Planktonic:

In-water Prevention Strategy
Substantial Supporting Data

Benthic:

In-water Prevention Strategy
Limited and Mixed Supporting Data

It is well established that vertical water column stability and long water residence times favor cyanobacteria over eukaryotic phytoplankton (Ibelings et al. 2016, Mitrovic et al. 2003, Paerl et al. 2016). Thus, the disruption of these conditions can, under certain circumstances, reduce nuisance HCBs (Havens et al. 2019, Lehman 2014, McDonald and Lehman 2013). Management strategies that decrease water levels or selectively release nutrient-rich bottom waters can be effective management tools that affect nutrient delivery to HCBs (Paerl et al. 2016). The geographic setting of the water body and lake depth will dictate which type of in-water management strategy is feasible based on water availability or lack thereof. For example, arid western regions of the United States may have more restrictions than eastern to midwestern regions.

Hypolimnetic withdrawal is the removal of nutrient-rich bottom waters in stratified ponds and lakes to eliminate nutrient supplies that support the growth of cyanobacteria in the epilimnion (surface layer) of the water body. Bormans, Marsálek, and Jancula (2015) reviewed this strategy and its use in multiple lakes and reported variable results. It has been successful in eliminating blooms of *Aphanizomenon* in Ford Lake, Michigan, while not having any effect on *Microcystis* or microcystin toxicity (Lehman, McDonald, and Lehman 2009). Further, destabilization led to diatom prevalence (McDonald and Lehman 2013). In Lake Mauensee in Switzerland, Gächter (1976) reported the disappearance of *Planktothrix rubescens* following withdrawal. This cyanobacterium was also reduced in a Slovenian lake following withdrawal and reduction in external loads (Vrhovšek et al. 1985). Little to no information is available on the impact of hypolimnetic withdrawal on benthic cyanobacteria mat communities. However, we do understand that benthic mats can acquire nutrients from the water column, the substrates, or from internal cycling of the mat (Vadeboncoeur and Steinman 2002). Benthic cyanobacteria are well adapted to oligotrophic lake conditions, largely due to increased light availability. Understanding the adaptations benthic mats have to low nutrients and higher water clarity, we hypothesize that mats would benefit or not be affected by hypolimnetic withdrawal.

Water level fluctuations (drawdown) may be defined as the lowering of the water level to expose littoral zone habitat and sediments, with the goal to switch the water body from a turbid, algae-dominated system to a clear-water, plant-dominated system (Scheffer et al. 1993). However, the timing of the water level drawdown is critical because summertime drawdowns can increase cyanobacteria production given the increased water retention time, increased water temperature, and nutrients (Bakker and Hilt 2016). In shallow lakes, lower water elevations at key times of the year may promote the growth of submerged and emergent macrophytes due to increased light availability and reduce the potential for cyanobacteria development (Coops and Hosper 2002, Scheffer and van Nes 2007). Mechanisms that indirectly affect cyanobacteria development during drawdown include exposure of overwintering cyanobacteria populations on surficial sediments to winter freezes, disruption and loss of colonizable habitat for benthic cyanobacteria (Turner et al. 2005), uptake of nutrients by macrophytes, excretion of allelopathic substances by macrophytes that may inhibit cyanobacteria growth (Hilt and Gross 2008), or development of macrophyte beds that support invertebrate and fish assemblages (Bakker and Hilt 2016). In contrast, water level drawdown is often used in deeper lakes to reduce aquatic nuisance plants and fish. Due to the timing of drawdown (for example, winter), the strategy generally limits the effectiveness of managing cyanobacteria blooms.

PLANKTONIC	**BENTHIC (DRAWDOWN)**

EFFECTIVENESS • Water body type: Lake/reservoir and rivers • 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 loading levels will impact effectiveness	**EFFECTIVENESS** • Water body type: Lake/reservoir and rivers • Benthic littoral zone • Depth: depth the lake can be drawn down • Trophic state: any • Mixing regime: any • Water body use: any • Winter drawdowns most effective • Duration of time sediments are exposed after drawdown will impact effectiveness • Precipitation pattern, system hydrology, and lake morphometry impact the ability to perform a drawdown
NATURE OF HCB • Repeating HCBs • Toxic and nontoxic HCBs • Hypolimnetic withdrawal targets several species • Prevention strategy	**NATURE OF HCB** • Repeating HCBs • Toxic and nontoxic HCBs • Attached benthic mats exposed after drawdown • HCBs susceptible to drying or freezing • Treatment and prevention strategy
ADVANTAGES • No waste or by-products produced • Readily available equipment • Reported water quality and ecological benefits • Minimal aesthetic impact • Run-of-the river reservoirs may lend better characteristics for the routing of water with bottom withdrawal to supplement convective mixing and to reduce HCBs • Successive winter drawdowns may improve trophic conditions the following summer and reduce the potential for HCBs	**ADVANTAGES** • Kills mats by drying or freezing • No waste or by-products • Readily available equipment • Access to nearshore for cleanup and repairs to structure • Flood control • Reduction of fine sediments in drawdown zone decreases nutrient availability
LIMITATIONS • High installation costs • High operational costs when pumping from depth is required • If no deep-water outlets are in the water body, there are infrastructure needs (electricity, piping) • Potential downstream discharge issues, including water quality, smell, fueling downstream blooms, and delivery of HCBs and cyanotoxins during flushing events • Not practical or effective on larger reservoirs • Drawdown may decrease shoreline stability and increase erosion and sediment deposition • Effectiveness of reservoir drawdown may depend on sediment characteristics and the potential for nutrient release from sediment and macrophytes upon rewetting	**LIMITATIONS** • Long-term drawdown management may allow for the invasion of organisms resistant to drawdowns • Fish may not have access to spawning grounds • Reptiles and amphibian habitat reduced/eliminated • Desiccated plant material may provide a nutrient pulse on upon refilling if not removed

