Planktonic:

In-water Intervention and Prevention Strategy
Substantial Supporting Field Data

Benthic:

In-water Intervention and Prevention Strategy
Limited Supporting Field 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 change the hydraulics by flushing (shorter water retention time) can be effective management tools that both affect nutrient delivery to HCBs and disrupt habitat conditions that favor HCB development (calm, warm water) in smaller water bodies (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.

In-water hydraulics may be defined as the movement of water such as surface waves or internal waves that are influenced by wind mixing, internal currents influenced by tributary inflows or discharge, stratified water layers influenced by density gradients, or concentrations that affect turbulent mixing within the water body (Starosolszky 1974). Disrupting seasonal stratification by changing reservoir hydraulics can promote the development of diatoms and green algae rather than cyanobacteria.

Lake and reservoir flushing may be defined as the passthrough of a large volume of water, preferably lower in nutrient concentrations, with sufficient velocity to flush lake water containing cyanobacteria downstream before cyanobacteria populations can regrow in the water body (Ibelings et al. 2016, Mitrovic, Hardwick, and Dorani 2010). Flushing reduces the water retention time (Romo et al. 2012) and disrupts water column stability, thereby minimizing the contact time between cyanobacteria and nutrients while eliminating calm waters that favor growth of buoyant cyanobacteria species (Anderson, Komor, and Ikehata 2014). *Reservoir flushing* may also be defined as the seasonal release of hypolimnetic water from thermally stratified lakes that are enriched with bioavailable nutrients from internal nutrient loading (Nürnberg 2007). The discharge of water before fall turnover reduces the amount of nutrient-rich hypolimnetic water that mixes with near-surface epilimnetic water and may reduce cyanobacteria blooms that occur post-turnover.

The frequency and velocity of flushing flows may also affect the proliferation of benthic cyanobacterial mats (Quiblier et al. 2013). Wood, Wagenhoff, and Young (2014) estimated the specific flushing flows necessary to reduce *Phormidium* cover below 20% for multiple locations in New Zealand rivers. A study across multiple New Zealand river systems demonstrated that accrual of this cyanobacterium also increased with time since the last flushing flow (McAllister et al. 2018). Stanfield (2018) derived river discharge thresholds that, once exceeded, removed attached benthic cyanobacteria in the upper Potomac River in Maryland.

PLANKTONIC	**BENTHIC**
EFFECTIVENESS • Water body types: Pond, lake/reservoir • Any surface area • Depth: Shallow • Trophic state: Eutrophic • Mixing strategy: Polymictic • Water body uses: Recreation, drinking water source • Requires more planning for water management • Reservoir releases of 80 million gallons/day (MGD) (critical flow velocity of 1 foot/second) have been effective in mitigating HCB development via suppression of stratification and cell washout • Reservoir releases of 800 MGD have been effective in removing an established HCB • Run-of-river reservoirs are more suitable for managing hydraulics given flow conditions	**EFFECTIVENESS** • Water body types: Flow-regulated rivers and canals • Any surface area • Depth: Shallow • Trophic state: Any • Water body uses: recreation and drinking water source • Requires planning for water management • Requires site-specific investigation to determine efficacy and appropriate velocity and frequency of flushing flows

