LAKE MANAGEMENT STRATEGIES FOR SOURCE WATER QUALITY MANAGEMENT

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Abstract. There is an overall increasing trend in algal blooms, most notably cyanobacteria-dominated algal blooms. Many water supply systems are plagued by such blooms, which places an added burden on the water treatment plant and increases operational costs. In addition to addressing the biomass from elevated algal/cyanobacterial growth, secondary metabolites, such as, taste and odor compounds must also be accounted for and sufficiently removed in the treatment plant. Furthermore, a group of toxic secondary metabolites produced by cyanobacteria, cyanotoxins have elevated concerns due to required tracking of potential toxins. Addressing these issues requires a holistic multi-barrier approach that encompasses treatment process improvements, short-term management and long-term restoration of the source water system, and watershed management. The focus of this paper will be on the source water component; it will outline both short-term management techniques that can minimize the impact on the water treatment plant and reduce the risk of cyanotoxin presence, and long-term restoration techniques to prevent excessive growth and blooms. A key point of the source water component is the need for more effective monitoring and data review as it will drive both short-term management decisions and long-term restoration options. Maintaining source water quality is imperative and requires active, data-driven management. Source water monitoring and data review are the first steps to mitigating excessive algal/cyanobacterial growth and blooms. Recommended strategies for source water management and the implications for water utilities will be presented.

INTRODUCTION

Algal blooms have become increasingly prevalent in the United States in both freshwater and salt water environments. While events such as red tides in Florida in 2017-18 have generated concerns about the environmental and economic impacts to local communities, there are concerns about how algal blooms may affect surface-water supplies. Water utilities are faced with more frequent and persistent periods of excessive algae growth in their surface water sources, especially reservoirs and impoundments that impact water treatment and result in taste and odor issues in the finished water. In addition, cyanobacteria (blue-green algae) blooms and the associated toxins have become a significant issue after the high-profile case in Toledo, Ohio in 2014 when a blue-green algae bloom (Microcystis) resulted in an order to *not drink the water* for three days. In 2015, the USEPA issued health advisory values for Microcystin (0.3 µg/L) and Cylindrospermopsin (0.7 µg/L) to assist water utilities in managing the potential health risks to their customers. The USEPA also added 9 cyanotoxins (6 microcystin variants, nodularin-R, Anatoxin-a, and cylindrospermopsin) and 1 group of cyanotoxins (total microcystins) to the fourth Unregulated Contaminant Monitoring Rule (2018 – 2020). Water utilities and source water managers are faced with an increasing and evolving problem with algae management that requires a comprehensive strategy that includes effective source water (and watershed) condition assessments, treatment options, improved predictive monitoring, lake restoration and management, and long-term watershed management to reduce nutrient loadings.

CONDITION ASSESSMENT

Assessing the conditions and ability to address issues caused by elevated primary producer growth, especially cyanobacteria is imperative. The conditions and ability of the treatment plant to assess issues such as Taste and Odor and cyanotoxin removal must also be assessed to outline goals for the source water and minimum raw water quality needed. Additionally, the treatment capacity sets the threshold for when short-term in-reservoir treatment is needed, largely algaecide. The physical, chemical, and biological conditions need to be assessed for source water systems to determine the current state and rate of water quality decline. This facilitates the planning and prioritization of management efforts. Current conditions along with potential futures within the watershed should be assessed to determine the level of effort needed to minimize the effect of land use and land cover on the source water quality.

MONITORING STRATEGIES

Algae and bacteria can be monitored through microscope enumeration and *in-situ* reservoir monitoring. The variance associated with microscopic enumeration presents several challenges when used as a primary monitoring tool. There are multiple sources of variance that hinder microscopic enumeration from representing *in-situ* conditions. Sources of variance include the spatial and temporal variance in the reservoir, volume of sample taken from the reservoir, volume of sample loaded on the microscope slide, the objective used, microscope camera (if used, limits field of vision), and density of the population. Within each source of variability, the probability of the enumeration being representative of in-reservoir conditions decreases. While there are ways to minimize the variation of microscopic enumeration, it should be paired with in-reservoir monitoring. It should also be noted that measures can be taken to ensure the microscope enumeration is representative of *in-situ* conditions, however, most of the equipment, personnel, and time are not always available.

