Survey of In Situ Strategies for Mitigation of Water Quality Impairments in North Carolina

~~March 1, 2016~~Presented for approval of the Environmental Management Commission

May 11, 2016

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Water Resources
ENVIRONMENTAL QUALITY

Contents

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Executive Summary

This document provides a ~~summary review~~survey and preliminary evaluation of ~~in-lake (also known as "in situ") and lakeside nutrient removal techniques~~ in situ strategies for their ability to mitigate nutrient-driven water quality impairments in waterbodies of the state. This report is provided for review by ~~prepared in consultation with~~ the Department of Environmental Quality and the Environmental Management Commission for their submittal to the Environmental Review Commission as directed by S.L. 2015-241 Section 14.5(d). ~~Generally, these technologies are designed~~Strategies reviewed involve activities conducted either directly in impaired water bodies or adjacent to them, intercepting and treating their inflows. The intent of these strategies is either to remove nutrients from a waterbody or to reduce a waterbody's sensitivity to existing nutrient inputs. Excessive nutrients in waterbodies can cause undesirable conditions including algal blooms, reduced oxygen, and fish kills. Staff identified the set of measures reviewed here as those with some record of effectiveness under independent review toward addressing problems associated with waterbody nutrient over-enrichment.

~~After reviewing the available scientific evidence, no single in situ technology or combination of technologies appears to be feasible for restoring North Carolina's large waterbodies, including the piedmont reservoirs and estuaries subject to nutrient management strategies. A comprehensive, adaptive, and science-based approach to reducing nutrient inputs to the watershed remains the most viable option for recovering these waterbodies from impairment. Based on available information, in situ strategies may be able to serve some adjunct role to watershed controls, but the dearth of trials for such technologies at large scales makes this possibility virtually hypothetical at this point.~~

In general, the potential utility of these measures to treat the types of large waterbodies that have been the subject of nutrient strategies to date in North Carolina appears either presently uncertain (including one under evaluation) or unlikely, depending on the measure. Probably the most significant finding is that, with the exception of the study underway on the epilimnetic mixer Solarbee in Jordan Lake, none of these measures has been tested at the scale or under the conditions prevailing in our nutrient-impaired waters. Of the set of practices reviewed, perhaps the most promising based on trials at smaller scales is a proprietary pump-and-treat process, Algal Turf Scrubber, which could be located lakeside. However, scale is likely to be a key limiting factor in applicability of this and certain other strategies such as dredging, dilution, food web manipulation and other lakeside pump-and-treat options. A second finding is that most of the in-lake strategies presented here have been tested, and in certain applications found successful, only in smaller, deeper, usually natural northern lakes. The very shallow, poorly stratifying, high-flow, high-sediment load character of our Piedmont reservoirs would present inherent challenges to strategies such as phosphorus inactivation, hypolimnetic withdrawal, and floating wetland islands. Finally, certain measures such as epilimnetic mixers, floating wetlands and lakeside options have been tested on or in southern waters with mixed results, and their utility at the scale and conditions described here remains uncertain. Epilimnetic mixers are currently under evaluation with an ongoing trial in Jordan Reservoir that may conclude in late 2018.

Some in situ and lakeside technologies show reasonably good potential utility for smaller, site specific applications to ameliorate eutrophication responses or ~~offset~~ reduce upstream nutrient inputs. Where sufficient independent evidence exists, technologies such as algal turf scrubbers and floating wetland islands are likely to ~~earn~~merit nutrient reduction credits ~~pursuant to an applicable~~contributing toward nutrient strategy load reduction goals. The Division will continue to investigate promising applications of these technologies as part of its broader nutrient management approach.

~~In situ and lakeside nutrient removal technologies each have their own intended benefits and drawbacks as discussed herein. However, some patterns are evident. Many technologies were developed for and tested in small scale applications, including stormwater ponds, wastewater basins, and small natural lakes. Scaling these approaches to larger waterbodies will likely pose serious operational and financial challenges. Importantly, independent research regarding the efficacy of these technologies at larger scales remains to be done. Where independent evaluations have been conducted in larger systems, specifically for epilimnetic mixers in Jordan Lake, improvements are not~~ yet ~~evident.~~

~~Additionally, large scale application of some technologies may be unwise if not entirely infeasible~~ t~~. Techniques~~It should be recognized that certain techniques like food web manipulation, dredging, or alum injection may result in unintended or unforeseen environmental consequences~~, and serious issues would need to be addressed during the permitting processes~~ either in situ or downstream. Dilution ~~may~~ would require large quantities of freshwater that are not practically available or would create use conflicts. ~~Technologies~~ Lastly, technologies that do not result in actual nutrient reductions ~~may simply shift~~ necessarily transfer nutrient ~~problems or impairments~~loads to downstream waters.

~~Finally, efficacy of in situ and lakeside technologies are generally predicated on first reducing upstream nutrient inputs to the maximum extent practicable. Nutrient management approaches that rely heavily on these technologies instead of reducing nutrient inputs to the watershed would appear to disregard the fundamental premise of the Clean Water Act, which seeks reduction of pollutants to waters of the United States. The US EPA notes in their guidance "…it is clear that nearly all (in-lake) restoration procedures will be quickly overwhelmed by continued high incomes of silt, organic matter and nutrients. Protection and watershed management are therefore paramount to restoration" (U.S. Environmental Protection Agency, 1990).~~

Where site-specific applications of these technologies are contemplated, waterbody-specific evaluations ~~should be performed~~are recommended before deployment. Notable factors governing how waterbodies respond to nutrients include (but are not limited to) their size, depth, physiographic location, configuration, drainage area-to-waterbody~~,~~ size ratio, and whether or not the waterbody is natural or constructed. Assessing total system assimilative capacity for nutrients and scaled capabilities of in situ measures is critical to estimating the potential benefits of these approaches for mitigating water quality impairments.

