria have been detected across the United States in marine, freshwater and estuarine systems and associated with adverse health outcomes. The intent of this paper is to focus on how to address risk in a recreational freshwater scenario when toxigenic cyanobacteria are present. Several challenges exist for monitoring, assessing and posting water bodies and advising the public when toxigenic cyanobacteria are present. These include addressing different recreational activities that are associated with varying levels of risk, the dynamic temporal and spatial aspects of blooms, data gaps in toxicological information and the lack of training and resources for adequate surveillance. Without uniform federal guidance, numerous states have taken public health action for cyanobacteria with different criteria. Vermont and Oregon independently developed a tiered decision-making framework to reduce risk to recreational users when toxigenic cyanobacteria are present. This framework is based on a combination of qualitative and quantitative information.

Keywords: Cyanobacteria Recreational risk Public health Microcystin

INTRODUCTION

Cyanobacteria, commonly referred to as blue-green algae, are found in many freshwater lakes and rivers across the world. Increasing awareness of the public health risks posed by cyanobacteria has resulted in a burgeoning interest among health officials, lake administrators, the public, and numerous stakeholders who rely on freshwater systems for a variety of purposes. In North America, the most likely exposure pathways to the toxins produced by cyanobacteria in freshwater systems are through recreational contact, contaminated drinking water, or the ingestion of dietary blue-green algae supplements. Exposure to marine cyanotoxins through contaminated fish and shellfish or recreational activities in saltwater are another public health concern. Our intent in this paper is to focus on the public health challenges associated with recreational exposure in freshwater systems to cyanobacteria and to describe the approach adopted by 2 states, Vermont and Oregon.

Human health effects from exposure to cyanobacteria are varied and include gastroenteritis, nausea, vomiting, fever, flu-like symptoms, sore throat, blistered mouth, ear and eye irritation, rashes, abdominal pain, visual disturbances, and potentially severe systemic effects such as hepatic failure, neurological damage, and death (Codd et al. 2005). In addition, cyanobacteria can illicit allergy-like symptoms (Heise 1949), which can include asthma, hives, and conjunctivitis. One of the most commonly reported health effects is skin reaction. A recent study examined acute skin irritant effects in healthy volunteers by skin patch tests with several taxa of potentially toxigenic cyanobacteria (Pilotto et al. 2004). Approximately 20% of the volunteers reacted to the extracts, with mild, self-limiting rashes. Interestingly, no dose–response relationship was established between skin reactions and the density of cyanobacteria.

The 1st recorded scientific observation of cyanotoxin poisoning occurred in 1878, involving cattle, horses, and dogs (Francis 1878). In 1931, the 1st reported human illnesses occurred in West Virginia, when about 9,000 people developed acute gastroenteritis from a cyanobacteria-contaminated drinking water supply (Veldee 1931). In 1959, several people where sickened by a common cyanobacteria, *Anabaena*, as a result of recreational contact in Saskatchewan, Canada (Dillenger and Dehnel 1960). Researchers reported illnesses in 50% of British military recruits who were swimming and canoeing in a lake infested with *Microcystis*, including the development of severe pneumonia in 2 recruits (Turner et al. 1990). In July 2004, Nebraska state environmental and health officials reported an outbreak of symptoms including skin rashes, lesions, blisters, vomiting, and headaches in more than 50 people that were skiing or swimming on Pawnee Lake (Walker 2005). Tests revealed the water was contaminated with microcystin, a common cyanotoxin. A recent summary of illness outbreaks from 1971 to 2000 associated with recreational water in the United States found that algae was implicated in 0.4% of the outbreaks reported (Craun et al. 2005). This number is likely underreported because most reporting to the Centers for Disease Control and US Environmental Protection Agency (USEPA) is voluntary from local and state agencies and blue-green algae is still a novel issue for many local jurisdictions. Furthermore, nearly a quarter of all reported freshwater outbreaks from 1971 to 2000 were of unknown etiology (Craun et al. 2005).