A phytoplankton net can be used to concentrate the in-reservoir population in a controlled manner rather than towing the net in the reservoir. Additionally, a continuous flow centrifuge (CFC) can also be used to concentrate the in-situ population. The key is to concentrate the samples to minimize variability associated with a grab sample. The concentration factor can be easily accounted for in the conversion of raw microscopic date to the desired output (e.g. cell/mL). Quantifying the concentrated phytoplankton community increases the probability that it is representative of the in-reservoir population. One approach for concentrating the phytoplankton community with a plankton net uses a known volume of water (~5 gallons), which is taken as a grab sample from the monitoring location in the reservoir, which can then be concentrated in lab using a phytoplankton net or CFC. Ideally, CFC is the preferred option as it is more suited for source water management, but the equipment is not always available.

Ideally, the concentrated phytoplankton community should be assessed using either a Sedgewick-Rafter or a Palmer-Maloney counting chamber. The Sedgwick-Rafter is a 1 mL counting chamber that can be used with either a 10x or 20x objective, and the Palmer-Maloney counting chamber is 0.1 mL counting chamber that is used with either a 20x or 40x objective. For both counting chambers, the methods of transects should be employed for enumeration, which requires four transects to be quantified. This approach is the statistically standardized method of enumeration that is reported in experimental Phycology laboratory manuals (Lobban et al. 1988). However, this is a time intensive process. One sample could take up to six hours to count, which is why it is challenging to utilize as a primary monitoring technique. However, if the microscopic enumeration is coupled with in-reservoir monitoring the number of transects can be decreased. The goal is to identify the composition of the population and density of colonies and rafts and length of filaments.

Additionally, visual identification of organisms can also be challenging, and relies heavily on morphology of filaments, colonies, or rafts. There are some staining techniques that can be used to determine the difference between organisms (such as Lugol's solution), which can be used to determine if an organism is green algae or cyanobacteria. For example, *Raphidiopsis* is a cyanobacteria genus that it is commonly misidentified as *Ankistrodesmus*. Assessing the colony formation can aid in ID as *Raphidiopsis* does not appear in colonies and *Ankistrodesmus* does. Furthermore, Lugol's solution can be used to decipher between the two genera as *Ankistrodesmus* stores starches and *Raphidiopsis* does not. Therefore, *Ankistrodesmus* will turn black when stained with Lugol's and *Raphidiopsis* will not. This is important as the *Raphidiopsis* genus contains species that are known to bloom and has shown to produce intracellular saxitoxin.

In-reservoir analysis can be achieved in a timely manner by utilizing an *in-situ* fluorescent probe capable of estimating photosynthetic pigments. Each auto-fluorescent pigment has unique excitation and emission wavelengths, which the fluorescent probe exploits to estimate the in-reservoir concentration (μg/L). Fluorescent probes (e.g., YSI EXO Sonde) can be equipped with a chlorophyll-*a* and phycocyanin probe. The chlorophyll-a probe is used to estimate all photosynthetic organisms, and the phycocyanin probes estimates the cyanobacteria population. The fluorescent probes can be used to assess the water column in 1-m increments generating a vertical profile at monitoring locations. The water column profile will provide important information about the vertical migration of the plankton community, which is partially governed by stratification, nutrient availability, and sunlight. While algae and cyanobacteria will grow/survive throughout the whole reservoir, certain areas will possess ideal conditions for algal and cyanobacteria growth, thus readily promoting excess growth. These areas are typically in the littoral zone of the reservoir, which are usually shallow, more stagnate areas near the shore. It is important to outline the areas and monitor accordingly as they promote excess growth and play a key role in minimizing the observed accumulation, which is a function of flow and wind patterns. Given the exponential growth characteristics of the algae and cyanobacteria, in-reservoir monitoring should be done as frequently as possible. Weekly or biweekly monitoring of the reservoir at consistent locations in 1-m increments is recommended.