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Introduction

The Division of Water Resources has prepared this study in consultation with the Department of Environmental Quality and the Environmental Management Commission for the Environmental Review Commission of the N.C. General Assembly in accordance with S.L. 2015-241. The full text of section 14.5(d), which details the scope of the study, can be found in Appendix I. Generally, this study is intended to provide an overview of the efficacy of in situ and lakeside treatment technologies and their potential role in North Carolina's nutrient management efforts.

The definitive guidance document on this topic is a 2005 publication entitled "Restoration and Management of Lakes and Reservoirs" by a group of emeritus professors recognized as leaders in lake management research (Cooke et al.). Staff contacted the lead author, Dr. Dennis Cooke, Professor Emeritus at Kent State University, who shared that there are no new techniques reviewed in scientific literature since the book's publication. As a result, more recent supplemental information was gleaned from other sources including the EPA Clean Lakes Program; North American Lake Management Society, N.C. Lake Management Society, online searches, and personal communications.

The techniques included are those recognized by experts, based on independent review, for in-lake control of planktonic algae, which is the most common problem with lakes and estuaries in North Carolina. In addition, emerging land-based, pump-and-treat type nutrient removal technologies with potential lakeside applicability are included. This report does not include evaluation of these strategies for applicability to estuarine waters. Estuaries involve different dynamics in a number of respects, and the set of potentially applicable measures would likely differ in good part from those presented here.

~~All options discussed herein are limited to some extent in their capacity to treat or mitigate nutrients from large waterbodies.~~ Reservoirs in North Carolina, including Falls of the Neuse, High Rock and Jordan Lakes, are impoundments of streams and rivers. ~~–~~The watershed areas draining to these impoundments are typically significantly greater per-unit area of lake than is this ratio for natural, glacially formed lakes that have been the focus of most of the strategies identified here. For the three named reservoirs, that ratio ranges from 41:1 to approximately 170:1. By comparison, this ratio for natural, glacial lakes is typically much smaller, often in the 5:1 to 20:1 range. In addition, soils in the watersheds of our reservoirs are generally considered fertile and erodible compared to soils in northern settings, and precipitation here is generally more year-round than in northern settings. As a result, ~~these~~ North Carolina impoundments ~~continuously~~ receive and collect significantly greater and more continuous influxes of sediment and nutrients from their watersheds per-acre of impoundment than do the natural lakes studied. These nutrient inputs create significantly more challenging ~~long~~ long-term requirements for in situ measures that were designed for use and tested in smaller, natural lake settings.

Depth is another parameter that significantly influences a lake's response to nutrients. Depths shallower than 20' generally stratify poorly or not at all. Stratification is a prerequisite condition for several of the strategies discussed. Mean depths of studied northern lakes generally ranged from 20' to over 100'. By contrast, 71% of lakes assessed by the Division across North Carolina have a mean overall depth of less than 20 feet. More important, average depths for nutrient impaired arms of our reservoirs are even shallower; for example, Jordan Lake (7.5' in Morgan Creek Arm), Falls of the Neuse Reservoir (8.2' upstream of Rolling View Recreation Area), and High Rock Lake (7.0' upstream of Crane Creek). These arms ~~do not stratify at all~~experience limited stratification, and are much more prone to bottom sediment-water column physical and chemical interactions, which would make some strategies difficult or not applicable.

Apart from these ~~watershed inputs~~characteristics, the sheer size of ~~these~~our impoundments also creates challenges. Falls, High Rock and Jordan Lakes have ~~a sizehave~~ surface areas of approximately 12,000, 15,000, and 14,000 acres, respectively. By contrast, lakes on which in situ strategies discussed here proved successful generally ranged in the 10's to 100's of acres size, while larger lakes relied heavily on watershed controls. Clearly the scaling

~~Scaling~~ of in situ measures to meet the large scale nutrient reduction needs of NC reservoirs would be ~~expected to~~potentially ~~be become~~ quite expensive. ~~All of the available technology has been developed to be used on small scale waterbodies such as wastewater ponds and holding basins, which are exponentially smaller than large reservoirs facing nutrient management strategies.~~ Costs outside of initial set-up or installation, such as providing supply of a key resource, operation, repair and maintenance may scale up disproportionately, especially with ongoing or increasing watershed nutrient inputs.

~~Independent research that evaluates the efficacy of these products is very limited in reservoirs across the southeast United States. Most information comes from vendors or manufacturers of various measures and focuses on small natural lakes. Case studies of successful implementation for available measures are uncommon.~~

~~When considering in-lake measures for mitigation or control of nutrient related impairments, there are multiple factors that must be recognized before attempting to evaluate their potential efficacy. Initially, there is an assumption that control of watershed nutrient sources have been established. Guidance documents emphasize the importance of first addressing watershed nutrient sources to the greatest extent possible. This is especially true for reservoirs given their large drainage-to-lake area ratios. Guidance from US Environmental Protection Agency states"…it is clear that nearly all (in-lake) restoration procedures will be quickly overwhelmed by continued high incomes of silt, organic matter and nutrients. Protection and watershed management are therefore paramount to restoration."~~

~~This is a major consideration for N~~orth Carolina~~C due to the fact that in reservoirs, the vast majority of nutrients come from the watershed. Some amount comes from lake sediments. In-lake measures can attempt to disrupt use of incoming nutrients (often sending them downstream) or the reuptake of sediment nutrients. Since this is treating symptoms of ongoing nutrient input over time, in-lake practices are continuous vs. one-time. The result of this is long-term cost planning to control both watershed and in-lake measures.~~

On the following pages, an overview and evaluation of all in-lake and lakeside technologies is provided.

Solar Powered Epilimnetic Mixing

At a glance…

- *Description:* Floating solar-powered water circulators, including Solar Bees deployed at Jordan Lake, are typically used to destratify lake waters. Their intended function is to reduce the effects of algal growth at the surface and increase oxygen conditions near the lake bottom.
- *State of science:* Most evaluations and case studies have been conducted on small waterbodies, with a small number of large reservoir applications. Deployments in larger waterbodies to mitigate nutrient impairments have not resulted in improved water quality conditions.
- *Designed primarily for:* Drinking water holding basins, small water supply reservoirs, wastewater ponds.