Currently, at least 46 species of cyanobacteria have been shown to produce toxins harmful to vertebrates (Chorus and Bartrum 1999). Some of the more common toxigenic genera include *Microcystis*, *Anabaena*, *Aphanizomenon*, *Lyngbya*, *Nodularia*, *Planktothrix*, *Nostoc*, and *Cylindrospermopsis*. The

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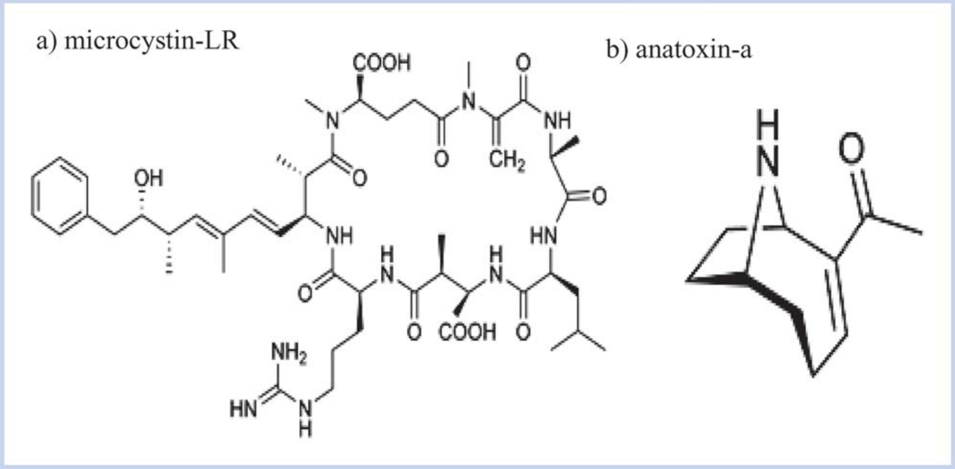


Figure 1. Molecular structure of (**a**) microcystin-LR and (**b**) anatoxin-a.

cyanotoxins that have been detected in freshwaters of Oregon include microcystin, anatoxin-a, and cylindrospermopsin, and microcystin has been detected in Vermont. It should be noted that cyanobacteria likely produce toxins that have not been characterized or are not commonly sampled. A recent example is the discovery of a neurotoxic amino acid, β-*N*-methylamino-L-alanine, which was detected in the vast majority of cyanobacteria tested (Cox et al. 2005) and might be associated with some neurodegenerative diseases (Murch et al. 2004; Ince and Codd, 2005). Microcystins are the most commonly detected freshwater cyanotoxins across the world (Chorus and Bartrum 1999). This toxin is produced by numerous taxa and has more than 95 known structural variants, including the most researched variant, microcystin-LR (Figure 1). Microcystin primarily targets liver cells. The mechanism of toxicity is the inhibition of protein phosphatases, resulting in high phosphorylation of cytoskeletal filaments, which can lead to internal hemorrhaging of the liver. Damage to the liver from subacute exposure is likely to go unnoticed up to levels near those that cause severe damage following acute exposure (Chorus et al. 2000), indicating a steep dose–response curve. From a chronic exposure perspective, microcystins are considered to be tumor promoters on the basis of studies in mice that were initiated with a known carcinogen (Falconer and Buckley 1989).

A neurological cyanotoxin of public health significance is anatoxin-a (Figure 1), which is produced by several cyanobacteria. Anatoxin-a is a cholinergic agonist that binds to neuronal nicotinic acetylcholine receptors. The molecular activity of anatoxin-a leads to overstimulation of muscle cells and possibly paralysis followed by asphyxiation (Carmichael 1997). In Oregon and Vermont, multiple dog deaths are suspected to be the result of exposure to anatoxin-a, which was detected in the water at the time of death in some incidents.

CHALLENGES

Many aspects of cyanobacterial behavior pose challenges to the protection of public health. The temporal and spatial variability in cyanobacterial growth are particularly difficult for monitoring recreational waters, especially when budgetary and staffing resources are limited. As an example, cyanobacteria can reach scum-forming densities or they can die off in 1 or 2 d. If monitoring is conducted weekly, these rapid blooms can be missed in a surveillance program. Many lakes are large and highly dendritic, with a large degree of spatial heterogeneity in cyanobacteria density. Often, the cove, arms, or slackwater areas are more conducive for scum formation, which might be missed in a sampling program. Some lakes could be more susceptible to bloom formation as a result of natural or anthropogenic eutrophication or through alteration of food web dynamics from the introduction of exotic species. Other waterbodies can be highly influenced by climatic factors that influence the potential for blooms.

