Manitoba Prairie Lakes: In-lake remediation treatment summary

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May 2016

Eutrophication is the process by which a body of water acquires a high concentration of nutrients—especially phosphates and nitrates, silt and organic matter—that typically promote excessive growth of algae. As the algae decompose, high levels of organic matter and the decomposition of organisms deplete available oxygen in the water column, causing the death of other organisms, such as fish. Eutrophication is a natural, slow-aging process for a water body; however, human activity greatly speeds up the process.

Eutrophication causes pronounced deterioration of water quality and is a widespread environmental problem, one that currently affects the quality of many of Manitoba's prairie lakes. As a result of excessive loading of nutrients, organic matter and silt, there is an overall increase in algal blooms, resulting in reduced water quality. Many prairie lakes may be eutrophic due in part to Manitoba's regional soil fertility, runoff patterns and geology, which encourage natural eutrophic conditions. However, human-induced nutrient loads from municipalities, agriculture, industry and other sources are contributing significantly to lake eutrophication in the prairies, significantly shortening a lake's lifespan.

The primary focus of lake restoration should be controlling the sources of nutrients into the lake, augmented by in-lake remediation treatments that focus on the "symptoms." The success of remediation treatments varies greatly from lake to lake, and it is generally agreed that these treatments should be considered after or alongside efforts to reduce and control external nutrient loads. In addition to point source controls, reductions in agriculture runoff of nutrients, reestablishment of wetlands and littoral zones, and restoration of channelized streambeds have been shown to restore many lakes. In-lake remediation options can be used to improve lake recovery while ensuring that costs, effectiveness, ease of implementation and above all, watershed sources of nutrients are managed.

Lakes are highly dynamic and interactive systems, and it is impossible to alter one characteristic without affecting other aspects of the system. A complex set of physical, chemical and biological factors influences lake ecosystems and affects their responsiveness to remediation and management efforts. These factors vary with lake origin, the regional setting and the watershed, and include hydrology, climate, watershed geology, watershed-to-lake ratio, soil fertility, hydraulic residence time, lake basin shape, lake biota, the presence or absence of thermal stratification, and external and internal nutrient loading sources and rates. Appropriate evaluation can determine the feasibility of controlling the primary sources of the most limiting nutrient. Various lake parameters serve as indicators for remediation treatment suitability, including:

- lake size and depth
- secchi depth (measurement of water clarity)
- chlorophyll-*a* (predictor of phytoplankton biomass)
- pH (acidity or alkalinity of a solution on a logarithmic scale)
- nutrient loading source (internal versus external source)
- sedimentation rate (accumulation of sediment within the lakes and is needed for estimation of the contribution of known sediment sources and loading)
- residence time (measure of how quickly water quality will change in response to increases or decreases in sources of contamination)
- flushing rate (percent of the lake volume replaced)
- longevity (duration of remediation treatment application).

This document summarizes identified in-lake remediation treatments analyzed in more detail in IISD's research and report in Manitoba Prairie Lakes: Eutrophication and In-Lake Remediation Treatments Literature Review to limit the effects of eutrophication on lake water quality. Common remediation treatment methods have been reviewed; however, it is not entirely exhaustive. It is suggested that this analysis and information be used in conjunction with more detailed analysis of a waterbody's limnological and morphological parameters before implementation. This summary document presents three biological treatments, five physical/engineering treatments and three chemical treatments for prairie lake eutrophication based on our study of literature.

Biological Treatment 1: Biomanipulation

DESCRIPTION

Biomanipulation involves the grazing of algae by large zooplankton—particularly *Daphnia*—that can be enhanced by eliminating planktivorous fish (fish that feed on planktonic food, including zooplankton or phytoplankton) through physical removal or increased piscivory (introduction of fish eating species). Food-web manipulations have been relatively successful; however, treatment longevity is limited and long-lasting results are rare. There is enormous variability in the likelihood of a positive outcome and uncertainty about the most common mechanisms determining successful and unsuccessful biomanipulation.

BENEFITS

- Water-quality improvements include increased transparency, decreased turbidity, decreased chlorophyll-*a*, total phosphorus (TP) and total nitrogen (TN) concentration.
- Generally, method is inexpensive.
- Does not require complex infrastructure.
- Does not require potentially toxic chemicals; however, chemicals such as rotenone have been applied.
- The introduction of piscivorous fish may enhance recreational fishing.

SHORTFALLS

- Resistance to grazing by large cyanobacteria.
- Replacement of fish predation by invertebrates (*Chaoborus*).
- Overstocking of piscivores.
- Long-term unsustainability of the fish populations.
- Nutrient transport by fish.
- Immigration by planktivores from other systems.
- Increased planktivory by invertebrates.
- Resuspension of sediments.

Treatment success is extremely variable and reasons for failure include:

- Poor timing of stocking.
- Inedibility of many algae common to eutrophic lakes (cyanobacteria).
- Insufficient numbers of fish removed.
- Low survival of stocked fish.

SUITABLE LAKE CONDITIONS

Lake size: In theory, there is no restriction on lake size, although lakes smaller than 25 hectares have had the highest percentage of success. Successful implementation in the literature ranged from 1.5–240 hectares.[2] However, one of the most effective biomanipulations was in Lake Mendota, WI (4,000 hectares).

Lake depth: Greatest probability to reduce algal biomass occurs in lakes less than 3 metres. Successful implementation from the literature review: 1.5–2.6 metres.