Technological Overview

Epilimnetic mixers have been utilized across the country to offset issues related to wastewater ponds and drinking waters intake sites. ~~Application~~ The Jordan Lake Solarbee application of this technology ~~most often~~ involves ~~disruption of thermal stratification in smaller waterbodies~~mixing of the upper zone of the waterbody, the epilimnion, by a solar-powered pump that draws water up from several meters deep and distributes it laterally across the surface, disrupting quiescent conditions and circulating flows vertically. ~~The machines work by both pulling water through an impellor and inducing flow in waters surrounding them. During these applications, stagnant waterbodies can be slowly mixed by pulling water from the bottom of a lake or basin and distributing it across the surface. This circulation destabilizes the physical thermal layering that occurs during warmer months of the year in still waterbodies. The effect can be beneficial if the circulation reduces biological growth near the surface and increases oxygen concentrations near the bottom.~~ This technology was originally developed for use in smaller scale basins such as water supply holding ponds and tanks, but has been applied in embayments of larger waterbodies as well. The technology can enhance the competitiveness of green algae versus less desirable blue green algae, providing a better food source for other organisms. It can also be designed to disrupt thermal stratification by pulling up deeper water, the hypolimnion, and mixing it into the upper layer.

When coupled with nutrient inflow reductions, Solarbees have proven effective at controlling taste and odor problems in small water bodies. Further, in small to moderately sized water-bodies they have effectively shifted algal communities away from HABs and towards more beneficial types of algae. The Lake Houston SolarBee case study demonstrated effective treatment of a hypolimnetic low oxygen situation in a large reservoir. Treatment alleviated drinking water problems not associated with nutrient reduction or mitigation (Bleth, 2007).

Technical Challenges for Large-Scale Application

The impact of epilimnetic mixers is limited by their ability to move a given amount of water per hour. The physical circulation of these machines is relatively slow as they are solar powered, and may take considerable time to mix the system they are used in. The technology requires that waters are calm

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enough and static with respect to incoming nutrient loads. ~~When used in bodies of waters such as reservoirs that have high nutrient inputs and changing flow conditions like those in North Carolina, the machines become less effective.~~ This is especially true when they are applied to mix only the surface of shallow waters that are not heavily stratified. This is the application design of the Jordan Lake Pilot Project. ~~Monitoring~~ For the first year of monitoring under the Jordan Lake pilot study, from July 2014 through September 2015, monitoring data ~~from this study~~ indicates no significant change in water quality from areas where the machines are placed in impaired areas versus control sites, or from historical- versus project area data (Division of Water Resources, 2015). In 2015, the General Assembly extended the pilot study until at least October 2018 to provide adequate time for a fuller evaluation of the Solarbees' performance. ~~Utilization of this measure in NC reservoirs does not appear to be effective as they do not have the ability to overcome the normal productivity of high nutrient systems. These create aesthetic issues as they float on the surface of the water, and are continually visible. They have the potential to create other user conflicts such as hazards to boating due to the density and amount of machines required to circulate large open waterbodies.~~

Cost Considerations

The Jordan Lake Pilot Project can be used as an example for mitigation of nutrients in large scale applications. The initial two-~~-~~year Pilot Project on Jordan Lake cost $1.3 million ~~and has shown no improvement in water quality in impaired areas~~ to deploy and monitor a total of 36 units. The extension of the project is funded at $1.5 million ~~and will~~to continue through October 2018. ~~With the quickly changing nature of Jordan Lake and continual high input of nutrients, it is not likely that improvements in water quality will be realized. Ongoing maintenance contracts must be purchased to provide repair and repositioning. Changing weather conditions and lake levels affect this type of measure significantly.~~

Permitting Considerations

The U.S. Army Corps of Engineers (hereafter USACOE) required an environmental assessment prior to permitting of the activity and subsequent leasing of the 36 individual anchor points for all machines located of Jordan Lake. The assessment resulted in approximately 1,500 comments from public and government agencies creating a delay in project implementation by 3 months. Staging areas for shipment of materials to North Carolina and permission to utilize access points along the lake were also required for the amount of equipment and space needed for onsite construction and machine deployment.

Hypolimentic Withdrawal

At a glance…

- *Description:* Pumping out of bottom waters or dam discharge from the lower portion of the water column.
- *State of science:* Few documented case histories.
- *Designed primarily for:* Deeper, n~~N~~atural stratified lakes where external nutrient loading has already been reduced.

Technological Overview

Hypolimnetic water (water at a lake bottom) is typically higher in nutrients and lower in oxygen than surface waters. Siphoning off these waters ~~is believed to~~and discharging them downstream removes phosphorus-rich bottom water from the lake system, which can ~~prevent mixing with surface waters, thereby accelerating phosphorus loss, and helping to~~ prevent algal blooms driven by phosphorus being re-suspended in the upper water column. ~~There are~~According to the USEPA (1990), a small Swiss lake reported success with this technique and a few documented case histories ~~for this technique to be considered an established and effective long-term approach~~were reported elsewhere. Though water from the hypolimnion is often discharged from dams for power generation, the procedure has largely not been evaluated for benefits to water quality ~~in respective reservoirs~~.

Technical Challenges for Large-Scale Application

~~Withdrawal could cause thermal instability, leading to destratification (or mixing) of colder nutrient-rich and low-oxygen bottom waters with warmer surface waters, inadvertently triggering an algal bloom or other problems such as fish kills.~~ Discharge water may require aeration (addition of oxygen) or other treatment, depending on chemical analysis of water withdrawn and quality of receiving waters. Nutrient problems can be shifted downstream with discharges containing high nutrients, low dissolved oxygen water, and possibly high ammonia, hydrogen sulfide and reduced metals. Withdrawal could cause thermal instability, leading to destratification (or mixing) of colder nutrient-rich and low-oxygen bottom waters with warmer surface waters, inadvertently triggering an algal bloom or other problems such as fish kills.

