Planktonic:

In-water Prevention Strategy
Substantial Supporting Field Data

Benthic:

In-water Intervention Strategy
No Available Supporting Field Data

Hypolimnetic oxygenation and aeration have been successfully used in lakes and reservoirs as physical controls to maintain oxygen levels in bottom waters while preserving thermal stratification and avoiding warming of the hypolimnion (Beutel and Horne 1999, Bormans, Marsálek, and Jancula 2015, Visser et al. 2016).

Hypolimnetic aeration or oxygenation systems control cyanobacteria by reducing concentrations of limiting nutrients (i.e., phosphorus) in the hypolimnion, with minimum mixing across the metalimnion to avoid the sudden introduction of nutrient-rich bottom waters into the epilimnion (Bormans, Marsálek, and Jancula 2015). Wagner (2015) summarized oxygenation efficacies for reducing cyanobacteria across a suite of case studies. Hypolimnetic aeration or oxygenation systems are most effective in systems that have or are expected to experience extensive internal nutrient loading and require remediation beyond periodic intervention strategies to protect the water quality and ecosystem (Bormans, Marsálek, and Jancula 2015). Often, hypolimnetic oxygenation is used in conjunction with external (watershed) nutrient controls and algaecide treatments (Bormans, Marsálek, and Jancula 2015, Moore and Christensen 2009, Visser et al. 2016).

Hypolimnetic oxygenation uses pure oxygen, whereas hypolimnetic aeration uses air to maintain oxygen levels and prevent the long-term storage of nutrients, encouraging natural cycling through the system rather than sudden entrainment into the epilimnion (Beutel and Horne 1999, Bormans, Marsálek, and Jancula 2015, Sahoo et al. 2015). Hypolimnetic oxygenation or aeration systems slowly release oxygen or air using pumps, pipes, diffusers, or submerged chambers (Cooke et al. 2005). Systems are grouped into three categories: (1) mechanical agitation, (2) injection of pure oxygen, and (3) injection of air through a full lift design, partial lift design, or downflow injection design (Cooke et al. 2005). The use of mixers, aerators, and diffusers to oxygenate a hypolimnion or induce artificial mixing is fundamentally different from the strategies that employ nanobubbles and ozonation. Nanobubble and ozonation strategies induce synthetic biochemical reactions rather than reinforce inherent biological or physical processes.

PLANKTONIC AND BENTHIC
EFFECTIVENESS • Water body type: Lake/reservoir, river • Any surface area • Depth: Deep; requires large hypolimnion; avoid in shallow, unstratified systems • Any trophic state, but typically most effective in eutrophic systems • Mixing regime: Meromictic, monomictic, or dimictic • Any water body use • Watershed nutrient loading levels will impact the effectiveness
NATURE OF HCB • Repeating HCBs • Toxic and nontoxic HCBs • Targets all algal species • Prevention strategy
ADVANTAGES • No waste or by-products produced • Readily available equipment • Successful full-scale implementation • Reported water quality and ecological benefits • Indiscriminate of algae species • Minimal aesthetic impact

LIMITATIONS
• High installation costs
• High operational costs associated with year-round use
• Needs infrastructure (electricity, piping, boat ramp, etc.)
• Limited scalability
• Potential water chemistry restrictions
• Potential sediment chemistry restrictions
• Potential unintentional biological impacts

Physical oxygenation or aeration methods may not operate satisfactorily if the water body is too shallow—even if stratification exists—as the density gradient may not be sufficient to resist thermocline attenuation while the hypolimnion is mixing (Bormans, Marsálek, and Jancula 2015). Physical oxygenation or aeration methods can cause a change in composition from cyanobacterial dominance to green algae and diatoms if the water body is deep enough to limit light availability and the oxygenation or aeration devices are well distributed horizontally over the lake (Bormans, Marsálek, and Jancula 2015, Visser et al. 2016).

Many examples of hypolimnetic aeration applications in lakes and reservoirs worldwide have been reported in the literature; extensive reviews include Beutel and Horne (1999), Cooke et al. (2005), and Singleton and Little (2007). Successful deployment of hypolimnetic oxygenation can delay stratification onset, establish a diatom population, allow this diatom population to persist longer, and remove limiting nutrients from the water column so that less nutrients are available in the epilimnion for cyanobacterial growth (Bormans, Marsálek, and Jancula 2015). Unsuccessful treatments that fail to mitigate HCBs are reported to have come from (1) inadequately sized aerators that do not account for increased BOD or increase diffusion of the limiting nutrient into the epilimnion, resulting in enhanced cyanobacterial growth; (2) low availabilities of trace metals required for limiting nutrient fixation; (3) lack of external load control; and (4) lack of sufficient operation time (Bormans, Marsálek, and Jancula 2015, National Research Council 2000). If these limitations are overcome, hypolimnetic aeration may reduce hypolimnetic nutrient accumulation and internal cycling and, ultimately, reduce the development of HCBs.

Adverse biological effects resulting from aeration have also been reported. Supersaturation of hypolimnetic water with N_2 might lead to a gas bubble disease in fish in some cases (Kortmann, Knoecklein, and Bonnell 1994).

However, some biological and ecological benefits may also result from aeration. Aeration allows for deeper zooplankton distribution and refuge from predators in the dark bottom waters during the day (McComas 2003). In addition, the expanded aerobic environment may enhance growth and expansion of cold-water fish habitat and population due to increased oxygen concentrations, increased visibility, and greater zooplankton density (Rieberger 1992).