Microscopy analysis of the reservoirs is imperative for algal/cyanobacterial monitoring. Given the small amount of sample required, and the high spatial and temporal variability observed in the reservoir, microscopy analysis should be coupled with in-reservoir assessment. Coupling microscopy analysis with in-reservoir assessment with a fluorescent probe generates a dataset that can drive management and treatment decisions. The dataset generated from this approach can be used to statistically assess seasonal and yearly trends, which is valuable when constructing a management plan geared toward prevention. Moreover, this approach will account for the composition of the plankton community, which is vital because the dominant organism will govern the treatment and management approach. Monitoring in-reservoir conditions with a fluorescent probe also allows for optimized algaecide treatment. The data generated by in-reservoir monitoring will aid in determining both the location and time of treatment. The composition of the phytoplankton community, which is determined by the microscopy analysis, will provide insight on which algaecide product and dose is best suited.

LAKE RESTORATION AND MANAGEMENT

In the past, the burden of addressing decreased or temporarily impaired water sources has fallen on the treatment plant. However, an interdisciplinary approach to source water management and remediation can lessen the burden on the treatment plant and increase raw water quality. The most effective way of addressing HABs/cHABs and subsequent taste & odor issues is by mitigating the driving forces. However, mitigation is problematic due to elusive driving forces that are not easily reversed. Combatting eutrophication and the effects of climate change are challenging and lack straight forward solutions. Furthermore, the management approach must not only account for current and future impacts from eutrophication but must also address the ecological damage of past conditions. The first step in addressing this issue is preserving current water quality and preventing of elevated growth and HABs/cHABs. Short-term management should promote maintaining and increasing observed water quality, which facilitates benefits in a timely manner that can then fund subsequent phases. Short-term management can offer stability, reduce the burden on the treatment plant, and lower chemical demand/usage (e.g. PAC).

The ideal approach couples limnology and water-resource engineering to provide sustainable and effective short-term management programs. A common issue that challenges numerous source water systems is elevated cyanobacteria growth, which can lead to geosmin and MIB issues. Elevated cyanobacteria can promote a further decline in raw water quality due to the endotoxins that surround the cell wall, which should not to be confused with cyanotoxins. Endotoxins further reduce the biodiversity in the system, which in turn promote cyanobacteria dominance and elevated growth as it is symptomatic of ecosystem imbalance. It is important to minimize cyanobacteria growth in a holistic and timely manner to protect against the elevated endotoxin presence and subsequent exposure as the cumulative effect can rapidly deteriorate source water conditions.

The most commonly used short-term management strategy for source water is copper treatment to reduce populations of primary producers that are associated taste and odor compounds and toxins. However, Hazen utilizes alternative management techniques to copper-based treatments, chiefly hydrogen peroxide-based treatments. Hydrogen peroxide treatment has shown to hold a biological residence through what is anticipated to be either a quorum sensing mechanism or horizontal gene transfer, which promote prolonged expression (approx. 8 weeks). Additionally, hydrogen peroxide treatment down-regulates expression of certain gene cluster associated (*mcyD* transcription) with microcystin synthesis (Qian et al. 2010). Moreover, hydrogen peroxide treatment does not leave a residual and can specifically target cyanobacteria unlike copper-based products by exploiting the physiological difference between prokaryotic cyanobacteria and eukaryotic algae. The aim of hydrogen-peroxide based treatment is to minimize photosyntheticly viable and secondary metabolite synthesis rather than promoting cell lysis and death of an established population. The effectiveness of hydrogen peroxide treatment is heavily contingent upon the treatment approach, which needs to be customized for each system based on unique characteristics. The goal of hydrogen-peroxide treatment is to target cyanobacteria by exploiting a physiological difference between prokaryotic cyanobacteria and eukaryotic algae to shift dominance away from cyanobacteria.