Cost Considerations

The strategy has relatively low annual operational costs, but there are a number of unknown costs including whether water withdrawn must be treated before being discharged to receiving waters, and whether dam upgrades are needed if withdrawal rates are increased. The effectiveness of this strategy is uncertain. Multiple withdrawal points around a lake would likely be needed, not just at a dam outlet in order to have a significant effect on lake impairments.

Permitting Considerations

Any intake structure would require a 404 permit/401 certification from USACOE and DWR. NPDES permits would be required for discharge to downstream receiving waters. Discharge waters would likely have very low dissolved oxygen concentrations, below standard, and would have to meet standard. This would be expensive to treat and options currently used to mitigate this scenario in existing hydroelectric facilities are not always successful. Temperature and other pollutant issues also need to be considered in the permitting process. This approach would also require a water allocation permit to local governments by EMC, an untested area relative to statute. In this case, the permittee may be the state.

Dilution

At a glance…

- *Description*: Addition of low-nutrient water to a lake.
- *State of science*: Very few documented cases.
- *Designed primarily for*: Where external sources of nutrients are controlled/diverted and there is close proximity to a reliable supply of low-nutrient water.

Technological Overview

The approach with dilution is to add large volumes of low-nutrient water to reduce overall nutrient concentrations in the waterbody and to flush out algal cells. There are very few documented cases of dilution or flushing as an in-lake treatment, mostly because large volumes of low nutrient water are not often available.

Dilution has shown to be an effective strategy in reducing nutrients and algae, as well as increasing transparency, as long as an abundant supply of low-nutrient water is available nearby enough to minimize the cost of treatment and transport of the dilution water. In a project involving Lake Moses in the State of Washington, the nearby abundant and low-nutrient Columbia River was successfully utilized as a dilution source. 70% reductions of total phosphorous and chlorophyll a were observed 10 years after dilution was initiated. This project is described as the largest in the world at the time and involved a 5.8%/day flushing rate for the impaired area, and 0.46% /day for the whole lake. Improvements from dilution were due largely to the reduction of nutrient concentration and by washout of algal biomass resulting from the increased exchange rate present during dilution/flushing events (Welch et al., 1992).

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Technical Challenges for Large-Scale Application

In addition to the primary limiting factor of an ample supply of low-nutrient water, there are a number of other limitations. ~~Lakes with low flushing rates and long residence times are poor candidates because the in-lake nutrient concentrations could actually increase unless the dilution water is free of phosphorus.~~ It is recommended to have a water and nutrient budget calculated for the lake, as well as a study of basin volume, if considering this option. Flushing rates of 10-15% of the lake volume per day are believed to be sufficient, but as an example this would be approximately 1,500-2,200 MGD for Jordan Lake. Dam outlet structures may not be capable of handling added discharge volume; an engineering upgrade may be required. Increased discharge volume could have negative impacts on habitat and aquatic life downstream, scour and erosion immediately below the dam and sediment deposition further downstream. Also, this could create potential conflicts with current users of the dilution water.

In the North Carolina piedmont, wells generally are not drilled for public water supplies for several reasons. The fractured bedrock has poor water yield, and it has ~~an~~ unconfined aquifers with potential for contamination. A large number of wells would be required to source sufficient water.

Cost Considerations

Feasibility depends on accessibility and distance to water source, need for pumps, pipes, and whether extensive engineering is required for dam outlet structure upgrade or repair.

Permitting Considerations

Dilution water would need to be tested and may need an NPDES discharge permit. In-lake structures would need a 401/404 permit.

Phosphorus Inactivation (Alum Injection)

At a glance…

- *Description:* Aluminum salts are added to a waterbody to capture, sink and isolate phosphorus.
- *State of science:* There has been almost no experience using this procedure in reservoirs.
- *Designed primarily for:* Shown effective in thermally stratified natural lakes up to 750 acres where nutrient diversion has occurred.

Technological Overview

Phosphorus inactivation involves the application of aluminum salts to the water column and lake bottom. Water column application results in an aluminum hydroxide floc (phosphorous precipitation) that settles to the bottom of the lake. Heavier doses are usually applied to the bottom of the lake in order to treat the sediment surface, which forms a barrier to prevent further phosphorus release (P inactivation). There has been almost no experience using this procedure in reservoirs; it has primarily been used in natural lakes. Additionally, this measure has only been documented to perform successfully in small lakes up to 750 acres, including in Long Lake, WA, Lake Morey, VT, and Kezar Lake, NH (USEPA, 1990). For comparison, Jordan Lake is approximately 14,000 acres. It has shown to be effective in thermally stratified natural lakes where sufficient nutrient diversion has occurred, where the lake flushing rate is relatively fast, and where nutrient recycling from sediments is negligible.

Technical Challenges for Large-Scale Application

Some phosphorous fractions, particularly the dissolved organic fraction, may be incompletely removed, enabling continued algal growth. This approach is more commonly used to create a chemical barrier on the lake bottom to prevent phosphorus from being re-suspended and re-mixed into the water column. Alum injections are most effective when applied once external nutrient loading to the lake has been diverted or suppressed. The aluminum salts added can be toxic to fish and other aquatic species. Specific chemistry of the lake (such as the pH) can lead to chemical reactions that result in toxic forms of aluminum being created. Dosage is therefore lake-specific. Additionally, sharp increases in water transparency following treatment may allow an existing weed infestation to spread into deeper water.

Constructed reservoirs like Jordan, Falls and High Rock Lakes are usually not good candidates for this approach because of the difficulty in limiting the inflow of nutrients. Additionally, high flows in these relatively shallow lakes may wash away the aluminum hydroxide floc that forms at the bottom of the lake or quickly cover it with another layer of nutrient-rich sediment.

Cost Considerations

There is a high initial cost for treatment requiring both chemicals and equipment. Repeated applications will be necessary at an unknown frequency determined by sedimentation rate or rate at which the aluminum hydroxide floc layer is covered or washed away.

