Harmful Algal Bloom Control Methods Synopses
Developed by the NEIWPCC HAB Workgroup's Control Methods – BMPs Focus Team (Northeast state health and environmental agency staff).

The New England Interstate Water Pollution Control Commission is a non-profit organization established through an act of Congress in 1947. NEIWPCC strives to: coordinate activities and forums that encourage cooperation among the states; educate the public about key environmental issues; support research projects, train environmental professionals, and provide overall leadership in the management and protection of water quality.

Harmful Algal Bloom Control Methods

Introduction

Background:

Cyanobacteria-associated harmful algal blooms (HABs) and their toxins are a growing concern in the Northeast. The frequency of HAB occurrence is on the rise and HABs have been associated with human health impacts including skin rashes, asthma exacerbation, gastrointestinal illness, and liver damage. Potential neurological impacts have also been suggested. Effects can be even more pronounced, sometimes even fatal, in animals ranging from cattle to dogs. HABs have direct implications for the use of waterbodies for recreation and drinking, and for the overall degradation of aquatic resources.
In the absence of federal cyanotoxin guidance (planned for development in 2015 and 2016), states continue efforts to keep recreational and drinking waters safe through HAB monitoring programs, outreach and education, and official regulations/guidance to prohibit or advise against use of affected waters. NEIWPCC coordinates a Harmful Algal Blooms Workgroup to facilitate regional dialogue and develop working documents addressing specific priority issues related to cyanobacterial blooms. Some of these priority topics for Northeast state agencies include methods for monitoring and analyzing cyanobacteria, sharing processes and procedures for issuing advisories and closures on affected waterbodies, and providing guidance for drinking water facilities on how to handle potentially toxic blooms in their water supplies.

The focus of this document pertains to another priority area from the workgroup, control or treatment methods to manage cyanobacteria. Our Control Methods – BMPs Focus Team, comprised of members of the larger HAB Workgroup, has developed this document as an introduction to HAB treatment methods. This document is targeted for lake communities, drinking water suppliers, and other lake managers who are interested in learning more about potential methods to treat HABs in their waterbodies.

Important Notes:

- Successful HAB treatment of larger lake systems is extremely difficult. While some have explored treatment of isolated reaches of larger waterbodies, the methods discussed in this document are more applicable to smaller lake systems. Pilot studies on larger lakes are in progress, but understandably, the costs associated with these methods are even more significant.
- Treatment methods are generally short-term fixes to larger nutrient loading issues. While bloom management techniques may be able to treat the symptoms, the root cause of blooms is usually loading of nitrogen and phosphorous. Effective watershed management to reduce nutrient pollution to a waterbody is often difficult, expensive, and time consuming. Regardless, it is key to reducing the occurrence and frequency of HABs and to addressing other water quality problems associated with eutrophication. Future updates to this document will include more information on strategies that may be effective as longer-term solutions to HAB issues (in concert with nutrient pollution management), such as biomanipulation.
- Many of the options below may also be effective for drinking water supplies, but special caution needs to be taken regarding the potential to lyse cells and release toxins into the water column. Drinking water suppliers should also consider any other sources at their disposal when assessing solutions to address a bloom in their main source water supply.
- Once a large HAB has formed, there are few options that are effective for removing it without risking the release of toxins. Many of the methods listed below are more likely to prove effective in preventing blooms if they are implemented prior to, or in the early stages of, bloom formation. They may be more aptly considered preventative measures than treatment methods.

This document IS an assessment, from individuals working in state environmental and health agencies in Northeast states and compiled scientific literature, of personal experience and scientific literature regarding a range of common HAB treatment methods. Other groups with relevant expertise, such as the NEIWPCC Ground Water / Source Water Protection Workgroup, were consulted as part of the development of this document. We discuss the method employed by each option for controlling blooms, application methods and dosing, and key considerations and limitations. It will serve as a starting place to explore options for controlling cyanobacteria blooms

This document IS NOT a comprehensive list of all possible treatment method options. It is not an endorsement of any given product or method, and any specific products that are mentioned are simply for reference or to provide an example. It is not a complete set of step-by-step guidance to treat a bloom in any specific waterbody or with any specific treatment method – we refer any parties interested in learning more to their state's permitting department, and to one of their local professional lake management consultants. Finally, the views expressed in this document are a product of the individuals involved: this document does not represent an official position of any state or federal agency or commission.

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Permitted Algaecides: Only use U.S. EPA- and State-approved algaecides - applications of other substances are illegal. Many states require certification prior to application. To find out more about restrictions in your state, see the list below. **Consult your state permitting department for more information, including dosage guidance.**

- EPA: http://water.epa.gov/polwaste/npdes/pesticides/NPDES-Pesticide-Permitting-Decision-Tool.cfm, & via *NPIRS - National Pesticide Information Retrieval System*): http://ppis.ceris.purdue.edu/Default.aspx.
- State NPDES Pesticides Contacts: http://water.epa.gov/polwaste/npdes/pesticides/NPDES-Pesticides-State-Contacts.cfm
- CT: http://www.ct.gov/deep/lib/deep/pesticide_certification/Supervisor/aweeds.pdf
- MA: http://water.epa.gov/polwaste/npdes/pesticides/NPDES-Pesticide-Permitting-Decision-Tool.cfm, http://water.epa.gov/polwaste/npdes/pesticides/upload/pgp_part9.pdf
- ME: http://www.state.me.us/dep/water/wd/aquatic-pesticide/index.html
- NH: http://agriculture.nh.gov/publications-forms/documents/registered-pesticide-products.pdf
- NY: http://www.dec.ny.gov/chemical/70489.html, http://www.dec.ny.gov/docs/water_pdf/pesticdefactsheet.pdf
- RI: http://www.dem.ri.gov/programs/bnatres/agricult/pdf/regpests.pdf
- VT: http://www.anr.state.vt.us/dec/waterq/permits/htm/pm_anc.htm