Some species of cyanobacteria prefer to grow at lower depths in the water column or have the ability to regulate their buoyancy, which present further challenges if the determination to issue a health advisory is based on the presence of visible scum or sampling only occurs near the surface. To address some of these considerations, we have suggested that surveillance programs focus on designated recreational areas if resources are limited, such as swimming locations, campgrounds, boat ramps, and other known sites that attract children and families (ODHS 2005). We also advocate for increasing the awareness and education among field staff and the public to assist in visually identifying and reporting blooms to enhance surveillance capabilities.

The factors that determine whether a bloom will produce toxins are poorly understood. Toxin production has been described as highly variable, both within and between blooms (Codd and Bell 1985). Significant differences in toxicity can occur within distances of only meters within the same bloom (Carmichael and Gorham 1981). The biotic and abiotic factors that influence toxin production have been examined in some taxa. Temperature and solar radiation have been suggested to play a role on toxin production in *Microcystis aeruginosa* (Van der Westhuizen et al. 1986; Codd and Poon 1988). Beyond the lack of understanding for toxin production, many data gaps exist in the toxicological studies of cyanotoxins. For microcystins, a provisional tolerable daily intake was developed by the World Health Organization on the basis of the LR variant only (Fawell et al. 1994). Numerous other variants of microcystins have known or unknown levels of toxicity that remain poorly characterized. At this time, no reference dose is available for anatoxin-a. Further toxicity studies are needed to determine the effect of

Table 1. Generalized list of primary exposure pathways of concern for cyanotoxins during recreational activities

Exposure potential	Recreational activity	Primary exposure pathways of concern
High	Swimming/wading	Ingestion
	Diving	Ingestion
	Water skiing/wake boarding	Ingestion/inhalation
	Wind surfing	Ingestion/inhalation
	Jet skiing	Ingestion/inhalation
Moderate	Fish/shellfish consumption	Ingestion
	Canoeing	Inhalation/dermal
	Rowing	Inhalation/dermal
	Sailing	Inhalation/dermal
	Kayaking	Inhalation/dermal
	Motor boating (cruising)	Inhalation
Low/none	Catch and release fishing	Dermal
	Hiking	Not applicable
	Picnicking	Not applicable
	Sightseeing	Not applicable

repeated exposures to environmental concentrations of cyanotoxins over a time span that ranges from a few days to several months. Even less information is available from rigorous epidemiological studies.

No single disease or symptom complex in humans can completely characterize exposure to cyanotoxins, making diagnosis difficult without surveillance of water systems. Many of the symptoms that can be caused by cyanotoxins overlap with those caused by other agents found in environmental waters, such as cercarial dermatitis and other protozoan, bacterial, or viral agents found in water. A specific diagnostic test for humans is not readily available. Water sampling for toxins after a suspected poisoning or illness is often delayed and might not accurately reflect the current conditions when exposure occurred. Furthermore, symptom or disease reporting from local health departments or physicians is expected to be low because cyanobacteria-related illnesses are still an emerging public health issue. Outreach activities to county health departments, especially those counties with historical cyanobacterial blooms, continue in Oregon and Vermont. Statewide websites have been established to track current and past advisories in Oregon and Vermont (www.oregon.gov/DHS/ph/envtox/maadvisories.shtml and http://healthvermont.gov/enviro/bg_algae/bgalgae.aspx, respectively).

