Characterizing and Mitigating Cyanobacterial Blooms in Drinking Water Reservoirs

Hunter Adams, Stephanie A. Smith, Sam Reeder, Emily Appleton, Butch Leinweber, Steve Forbes, Polly Barrowman, Greg Ford, Keisuke Ikehata, and Mark Southard

Key Takeaways

Successful detection and treatment of cyanobacterial blooms benefit from a thorough understanding of them.

The sooner a harmful algal bloom is detected and identified, the easier and less expensive it will be to eliminate it.

Many tools are available to refine monitoring and mitigation methods; research and technological advances continue to help support water utilities' efforts.

A laboratory in Wichita Falls, Texas, has developed a proactive, multifaceted approach to address the complexities of monitoring and mitigating blooms.

Layout imagery by mivod/Shutterstock.com

The term *algae* is not a strict biological classification; rather, it encompasses a very broad group of organisms ranging from ubiquitous single-celled bacteria to the giant seaweeds that form kelp forests in marine habitats. What they all have in common is that they perform photosynthesis—the biological conversion of carbon dioxide and water into glucose and oxygen, fueled by light energy from the sun. A second commonality algae share is the pigment chlorophyll a, which is responsible for their green color and is a requirement for performing oxygenic photosynthesis. Although cyanobacteria are commonly called blue–green algae, Table 1 provides some of the major differences between freshwater algae and cyanobacteria.

The characteristic bluish tint of cyanobacteria comes from the accessory pigment phycocyanin. In marine environments, cyanobacteria are often enriched with another accessory pigment called phycoerythrin. The anucleated cells and rich blue pigment are why they are referred to as cyanobacteria, and it is this group that often leads to major challenges during harmful algal blooms (HABs).

Certain inherent biological capabilities enable cyanobacteria populations to grow rapidly (bloom) when the conditions are right. In general, cyanobacteria grow better in warmer temperatures, which is why HABs are commonly seasonal. Unlike most eukaryotic algae, which are obligated to the carbon-fixing lifestyle (called autotrophic growth), some cyanobacteria can grow on fixed carbon sources (heterotrophic growth). The exceptions for heterotrophic eukaryotic algae include some unicellular green algae, golden algae, euglenids, and dinoflagellates that can exist as apochlorotic (colorless) parasites. Further, certain cyanobacteria can form specialized cells that are capable of nitrogen fixation, the conversion of atmospheric dinitrogen into biologically useful nitrogenous compounds.

In freshwater environments, the condition that most often stimulates cyanobacteria is the introduction of nitrogen and phosphorus. Even the nitrogen-fixers are stimulated by nitrates, which are biologically less taxing to use than atmospheric nitrogen. Phosphorus is the nutrient that usually acts as the limiting factor for cyanobacterial growth in aquatic environments, so it is the main nutrient for stimulating HABs.

HABs present several challenges for drinking water treatment, reservoir management, and public health. Many cyanobacteria exist as autonomous single cells, but some form cellular aggregations that range from microcolonies to chains and thick mats of growth that can clog filters and undermine primary clarification. Most HABs also produce taste and odor (T&O) compounds such as geosmin and 2-methylisoborneol (MIB). These compounds don't have health effects, but they are unacceptable to consumers and can be expensive to remove with treatment processes like activated carbon filtration or ozonation.

When blooms recede, the biomass that dies off becomes food for heterotrophic bacteria that will consume oxygen through their respiratory activities. This leads to hypoxic (less than 5 mg/L dissolved oxygen) or anoxic conditions that cause fish kills and harm other aquatic life. Cyanotoxins that can be produced by cyanobacteria include the liver toxins microcystins,

Characteristics of Freshwater Algae and Cyanobacteria

Characteristic	Freshwater Algae	Cyanobacteria
Cell type	Eukaryotic	Prokaryotic
Pigments	Chlorophylls a and b Carotenoids Xanthophylls	Chlorophyll a Phycocyanin Phycoerythrin
Energy production	Autotrophic	Autotrophic and heterotrophic
Reproduction	Sexual	Asexual
Toxin production	None affecting humans	Yes
Taste and odor production	Yes	Yes