NATURE OF HCB • Effective on most types of cyanobacteria in the epilimnion • *Microcystis* colonies in sheltered inlets or bays may be less affected by flushing • Large releases of 80 MGD were effective in suppressing *Anabaena circinalis* • In stratified lakes, flushing may not affect cyanobacteria in the metalimnion • Delay timing of occurrence for nitrogen-fixing (*Aphanizomenon*) and non-nitrogen-fixing taxa (*Microcystis*) • Change in algal composition favoring diatoms • Intervention and prevention strategy	**NATURE OF HCB** • Repeating HCBs • Toxic and nontoxic HCBs • Developmental stage of mat: Early developmental stages require more shear stress to dislodge than later developmental stages. • Substrate type: Mats on stable and heterogeneous substrates require more shear stress to dislodge than homogenous and mobile substrates. • Species of interest: Cyanobacteria species have various adaptations to resist stress.
ADVANTAGES • Variability in regional rainfall patterns may benefit flushing capability, influence water residence time and stratification, and change cyanobacteria dominance and persistence • Horizontal flushing by increasing the flowthrough of water can reduce HCB development via reduction in nutrient supply • Does not require capital or equipment investment • Weigh the cost of water versus intangible cost of closing water body due to HCBs • A series of reservoirs may be managed to store and release water for the benefit of flushing a downstream reservoir • Numerical modeling may indicate that changing reservoir hydraulics or flushing may or may not improve nutrient water quality or HCB conditions • Short pulses of water spread out over the season may be as effective as one flushing event for planktonic species	**ADVANTAGES** • Costs can be low (water body is flow-regulated) • Benthic mats can be successfully removed under appropriate site-specific conditions. • No waste or by-products produced • No direct cell lysing
LIMITATIONS • Large volumes of low-nutrient water are needed to flush a reservoir • Variable costs; can be low to expensive • Not practical or effective on larger reservoirs • Drinking water or irrigation reservoirs generally do not have the luxury of water surplus for flushing • Requires more long-term planning to coordinate flushing events • Changing reservoir hydraulics may warm the bottom water, affecting cold-water fisheries • Potential for downstream impacts related to HCBs and cyanotoxins during flushing events	**LIMITATIONS** • Water body (river or canal) is flow-regulated • Water availability for flushing flow • Long-term planning to coordinate flushing events • Potential for downstream colonization by dislodged mat material

Flushing management strategies have been moderately effective in eutrophic lakes and reservoirs of less than 125 surface acres (Cross et al. 2014, James, Eakin, and Barko 2004, Pawlik-Skowronska and Toporowska 2016), as well as in some larger reservoirs, provided that sufficient flows are available (Qin et al. 2010). Releases of 80 MGD with a critical flow velocity of 1 foot/second have been effective in mitigating HCB development in a large reservoir by suppressing thermal stratification along with cell washout. Reservoir releases of 800 MGD have been effective in removing an established HCB (Lehman 2014).

Flushing flows in rivers can successfully remove benthic cyanobacteria mats, but site-specific factors play a major role in the effectiveness of the treatment strategy. Substrate type, flow velocity, time between flushing flows, species and developmental stage present, size of the benthic population, and physical catchment conditions all play a part. Heath et al. (2013) determined that *Phormidium* sp.mat cover in a river system was greatest on stable substrates like boulders and cobbles. Velocities of 1.5–2.3 m/s effectively removed *Phormidium* sp.mats from less stable substrates like sand, fine gravel, and gravel, while those velocities only reduced mat coverage on boulders and cobbles. Heterogeneous substrates were also found to favor *Phormidium* sp.mats (Heath et al. 2013). The developmental stage of the mat should also be considered, as mats in their early developmental stages require more shear stress to remove than those in later phases (McAllister, Wood, and Hawes 2016). Fovet et al. (2012) found that algal biomass (Chl a) recovered 15 days after a flushing flow in a canal. So, as part of their management of benthic algae, flushing flows were performed every 2–3 weeks.

Regional rainfall patterns may benefit flushing 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 changing the reservoir hydraulics or flushing will be beneficial for the reservoir. The cost of raw water and limited supplies in many regions of the United States may also influence the decision to implement this lake management strategy. In these cases, the intangible cost (economics) of closing a water body due to HCBs should also be considered.

COST ANALYSIS

Financial costs depend on site-specific geographic settings and water availability. For example, if hydroelectric facilities are run-of-the river facilities, the financial tradeoffs of water, electric power, and public perception must be thoroughly vetted before hydraulic, flushing, 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.

Relative cost per growing season: Hydraulic flushing

ITEM	RELATIVE COST PER GROWING SEASON
Water Availability	$$–$$$
O&M Costs	$–$$$
OVERALL	**$$–$$$**

REGULATORY AND POLICY CONSIDERATIONS

Nearly all in-water prevention and intervention techniques, including flushing 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 (and to 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 hydraulic, flushing, and drawdown techniques may include but is not limited to Clean Water Act Sections 401 or 404 permitting, NPDES permitting, drawdown permitting, or 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.

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