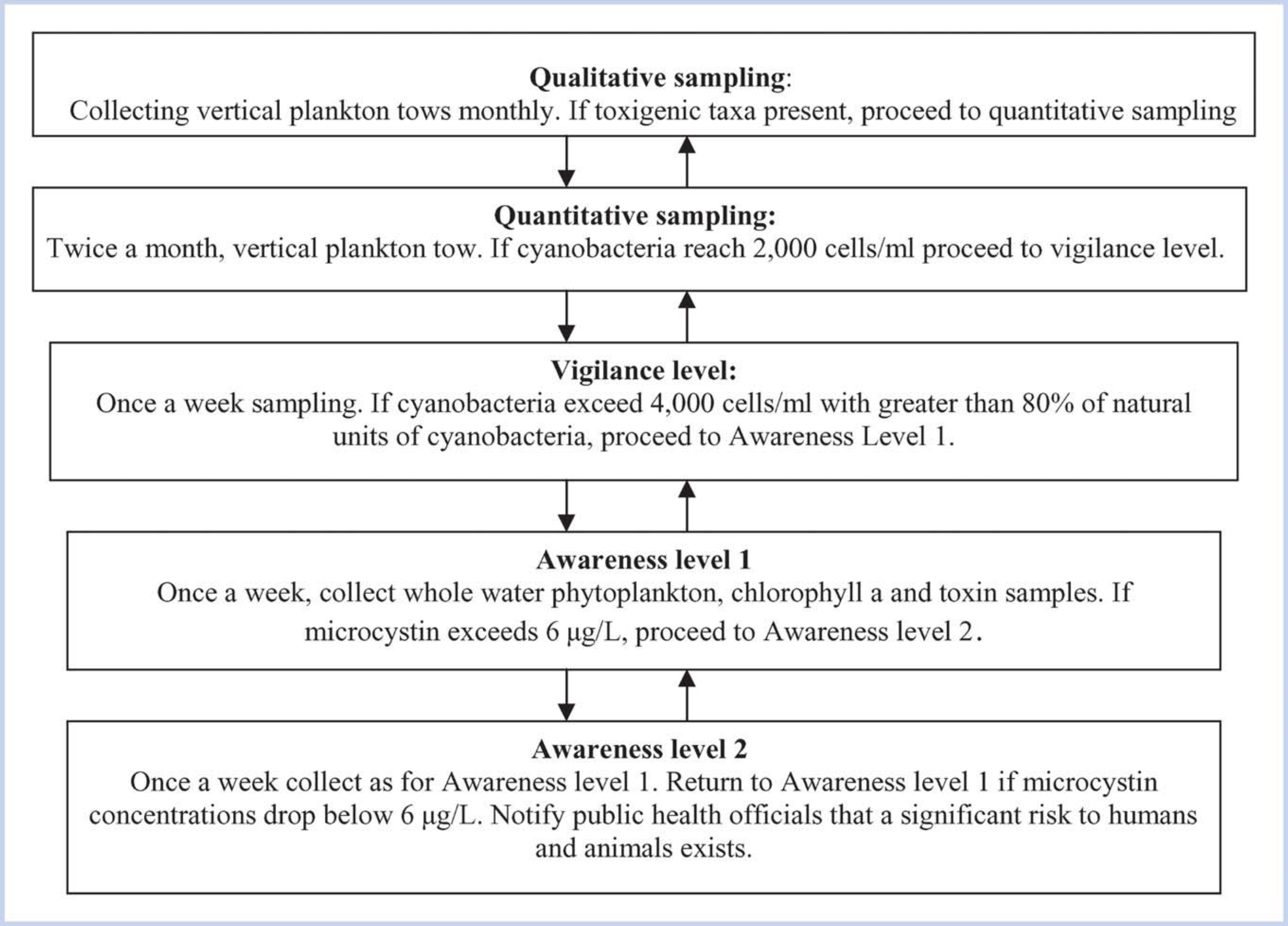
EXPOSURE ASSESSMENT

In recreational waters, the exposure to cyanotoxins can occur through oral ingestion, aspiration of water into the lungs, inhalation of mist, and dermal contact. Different recreational activities are associated with differing risk levels when toxigenic blooms are present (Table 1). It should be noted that Table 1 is a general outline and the primary exposure pathway of concern depends on the details of the activity. For instance, if a canoe capsizes, the primary concern could change from dermal exposure to incidental ingestion or aspiration of water.