Table 1

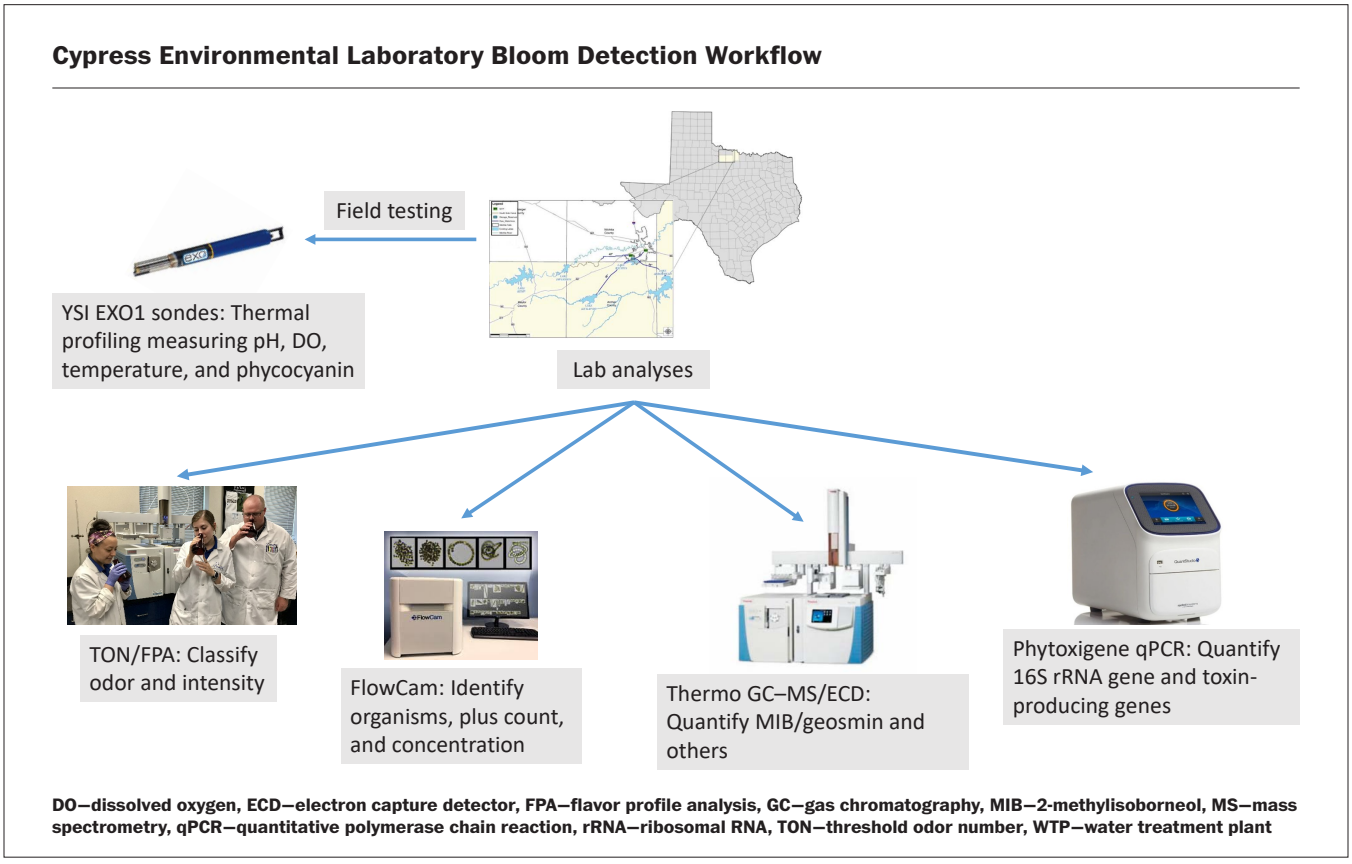

Figure 1

nodularins, and cylindrospermopsin, as well as the neurotoxins anatoxin-a and saxitoxin (WHO 2021). It is much more difficult to mitigate the effects of a HAB when it is at its peak in comparison with early detection combined with quick identification of the algae present and the associated problems, which is the best strategy for HAB mitigation.

Bloom Monitoring and Detection

An example of a community facing HABs is the City of Wichita Falls, Texas, which has a surface water system with four sources of supply for treatment: Lake Arrowhead, Lake Kickapoo, and the Lake Kemp/Lake Diversion system. The Public Water System (PWS) has three conventional treatment trains and one advanced treatment train at the Cypress Water Treatment Facility and two conventional treatment trains at the Jasper Water Treatment Facility.

After experiencing decades of T&O events due to cyanobacterial blooms, an integrated monitoring program was established in 2016 (Adams et al. 2018). The program has grown and expanded over the past five years, with a focus on increasing a proactive, multifaceted approach to monitoring and mitigation of blooms (Adams et al. 2021a). Understanding a bloom and its growth phases is key to detection and reducing the costs of mitigation.

To overcome the challenges associated with the complexity of detecting and mitigating blooms, T&O compounds, and cyanotoxins in source and treated waters, the City of Wichita Falls Cypress Environmental Laboratory (CEL) developed a monitoring plan that merged analyses from its microbiological and analytical laboratories while optimizing the water system's existing treatment technologies (Southard et al. 2021). The CEL integrated analytical approaches to determine when treatment changes are needed and where to focus testing efforts until blooms and T&O events subside.

The CEL employs a multifaceted approach to monitoring blooms, as shown in Figure 1. Source lakes, a holding reservoir, and both water treatment facilities are monitored on a seasonal schedule. Warmer summer months are scheduled for sampling three to five days per week,

while colder winter months are only sampled one day per week. When a bloom event is detected, the water purification superintendent is notified, and tests are conducted more frequently. Increased testing remains in effect until blooms subside. The detection strategies employed by the CEL are discussed in the following subsections.

Certain inherent biological capabilities enable cyanobacteria populations to grow rapidly (bloom) when the conditions are right.

In Situ Water Quality Monitoring for HABs

Multiparameter water quality sondes can be useful for early HAB detection and for following the course of a bloom to support in- and out-of-plant treatment options. Parameters that are helpful to track include water temperature, dissolved oxygen (DO), pH, and the photosynthetic pigments chlorophyll and phycocyanin. Sondes may be deployed continuously at a fixed monitoring station if antifouling measures, such as a central wiper, are employed.

DO concentration is indirectly proportional to temperature; e.g., high temperatures allow less DO to remain in water. DO can also respond directly to cyanobacterial growth. During periods of high photosynthetic activity, DO can exceed levels of 100% saturation in the water. DO concentrations plummet in the late stages of a bloom as heterotrophic bacteria degrade the dead algal biomass. Increased pH can indicate bloom growth as DO levels first increase, then drop; during growth, dissolved carbon dioxide is metabolized and decreases faster during increased photosynthetic activity than it is generated during cellular respiration. These parameters and others are described elsewhere as they relate to HABs (Smith 2019).

Photosynthetic pigments enable in-source detection of changes in cyanobacterial populations, which can drive sampling regimens and deepen understanding of bloom events. Conveniently, photosynthetic pigments are fluorescent molecules that absorb light at one wavelength (excitation) and then release light of a longer lower energy wavelength (emission). The measure of pigments can be useful in quickly determining the relative abundance of algae and cyanobacteria present in reservoirs by measuring how pigment concentrations fluctuate in the environment (Smith 2021).

Algae and cyanobacteria both produce chlorophyll a, while phycocyanin is produced almost exclusively by cyanobacteria—exceptions being red algae and cryptomonads (Table 1).

Changes in pigment concentrations can indicate whether a bloom is emergent, what type of algae may predominate, whether source water monitoring should be increased, and when and where samples should be collected. With the samples, organism classification can sort them into functional groups (T&O producers, filter cloggers, etc.) and measure cell abundance, allowing the assessment of whether a T&O event is likely to occur and which organism might produce the bloom. With data collected annually, a PWS can develop a sense or even a formal model for predicting an event based on early-bloom data.

Lab Analysis for HABs

The chemistry of T&O compounds is complex and the problems they create can be subjective, making their detection difficult, especially at trace levels (Burlingame & Doty 2018). Just as no single analytical chemistry method can detect all chemical contaminants in water, no single method can provide all the answers to T&O questions (Dietrich et al. 2003).

Threshold Odor Number/Flavor Profile Analysis (FPA)

Sensory methods are reliable when used correctly, directing analyses to likely target compounds (Adams et al. 2021b). Analysts refer to the Standard Method (SM) 2170 T&O wheel categories (*Standard Methods* 2017), which can point out the appropriate analytical method to determine T&O compound concentration. Threshold odor number testing is performed by SM 2150B (*Standard Methods* 2017) to determine the magnitude of a T&O event, while a modified FPA is performed by SM 2170 (*Standard Methods* 2017) to determine what type of odor is present.