As a control strategy, hypolimnetic withdrawal from stratified systems is most effective in systems where internal nutrient loads are the primary cause of the HCB and external nutrient loads are declining or low. Withdrawal can result in destratification and increases in nitrate deeper in the water column. Further, there may be total phosphorus concentration thresholds for some species. Bormans, Marsálek, and Jancula (2015) reported that cyanobacteria declined when epilimnion total phosphorus levels were less than 25 µg/L. This might suggest that hypolimnion total phosphorus levels >25 µg/L could be an indicator for selecting use of withdrawal as a strategy to consider in HCB control. In addition, Lehman, McDonald, and Lehman (2009) noted that *Aphanizomenon* was found when the total nitrogen/total phosphorus ratio approximated 48, while *Microcystis* was common at ratios approximating 70. Other metrics could be used for assessing cyanobacteria (or noncyanobacteria) following hypolimnetic withdrawal; however, successful reductions in cyanobacteria may not always occur (see Table 1 in Bormans, Marsálek, and Jancula 2015, Dunalska et al. 2014).

Withdrawal can be accomplished through pumping sub-thermocline water from depth into downstream areas. A special withdrawal tube—an Olszewski pipe, with openings set at depths below the thermocline—has been used in the past. In lakes or reservoirs with dam outlets at depth, if those outlets are deeper than the thermocline, then opening the outlets following stratification and nutrient accumulation at depth could remove the regenerated nitrogen and phosphorus, thereby limiting access by cyanobacteria populations in the epilimnion.

At Milford Reservoir in Kansas, which has a surface area of over 15,000 acres, the management plan implemented since 2017 incorporates a spring drawdown that exposes a broad shallow area in the upper portion of the water body; this is specifically designed to reduce habitat where cyanobacterial blooms develop (USACE 2019). While some studies have found success implementing drawdowns to control benthic cyanobacteria, others, such as Turner et al. (2005), saw no significant effect of three consecutive winter drawdowns. Despite loss of colonizable substrate, Turner et al. (2005) attributed their observations to short turnover times of benthic cyanobacteria, mobility, and increases in algae associated with nutrient pulses.

Regional rainfall patterns may impact capability, influence water residence time, and change cyanobacteria dominance and persistence (Jagtman, Van der Molen, and Vermij 1992, Larsen et al. 2020). Other environmental factors—such as thermal stratification, water temperature, and potential fisheries—should be considered before implementing this strategy (Nelson et al. 2018). Often, numerical modeling can help evaluate these environmental factors and determine whether hypolimnetic withdrawal or drawdown will be beneficial for the reservoir. The cost of raw water and limited supplies in many regions of the United States may also be a deciding factor. In these cases, the intangible cost (economics) of closing a water body due to HCBs should also be considered.

COST ANALYSIS

Deploying and securing an Olszewski pipe is not inexpensive and pumping from depth will require power. Labor for maintenance and operations should be moderate and limited to the periods following stratification.

Relative cost per growing season: Hypolimnetic withdrawal

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

Financial costs depend on site-specific geographical settings and water availability. For example, if hydroelectric facilities are associated with run-of-the-river facilities, the financial tradeoffs of water, electric power, and public perception must be thoroughly vetted before hypolimnetic withdrawal or drawdown management strategies are implemented. In the arid West, water availability and the cost of water severely limit the feasibility of hydraulic or flushing strategies, although water level drawdown may be more practical in this region.

REGULATORY AND POLICY CONSIDERATIONS

Nearly all in-water prevention or intervention techniques, including hypolimnetic withdrawal and water level drawdown, will require some form of permitting or approval at the federal, state, or local level (Holdren, Jones, and Taggart 2001). Because these management strategies have the potential to flush sediment, nutrients, cyanobacteria (cyanotoxins), and other metalloid or hydrocarbon compounds to downstream regulated water bodies (as well as affect streamflow and water availability downstream), the state water quality regulatory office is the most appropriate agency to contact early in the planning phase.

Regulatory planning for hypolimnetic withdrawal or drawdown techniques may include but is not limited to Clean Water Act Sections 401 or 404 permitting, NPDES permitting, drawdown permitting, and water rights administration permitting. Depending on the scale of the project and the extent of stakeholders, permitting could take months to years, so planning is critical. Implementing these techniques as short-term intervention approaches also depends on the size of the water body, its physical characteristics, and its environmental setting, thereby requiring extensive planning. Local and state officials should be contacted regarding permitting and use, particularly for potential impacts downstream from nutrient-rich, potentially sulfidic bottom waters.

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