Ingestion of water can occur through both incidental and intentional pathways. Incidental ingestion is more likely to occur in recreational waters compared with intentional ingestion, especially in turbid or discolored waters. The risk of incidental ingestion is particularly high for children playing in nearshore areas where scums tend to accumulate. A possible scenario for the intentional ingestion of recreational water is the use of lake or river water for drinking or cooking purposes, especially by campers and hikers. It is likely that some people believe that boiling, filtering, or treating contaminated water with conventional outdoor equipment will eliminate the risk posed by toxins, which in many cases are ineffective against cyanotoxins. In addition, it is important to identify recreational waters that might serve as drinking water sources. This includes water users at the affected waterbody, such as private homes, campgrounds, lodges, and ranger stations and those with intakes downstream.

Inhalation or aspiration of toxin is more likely through activities in which the toxin is aerosolized in water droplets, such as wake boarding, water skiing, or diving activities. The toxicity of cyanotoxins tends to be higher when the toxin enters through the respiratory tract, compared with the oral ingestion pathway (Chorus et al. 2000).

A frequent question in Oregon and Vermont is the health risk posed by consuming fish caught during a bloom. Studies have shown that microcystin mainly accumulates in the liver and viscera of fish, although it has been detected in the fillet (Vasconcelos 1999; de Magalhães 2001; Mohamed et al. 2003). In addition, shellfish have been shown to accumulate cyanotoxins in edible tissue (Vasconcelos 1999; Sipia et al. 2001). A recent study examined the bioaccumulation of microcystin in several trophic levels of freshwater fish (Xie et al. 2005). Levels of microcystin-LR and -RR were measured in various organs and compartments of fish during a dense



Qualitative sampling:
Collecting vertical plankton tows monthly. If toxigenic taxa present, proceed to quantitative sampling

Quantitative sampling:
Twice a month, vertical plankton tow. If cyanobacteria reach 2,000 cells/ml proceed to vigilance level.

Vigilance level:
Once a week sampling. If cyanobacteria exceed 4,000 cells/ml with greater than 80% of natural units of cyanobacteria, proceed to Awareness Level 1.

Awareness level 1
Once a week, collect whole water phytoplankton, chlorophyll a and toxin samples. If microcystin exceeds 6 μg/L, proceed to Awareness level 2.

Awareness level 2
Once a week collect as for Awareness level 1. Return to Awareness level 1 if microcystin concentrations drop below 6 μg/L. Notify public health officials that a significant risk to humans and animals exists.

Figure 2. Tiered surveillance and notification system used by Vermont for cyanobacteria.

bloom of *Microcystis* and *Anabaena*. Although most of the microcystin content was detected in the blood, bile, gut contents, and liver, the muscle content averaged 1.8 μg microcystin/g tissue dry weight, with the highest accumulation in fish occupying the upper trophic levels. From their conclusions, 100 g (~4 oz) of fillet can contain up to 25 times the tolerable daily intake for microcystin.

In Oregon, anglers are encouraged to thoroughly clean the fillet and discard gut contents and organs before cooking. During particularly dense blooms of toxigenic species or high toxin production, anglers have been advised to avoid consuming fish from those waters. It should be noted that microcystins are heat stable and not broken down by the heat generated through cooking (Harada et al. 1996).

VERMONT APPROACH

Cyanobacteria 1st made news in Vermont when 2 dogs died in Lake Champlain after playing in a bloom. The cause of death was determined to be from cyanobacterial toxins. Since then, the Vermont Department of Health and the University of Vermont have collaborated in monitoring the lake for cyanobacteria and 2 toxins, microcystin and anatoxin-a. Lake Champlain is the major lake in Vermont and shares lakefront with Canada and New York state. One particular part of the lake, Missisquoi Bay, which is the tributary of the Missisquoi River, has been heavily contaminated with microcystin-producing cyanobacteria (Watzin et al. 2003). Peak concentrations occur annually in August.