Flow-Imaging Microscopy

Traditional microscopy methods are slow, cause eye fatigue, and are not ideal when trying to perform rapid sample analysis for real-time lake or reservoir treatment decisions. Instead, utilities may consider a high-throughput, semi-automated benchtop instrument that combines the technology of a microscope, digital imaging, and flow cytometry to rapidly capture images and information on cyanobacteria, microalgae, and other particles. Particle images can be analyzed, and the instrument can be "trained" using image recognition algorithms to identify and count organisms of interest.

When used for lake and reservoir monitoring, this instrument has proved to be a cost-effective monitoring

solution. By allowing managers to quickly view community composition within a sample, it is an early warning system for the detection of both T&O and potential cyanotoxin events. Newer models use a red laser (633 nm) to excite phycocyanin and chlorophyll a. Semi-automated sorting of cyanobacteria from other algae, diatoms, and detritus can provide utilities an overview of cyanobacteria growth in their lake or reservoir in a matter of minutes. The images of particles can be used to build libraries that allow for fast taxonomic identification of organisms of interest.

Gas Chromatography (GC)/Mass Spectrometry (MS)
GC is a separation method in which components of a solution are separated in a heated oven carried by a gas mobile phase such as helium or nitrogen. The separated components are measured by a detector—e.g., mass spectrometer, electron capture detector, or flame ion detector. This type of instrumentation allows for the separation and detection of volatile organic compounds and semi-volatile organic compounds, such as geosmin, MIB, and other T&O compounds. A recent study including sample stability, hold times, and preservation provides an example of volatility for 18 common T&O compounds (Pochiraju et al. 2021).

FPA results can indicate what type of GC method to run for compound determination. SM 2170 groups T&O compounds into four taste categories and eight odor categories on a T&O wheel (*Standard Methods* 2017). The descriptors loosely reflect chemical compositions, which help explain why certain treatments are more effective for a particular group of odors (Burlingame et al. 2011). These categories can then be used to highlight possible targets of interest.

Scans performed by a single quadrupole mass spectrometer provide a qualitative fingerprint of a mixture's components. Compounds may be detected well in scanning mode only when their concentrations are high because of interferants and low sensitivity over large mass ranges, but selected ion monitoring (SIM) can improve resolution. GC–MS analysis can indicate if T&O compounds are already present in the water column, while identification of organisms indicates that heightened monitoring is prudent even if the compounds have not been detected (Buerkens et al. 2020a). The presence of a bloom does not mean that the organisms are toxic or producing T&O compounds. However, the absence of T&O compounds does not mean that a problem is not emergent (Westrick & Szlag 2018). T&O compounds can be detected and quantified by SIM GC–MS using methods as described by Adams et al. 2020.

Quantitative Polymerase Chain Reaction (qPCR)
PCR is a molecular assay used in research and molecular diagnostics to replicate a small amount of DNA to produce a larger sample size and determine presence or absence of target sequences, while qPCR enables the quantitative measure of the amount of DNA present in a sample. These probe-based assays are highly specific, meaning that if the genes of interest are not present, there will be no detection or amplification.

Several classes of cyanotoxins are associated with cyanobacteria, but most are either hepatotoxins (causing damage to the liver) or neurotoxins (causing neurological damage). The hepatotoxins include microcystins, nodularins, and cylindrospermopsin, while saxitoxin is the primary neurotoxin produced by cyanobacteria. For HABs, there are commercialized assays are available that target and standardize the following genes for qPCR:

- 16S ribosomal RNA gene for total cyanobacteria presence
- *mcyE/ndaF* for microcystins/nodularins
- *cyrA* for cylindrospermopsin
- *sxtA* for saxitoxin

Understanding a bloom and its growth phases is key to detection and reducing the costs of mitigation.

Bloom Mitigation

When a cyanobacterial bloom begins, water quality data should be systematically collected to guide mitigation. Monitoring-plan detections act as triggers that increase testing and/or indicate needed changes in treatment. Mitigation strategies to use early in the process include aerating the water near reservoir intakes, alternating intakes (source switching), adjusting the pH to deter pH-sensitive organisms, and using algaecides. The goal is to control cyanobacteria through proactive monitoring before blooms can cause water quality problems (Taylor et al. 2006).

Most systems incorporate a multibarrier approach, combining reservoir management strategies with physical pretreatment, physical removal, conventional treatment, biological treatment, oxidation, and/or adsorption (Waer 2006). If an algal bloom occurs for Wichita Falls, the utility switches sources to the lake without the bloom, while the lake with the bloom is treated with copper sulfate ($CuSO_4$)

Lake Arrowhead Bloom Treated With Copper Sulfate and Citric Acid, June 2021

Figure 2

and citric acid ($C_6H_8O_7$). If blooms occur in both lakes, then treatment at the plant changes:

- Addition of chlorine dioxide (ClO_2) as a raw water primary disinfectant
- Addition of potassium permanganate ($KMnO_4$) in the plant lagoons and clarifiers
- Addition of powdered activated carbon (PAC) in the clarifier mix zone to adsorb and settle out T&O compounds

At these times, the laboratory increases testing and chemical addition in the plant or source waters until the bloom subsides.

Chemical oxidation can destroy cyanobacteria and their metabolites (T&O and cyanotoxins). ClO_2 is a preoxidant that can effectively remove geosmin and MIB. $KMnO_4$ is also commonly used early in treatment processes to maximize contact time, but it is less effective than ClO_2. Unlike many other oxidants, $KMnO_4$ produces little to no disinfection byproducts, and it also helps demobilize algal cells and settle them out before contact with a disinfectant, preventing cellular lysis and the release of intracellular compounds into the water. However, $KMnO_4$ is not as effective as other oxidants at removing geosmin and MIB and can discolor water at high doses—e.g., turn the water purple.

Ozonation, especially when it is combined with hydrogen peroxide (H_2O_2), can effectively destroy both geosmin and MIB (Wert et al. 2014, Westerhoff et al. 2006). Ozonation requires on-site generation, as does ClO_2, so both require skilled operators to monitor and control these systems. Adsorption is a highly effective treatment, and dosing PAC early in the treatment process before clarification allows time for organic compounds to adsorb onto the carbon particles and settle out. PAC is also commonly used with $KMnO_4$.