Algaecides

Background:

Chemical control of algae in water supply storage has been a widespread water quality management practice for over 100 years. Algae blooms can clog filters and otherwise increase treatment costs and efforts. Historically, copper sulfate and other algaecides have been used to destroy or breakdown this excessive biomass before it enters the drinking water treatment plant. Other methods involving metals (Al, Fe, Cu, Ag, Ca), photosensitizers (hydrogen peroxide, phthalocyanines, TiO2), herbicides, and chemicals derived from natural compounds have proven effective in managing HABs as well. Chemical methods have been regarded as economical and fast-working, but frequently have a higher likelihood of toxicity and non-target response than other available methods.

Advantages and disadvantages of chemical measures for management of cyanobacterial blooms (adapted from Jancula & Marsalek 2011 - see reference for a full review of each method)

Method or technique	**Advantages**	**Disadvantages**
Metals with the mode of action based on cell toxicity (copper, silver)	– Extremely low price	– Toxicity against non-target species – Accumulation in the environment – Release of toxins from algal cells after treatment
Hydrogen peroxide	– Low price – Low toxicity for non-target species – Fast degradability – Selective towards cyanobacteria	– Risky manipulation with concentrated hydrogen peroxide – Fast degradability (short time of action) – Risk of release of toxins from algal cells after treatment (however, strong oxidant component may enhance toxin degradation)
Phthalocyanines	- High toxicity towards photoautotrophs – Biodegradable	– Insufficient knowledge about toxicity towards fish and macrophytes – Blue/green coloration – Risk of release of toxins from algal cells after treatment
Titanium dioxide and other insoluble photosensitizers	– Toxicity towards photoautotrophs via ROS production	– Insoluble in water
Herbicides (diuron, endothal, atrazine, simazine and others)	– Low price – Toxicity towards photoautotrophs	– Toxicity against non-target species – Accumulation in the environment – Toxic residues – Release of toxins from algal cells after the treatment
Chemicals derived from natural compounds	– Effective in low concentrations – Biodegradable – Natural products	– Preparation of extracts or isolation of alkaloids in high amounts – Unknown toxicity towards other non-target species – Price for extraction/synthesis – Risk of release of toxins from algal cells after treatment

Post-Treatment Considerations:

- **Intercellular Toxins:** Lysis of cells can occur through chemical treatments, and can cause the release of toxins, taste and odor compounds, and other potentially problematic dissolved organic compounds. This can greatly reduce the effectiveness of coagulation, sedimentation, and even filtration during drinking water treatment, processes that can effectively remove cyanotoxins when contained within intact cells. It is possible for dissolved toxins to remain at problematic levels in waterbodies for several weeks or more.

- **Environmental Effects:** Some argue that chemical treatments such as copper sulfate do not cause extensive environmental damage when properly applied, but this has been an issue of debate for some time (Jancula & Maršálek, 2011). It is also important to remember that copper and other heavy metals are not biodegradable, and once they have entered the environment their potential toxicity is controlled largely by their speciation or physicochemical form (WHO, 1999). It is possible to reduce the total metal needed under certain conditions using chelated products that keep copper in solution longer.

Application Frequency/Dosing:

- **Drinking Water Supply Treatment:** It has been common for water suppliers to simply treat blooms as they occur or treat at fixed intervals, as waiting for full bloom conditions to initiate treatment can lead to more toxin release. Also, bloom conditions often raise pH and dissolved organic carbon levels, and this tends to diminish the effectiveness of treatments such as copper sulfate. The current thinking suggests that fixed interval treatments should be avoided, and treatment should be triggered by changes in water quality that indicate a cyanobacteria bloom could be on the way. Historical records of bloom occurrence, raw water turbidity, and changes in filter backwash frequency can be effective starting points to begin optimizing algaecide treatments.

- **General Algaecide Application Recommendations:**
  Alkalinity, pH, and DOC can be used to predict effectiveness of algaecides. For instance, copper chelates are recommended over copper sulfate when high DOC or alkaline pH conditions are present.

  Given that cyanobacteria tend to accumulate near the surface (especially under calm conditions), it is possible to take advantage of these buoyancy characteristics and accumulation in the surface layer of a stratified lake to achieve optimum dosing and minimize chemical use. Furthermore, if scums can be identified, treatment should be concentrated in these areas.

  Furthermore, applying early in the morning has shown to be effective - cyanobacteria tend to be most buoyant at this time and are likely to be near the surface if conditions are calm. Morning treatments are also often better because pH is lower at this time (photosynthesis throughout the day tends to drive up pH as CO_2 is taken up by cells.

  These are simply general recommendations and considerations when exploring algaecides as a HAB treatment option. Manufacturers provide advice on the use and application of their products - comply with all recommendations. Furthermore, only use U.S. EPA- and State-approved products - applications of other substances are illegal! **Consult your state permitting department for more information, including dosage guidance.**

- **Application Methods:**
  - Spraying (most effective): Dilute product into chemical spray tank. Target spray to areas with visible blooms if possible.

  - Spot Treatment: Using the same spraying method as listed above, spot treatment can be used for intermittent treatment. Especially useful when a breeze concentrates cyanobacteria on one shore.
  - Dragging Bags: Towing water-permeable bags of copper behind a boat is another common application method, but disadvantages include that it is labor intensive, dosages are harder to control, and chelated products cannot be applied in this manner.