A tiered system was established for surveillance of cyanobacteria in Lake Champlain (Figure 2). The surveillance begins with qualitative sampling that progresses in frequency of monitoring as blooms develop. Lake Champlain has 14 monitoring locations and the University of Vermont and volunteers collect samples. The Vermont Department of Environmental Conservation assists with monitoring for the presence of blooms and sample collection by boat. The guideline for beach closings is the visible presence of cyanobacterial scum. Beach reopening can occur if no visible scum is present and the concentration of microcystin-LR is 6 μg/L or less. The 6 μg/L guidance value was based on a recreational childhood swimming scenario outlined below.

$$\text{Guidance value}(\mu\text{g/L}) = \frac{\text{TDI} \times \text{BW}}{\text{IR}}$$

The tolerable daily intake was developed by the World Health Organization on the basis of repeated oral administration of microcystin-LR in mice and effects on the liver. The tolerable daily intake of microcystin-LR is 0.04 $\mu\text{g} \cdot (\text{kg body weight})^{-1} \cdot \text{d}^{-1}$. A body weight of 15 kg was used to represent a child. An ingestion rate was based on USEPA guidance for incidental ingestion of surface waters, in which 0.05 L/h is accidentally ingested (USEPA 1991; Dang 1996). For this guidance, it was assumed that a child would swim for up to 2 h in a single day.

Vermont has 2 types of postings for beaches. One is an informational poster to raise public awareness of cyanobac-