With data collected annually, a treatment plant can develop a sense or even a formal model for predicting an event based on early bloom data.

Case Study: June 2021 Bloom Cycle

A bloom event struck the city of Wichita Falls in June 2021 in Lake Arrowhead, which is a dystrophic lake due to high suspended solids and turbidity from clay. Temperatures had been cooler than normal, with

above-average rainfall during the previous several months. A cold front in early June, followed by a quick rise in temperature with heavy rains, created perfect conditions for a bloom.

The bloom was detected using flow-imaging microscopy, then measurements were taken to characterize the bloom, using a sonde at every foot of depth at the intake and upstream of the intake; samples were collected at the surface, middle (12–15 feet), and lake floor (24–30 feet). The lake was treated with $CuSO_4$ and $C_6H_8O_7$ at 1 mg/L, and profiling and sampling occurred within two days to gauge the effectiveness of the algaecide (Figure 2). $C_6H_8O_7$ lowers the pH at the dosing point, which increases the solubility of the copper and its effectiveness as an algaecide.

General Water Quality

Initial temperatures taken at the peak of the bloom showed a high of 30.7°C at the surface and 22.1°C at the lake floor (Figure 3). DO variations are normally within 1–2 mg/L throughout the water column, but measurements showed 10.8 mg/L at the surface and 3.8 mg/L at the lake floor. A thermocline, a change >1°C per foot of depth, was observed at 20 feet, with a reduction of 1.7°C and 2.1 mg/L DO in 1 foot of depth. Temperature and DO trends were directly proportional throughout the water column.

After $CuSO_4$ treatment (postbloom in Figure 3), there was a less pronounced variation in temperature, with the steepest decline at 29 feet, and a reduction of DO of only 0.2 mg/L throughout. This is a testament to the rapid swings in DO that can be seen during bloom periods because as blooms grow, photosynthetic activity increases and DO rapidly increases (Smith 2019). This is followed by a rapid DO depletion as blooms die, which can lead to hypoxia if left untreated.

The pH of Lake Arrowhead is normally between 7.9 and 8.2, but during this event the pH increased to 8.9 (Figure 4). The pH was elevated throughout the water