- **Safety:** Follow guidance provided by supplier on safe handling. Wear protective clothing, boots, gloves, and goggles. Use air filter masks if the chemical is in powdered form.

Equipment Required:

Algaecide product, boat, protective clothing (gloves/goggles/boots), and chemical spray tank or bag/sock and rope.

Cost:

See table above for a general comparison of costs. To provide a specific example, copper sulfate has historically been considered the most effective control method for algae based on cost alone. Costs could change significantly depending on the frequency of treatment, regional suppliers and prices, and dosage required for a specific waterbody. Assuming a dosage rate of 2.7 pounds per acre foot (following the recommendation of one product), treatment for a 50 acre lake would be expected to cost under $5,000 per bloom event if applied properly so as to only treat when cyanobacteria are congregated on the surface layer. This does not include any additional monitoring costs incurred.

Limitations/Considerations:

- **Cell Lysis:** Algaecides must be used with particular caution to avoid release of intracellular toxins. Algaecides should be used when cell numbers are low to avoid excessive toxins or taints following rupture of the cells. This should be checked by conducting post-treatment monitoring of toxin levels and cell counts.
- **Chemicals and Water Quality Standards:**
  - Chemicals used for algaecides must not be applied in doses that would cause the waterbody to exceed applicable water quality standards criteria.
  - Chemicals in algaecides do not degrade, and once applied, may persist in waterbodies indefinitely. Caution needs to be taken to avoid accumulation of algaecide chemicals such as copper in sediments.
- **Non-Target Organisms:** Algaecides can be toxic to non-target organisms. Follow state guidelines on dosing.
- **Short- vs. Long-Term Management:** Algaecides are generally a short-term solution to a pending bloom, but do not prevent future blooms post-application. Ongoing application could be needed if this is the only treatment method used.
- **Permitted Algaecides:** Only use U.S. EPA- and State-approved algaecides - applications of other substances are illegal. Many states require certification prior to application.
  - To find out more about restrictions in your state, see the list below. **Consult your state permitting department for more information, including dosage guidance.**
- **Waterbody Characteristics:** Determine current pH, alkalinity, and DOC to identify the most effective algaecide.
  - When possible, determine a waterbody-specific dose rate.

- **Drinking Water Supply Treatment:** Treatment should be triggered by changes in water quality that indicate an upcoming cyanobacteria bloom.
    - Historical records of bloom occurrence, raw water turbidity, and changes in filter backwash frequency can be effective starting points to begin optimizing algaecide treatments. This may require developing a formal water quality monitoring program.
- **Monitoring:** For all algaecides, monitor for effects on target and non-target organisms as well as cyanotoxin and treatment chemical concentrations before, during, and following application.

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Barley Straw

Background:

The use of decomposing barley straw for the control of algae and cyanobacteria has been the subject of considerable interest and investigation since the early ‘90s (Welch et al. 1990, Newman and Barrett 1993, Jelbart 1993, Barrett et al. 1996). Laboratory studies have suggested algistatic effects on both green algae and cyanobacteria. Several causes have been suggested for the observed effects, including the production of antibiotics by the fungal flora responsible for the decomposition, or the release of phenolic compounds such as ferulic acid and p - coumaric acid from the decomposition of straw cell walls (Newman and Barrett 1993).

While reservoir trials with barley straw appeared to confirm these laboratory observations (Barrett et al. 1996, Everall and Lees 1996) other trials resulted in no observable effect (Jelbart 1993, Cheng et al. 1995). More recent studies have confirmed the effectiveness of barley straw treatment for in situ treatment, noting in one case study that algal communities shifted from cyanobacteria to diatoms (Islami & Filizadeh 2011) and in another that this could be a viable method in larger lakes in the United States (Haggard et al. 2013).

Because of its affordability and ease of use barley straw is used in many reservoirs and dams in the United Kingdom with positive results. A fact sheet prepared by the Centre for Hydrology and Ecology’s Centre for Aquatic Plant Management (2004) in the U.K. details the application and mechanism of the effect of barley straw for the control of algae in a range of water bodies. It has been proposed that DOC from the barley straw forming hydrogen peroxide in the water is the cause of algae growth inhibition.

Post-Treatment Considerations:

Note: for more information, see *Centre for Ecology and Hydrology - Centre for Aquatic Plant Management’s Information Sheet 1: Control of Algae with Barley Straw (2004).*

- **Dissolved Oxygen Consumed During Decomposition:** Chorus and Mur (1999) do not recommend using barley straw due to the consumption of dissolved oxygen during the decomposition process. This is especially pertinent if dissolved oxygen is already low in a given waterbody.

- **Compounds Produced:** According to the Centre for Ecology and Hydrology’s (2004) information sheet, decomposing straw does not have any effect on higher plants. Their experiments have showed that the suppression of dense algal growth has allowed other aquatic plants, including flowering plants (macrophytes), to recolonize waters which were previously dominated by algae. However, Chorus and Mur (1999) do not recommend using barley straw due to the possibility of the production of unknown compounds (possibly toxic, or odor –producing).

  The Centre’s information also declares that there are no reports of harmful effects on invertebrates or fish except in a few instances where excessive amounts (100 times the recommended dose) of straw were applied to small ponds and the water became deoxygenated.