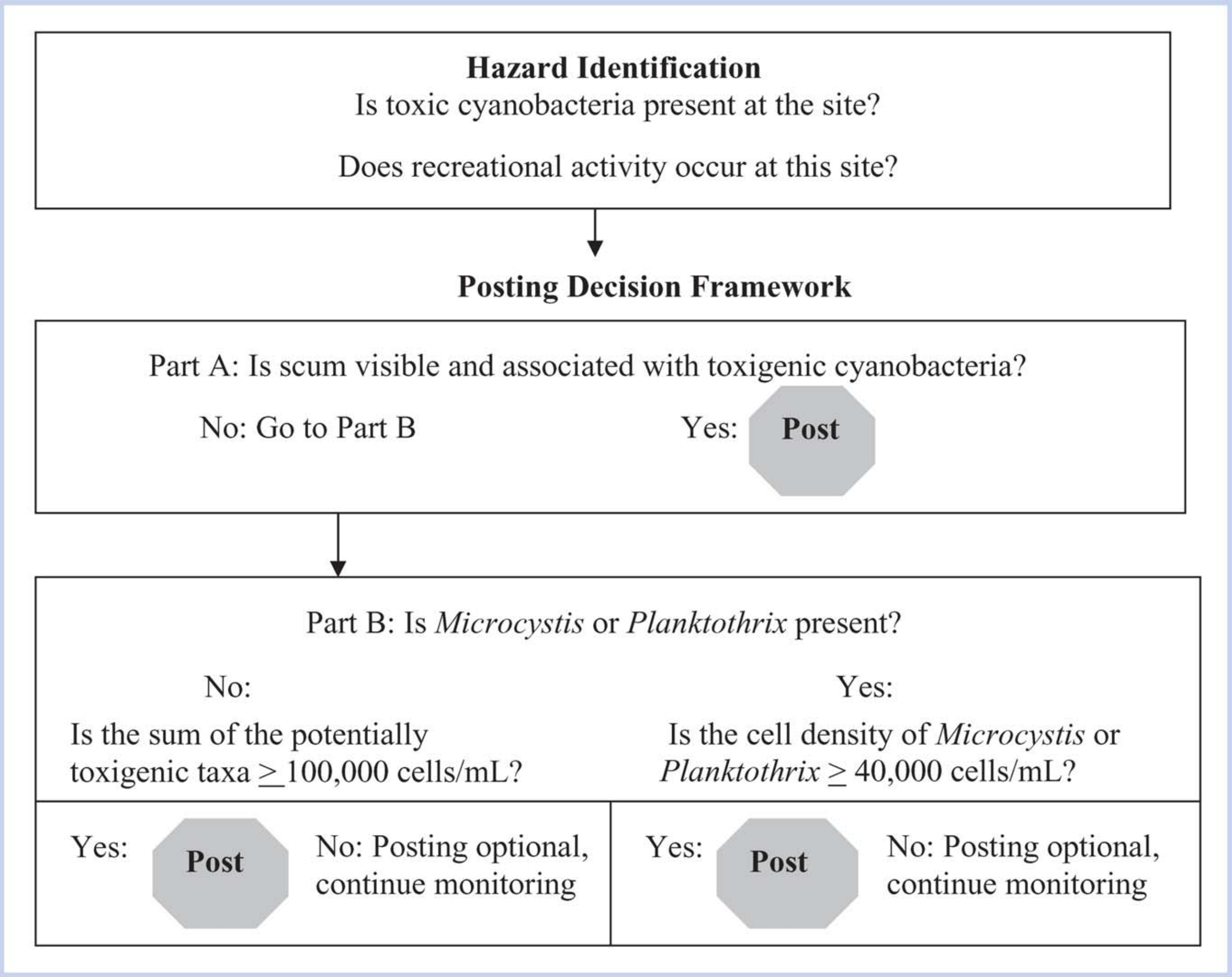


Figure 3. Decision framework for issuing advisories in recreational waters in Oregon for cyanobacteria.

teria and scum formations and the other is a "Beach Closed" sign for public swimming beaches. Private property is not posted. A website with a map is updated weekly to reflect results and locations of the testing program. The website uses a color-coded schematic to identify generally safe, low-alert, and high-alert areas. The website also hosts fact sheets and press releases for public education.

The Vermont Department of Health has been training local town Health Officers to identify cyanobacteria and to take water samples in lakes and ponds with public beaches. These samples are analyzed for microcystin toxin. Sampling kits for microcystin are available to Health Officers and state environmental personnel to test the water for toxin. The state does not have the capacity to provide test kits for anatoxin but hopes to develop this ability in the near future.

OREGON APPROACH

Currently, several waterbodies in Oregon are monitored for toxigenic cyanobacteria. These include publicly owned recreational waters, privately owned lakes, and some drinking water systems. A variety of stakeholders administer the lakes, including federal, tribal, state, county, and city governments; utility companies; and private corporations or landowners. In past years, the decision-making process for issuing and lifting advisories varied with the managing jurisdiction of that waterbody. In 2004, an interagency cyanobacteria taskforce was created with representation from government agencies, academia, and the private sector. One intention of the taskforce was to adopt statewide public health guidelines for issuing and lifting advisories in recreational waters when toxigenic cyanobacteria are detected.

In 2004 and previous years, Oregon lakes were posted when toxigenic cell densities exceeded 20,000 cells/mL, corresponding to an Alert Level III according to World Health Organization recommendations. In 2005, the interagency blue-green algae task force recommended 2 mechanisms to issue an advisory in Oregon for recreational waters (Figure 3). The 1st mechanism is the identification of visible scum dominated by potentially toxigenic cyanobacteria. This observation, which is often determined by trained field staff, will result in the immediate posting of the affected waterbody. Scum formation could increase toxin production by orders of magnitude in a few hours (Chorus and Bartrum 1999). The 2nd mechanism uses cell density to trigger an advisory. The task force recommended that advisories be posted if the cell density of total toxigenic cyanobacteria equals or exceeds 100,000 cells/mL, unless the bloom has *Microcystis* or *Planktothrix* species. The World Health Organization guidance for a moderate health alert is

100,000 cells/mL (Chorus and Bartrum 1999) on the basis of a risk management decision by the interagency task force.

A lower guideline of 40,000 cells/mL was recommended for advisories for blooms that contain *Microcystis* and *Planktothrix*. The lower guideline is based on the premise that these 2 genera are more likely to produce microcystin toxin compared with other genera, such as *Anabaena* (Codd et al. 2005), and the observation that almost all *Microcystis* strains are toxigenic (Carmicheal 1995). The lower *Microcystis* and *Planktothrix* guideline is estimated to correlate with the production of 8 μg/L of microcystin (Chorus and Bartram 1999), which is the guidance value used by Oregon. Posting of a waterbody is accompanied by a press release to various media outlets.

In addition to recommendations for the posting of advisories, the task force outlined guidance for retracting advisories. Cyanotoxins, if produced, are typically found within the cell during most of a bloom event. As the bloom senesces, toxin can be released into the dissolved phase of the water when the cells die and lyse. The released toxin will dilute and eventually degrade over time. However, the risk of exposure to dissolved toxin immediately after the peak of a bloom must be addressed because cyanotoxins can persist even though the bloom has dissipated (Lawton et al. 1994). An additional risk factor is that the water will appear more inviting for recreational activities as the clarity increases, thus elevating the potential for exposure during this period.