Short-term management practices should be optimized to increase the observed benefit and minimize any adverse impacts associated with management practices (e.g. ecotoxicity). The goal is to shift short-term management from reactive to a preventative approach, which can be achieved with customized management strategy that utilizes the findings from monitoring data.

Short-term management is highly beneficial. However, the root of the ecosystem imbalance and overproduction leading to reduced water quality needs to be addressed. Therefore, it is vital to develop a long-term source water restoration plan to marginalize the driving forces behind reduced raw water quality, such as elevated primary producer growth and associated secondary metabolites (e.g. geosmin, MIB). The long-term restoration plan will also aim to overcome the implications of past damage, reduced biodiversity, nutrient accumulation, and protect against future stressors. The impact of climate change on the future of source water systems as it pertains to cyanobacteria and associated geosmin, MIB, and cyanotoxins is important as it will further stress the system and favor cyanobacteria. Therefore, it is important to note only restore the system but to increase its resiliency. It is helpful to consider the source water system as a biological reactor used to promote stability and nutrient loss from the internal overloaded cycles, and to support the reestablishment of healthy balance following a disruption from more extreme weather events.

Constructing a long-term source water restoration plan to address the causes of reduced raw water quality is imperative as each design is complex, with multiple phases, and must be implemented in a spatially complimentary manner. Therefore, it is important to construct a restoration plan that incorporates designs, prioritization, preliminary studies, implementation phases, monitoring, and post-implementation maintenance. Delineating the appropriate techniques, integrating techniques, finalizing the design, and outlining milestones in the implementation process on the front-end will ensure timely forward progress and a successful implementation.

Additionally, proper design of such remediation and restoration techniques requires a considerable amount of planning and preliminary data collection to assure success. A key aspect that goes into the planning phase is the collection of baseline data that can be used to assess the performance and benefit of such restoration efforts. Ideally, the planning phase would also include bench-scale and pilot-scale testing to ensure optimized phytoextraction rates and allelochemical secretion. Additionally, each system will have a unique restoration plan that is tailor-made based on observed conditions and stressors. Some of the general techniques that are commonly used are hypolimnetic oxygenation, littoral zone restoration, floating wetland, and Hazen's custom hydroponic phytoremediation in littoral and transitional (littoral to limnetic) zones. The goal of the restoration plan is to stabilize the ecosystem, address past accumulation of nutrients, and protect the system against future conditions and influent loads.

Hypolimnetic oxygenation can be effective at minimizing the phosphorus flux from sediment. The goal is to minimize the potential for phosphorus flux with minimal disruption to the system. Hypolimnetic oxygenation requires careful design and control. For example, it is important to not induce mixing as it will increase the hypolimnetic oxygen demand; thus negating the intent as anoxic conditions will promote phosphorus flux from sediment. Further, mixing the water column will put more nutrients into the epilimnion without actively switching dominance away from highly competitive cyanobacteria. Action needs taken to switch dominance to ensure suppression of cyanobacteria. Additionally, oxygenation is more effective than aeration in this aspect due to the atmospheric nitrogen introduced by aeration. Diazotrophic cyanobacteria will benefit from the gaseous nitrogen, which will subsequently provide a competitive advantage. It is also important to note the role of biological communities on the release of bound phosphorus through the extracellular enzyme phosphatase, which is synthesized and released based on dissolved phosphorus concentrations. Additionally, the impact on the nitrogen cycle should also be accounted for as elevated oxygen will suppress the synthesis of nitrate reductase enzyme. Nitrate reductase is an iron and molybdenum containing enzyme that facilitates the first step in both pathways of dissimilatory nitrate reduction, which are nitrate ammonification (end product is ammonia) and denitrification (end product is nitrogen gas). This is important because dissimilatory nitrate reduction is the ideal mechanism to address agricultural and sewage pollution as it plays a vital role in completely degrading complex organic matter to terminal end products and depletes pore-water nitrate (Konhauser 2007). Further, the ideal pathway of dissimilatory nitrate reduction is denitrification as it promotes nitrogen losses from the internal cycle, whereas nitrate ammonification promotes recycle.