Permitting Considerations

This scenario, like others, would have to be further explored because it is untested in North Carolina. Studies would be required to assure that the aluminum would not be harmful to aquatic system. It would also likely require a NPDES wastewater permit, since aluminum salt would be injected into the lake. USACOE could require an environmental assessment study in addition to an evaluation of purpose and need.

Dredging

At a glance…

- *Description:* Scoop or pump out upper sediment layer from a lake bottom.
- *State of science:* Mixed results with some successes.
- *Designed primarily for:* Unclear; rarely done for nutrient control in reservoirs.

Technological Overview

Upper sediment layers have the highest concentration of nutrients. Dredging is most often performed to maintain or restore lake volume and navigation channels or remove nuisance macrophyte growth, not to limit the effects of excess nutrients. Dredging to control algae and nutrient cycling has shown mixed results. Dredging could increase depth in shallow areas, resulting in increased circulation and less algae growth. Accrual rates of incoming sediment need to be evaluated to determine applicability. Any beneficial effects of dredging can be reversed in relatively short time in reservoirs due to the continual input of sediment. This approach is better for lakes with relatively small watershed-to-lake surface ratios (e.g. 10:1). Jordan Lake's ratio is 77:1. ~~This measure is recommended only in combination with watershed, sediment, and nutrient controls in place.~~

Technical Challenges for Large-Scale Application

Dredging disturbs or destroys bottom habitat. This measure eliminates part of the food web base such as benthos and mussels, including food for bottom feeders and others. It can also eliminate bottom-dwelling fish habitat. Dredging activity can re-suspend nutrients, potentially causing algal blooms, oxygen depletion, and fish kills.

Sediment dredging represents a major intervention to the lake ecosystem with possible negative aspects, the most obvious being the destruction of benthic organisms. If the lake basin is dredged completely, two to three years may be necessary to re-establish benthic fauna (Cooke et al. 2005)

Sediment removal may not necessarily bring the desired effects, especially if the external nutrient load to the lake or reservoir remains sufficiently high for cyanobacterial biomass growth. For example,

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dredging of a thick sediment layer from a 99-acre fishpond in the Czech Republic resulted in a negative phosphorus budget (more phosphorus was trapped than released by the sediments) and an absence of cyanobacterial blooms. However, due to the unchanged external nutrient load, this change was temporary and cyanobacterial blooms reappeared within five years after dredging (Pokorny and Hauser, 2002).

Cost Considerations

This measure is very expensive and equipment-intensive. It involves dredging, storage, transport & disposal of spoil, a slurry of 80-90% water. The frequency of periodic re-dredging should be evaluated carefully considering the often large watershed scale of impaired waterbodies. North Carolina reservoirs assimilate a large amount of sediment from their respective watersheds. No effectiveness numbers are available for nitrogen and phosphorus. This approach is rarely taken for nutrient management and has not been studied.

Besides nutrients, spoil materials may contain heavy metals, PCBs, volatiles, or other pollutants. Chemical analysis will dictate suitable types of storage and disposal sites. Site availability, proximity to lake, and required handling greatly affects storage and hauling cost.

Permitting Considerations

Dredging would potentially warrant an environmental assessment. Required permitting would include a USACOE 404 permit and a DWR 401 permit. Demonstration of no practical alternative would be necessary. Mitigation could be required as part of the permit process. Impacts to the bottom habitat would need to be investigated. A potential moratorium may be needed during fish spawning season. During the disposal/storage phase, chemical analysis would dictate requirements for site specific storage options. DEQ would need to seek approval via Division of Waste Management. If spoil material is deemed to be clean, it could potentially be used at a fill site, if not, lined permitted landfills would need to be used, or maybe land farm application.

Food Web Manipulation

At a glance…

- *Description:* Alteration of existing food webs to increase algae consumption.
- *State of science:* Poorly understood, site specific data are needed to understand.
- *Designed primarily for:* Small, shallow natural lakes.

Technological Overview

This measure most often attempts to increase algae-eating zooplankton by eliminating small panfish that eat zooplankton. Options for removal of fish are: poison, physical removal of plankton-eating fish, or stocking piscivorous predator fish to eat small plankton-eating fish. This option is poorly understood in highly productive systems such as Jordan and High Rock Lakes, since almost all examples are in natural lakes. There are few sustained successes. This approach is more likely successful in small, shallow (<10 feet) ~~natural~~ lakes where populations are more easily managed. ~~Reduction of external nutrient loading is a prerequisite to decrease the driver of ongoing algal blooms.~~

Technical Challenges for Large-Scale Application

Food web manipulation is challenging to carry out in well-studied systems and is unstudied in reservoirs. There are inherent difficulties in controlling ecological systems. Populations cycle at every level, and timing is a significant issue that is difficult to manage effectively. A successfully increased "algae eater" population may add significant nutrients for more algal growth as it dies off, resulting in a destabilization of the system. Adding top predator fish alone may not ~~make much of a dent~~significantly impact a~~i~~n algae population and zooplankton populations must be large enough and available year round to sustain predators. Where algal assemblages are dominated by undesirable blue-greens, increasing algae eaters may not be successful.

A potential method to reduce cyanobacterial blooms is enhancement of direct grazing by herbivorous fishes. However, a number of studies report that the metabolic activity of phytoplankton after gut passage remains unaffected or even increases (Drabkova and Marsalek, 2007). Cyanobacterial growth may even be supported by the presence of herbivorous fishes due to increased nutrient release from digested macrophytes – an effect termed icthioeutrophication (Opuszynski, 1978).

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Falls, Jordan and High Rock Lakes all have significant blue-green algae populations. In largely unstudied reservoirs, unanticipated consequences to the lake's ecology are likely. Continuous management would be necessary due to continued high nutrient inputs, inherent environmental and biological variability, and continuous large management efforts from year to year. Resistance from anglers could be expected if restrictions are imposed to help ensure success of stocked "predatory" fish.