The following criteria are recommended by Bormans, Marsálek, and Jancula (2015) in agreement with those proposed by Schauser, Lewandowski, and Hupfer (2003) and Hickey and Gibbs (2009). You should consider these criteria before choosing a physical oxygenation or aeration mitigation strategy:

1. Define the critical limiting nutrient level needed to achieve the predicted outcome.
2. Assess the dynamics and relative role of internal nutrient loading compared to external loading.
3. Assess the sediment characteristics to determine whether internal loading can be controlled.
4. Quantify the link between internal load and cyanobacterial biomass.
5. Scale the treatment as a function of the internal load and the size of the lake.
6. Evaluate the potential to cause adverse effects to aquatic biota.
7. Set a long-term monitoring program before, during, and after the treatment.

COST ANALYSIS

The costs of installing and maintaining a hypolimnetic oxygenation or aeration system are relatively high, mostly due to operating costs associated with the generally continuous operation for successful applications. Costs are also dependent on the type of equipment and local power rates (Bormans, Marsálek, and Jancula 2015). Increased availability and performance of photovoltaic technologies may help mediate power costs. Aerators are usually installed in spring and run during the whole summer (growing) season until autumn (Bormans, Marsálek, and Jancula 2015). The costs associated with this method are not often reported in the literature. Costs of oxygen injection estimated by Hickey and Gibbs (2009) were around $2,500/ha/year, while Cooke et al. (2005) reported overall costs for an average of 15 lakes in the United States of $3,000/ha/year. A hypolimnetic aeration system installed in the late 1990s in Amisk, Canada, reported capital costs of $30,000 and operating costs of about $49,000/year (Prepas and Burke 2011). Procedures for sizing hypolimnetic aerators, and thus determining lake-specific cost estimates, are described in detail by Ashley (1985), Little (1995), and Lorenzen and Fast (1977). Other estimates can be found in Appendix C.2. of HCB-1 (ITRC 2021).

Relative cost per growing season: Hypolimnetic oxygenation and aeration

ITEM	RELATIVE COST PER GROWING SEASON
Material	$$
Personal Protective Equipment	$
Equipment	$$$
Machinery	$$$
Labor	$$
O&M Costs	$$$
OVERALL	**$$$**

REGULATORY AND POLICY CONSIDERATIONS

Before implementing a management action, you should establish a cause–effect linkage between the problem and the proposed management approach (Hickey and Gibbs 2009, USEPA 2000). Because multiple stressors and environmental factors frequently combine to cause the effects observed in aquatic ecosystems, an integrated approach with multiple management measures is often required to holistically address ecological issues in lakes. The decision to introduce a hypolimnetic oxygenation system should be based on a thorough understanding of the factors contributing to recurrent blooms and preliminary research to establish that an artificial oxygenation approach is a feasible option for reducing the frequency and severity of HCBs.

Following Hickey and Gibbs (2009), the preliminary work would involve:

- Characterizing the main drivers likely to be responsible for the HCBs occurring in the lake. Specifically, information would be needed on:
    - the physical characteristics of the lake:
        - volume
        - depth
        - clarity
        - stratification
        - deoxygenation (including duration of anaerobic conditions)
    - annual variation in the concentrations of major nutrients
    - input and output budgets for the major nutrients
    - annual changes in algal biomass and species
    - information on geothermal inflows
- Determining the stratification classification and assessing whether the lake forms a stable stratification (USDA 1999).
- Determining that sediments will release nutrients under realistic conditions, particularly anaerobic conditions (sediment core measurements or hypolimnetic nutrient measurements).
- Considering other potential treatment options to address internal nutrient loading, including:
    - hydraulic flushing
    - sediment dredging
    - other source control measures, such as phosphorus-binding compounds

This assessment must also include social and cultural values that must be considered on a case-by-case basis with public and multiagency consultation, which may uncover concerns with a specific product or approach. The selection and decision-making process may need to be modified accordingly. Any supplementary watershed controls or algaecide treatments must comply with policies and regulations as enacted by the appropriate oversight agency or authority. For some lakes, additional approval may be required from the U.S. Fish and Wildlife Service and the National Oceanic and Atmospheric Administration's National Marine Fisheries Service under the ESA if endangered, threatened, or otherwise special status species are present, or if the lakes are in conservation land (USFWS 2020). Special consideration for protection of native or indigenous species may be made.

CASE STUDY EXAMPLE

Newman Lake, Washington, U.S.: In the late 1960s and early 1970s, summer and fall blooms of cyanobacteria began to occur in Newman Lake. Through the next decade, these blooms intensified and became an annual occurrence. A restoration feasibility assessment of the lake and watershed indicated that a major portion of phosphorus loading (~83%) was attributable to internal recycling associated with summer hypolimnetic oxygen depletion. In 1972, a Speece cone for hypolimnetic oxygenation was installed to supplement watershed controls and alum treatments. More details are provided in Moore and Christensen (2009).

Average summer volume-weighted total phosphorus declined from pre-restoration levels exceeding 50 µg-P/L to an average of 21 µg-P/L over 7 years. Most notably, peak annual biovolumes of cyanobacteria and their representation within the phytoplankton community decreased substantially, with increased prevalence of diatoms and green and golden-brown algae.

Overall, the response to nutrient reduction at Newman Lake is consistent with worldwide observations that emphasize the need for long-term perspectives and commitment in lake restoration and management. Continuation of internal load controls and increased emphasis on external nutrient abatement have been implemented to supplement positive water quality trends, despite future development increases and land use changes.

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