The littoral zone is an important habitat within the aquatic system. A healthy littoral zone will contain a number aquatic macrophytes both fully and partially submerged and an array of invertebrates and vertebrates. It can serve as an internal buffer shielding the limnetic zone from an array of adverse impacts such as precipitation-drive pulse input of nitrogen and phosphorus to the aquatic system. The zooplankton community in the littoral zone differs from the limnetic zone in both diversity and quantity. Most notable are heavier crustaceans, such as Daphnia, Copepods, and some Rotifers. The denser more diverse zooplankton population in the littoral zone puts more grazing pressure on the phytoplankton community. A healthy zooplankton community can rapidly turnover a large portion of primary producers. Tadpoles are nother notable organism in the littoral zone, which are significant consumers of primary producers. The periphyton in the littoral zone is an important ecological and pollution indicator. Deterioration of the littoral zone and the destruction of necessary habitats for invertebrates from erosion hinders the dynamics and balance between periphyton. Assessing and outlining ways to restore the littoral zone will significantly aid in balancing the ecosystem and reestablishing the competitive order. The approach to littoral zone restoration is highly-dependent on in-situ conditions and vulnerability during precipitation events. A few examples include bank stabilization by both plants and wiring, native submerged plants that promote biofilm formation and support larger zooplankton, aquatic macrophytes (e.g. tall grass), and minimize or eliminate copper-based algaecide treatments in littoral zone. Therefore, excessive growth of primary producers, such as cyanobacteria can be suppressed. Additionally, the aquatic system will have an internal buffer, which can preserve water quality long-term.

Floating wetlands are carefully constructed ecosystems that reside in the photic zone that promote native species, remove nutrients (e.g., nitrogen, phosphorus), trace metals (Fe, Mg, Mn), and naturally suppress phytoplankton communities. A floating wetland is a generic name for phytoremediation with no standardized approach. There are numerous ways to design and implement this phytoremediation approach. However, the mat-based design has limitations due to shading of the photic zone. This hinders the restoration process and suppresses all photosynthetic organisms, which negatively impacts the food web. Therefore, Hazen utilizes an approach that is similar to hydroponic growth systems. This approach differs greatly from traditional phytoremediation techniques as it is less invasive. Furthermore, the root system is directly exposed to the photic zone. The root systems also promote biofilm production comprised of an array of common heterotrophic bacteria (species from the *Pseudomanas* genus) that have enzymes capable of breaking down 2-MIB, Geosmin, and cyanotoxins. First and foremost, phytoremediation should utilize native aquatic macrophytes. Multiple native aquatic macrophytes should be utilized so that the entire grow season has equal treatment. Furthermore, the root systems will release an allelochemical that will naturally suppress phytoplankton growth. Implementing phytoremediation aids in balancing the ecosystem, addressing increased nutrient loading. One benefit to utilizing phytoremediation is the ability to remove nutrients from the aquatic system. Once the plant has incorporated common macronutrients (nitrogen and phosphorus), the biomass can be harvested, removing the nutrients from the internal aquatic system. This benefit is especially important when addressing legacy nutrients.