Biomanipulation is usually not very effective in highly eutrophic reservoirs and lakes where total phosphorus concentrations exceed 100 ug/L. Effective examples of biomanipulation apply to relatively small water bodies due to the great difficulty of continuously manipulating fish populations. This is impractical in large lakes and reservoirs (Drabkova and Marsalek. 2007).

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Food web manipulation may be effective in enhancing the reduction of internal nutrient loading in a reservoir, provided external loading from point and non-point sources in the watershed are reduced and stabilized (Benndorf et al. 2002).

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Cost Considerations

Cost is largely unknown and specific to each lake. All approaches – fish removal, poisoning and disposal, and predator stocking - are likely expensive and would incur annual management costs.

Permitting Considerations

Permitting issues would need to be further explored. If fishes were introduced to any system, the request would need to go through Wildlife Resource Commission. Recommendations for individual lakes would need review by WRC staff biologists.

Floating Wetland Islands (FWI)

At a glance…

- *Description:* Man-made floating mats that use plants and microbes to uptake nutrients.
- *State of science:* Emerging technology
- *Designed primarily for:* In North Carolina, there have been lab tests for using floating wetlands to treat captured runoff and field-tests have been conducted on raw wastewater and waste water lagoons. Field testing for stormwater ponds has also been conducted.

Technological Overview

Floating wetland islands are artificial mats on which plants roots grow in the water below the mats and uptake nutrients. Microbes living on the roots also uptake nutrients. Hanging roots can also serve as a curtain that slows down water flow and allows solids to fall out. These are marketed as multi-functional for several purposes, including denitrifying surround waters (root and microbe uptake), channeling nutrients into fish populations for increased fish growth and population, creating aquatic habitat, and improving aesthetics.

Floating w~~W~~etland i~~I~~slands have been launched in several lakes around the country, but none as large as Falls or Jordan Lakes. North Carolina State University (NCSU) recently completed a study on retrofitting two stormwater ponds with FWIs, ~1 acre and ~0.1 acre. NCSU showed a sliding scale of nitrogen removal for wetlands that covered 20% to 50% of pond. Minimal phosphorus removal occurred. These have been shown to be effective for wastewater treatment. We were also told that benefits are being shown in stormwater ponds and even smaller scale lakes.

Floating wetland islands have been deployed as part of a multifaceted approach to reducing nutrient pollution impacts. For example, in Pennsylvania's 633-acre Harvey Lake, four floating wetlands were included as part of comprehensive stormwater implementation plan that also called for stream restoration and 38 urban BMPs. The plan was successful, resulting in the removal of Harvey's Lake from Pennsylvania's list of impaired waters (EPA, 2015).

It is estimated that a 250 ft^2 floating wetland island has the surface area of approximately one acre of natural wetland (Lubnow, 2014). Once installed and positioned, the islands serve as nutrient sinks, particularly for phosphorus. Microbial communities in and beneath the islands assimilate phosphorus, where it is then sequestered into living biomass (Lubnow, 2014). Studies have estimated that the amount of phosphorus removed by one, 250 ft^2 island is approximately 10 pounds of total phosphorus per year (New Jersey Department of Environmental Protection, 2014). Since one pound of phosphorus has the potential to generate up to 1,100 pounds of wet algae biomass, one 250 ft^2 island has the potential to prevent up to 11,000 pounds of wet algae biomass (Lubnow, 2014).

Floating wetland islands tend to be most cost-effective for lakes that have water column total phosphorus concentrations at or greater than 0.1 mg/L (Lubnow, 2014). Cost estimates for floating wetland islands may range from $3 to ~~$11 per ft^2 on up to~~ $46 per ft^2. Assuming that 10% of the surface of a 20-acre lake cove would be installed with floating islands, approximately 2 acres (or 87,120 ft^2) of

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floating islands would be needed. This coverage equates to an installation cost of approximately $260,000 to $4 million. Operation and maintenance costs would be approximately $13,000 to $200,000 per year at an assumed 5% of installation cost (Lyon, S. et al., 2009).

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Technical Challenges for Large-Scale Application

According to the NCSU study, large portions of the water body, up to 50%, may need to be covered by FWI to realize significant nutrient uptake benefits. Wetlands could provide habitat for birds and other aquatic animals that could contribute nutrients (feces), although anecdotal evidence suggests that after vegetation gets high enough, geese avoid wetlands due to threat of predators. In NCSU examples, wetlands created a foothold for vegetation that can overtake the pond. On larger scales, FWIs could require significant ~~ongoing maintenance and~~ upkeep ~~, especially~~ in open waterbody applications where they may be dislodged during high wind or flow events. ~~Vegetation must also be maintained in an active growing state for maximum nutrient removal. This requires frequent biomass removal such as pruning, harvesting and replanting.~~ Once established, vegetation can be self-sustaining. However, periodic maintenance would be required to remove trees that can grow from seeds brought in by birds or other vectors, as their mass would eventually sink the island.

Cost Considerations

NCSU's projects spent about $100,000 to install floating wetlands on the two ponds. This was to install FWIs that cover 9% of a 1-acre pond and 18% of a .1 acre pond. Minimal benefits resulted from these installations, and NCSU suggested that more of the surface area be covered, up to 50% to see significant results.

This is a very young technology. Costs to restore a lake the size of Jordan or Falls are unknown and would need further research and investigation. Jordan Lake applications utilizing 20-30 acres of FWI would be estimated to require of $15-20 million in capital costs and approximately $500,000 per year in O&M costs.

Permitting Considerations

The USACE would require an Environmental Assessment similar to the Jordan Lake Solar-Bee project.

Algal Turf Scrubbers® (ATSTM)

At a glance…

- *Description:* Lakeside technology where water is diverted temporarily into a raised ~~channel~~ flow way where algae are cultivated to remove nutrients.
- *State of science:* There are a number of places where it's being used, but like other pump and treat options, it seems to be a fairly young technology when it comes to treating streams and larger water bodies. Several cases exist in Florida. The City of Durham had a feasibility study done for its use to help meet load reduction requirements of the Falls nutrient strategy and, based on its comparatively good cost-effectiveness, in late 2015 initiated operation of a pilot-scale project that treats lake water from Falls Lake.