Application Frequency/Dosing:

Note: for more information, see *Centre for Ecology and Hydrology - Centre for Aquatic Plant Management (2004) Information Sheet 1: Control of Algae with Barley Straw.*

- **Drinking Water Supply Treatment:** Not recommended, as compounds released by barley straw are not understood enough for use in public water supplies.

- **Application Methods:**
  The best way of applying straw varies with the size and type of water body - fast flowing rivers and streams would be treated differently from lakes and reservoirs (both in terms of application method and location).

- **Barley Straw Application/Dosing:** The Centre for Aquatic Plant Management's information sheet describes the process by which barley straw works: activity is only produced if the straw is rotting in well aerated conditions. In turbid or muddy waters, it may be necessary to add more straw than in clear, mud-free waters. The Centre's barley straw guidance document provides detailed information on application - reference this and other sources when planning dosage.

- **Other Plant Species:** While other plant materials have been tested and purported to be somewhat successful, further case studies need to be conducted before recommending consideration as a viable treatment method. See the Biologically Derived Control section for more information.

- Manufacturers provide advice on the use and application of their products - comply with all recommendations. Furthermore, barley straw may be considered an algaecide by state permitting departments. Only use U.S. EPA- and State-approved products! **Consult your state permitting department for more information.**

Equipment Required:

Barley product, bundling method, anchoring system.

Cost:

Barley straw is considered a low-cost, natural, low-maintenance alternative to other methods. Assuming a dosage rate of 225 pounds per acre, treatment for a 50 acre lake might cost around $25,000.

Limitations/Considerations:

- **Dosage:** Recommended application dosage of barley straw is not completely understood. Literature below provides recommendations on dosage rates. Additional guidance should be available from straw manufacturers.
- **Dissolved Oxygen:** Barley straw lowers DO in the waterbody as it decomposes. Application should be avoided under conditions of prolonged warm weather, and the lowest dosage required should be used.
- **Turbidity:** Barley straw is less effective in more turbid scenarios, as the compounds released will quickly be bound up and effectiveness will be very limited.
- **Compounds Produced:** Chemicals released by the decomposition of barley straw, while believed to be harmless to other organisms, are not well known. Caution needs to be taken to avoid effects on non-target organisms.

    - **Drinking Water Supplies:** Given poor understanding of compounds involved, use in drinking water supply situations is not recommended. The waterbody should be monitored over the course of the season both to avoid adverse effects and to determine when more straw is needed.
- **Short- vs Long-Term:** Algaecides are generally a long-term (i.e., full-season) solution to bloom. They will not be as effective in treating blooms rapidly once they have formed.
- **Permitted Algaecides:** Only use U.S. EPA- and State-approved methods - applications of other substances are illegal. Many states require certification prior to application.
    - Manufacturers provide advice on the use and application of their products - comply with all recommendations. Furthermore, only use U.S. EPA- and State-approved products! **Consult your state permitting department for more information.**

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Biologically Derived Control

Background:

An emerging cyanobacteria control method, Biologically Derived Control refers to biologically derived (but non-antibiotic) substances that limit cyanobacteria growth. Depending on the specific substance and other conditions, the effects may be either algistatic or algicidal. Antialgal Biologically Derived Substances (BDSs) are generally classified in two categories: extracts of plants, and identified natural chemicals from plants and microorganisms. The identified chemicals category refers to the specific chemicals within extracts that are hypothesized to be the cause of inhibitory effects. We have devoted an entire section to barley straw as a plant whose extracts exhibit antialgal properties, but many more plants are suspected to produce compounds that inhibit algal growth.

Unlike many algicidal chemicals that can also eliminate non-harmful or beneficial organisms, BDSs may be able to specifically target cyanobacteria. Some BDSs have exhibited limited or no effects on non-target organisms and easily biodegrade in the environment, making them a promising potential solution to HABs control. However, research into the effectiveness of BDSs still in early stages - more studies are needed to assess the viability of many of these extracts or compounds.

Post-Treatment Considerations:

The ecological risks of most BDSs are still unknown - there is a possibility for harmful effects on non-target organisms, but there is also a possibility that some BDSs may have no or low toxicity to aquatic animals and humans. One of the benefits of BDSs is that they biodegrade readily and quickly in aquatic environments.

Application Frequency/Dosing:

- **Drinking Water Supply Treatment:** More information on BDSs is needed before they can be recommended for use in source waters for drinking water facilities. Possible toxicity factors for humans and the capability of drinking water facilities to extract toxins from intake water need to be better understood before treating drinking water supplies with BDSs.

- **Dosing:** The current array of studies for most BDSs has not shown enough standardized dosing and methodology to accurately determine effective concentrations for application. Furthermore, different species and different strains of cyanobacteria have exhibited significantly different responses to the same compound. On the other hand, there may also be opportunities for synergistic effects when combining BDSs. We will continue to update this document with additional references as further studies are released.

- When reaching manufacturing stage, producers will provide advice on the use and application of their products - comply with all recommendations. Furthermore, only use U.S. EPA- and State-approved products! **Consult your state permitting department for more information.**

Equipment Required:

Best method of application TBD. Extracts usually involve chopping and preparing plants and then installing them near waterbodies to release compounds, while the compounds themselves could be applied directly in a more concentrated form.

Cost:

This technology is still too early in its development to determine costs, but at the moment the costs of preparing BDSs are high.