The task force recommended that an advisory be lifted after a waiting period of 2 weeks once the cell density of potentially toxigenic blue-green algae falls below recommended guidelines and with sufficient evidence that the bloom is continuing to decline. Evidence of a declining bloom can include decreasing cell density of potentially toxigenic cyanobacteria and increasing lake clarity measured with a Secchi disk or particle counter. If toxin analysis is conducted, an advisory may be lifted 1 week after the cell density falls below recommended guidelines, if microcystin is below 8 μg/L. The guidance value of 8 μg/L was derived in a similar manner to the process used by Vermont, with the difference that 20 kg was used as the default child body weight in Oregon. It should be noted that these advisories are not lake closures. Rather, they are intended to provide the public with information that indicates a public health hazard might exist. Under extreme conditions, or if evidence exists of illness, the appropriate jurisdiction for a waterbody can invoke an official closure.

An essential part of the educational and outreach efforts for cyanobacteria is the posting and distribution of informational signs and pamphlets. Ideal places to post include kiosks, docks, bulletin boards, trailheads, campgrounds, and other visible locations that advise on the effects and symptoms that are possible with exposure to cyanobacteria. Posted information should include a notice that not all waters can be monitored all the time and scummy, turbid, or discolored waters should always be avoided. A further notice should warn that children, individuals with pre-existing medical conditions, and the elderly are considered susceptible populations. Oregon State Public Health maintains a Web-based listing of current and past advisories across the state.

NATIONAL RESPONSE

In December 2004, the Harmful Algal Blooms and Hypoxia Research and Control Act (HABHRCA) was reauthorized and expanded to include freshwater and cyanobacteria. This act forms the basis for the reestablishment of a federal interagency task force. As part of the proposed scientific assessment of freshwater harmful algal blooms, the frequency and occurrence of significant blooms will be assessed from an ecological and economic perspective. In addition, HABHRCA established priorities and guidelines for an interagency research program to gain a better understanding of the causes, characteristics, and effects of harmful algal blooms in freshwater locations. Finally, HABHRCA will identify ways to improve coordination and reduce duplication of efforts among federal agencies and departments.

In addition to the expanded role of HABHRCA, there have been some promising recent developments at the federal level by various agencies. The National Toxicology Program has nominated 2 cyanotoxins for toxicity testing. The Centers for Disease Control has provided some financial and technical assistance to a limited number of states and plans to conduct a health outcome study in a recreational setting. In 1998, the USEPA included cyanobacteria and their toxins on the Contaminant Candidate List, which is a list of known or potential drinking water contaminants for regulatory consideration. Currently, the United States has no drinking water or recreational guidelines or regulations for cyanotoxins, prompting states to use information and guidance from the World Health Organization or other countries. Recently, the USEPA sponsored an international symposium on cyanobacteria and harmful algal blooms in September 2005, in part to meet the mandates of the HABHRCA (ISOC-HAB 2006). Other agencies, such as the US Geological Survey, the Army Corps of Engineers, and the US Fish and Wildlife, have been active in monitoring and management issues with cyanobacteria as well.

Although the recent attention at the federal level and the goals of the HABHRCA are laudable, we advocate for stronger research and funding on public health issues, including relevant toxicological and epidemiological studies. The extent for cyanotoxins to contaminate fish and other food items, the lack of reference or tolerable doses for many cyanotoxins, improved monitoring techniques for recreational waters, and research directed toward determination of toxigenic strains and toxin production are needed. These should be accompanied by outreach efforts toward county health departments, veterinarians, and local physicians in areas that have high water recreation activities and a history of toxigenic blooms. We hope that more effort will be directed toward addressing these public health concerns and providing national guidance for cyanobacteria in recreational scenarios. Until this occurs, various states, counties, and other entities will continue to apply diverse criteria to address cyanobacteria or ignore the problem altogether.

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