- *Designed primarily for:* Water temperature between 60 and 90 degrees Fahrenheit are optimal. These measures are somewhat scalable, so areas with larger flows more may be more effective.

Technological Overview

Water is pumped from the stream or lake and discharged onto a slightly inclined rectilinear flow way with an impervious liner substrate. The substrate cultures a diverse, natural and local assemblage of attached benthic algae, bacteria and phytoplankton. After water passes over the substrate where nutrients and bacteria are removed, the water is released back into the stream/lake. Algae is periodically harvested and used for fertilizer, energy, or disposed of. The City of Durham is currently evaluating this technology in light of its Falls Lake and Jordan Lake nutrient reduction efforts.

Technical Challenges for Large-Scale Application

~~This measure shares many of the same limitations as other pump and treat options. In order to do~~This measure is scalable and a facility can potentially treat up to 30 MGD. To achieve large~~-~~scale nutrient removal, algal turf scrubbers require commensurate ~~large acreages of~~ land ~~are needed~~ area for facilities. For example, according to the feasibility study provided to Durham by the manufacturer (Durham, 2013), a facility that accepts 25 MGD ~~that treats~~can remove approximately 10,000 – 23,000 lbs nitrogen per year ~~would require~~ using a land area of 10 acres. A scaled up example could be Jordan Lake. As described in the Purpose and Scope rule of the Jordan nutrient strategy, Jordan's nitrogen reduction requirements in 2001 were around 500,000 lbs N ~~and have increased three to four times due to development since 2001. Extrapolating, this could~~. Applying the manufacturer's modeled removal rate range above to Jordan Lake's reduction need would require a ~~1,000-2,000~~220 - 500 acre facility (facilities) to treat the entire lake. Disposal of harvested algae is also a consideration, though it may be given away or sold for fertilizer or energy. For large scale installations, road access, power supply, and piping would be required to get water to and from the facility. Temperature must be considered with this option, as these facilities are more effective in warmer weather. Operational shut-downs may be required in colder weather, particularly below freezing. Topography must also be appropriate, as the systems need a fairly flat surface for a large facility that provides a very gently sloping surface for water to flow across.

Cost Considerations

The technology seems to be effective for nutrient removal at small scales, and while it is scalable there are likely practical limits that would make treating the entirety of Jordan Lake infeasible. Lacking that evaluation, based on Durham's Feasibility Study of 10 potential sites in the Falls Lake watershed, costs for the five Falls lakeside sites, each processing flows of 10-25 MGD of lake water, are projected from \$19 to \$79 per pound of nitrogen removed, based on a 20-year present worth cost (Durham, 2013). Applying this smaller-scale cost-effectiveness rate to Jordan Lake, based on an assumed 500,000 pound-per-year nitrogen reduction need, annual costs could be \$9 million to \$40 million to meet the full nitrogen reduction need for Jordan Lake. Comparatively, the average cost-effectiveness of conventional stormwater BMPs on new development was estimated at \$264 per pound of nitrogen for wet ponds and \$573 per pound for large bioretention area (RTI, 2007). ~~Retrofits~~Stormwater retrofits on existing

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development could be several times more than this. For example, the cost of retrofitting bioretention in urban areas of the Piedmont can be $2,078 per pound (James River Association, 2013).

~~This measure is scalable and a facility can potentially treat up to 30 MGD. For comparison purposes, Jordan Lake contains approximately 15 billion gallons in its entirety. The technology seems to be effective for nutrient removal at small scales, although it appears infeasible to treat entire lake. Based on Durham's Feasibility Study of 10 different sites with varying withdrawals, costs can range from $20 to $650 per lb. of nitrogen removed, based on a 20 year present worth cost. Comparatively, the average of conventional BMPs on new development was estimated to be $57. Retrofits on existing development could be several times more than this. Based on a rough estimate of 2 million pound nitrogen reduction per year, annual costs could be $40 million to $1.3 billion for entire lake reductions in Jordan Lake. Phosphorus removal costs are estimated $136 per pound of P to $7,000 per pound.~~

Permitting Considerations

The N.C. Wildlife Resources Commission has reservations about allowing these facilities on lakefront land devoted to wildlife and recreation, which may require facilities to be located further away from the lake. An environmental assessment was required for Durham's Falls lakeside pilot project. A similar assessment would be required for a full-scale facility to evaluate potential environmental impacts, impact avoidance, and mitigation options.

~~Agencies such as NCWRC and USACOE both have serious reservations about allowing these facilities on their lands and would require request and authorization. An environmental assessment would likely need to be done to evaluate potential impacts (habitat quantity and quality, in stream flow, downstream water users, water quality, etc.), impact avoidance, and mitigation options. Multiple permits may be necessary from DWR. Exact permitting details would need to be further investigated.~~ Discussions with DWR permitting staff indicate that 401/404 permits ~~would~~ may be required for the intake and outlet structures. An NPDES permit for discharge ~~would~~ may also be necessary, ~~which~~ but could potentially be covered with a stormwater permit instead of wastewater.

~~If any lake water is lost during treatment (evaporation),~~ the ~~EMC must grant a withdrawal allocation. This has always been done for municipalities, so it is not clear how this process would unfold if the state proceeded with this practice.~~ Depending on how the algal product/waste is disposed, this measure may require a permit from the Division of Waste Management.

Algae Wheel

At a glance…

- *Description:* Potential lakeside technology where a wheel is partially submerged in nutrient-rich water, rotated by air bubbles to promote algae growth with oxygen, bacteria and sunlight.

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- *Extent of Science:* Available information is specific to wastewater treatment, none in North Carolina. Like all of these pump and treat systems, it appears to be a fairly young technology.
- *Designed primarily for:* Currently this technology seems to be limited to wastewater treatment.