Limitations/Considerations:

- **Effectiveness of Compounds:** BDSs have sometimes shown low efficiency of algae removal. It is also possible that cyanobacteria can adapt to the inhibitory effects of some BDSs and become resistant to them. Some of the most promising compounds are listed below.
    - L-lysine
    - Anthraquinone-59 (2-[methylamino-N-(10-methylethyl)]-9,10-anthraquinone monophosphate)
    - Biocide SeaKleen
    - Leachates of *E. equisetina* root
    - Barley straw (see section on barley straw for more information)

- **Non-Target Organism Effects:** Ecological and human health effects of many BDSs are not currently well-understood. Further studies on these compounds should focus not just on their cyanobacterial inhibitory properties but also their potential toxicity to non-target aquatic organisms and humans.

- **Under Development:** BDSs are still in early stages of development as a HAB control method. Many are still difficult to obtain. Consult manufacturers and state permitting departments for information on the development and official approval of this technology.

- **Release of Toxins:** Some BDSs may cause cyanobacterial blooms to release toxins.

- **Treatment Timing:** BDSs will likely be more effective as a preemptive control measure, rather than as a reactionary post-bloom treatment. This will also reduce the risk of large/concentrated toxin releases.

- **Permitted Algaecides:** Some BDSs have algicidal properties, and may be regulated under algaecide/herbicide permitting. Only use U.S. EPA- and State-approved methods - applications of other substances are illegal. Many states require certification prior to application.
    - When reaching manufacturing stage, producers will provide advice on the use and application of their products - comply with all recommendations. Furthermore, only use U.S. EPA- and State-approved products! **Consult your state permitting department for more information.**

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Shao J., Li R., Lepo. J.E., Gu J. (2013) Potential for control of harmful cyanobacterial blooms using biologically derived substances: Problems and prospects. Journal of Environmental Management 125: 149-155.

- *Note: This article lists numerous other studies on various control methods.*

Circulation

Background:

Lakes that thermally stratify during warm summer weather are often susceptible to some of the highest concentrations of cyanobacteria. For these dimictic lakes, during stratification the water stratum adjoining the bottom sediments, the hypolimnion, becomes depleted of oxygen and contaminants such as ammonia, phosphorus, iron and manganese can be released from the sediment in a soluble form. This increase in nutrient levels can stimulate growth of cyanobacteria - species such as *Microcystis* and *Anabaena* take advantage of both the light near the surface and increased nutrient levels below the surface (at the thermocline) by migrating vertically within the water column by means of buoyant internal gas vacuoles. Polymictic lakes can also be prone to HABS. Cyanobacterial dominance in polymictic systems is more likely influenced by factors such as nutrient loading, temperatures, light intensity and pH.

This section discusses the waterbody mixing tactics that have been employed to limit the competitive advantages of cyanobacteria, thereby reducing toxic cyanobacteria blooms:

- **Artificial destratification** involves increasing the circulation of water that circulates between the shallower and deeper layers of the waterbody, and has been shown to be effective in a range of situations (Reynolds et al 1983, Heo & Kim 2004, Becker et al. 2006). This can be achieved by introducing a plume of bubbles near the bottom of the reservoir (bubble plume aeration), or by installing other mechanical mixing systems. A circulation pattern is set up that reduces the differences in temperature, oxygen and nutrients between the top and the bottom waters. Artificial destratification can reduce algal growth by:
    - Mixing algae deeper into the water column and starving them of light.
    - Subjecting cyanobacterial cells to rapidly changing pressure to disrupt (“break”) their natural buoyancy adjustment.
    - Reducing the sediment phosphorus load available to the water column by decreasing the likelihood of anoxia, thereby starving the algae of nutrients.
- **Epilimnetic circulators** involve artificial mixing, but only within the epilimnion - it does not DE-stratify lakes. There has been very little peer reviewed research on these systems, and anecdotal accounts report mixed results. It is unclear exactly what causes these systems to be effective (even manufacturers such as SolarBee note this), but some hypotheses suggest that:
    - Mixing supports stronger communities of (a) zooplankton that consume cyanobacteria, or (b) cyanophages that kill cyanobacteria.
    - The same buoyancy disruption method mentioned above for artificial destratification takes effect.
    - “Good” green algae are brought back to the surface by the intake and distribution of these systems and are able to compete with cyanobacteria, which otherwise would have a competitive advantage in buoyancy regulation (Huisman et al. 2004).
- **Hypolimnetic oxygen injection** involves oxygenating the hypolimnion without affecting stratification and the thermal density gradient. It is mainly used to control internal phosphorus loading and avoid coldwater fish die-offs due to an anoxic hypolimnion. While useful for those purposes, it has not been used as a method to address HABs, as it does not affect the epilimnion where cyanobacteria are prevalent.

Post-Treatment Considerations:

- Oversized systems may cause sediments and sediment nutrients to be re-introduced to the water column at first. Although long-term reductions in sediment nutrients available to algae would be expected, the short term results could actually be an increase of available nutrients leading to the proliferation of algae.
- Undersized systems can cause only partial destratification, and may perversely end up promoting cyanobacterial dominance instead.

Application Frequency/Dosing:

Note: Manufacturers provide advice on the use and application of their products - comply with all recommendations. It may be necessary to iteratively refine procedures for individual situations.

- **Drinking Water Supply Treatment:** Circulation systems are typically activated before the onset of conditions that encourage blooms, serving to discourage cyanobacteria growth. Increasing circulation could bring cyanobacteria deeper into the water column, potentially close enough to be drawn into some drinking water intakes. If the intake is that shallow, though, strong winds may already do the same thing.

- **Application Timing:** Destratification is normally employed during late spring, summer and autumn depending upon the latitude and altitude which affect the amount of surface water heating. Regular temperature profiles will provide information on how well-mixed a waterbody is. Epilimnetic circulators like SolarBee usually run throughout the summer to discourage cyanobacteria growth.