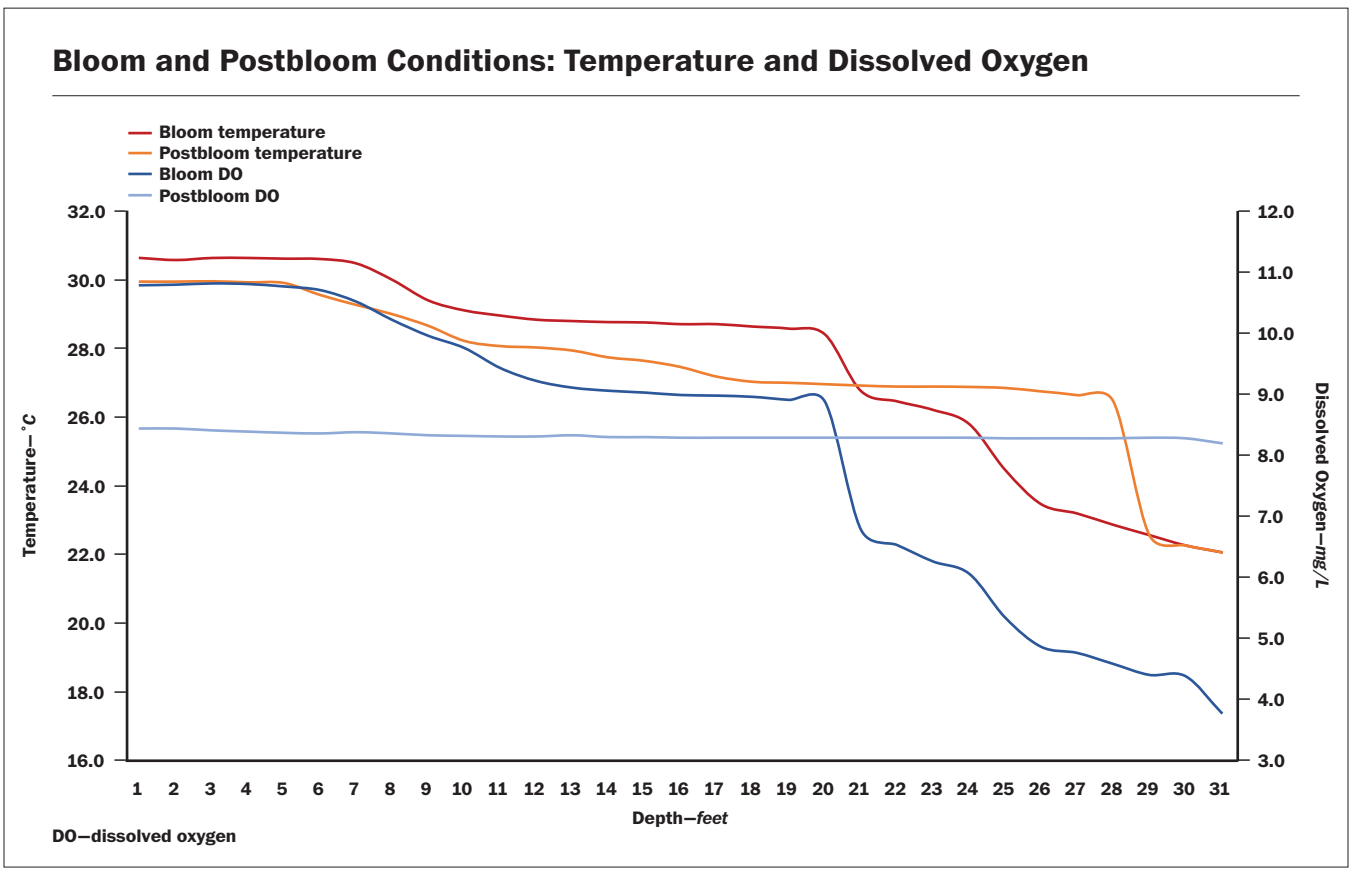

Figure 3

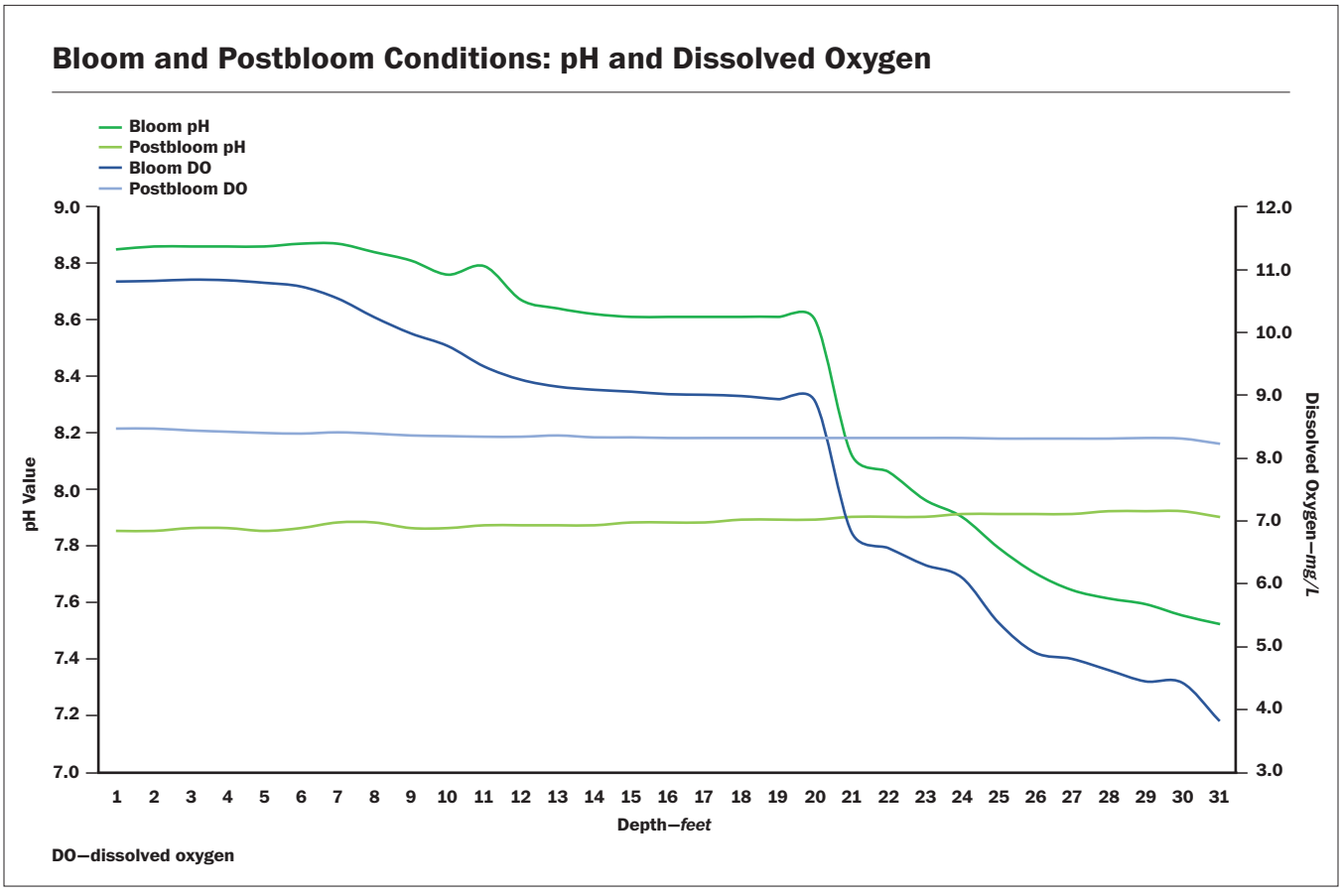

Figure 4

column and showed a sharp decline along with DO at the 20-foot thermocline. Postbloom pH after $CuSO_4$ treatment was measured in its normal range at 7.9 and remained consistent along with DO throughout the water column. pH and DO trends were directly proportional throughout the water column.

Pigments, Counts, and T&O

The geosmin concentration was measured at 1,050 ng/L during the peak of the bloom, with *Dolichospermum* (formerly *Anabaena*) counts at 1,837 chains/mL, and phycocyanin at 1.6 mg/L (Figures 5 and 6). After $CuSO_4$ treatment, the geosmin level decreased to 27 ng/L, with a reduction in *Dolichospermum* counts to 177 chains/mL, and phycocyanin down to 0.4 mg/L. The bloom was localized in the epilimnion, likely a result of the dystrophic nature of the lake and the presence of a thermocline. These data show a strong correlation between elevated concentrations of phycocyanin when cyanobacteria are present, and a sharp decline after $CuSO_4$ treatment.

Geosmin was also drastically reduced when the geosmin-producing *Dolichospermum* were killed. Saxitoxin-producing genes (*stxA*) by qPCR were also detected during the bloom at a low level of 0.31 gene copies/µL, and they fell below nondetect of <0.20 gene copies/µL after $CuSO_4$ treatment. Samples were analyzed for saxitoxin by enzyme-linked immunosorbent assay and were found to be nondetect at <0.05 µg/L.

Economic Impact of Early Detection

Since this monitoring program was put in place, the City of Wichita Falls has detected and mitigated 13 T&O events in its source waters and one produced in its filter

Elimination or reduction of blooms in the source water is less expensive than removal at the treatment plants.

media, spanning a total of 18 months over the past five years. Eleven events were narrowed down to a specific cyanobacteria taxon, including *Dolichospermum, Aphanizomenon, Microcystis,* and *Peridinium*. The plan's ongoing success relies on its integrated approach, bringing in multiple monitoring technologies from microbiology and analytical laboratories, with a heavy focus on proactive monitoring to avoid costly treatment mitigation during blooms.

This proactive approach allows the system to quickly respond to events and eliminate customer complaints. The plan is not foolproof, but the different layers provide multiple barriers to cover if one aspect fails. Early warning also saves money on chemicals; treatment of a bloom in its nascent stages is critical because large blooms are difficult to treat, requiring more chemicals and driving up mitigation costs (Buerkens et al. 2020b).

When bloom events in reservoirs are detected early, algaecide can eliminate the problem while in the early exponential growth stage (Figure 7). Lag phase is the initial stage when a cyanobacterial population's cells adjust to the environment, but conditions can quickly shift, driving the exponential phase in which cell counts continuously double for a period of time. The number of new cells appearing per unit of time is proportional to the present population. The stationary phase occurs when exponential growth ceases but the cells remain metabolically active, which may produce T&O compounds and/or cyanotoxins.