Technological Overview

These are used mostly in wastewater treatment to replace conventional biological aeration systems. Systems use bubbles to rotate wheel, then algae grows on the surface using oxygen and bacteria. The Algae Wheel is usually marketed in green houses to utilize warm temperatures and sunlight to grow algae, which is harvested, then discarded or used for fertilizer or energy.

Technical Challenges for Large-Scale Application

Nutrient concentrations in lakes are much less than in wastewater treatment lagoons, and nutrient levels in lake waters may not be sufficient for this technology to be effective. These systems only treat very low flows, with low surface loading rates, so multiple units would be needed to accommodate nutrient load in large reservoirs. Projects would require land area adjacent to waterbodies for a facility, road access, power supply, and piping to and from facility. These also require disposal of waste algae product.

The City of Durham approached a company to look into this for treating streams and lakes, but the company did not show much interest, possibly because it was not a wastewater application.

Cost Considerations

Financial scalability is a concern. In one wastewater treatment plant example, $650,000 was spent for 1 unit to treat 100,000 gallons per day (Jordan Lake has about 15 billion gallons). Treating all the water in the lake appears to be much more expensive than water supply management. However, not knowing how effective it would be in a lake, it is not certain how much of the lake would need to be treated.

Permitting Considerations

Permitting considerations are similar to those described for algal turf scrubbers.

AquaLutions™ AquaFiber

At a glance…

- *Description:* Patented proprietary nutrient and algal removal that uses chemicals and dissolved air flotation; a lakeside technology.
- *State of science:* Emerging technology
- *Designed primarily for:* Potentially anywhere

Technological Overview

AquaLutions AquaFiber is a proprietary device that the Division was unable to obtain much information about. Generally, the technology involves pumping and treating water with chemical additions and dissolved air flotation and removing waste. This is a relatively new technology. It has been used in one Florida case for 3 or 4 years and shows good phosphorus removal potential. Nitrogen reductions are limited. The City of Durham had a feasibility study done for this technology, the results of which indicated excellent phosphorus removals around 90% but poor nitrogen removals. The City ultimately chose to develop a pilot scale operation of the Algal Turf Scrubber.

Details of the process are not clear, but the systems appear to be available for use anywhere, with consideration for land area and facilities.

Technical Challenges for Large-Scale Application

AquaFiber would require land area for a facility to house the project. The process would require use or disposal of the waste product (fertilizer, energy, landfill). Road access, power supply, piping to and from facility are all consideration for installation near the waterbody in question. Also, this approach appears to do well with phosphorus removal but not nitrogen removal.

Cost Considerations

It is a scalable process, ~~as small or large as necessary~~within practical limitations. It could be effective for phosphorus removal on relatively small scales (up to 30 MGD) although not so much for nitrogen. This measure could be extremely expensive and infeasible to treat the entire lake.

Permitting Considerations

Because this lakeside pump and treat option would involve adding chemicals, toxicity tests would have to be conducted before an NPDES discharge permit could be issued. Other permitting issues are similar to those described for the algal turf scrubber.

Conclusions

This report offers a high-level overview of independently evaluated in situ lake and lakeside techniques for potential use in North Carolina's impaired reservoirs. The intent of these practices is either to remove nutrients from a waterbody or to reduce a waterbody's sensitivity to existing nutrient inputs.

Recognizing the challenges outlined in the Introduction regarding application of the set of practices reviewed to North Carolina reservoirs, the most promising practice based on smaller-scale trials may be a proprietary pump-and-treat process, Algal Turf Scrubber, which could be located lakeside. Scale is likely to be a key limiting factor in applicability of this and certain other strategies such as dredging, dilution, food web manipulation and other lakeside pump-and-treat options. Floating wetland islands are an in-lake practice that may provide nutrient benefit along with habitat to support an improved food web, with perhaps the least potential among the practices for unintended negative consequences. In terms of scale evaluations, a proprietary epilimnetic mixing device, Solarbee, is currently under evaluation in Jordan Lake. It is being monitored by both the Division and researchers at North Carolina State University, and results may be available in late 2018. Other practices reviewed would appear to face prohibitive challenges in this state's reservoirs.

Lake-specific evaluations ~~should be performed~~are recommended prior to initiating any mitigation measures. Individual characteristics of waterbodies dictate specific needs that must be considered ~~if treatment options are to be considered~~. Assessing total system assimilative capacity for nutrients and capabilities of in situ measures is critical to estimating the potential of these approaches. This will provide a more feasibility-driven approach towards identifying the mass balance of waterbody nutrients and the amount of mitigation needed in relation to the potential reductions or treatment available from in situ measures.

~~Furthermore, nutrient sources from watersheds should continue to be addressed. All potential in situ and lakeside approaches have only been proven feasible in relatively small natural lakes. In some cases, applying in situ measures to reservoirs in North Carolina will only address symptoms created by watershed scale issues. The scale to which these options would need to be expanded to can lead to extremely expensive projects when applied to entire reservoirs. These options are all long term scenarios that require multiple treatments or continuous operation and provide unproven results in flowing systems.~~

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Appendix I: S.L. 2015-241 §14.5(d)

The Department and Commission shall study in situ strategies beyond traditional watershed controls that have the potential to mitigate water quality impairments resulting from aquatic flora, sediment, nutrients, or other water quality variables that impair or have the potential to impair water bodies of the State. In addition to a survey and evaluation of currently available in situ strategies, the Department and Commission shall assess the potential efficacy of in situ strategies in other water bodies of the State, and consider the utilization of in situ strategies in their development, review, and modifications of basinwide water quality management plans or related water quality mitigation modeling. The Department and Commission shall provide a report on their study to the Environmental Review Commission, the Fiscal Research Division, and the chairs of the Senate Appropriations Committee on Natural and Economic Resources and the House Appropriations Committee on Agriculture and Natural and Economic Resources no later than April 1, 2016.