- **Safety:** Any devices that protrude out of the water (e.g., SolarBees) should be marked with flagging and night beacons to warn boat traffic. Further informational signage at boat launches should also be used.

- **Products Available:** *Note: A detailed description and comparison of the use of aerators and mechanical mixers to control cyanobacteria is provided in the CRC Report 59 (Brookes et al., 2008). Design considerations can be found in the WQRA Report (2010).*

  - **Bubble Plume Aerators:** Bubble plume aerators operate by pumping air through a diffuser hose near the bottom of the reservoir. As the small bubbles rise to the surface they entrain water and a rising plume develops. This plume will rise to the surface and then the water will plunge back to the level of equivalent density.

  - **Mechanical Mixers:** Mechanical mixers are usually surface-mounted and pump water from the surface layer downwards towards the hypolimnion, or draw water from the bottom to the surface.

- **Design:** It is important to apply the appropriate mixing processes for a particular water body. Schladow (1993) describes in detail a method for the design of destratification systems for water bodies impacted by cyanobacteria blooms. Manufacturers provide advice on the use and application of their products - comply with all recommendations. Furthermore, only use U.S. EPA- and State-approved products - applications of other substances are illegal! **Consult your state permitting department for more information, including dosage guidance.**

Equipment Required:

Mixing/Aeration Device, Anchoring System, Power Lines (for non-solar powered systems)

Cost:

- Mechanical Mixing:
    - SolarBee Device: Depends on device purchased, number, and contract (owned vs. rented/leased)
    - $150,000 for three devices in Portland case study. (http://www.oregonlive.com/gresham/index.ssf/2010/05/solarbees_have_mixed_effect_on.html)
    - $1.27 million contract to rent 36 SolarBees from Medora for a two-year project. (http://www.fayobserver.com/news/local/article_969340a7-b84b-5209-af7d-41334ba9f74f.html)
    - 20 installed at $40,000 per device or $1,100 per month lease option. (http://www.c40.org/case_studies/lake-houston-solar-bee-pilot-project)
    - Depending on the device(s) purchased), one could expect a summer trial to cost anywhere between $10,000 and $20,000 per device.

Limitations/Considerations:

- **Artificial Destratification:**
    - **Effectiveness Unclear:** Artificial destratification's effects in controlling algae have been variable (McAuliffe & Rosich 1990, Barkoh et al., 2010, Hobson et al. 2012): the interactions between the effects of destratification, the availability of nutrients, and cyanobacterial growth are still not fully understood.
        - Especially in larger waterbodies where numerous devices are needed, it is very unclear whether these systems are effective.
        - Due to uncertainties in successfulness, leasing/renting devices to pilot before purchase may be prudent.
    - **Water Depth:** Destratification systems operating in deep reservoirs (mean depth >15m) have generally been more successful in changing the composition of the phytoplankton community (Visser et al. 1996, Heo & Kim 2004), while studies in shallower water bodies show less impact (Bariero et al. 1996, Sherman et al. 2000). Even in deep reservoirs destratifiers may not be able to prevent the development of a stratified surface layer, outside of the immediate influence of the plume or mixer, which means that there is still a habitat for buoyant cyanobacteria to exploit (Heo & Kim 2004).
- **Epilimnetic Circulation:**
    - **Effectiveness Unclear:** There are very few peer reviewed papers on this method - it is still unclear how effective these devices can be. Some case studies have shown few effects outside of the immediate area of the device (Upadhyay et al. 2013).
        - Due to uncertainties in successfulness, leasing/renting devices to pilot before purchase may be prudent.
    - **Lake Size:** Effectiveness in large lakes, which typically require multiple circulation units, is not clear.

- **Both:**
    - **Algae/Bacteria Communities:** Some argue that decreases in local scum formation by destratification and epilimnetic circulation are not accompanied by any actual reduction in total cyanobacteria levels - that the cyanobacteria are just being spread around and mixed. Others argue that total algae increases, but the community of algae shifts away from cyanobacteria dominance. As data from current projects becomes available, they will hopefully provide insight into what is happening with these systems and what results can be expected.
    - **Less Potential for Environmental Damage:** Artificial destratification/circulation units are unique in that there is less potential environmental harm than can be caused by improper application of a chemical.
    - **Lake Size (Coverage):** Destratifiers have been shown to mix the surface layers close to the mixing device but areas of the water body further away from the immediate influence of the mixing may remain stratified and provide a suitable environment for cyanobacterial growth.
    - **Lake Depth:**
    - **Stratification Characteristics:** It is essential to understand the thermal structure of the lake to get best results.
    - **Design:** It is very important to size units and lake systems correctly. For instance, for bubbler units, too much mixing energy leads to sediment resuspension, and too little leads to partial stratification (which can lead to blooms). The aerator configuration will depend upon the reservoir size, depth and the maximum temperature stratification.
        - Detailed guidance on the design of an aeration system, including conceptual design, hydrodynamic modelling of the conceptual design and pneumatic and practical design, are given by Schladow (1993) and Singleton & Little (2006).
        - Intermittent mixing can be worse than no mixing - equipment failures need to be avoided.
    - **Monitoring:** Employ a monitoring plan to track effects of destratification on causal water quality parameters (pH, temperature, P) in addition to cell concentrations and other result-oriented parameters.
        - If a system does not appear effective in achieving mixing, consider modification or removal. If the mixing is not reducing HABs as desired, consider removing.