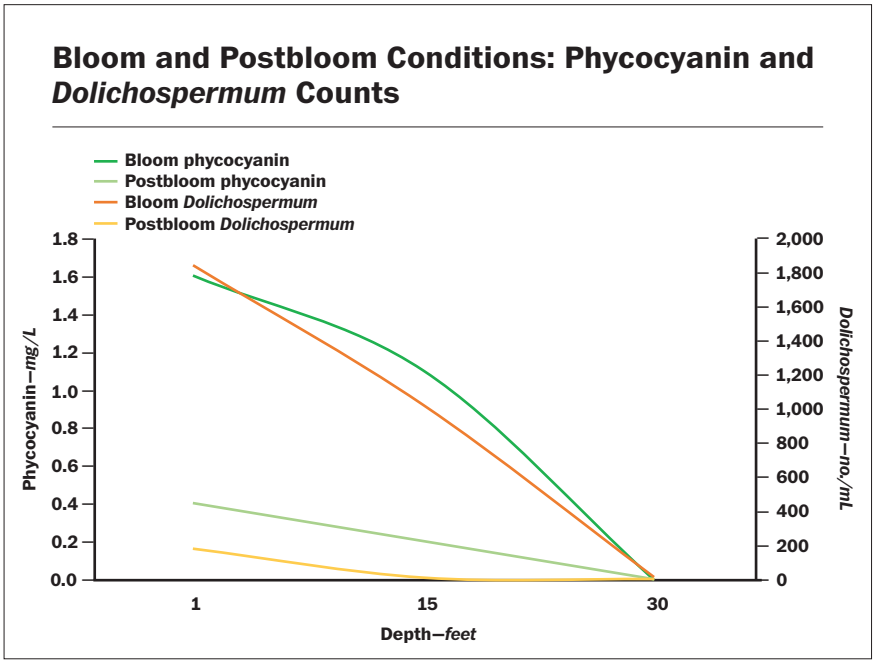

Figure 5

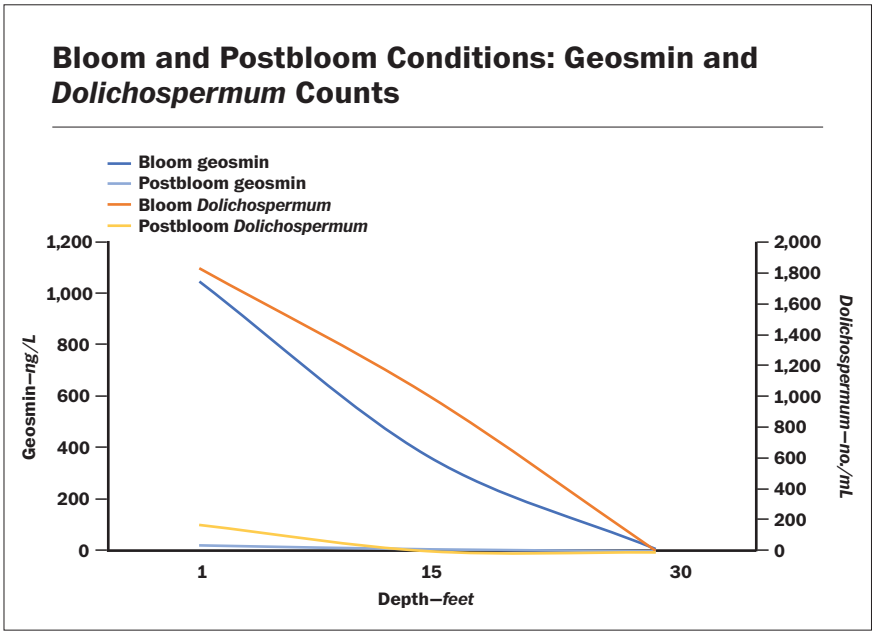

Figure 6

During the death phase, cyanobacteria die from lack of nutrients, temperature, DO, competition, or treatments such as algaecides. The death phase can level off, leading to a short lag phase followed by another exponential phase if conditions continue to be favorable. If left unchecked during the early exponential phase, cell counts can quickly multiply from a few hundred per milliliter to thousands. This creates a new set of issues once the cells make it into the treatment plants—e.g., removal of cells,

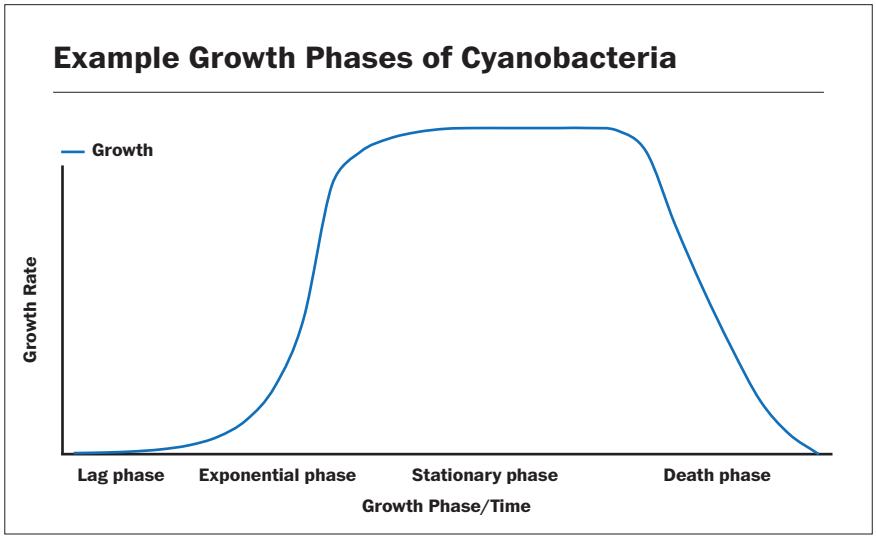

Figure 7

T&O compounds, and cyanotoxins, which points to the benefit of early detection and mitigation.

Elimination or reduction of blooms in the source water is less expensive than removal at the treatment plants. When cells are destroyed by oxidants during disinfection at the plant, intracellular T&O compounds can be released. These compounds are not removed by conventional filtration, so an adsorbent like PAC or granular activated carbon filters is needed, driving treatment costs up from spot-treating blooms in-reservoir to more expensive continuous in-plant treatment until the bloom subsides (Figure 8).