WATERSHED MANAGEMENT

One of the long-term goals for management of algae blooms in water supply reservoirs should be to reduce the loadings for nutrients, primarily phosphorus, although nitrogen can be the limiting nutrient in some situations. In 2009, Dobbs et.al. compared available data on total phosphorus and nitrogen in freshwater rivers and lakes across all 14 USEPA nutrient ecoregions and over 90% of the rivers exceeded reference values for nutrients (Dobbs, et al., 2009). Recognizing the potential impacts on unchecked nutrient loadings the USEPA developed recommendations for development of numeric nutrient criteria (NNC) in 2012 but few states have implemented NNC and limited progress in actual nutrient reductions have been documented (ACWA, 2017; https://www.epa.gov/). This gap in regulatory requirements for nutrient reductions leaves much of the responsibility for nutrient management to local governments and utilities that have water supply reservoir eutrophication issues.

To effectively address nutrient loadings, water resource managers should be focused on working with local governments, land owners, and agricultural interests to develop strategies for reducing nutrient loadings to water supply watersheds. In Georgia, and most states in the southeast, the ability of water utilities to address non-point source loadings to water supply watersheds is limited as utilities rarely have land use permitting and/or planning authority. Therefore, more collaborative strategies and demonstration projects are likely to have the most benefit. For example, water resource managers may consider developing a water assessment, consistent with the USEPA 9-element plan (USEPA, 2008), to identify existing conditions, primary nutrient sources, potential target areas for watershed improvements, and funding sources for implementation. Often the water resource manager or utility owns land or buffers around the reservoir that may be used to implement best management practices or stream restoration projects to directly improve water quality or reduce nutrient and sediment loadings. In many states, Section 319 grant funding may be available to support project implementation.

The focus for watershed management should be on the need for long term reductions in nutrient and sediment loadings from the watershed. While this may be the most problematic element of the *watershed to tap* strategy, it is a critical component of a comprehensive strategy for water supply reservoir water quality management and protection.

CONCLUSIONS

By increasing source water quality and optimizing management, the burden on the treatment plant can be reduced and a cost benefit can be obtained due to the increased treatability. The multi-tiered approach will include both short-term and long-term management strategies geared towards preservation of water quality and prevention of HABs/cHABs and taste and odor issues. The short-term approach will include a multi-product algaecide with the option of coupling with in-situ Alum feed. This short-term approach will provide the needed suppression while accounting for long-term adverse effects. This will allow time to plan, design, budget, and implement long-term management strategies. The long-term management techniques described herein are imperative to balancing the ecosystem, which is the most effective way of improving water quality, preventing HABs/cHABs and subsequent taste and odor issues, and optimizing operations at the treatment plant.

REFERENCES

Association of Clean Water Administrators, 2017. Nutrient Reduction Progress Tracker Version 1.0-2017. Report published by ACWA. 31 pp.

Dobbs, Walter K., Wes W. Bouska, Jeffrey L. Eitzmann, Tyler J. Pilger, Kristen L. Pitts, Alyssa J. Riley, Joshua T. Schloesser and Darren J. Thornburgh. 2009. Eutrophication of U.S. Freshwaters: Analysis of Economic Damages. Environmental Science and Technology, 43(1):12-19.

https://www.epa.gov/nutrient-policy-data/state-progress-toward-developing-numeric-nutrient-water-quality-criteria

Konhauser, K. (2007) Introduction to Geomicrobiology. Blackwell Publishing.

Lobban, C., Chapman, D., Kremer, B. (1988). Experimental Phycology Laboratory Manual. Cambridge University Press.

Qian, H., Yu, S., Sun, Z., Xie, X., Lui, W., Fu, Z. (2010). Effects of Copper Sulfate, Hydrogen Peroxide, and N-phenyl-2-naphthylamine on Oxidative Stress and the Expression of Gene Involved Photosynthesis and Microcystin Disposition in Microcystis Aeruginosa. Aquatic Toxicology 99:405-412.

United States Environmental Protection Agency, 2008. Handbook for developing watershed plans to restore and protect our waters, Washington, D.C.: Office of Water, Nonpoint Source Control Branch, United States Environmental Protection Agency.