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Flocculants

Background:

Flocculants such as aluminum sulfate, sodium aluminate, native clays, chitosan, and Phoslock (lanthanum clay) limit HABs by addressing phosphorus, the key cause of eutrophication in many waterbodies. Flocculants reduce growth of phytoplankton species by binding and settling out biologically available phosphorus. When previously nitrogen-limited lakes become phosphorous-limited post-application, phytoplankton productivity and biomass are usually reduced and lakes shift away from cyanobacterial dominance to other species.

The active ingredients in flocculants form strong bonds with phosphorus and settle out to the bottom of the waterbody. The process can take as little as one day for some products. The resulting material may form a deposit on top of the sediment, on the lake bottom. Smaller doses will remove phosphorous in the water column, while much larger doses of some flocculates have been used to control future release of phosphorous from the sediment. Effectiveness of flocculants relies in part on dosage, but also heavily relies upon the solubility of the flocculant's bound forms in water. If applied properly, bound phosphorus is expected to remain generally unavailable to aquatic organisms.

Some products may prove toxic to aquatic life if improperly applied, potentially leading to fish kills and effects on benthic insects. In the case of alum, Kennedy and Cook (1982) posit that pH should remain within the 5.5-9.0 range to keep dissolved aluminum concentrations, the form toxic to aquatic organisms, at safe levels. To achieve this, alum applications are closely monitored and often buffered to ensure that pH remains within the prescribed range.

Flocculants have also been used to directly bind the cyanobacteria themselves. However, when used for nutrient control, alum and similar products would better be described as sediment treatments than algaecides. The goal is to bind phosphorous, not bind the HABs themselves. This distinction is critical for whether these products are considered algaecides, or instead nutrient management strategies.

Post-Treatment Considerations:

Considerations for flocculant treatment differ depending on the chemical used. Some flocculants form high-volume flocs that may require removal from the waterbody after treatment to avoid a thick layer of coating over the sediment surface. For others, the active ingredients may be toxic to aquatic organisms if not applied properly. Consult manufacturers and state permitting departments for more information.

Lanthanum-based products have incited significant debate over their toxicity in the doses recommended for application in waterbodies. While some studies report no adverse environmental effects at the dosage levels used to manage biologically available P in surface waters, elevated levels of free lanthanum may remain in the water column under certain conditions. Concerns have also been expressed regarding toxicity to benthic organisms such as snails and mussels whose habitat will be most affected by the settling flocculant (Chassard-Bouchaud & Hallégot, 1984). A recent study showed that lanthanum can be bioavailable to and taken up by marbled crayfish (Oosterhout et al. 2014).

Application Frequency/Dosing:

- **Drinking Water Supply Treatment:** Given that there are no significant human health concerns and that this method does not affect the cells directly (very little risk of lysing), flocculants are seen as a viable option to address HABs in drinking water supplies. They reduce HAB prevalence by addressing the source of the problem. Determine if products are NSF/ANSI Standard 60 certified for use in drinking water, but also, all use must also be approved by the appropriate state agencies.

- **Dosage:** Treatment for particulate removal in the water column uses much smaller doses than those required for sediment phosphorus release control. In order to calculate application dosing, one must first estimate overall biologically available P in the system (in the water column and in the upper sediment layers) and P loading rates. Single or multiple application strategies are potentially viable, depending on uncertainties involved in P levels and input rates.

- **Water Chemistry:** Waterbody characteristics may increase the likelihood that elevated levels of the active ingredient will remain in the water column following application. Further caution is warranted under low alkalinity, very low concentrations of biologically available P, and/or very low concentrations of dissolved organic matter. For alum, dissolved Aluminum can reach levels toxic to aquatic organisms if pH moves outside of the 5.5-9.0 range.
    - **Pre-Application:** Pre-application monitoring and laboratory "jar tests" can be used to assess whether there is a risk of unbound compounds remaining in the water after application. In these cases, a series of smaller doses can be applied.

- Manufacturers provide advice on the use and application of their products - comply with all recommendations. Furthermore, only use U.S. EPA- and State-approved products! **Consult your state permitting department for more information.**

Equipment Required:

Flocculant product, boat, protective clothing (gloves/goggles/boots), and chemical spray tank.

Cost:

- Flocculants are not generally as cheap as other treatment methods such as copper sulfate. On the other hand, by targeting the source of problems, they may prove a cheaper long-term solution, requiring fewer total applications:
    - **Example - Phoslock:** Expected to fall within a range of $200 - $400 per pound of biologically available P immobilized.
    - **Example - Alum (aluminum sulfate):** Alum treatments have been common in lakes for decades. Costs are expected to fall within a range of $15 - $25 per pound of biologically available P immobilized. Per acre, there are cost estimates as low as $280 per acre and as high as $1000-$5000 per acre, depending on the form of alum used, equipment rental or purchase, labor, whether the whole lake is treated or just deep portions, and whether the objective of treatment is precipitation or inactivation.