As an example with the City of Wichita Falls, two reservoir treatments of $CuSO_4$ over the course of one month at the reservoir intake costs about $4,000 each, while three reservoir treatments of $CuSO_4$ and continuous in-plant treatment with PAC and $KMnO_4$ have cost up to $8,000 the first week and $28,000 by the end of the month. Early treatment could save more than $20,000 during the course of the month, assuming the bloom was killed with the initial $CuSO_4$ treatment and in-plant treatment was not necessary.

When a cyanobacterial bloom begins, water quality data should be systematically collected to guide mitigation.

Advances in Cyanobacteria Characterization and Mitigation

Blooms are a ubiquitous issue, occurring worldwide and costing utilities millions of dollars annually. Utilities should consider the benefits of remote monitoring at multiple locations within a reservoir—e.g., intake, upstream of intake, and tributaries. Early warning of bloom formation allows for rapid spot treatment with an algaecide, which reduces costs. These warnings can be provided using equipment such as sondes or by using satellite imaging as with the US Environmental Protection Agency's (EPA's) Cyanobacteria Assessment Network Application (CyAN app), an approach that provides data in near-real time.

The science around cyanobacteria is quickly advancing, with new research on monitoring technologies and advanced treatments. The following sections highlight recent developments and resources.

Interstate Technology and Regulatory Council (ITRC)

In 2021 the ITRC published an open access document, *Strategies for Preventing and Managing Harmful Cyanobacterial Blooms (HCBs)*, focusing on planktonic cyanobacteria; a companion is underway that examines benthic cyanobacteria (ITRC 2022, 2021). This is an interactive resource that includes the latest research, focusing on monitoring, communication strategies, response planning, and management of blooms and nutrients. It also contains an in-depth visual guide and updated taxonomical links.

World Health Organization (WHO)

The WHO published an open access document, *Toxic Cyanobacteria in Water*, in 2021 as a revised edition. It reviews current knowledge about cyanobacteria, cyanotoxins, occurrences, exposure, nutrient loading, bloom monitoring, managing risk, laboratory analyses, and public health surveillance. It takes a multidisciplinary approach, with a specific focus on public health.

EPA

In 2021 EPA released the free CyAN app in collaboration with the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration,

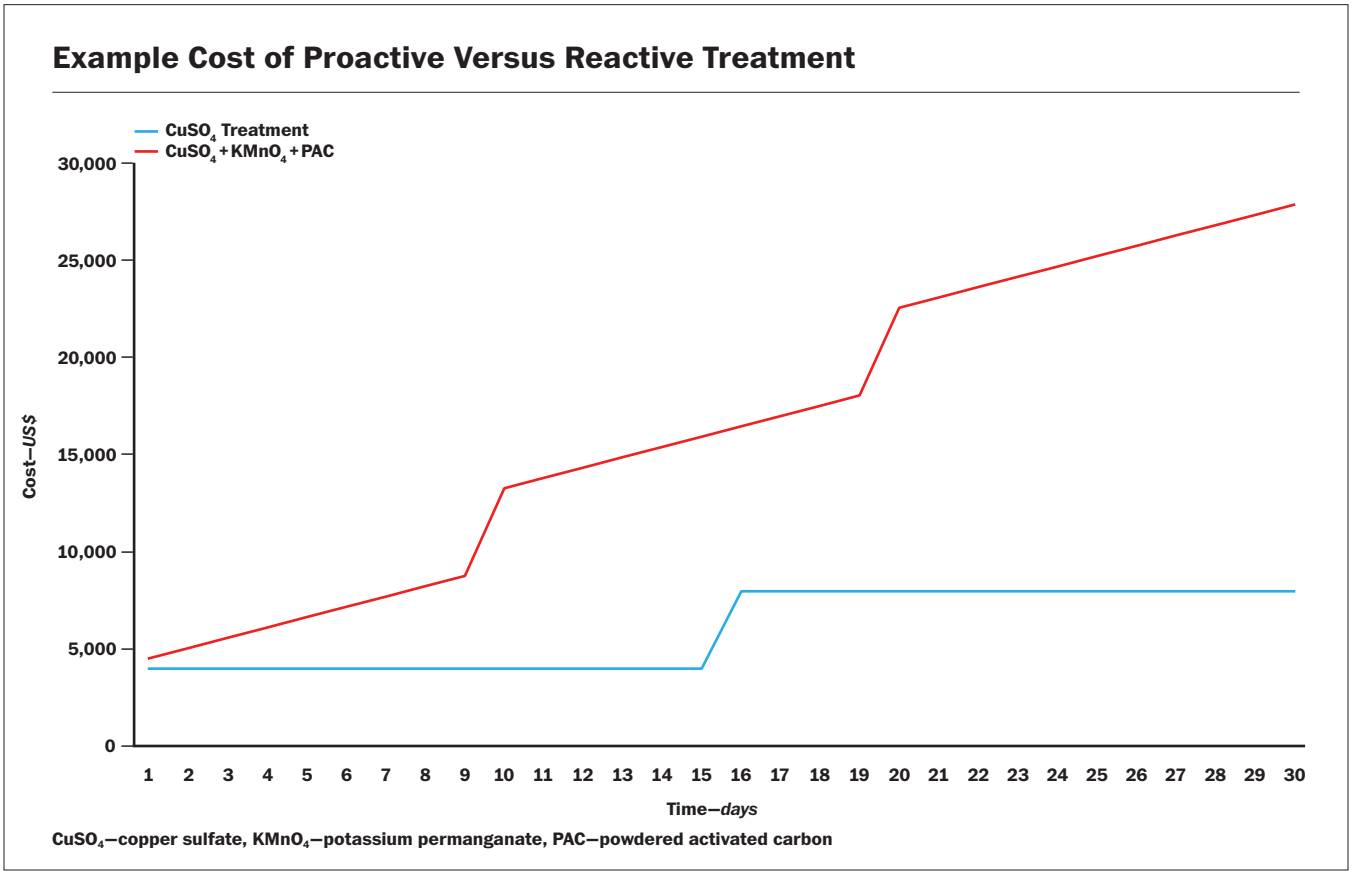

Figure 8

and the US Geological Survey. It is customizable and can be used on mobile devices, providing satellite bloom data from more than 2,000 lakes in the United States. It was developed for frontline workers as well as reservoir and water system managers to make data-driven decisions about blooms in their water bodies. The CyAN app can be used to determine when samples should be taken and when to issue public health advisories.