Limitations/Considerations:

- **Dosage:** An understanding of current system biologically available P and P loading is needed to calculate dosing. Dosages will differ depending on objective (water column flocculation vs sediment phosphorus release control).
- **Waterbody Characteristics:** Waterbody characteristics may increase the likelihood that elevated levels of the active ingredient will remain in the water column following application. Further caution is warranted under:
    - Low alkalinity (<20 mg/L)
    - Very low concentrations of biologically available P (<0.0005 mg/L)
    - Very low concentrations of dissolved organic matter

  - pH outside of the range 5.5-9.0 (for alum)
- **Flocculant Volume:** Some flocculants form high-volume flocs that may require removal from the waterbody after treatment.
- **Cost:** Some flocculants are more expensive treatment options than some other standard methods, especially if repeated treatment is required.
- **Drinking Water Supplies:** Many flocculants are considered safe for drinking water treatment - see NSF/ANSI Standard 60 certification and also consult your state permitting department.
- **Short- vs Long-Term Management:** Chemical controls are generally a short-term solution to a pending bloom. Flocculants are more of a medium-term solution in that they address nutrient pollution as a source of eutrophication and continue to be effective for weeks after the initial application. Long-term effectiveness may be achieved a sediment nutrient release treatment is properly dosed and applied – it could control internal phosphorus loading for decades. However, if external P loads are the main driver of excessive algae, sediment treatments may only control algae for a season or less, and ongoing application as P loading continues would be a costly long-term solution.
- **Non-Target Organisms:** While some studies report no adverse environmental effects at the dosage levels used to manage biologically available P in surface waters, other studies have shown that some species may exhibit significant effects.
- **Permitted Algaecides:** Only use U.S. EPA- and State-approved methods - applications of other substances are illegal. Many states require certification prior to application.
  - Manufacturers provide advice on the use and application of their products - comply with all recommendations. Furthermore, only use U.S. EPA- and State-approved products! **Consult your state permitting department for more information.**

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Ultrasound – Sonic Blasters

Background:

Ultrasound is a well-established technology but only recently has it use been applied to controlling algal blooms. Ultrasound works by a phenomenon known as acoustic cavitation which occurs when sound waves of over 20 kHz travel through a liquid medium. Ultrasound is transmitted via waves which alternately go through rarefaction and compression cycles in the liquid through which it passes. During this process small cavities (microbubbles) are created. Ultrasound causes damage to cell walls and membranes when these microbubbles collapse within the vicinity of the cells. This type of damage applies to bacterial and algal cells. Bacterial cells have been successfully removed by up to 100% using ultrasound. Implementation of ultrasound technology to remove bacterial cells from plant-scale wastewater systems has already been accomplished. The most efficient system for bacterial cell removal uses high frequency (1 MHz) to break up cell aggregates and then low frequency (20 kHz) to kill the cells.

Cyanobacterial gas vacuoles may be particularly susceptible to damage from ultrasound. When ultrasound was applied gas vacuoles burst and photosynthetic apparatus was damaged (Purcell 2009). The cyanobacteria species *Microcystis aeruginosa* was most susceptible, incurring a removal rate of 65%. Green algae had breakage of cell colonies after treatment with low frequency ultrasound. A comparative study using a plant implemented flow-through ultrasound unit on bacterial species (*Bacillus subtillus*) and green algal species (*Scenedesmus capricornutum*) resulted in a higher kill rate for the bacterium, 85% compared to 60% for the green alga. At present, understanding of bacterial responses to ultrasound is extensive but algal studies have concentrated on one division, the cyanobacteria, and specifically one species, *Microcystis aeruginosa*.

Application Frequency/Dose:

Dependent upon end goal, ranges from intermittent to continuous. Cell recovery can occur within 24hrs as gas vacuoles reform, so treatment must be repeated to be effective unless there is a way to capture sedimented cells. Research indicates that low frequency may provide more complete destruction of gas vacuoles because of better cavitation. Manufacturers such as SonicSolutions provide advice on the use and application of their products - comply with all recommendations. Furthermore, only use U.S. EPA- and State-approved products! **Consult your state permitting department for more information.**

Equipment Required:

Emitter of the size appropriate for the area being treated or multiple units for larger areas, power source

Cost:

Expected to be significant in larger water bodies because of the need for multiple units and the electricity to run them. May be acceptable for smaller water bodies. For reference and comparison to other method costs, a 50 acre lake would most likely require approximately 5 of the most powerful model of the devices (depending on the lake shape and desired results), costing around $24,000 for the devices, not counting ongoing maintenance/power costs.

Limitations/Considerations:

- **Line of Sight:** Ultrasound requires direct line of ‘sight’ to be effective. It has been shown to be useful in small ponds, industrial facilities and similar systems of standard shape. Shoreline undulations, woody structure, rocks, debris and aquatic vegetation found in natural lakes will interfere with sound waves. Multiple units would be required to adequately treat large water bodies.
- **Frequency Effectiveness Varies:**

  - Response to ultrasound is not consistent across algal taxa and frequency must be suitable to the current population of algae in order to be effective. Frequencies will need to be adjusted as populations change.
  - Frequency level will influence treatment results. Lower frequency produces better cavitation and apparently higher sedimentation rates, but cells can regenerate gas vacuoles and recover their buoyancy over time. Higher frequencies may disrupt cell membranes or create free radicals, which kills cyanobacterial cells but may also affect non-target organisms.
- **Cell Lysing:** Cell disruption may lead to the release of intracellular cyanotoxins. Production of free radicals may also lead to production of microcystin (see hypothesis from Canadian researchers who suggest that microcystin may be protective of radicals like hydrogen peroxide).
- **Effects on Non-Target Organisms:** Effects on non-target organisms have not been fully investigated. Anecdotal evidence and limited research suggests that fish and *Daphnia* are not affected by frequencies used to limit algal growth. However, ultrasound has been shown to be an effective method of treating ballast water to kill planktonic organisms that are potentially invasive. Intensity and duration of treatment will need to be monitored so as to limit effects on non-target organisms.

Recommendations:

More case studies are needed to assess the effectiveness of this technology. States choosing to allow ultrasound treatment for cyanobacteria should monitor target and non-target organisms before, during and after treatment to assess success and non-target effects.

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