Association of Public Health Laboratories (APHL)

APHL published in 2021 an open access reference, *Cyanotoxins: A Guidance Document*; it is directed toward laboratories as an updated edition, providing resources for environmental and public health laboratories considering implementation of freshwater cyanobacteria and cyanotoxin testing. There are sections on updated federal, state, and WHO guidelines; a survey of methods and their limitations; and sections on sampling, partnerships, reporting, and public messaging.

The science around cyanobacteria is quickly advancing, with new research on monitoring technologies and advanced treatments.

AWWA

AWWA is in the process of approving a second edition of Manual M57, *Algae: Source to Treatment* (AWWA 2010). This edition will focus on eukaryotic algae and cyanobacteria, covering sampling and detection methods for cells, T&O compounds, and cyanotoxins, as well as updated classification, biology and ecology, and treatment and removal methods. New chapters cover remote sensing and molecular methods.

The Water Research Foundation (WRF)
WRF project 5080, *Assessment of Vulnerability of Source Waters to Toxic Cyanobacterial Outbreaks*, is underway. This project will evaluate existing data collected by water utilities, and it will produce an algorithm to be used in-bloom modeling and forecasting using water quality data. More than 30 utilities from across the United States are participating.

T&O Monitoring: An Evolving Process

The water industry continues to improve its understanding of why blooms occur, how to rapidly detect blooms and their metabolites, and ensure the tap water remains issue-free. As demonstrated by the City of Wichita Falls CEL, a proactive approach that harnesses the science driving bloom events can improve aesthetic water quality and customer perceptions of tap water.

Acknowledgment

The authors would like to thank the plant operators and mechanics who treat the lakes and make treatment changes at the plants when triggers are hit. They ensure that necessary adjustments are made after laboratory analysts produce the data.

About the Authors

Hunter Adams is the environmental laboratory supervisor at the City of Wichita Falls, Texas; hunter.adams@wichitafallstx.gov.

Stephanie A. Smith is a product segment manager at YSI-Xylem, Yellow Springs, Ohio.

Sam Reeder is the senior laboratory technician at the City of Wichita Falls, Texas.

Emily Appleton is a laboratory technician at the City of Wichita Falls, Texas.

Butch Leinweber is a maintenance supervisor at the City of Wichita Falls, Texas.

Steve Forbes is an operations supervisor at the City of Wichita Falls, Texas.

Polly Barrowman is the water markets manager at Yokogawa Fluid Imaging Technologies, Scarborough, Maine.

Greg Ford is the director of business development at Phytoxigene, San Diego, Calif.

Keisuke Ikehata is an assistant professor at Texas State University in San Marcos, Texas.

Mark Southard is the water purification superintendent at the City of Wichita Falls, Texas.

https://doi.org/10.1002/awwa.1901

References

Adams H, Southard M, Reeder S, et al. 2021a. *J AWWA*. 113:6:10. https://doi.org/10.1002/awwa.1743

Adams H, Reeder S, Southard M. 2021b. *J AWWA*. 113:8:40. https://doi.org/10.1002/awwa.1786

Adams H, Southard M, Reeder S, et al. 2020. A Turnkey Protocol for Detecting Taste and Odor Compounds in Drinking and Surface Waters by Gas Chromatography–Mass Spectrometry and Electron Capture Detector (GC–MS/ECD). *LC GC N Am*. 38:11:15.

Adams H, Buerkens F, Cottrell A, et al. 2018. *Opflow*. 44:12:20. https://doi.org/10.1002/opfl.1113

AWWA. 2010. Manual of Water Supply Practices M57, *Algae: Source to Treatment*. AWWA, Denver.

Buerkens F, Smith S, Ford G, et al. 2020a. *Opflow*. 46:10:10. https://doi.org/10.1002/opfl.1437

Buerkens F, Kilgore T, Adams H. 2020b. *Opflow.* 46:11:16. https://doi.org/10.1002/opfl.1454

Burlingame GA, Doty RL. 2018. *J AWWA*. 110:12:E1. https://doi.org/10.1002/awwa.1147

Burlingame GA, Booth SDJ, Bruchet A, et al. 2011. *Diagnosing Taste and Odor Problems Field Guide*. AWWA, Denver.

Dietrich AM, Burlingame GA, Hoehn RC. 2003. *Opflow*. 29:10:10. https://doi.org/10.1002/j.1551-8701.2003.tb01731.x

ITRC (Interstate Technology & Regulatory Council). 2022. *Strategies for Preventing and Managing Benthic Harmful Cyanobacterial Blooms (HCBs)*. ITRC, Washington.

ITRC. 2021. *Strategies for Preventing and Managing Harmful Cyanobacterial Blooms (HCBs)*. ITRC, Washington.

Pochiraju S, Hoppe-Jones C, Adams C, et al. 2021. *Wat Res X*. 111:100099. https://doi.org/10.1016/j.wroa.2021.100099

Smith SA. 2021. *Phycocyanin in HAB Monitoring: Dispelling Three Myths*. YSI/Xylem, Yellow Springs, Ohio. https://bit.ly/3rQg1f2

Smith SA. 2019. *J AWWA*. 111:11:14. https://doi.org/10.1002/awwa.1392

Southard M, Adams H, Reeder S, et al. 2021 (2nd ed.). *Taste & Odor Guidance Manual*. City of Wichita Falls, Texas.

Standard Methods for the Examination of Water and Wastewater. 2017 (23rd ed.). APHA, AWWA, and WEF, Washington.

Taylor WD, Losee RF, Torobin M, et al. 2006. *Early Warning and Management of Surface Water Taste-and-Odor Events*. AWWA Research Foundation, Denver.

Waer MA. 2006. *Opflow*. 32:6:1. https://doi.org/10.1002/j.1551-8701.2006.tb01868.x

Wert EC, Korak JA, Trenholm RA, et al. 2014. *Wat Res*. 52:251. https://doi.org/10.1016/j.watres.2013.11.001

Westerhoff P, Nalinakumari B, Pei P. 2006. *Ozone-Sci Eng*. 28:5:277. https://doi.org/10.1080/01919510600892836

Westrick JA, Szlag D. 2018. *J AWWA*. 110.8.E1. https://doi.org/10.1002/awwa.1088

WHO (World Health Organization). 2021 (2nd ed.). *Toxic Cyanobacteria in Water*. WHO, Geneva.