Phosphorus load: 1.0–14 kg hectare^{-1} year^{-1}. [3]

Lakes with external P loadings below 0.6 g P m^{-2}yr^{-1} have a higher probability for biomanipulation to reduce algal densities.[4]

Total Phosphorus: Successful implementation in the literature range from 0.05–1.4 mg L^{-1}.[5]

The recommended lake total phosphorus concentration is less than 100 µg L^{-1}.

Chlorophyll-*a*: 21–300 µg L^{-1}.

Successful implementation in the literature ranged from 80–116 µg L^{-1}.

Secchi depth: 0.9–2.9 metres.

Longevity: Enormous variability in success. Multiple restocking events might be necessary.

COST

Twin Lake, MN (8 hectares):[6]

Capital cost: USD 216,000. Total project cost (20-year project lifespan): USD 273,000.

Lake Nokomis, MN (82 hectares, walleye stocking):[7]

USD 12,700 per year, plan for 10 years. Total project cost (10-year project lifespan): USD 127,000.

Biological Treatment 2: Floating Treatment Wetlands

DESCRIPTION

Wetlands rely on natural processes to biologically filter water as it passes through shallow areas of dense aquatic vegetation and permeable bottom soils. Floating treatment wetlands (FTWs) are composed of an artificial platform containing emergent macrophytes. The primary mechanisms for nutrient removal are microbial transformation and uptake; macrophyte assimilation; absorption into organic and inorganic substrate materials; and volatilization.

BENEFITS

- Relatively inexpensive compared to physical and chemical remedial treatments.
- Rooted macrophytes extract nutrients from both the sediment and the water column.
- Reduce redox potential and anoxic conditions.
- Harvesting platform plant material and the removal of biomass can further reduce nutrient concentration.
- Increase wildlife habitat.
- Reduce local nuisance insect populations.
- Increase waterbody aesthetics.

SHORTFALLS

- Little to no adverse effects on lake quality mentioned in the literature.
- Potential effects on N:P ratio, with effects on cyanobacterial growth.
- Potential to restrict access or reduce available area for recreational use.
- Potential for anoxic conditions with high lake surface coverage.

SUITABLE LAKE CONDITIONS

Floating wetland treatment is suitable for a wide range of lake characteristics and water-quality conditions. For example, FTWs were installed at two lakes of differential phosphorus concentrations at the IISD Experimental Lakes Area in 2015: Lake 227 (which has been famous for phosphorus additions since 1969) and Lake 114 (a natural, background lake). Both platforms successfully sequestered nutrients in the plant material; however, the excess phosphorus of Lake 227 enhanced cattail productivity and nutrient uptake.

The size of the system is an indicator of effectiveness, where platform characteristics (design, size, macrophyte species) and specific lake characteristics (temperature, pH, TP, TN, Chl-*a*) will determine nutrient reduction.

Lake size: Application is successful and suitable to a wide range of lake sizes; however, it is most efficient in small lakes, ponds, small reservoirs and retention ponds.

Depth: Minimum water depth should be greater than 1 m to prevent platform plants from rooting into lake bottom sediment. Ideal depth is 1.5–2 metres.

Longevity: With relatively low maintenance and secured placement, FTWs will continuously sequester nutrient in the plant material. Harvesting material increases nutrient removal and longevity.

FTWs were installed at Cargill Lake (58,675 m^2), a treatment wetland (1,312 m^2) and a stormwater retention basin (99,531 m^2) at Fort Whyte Alive in Winnipeg, Manitoba to assess phosphorus uptake in the plant material. A standardized equation determined the percentage surface cover of FTWs on a waterbody with a desired percentage of phosphorus reduction and the assumption phosphorus will be extracted when cattail is harvested.[8]

- Cargill Lake: FTWs would need to cover 29 per cent of the surface area of the lake to reduce total phosphorus by 10 per cent year. Cargill Lake's mean TP was 0.00018 g P L^{-1} and the reduction scenario was set to the safety standard exceedance guideline of 0.000025 g P L^{-1}.
- Lake Devonian (mean TP 0.0006 g P L^{-1}): FTWs would need to cover 70 per cent of the lake's surface area to reduce total phosphorus by 5 per cent.

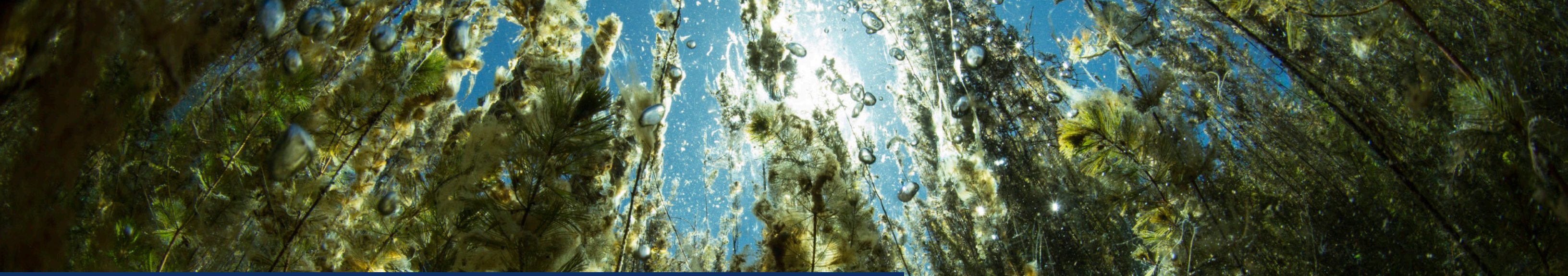
COST

Cost determined by water-quality goals and specific lake conditions, e.g., lake size.

FWT platforms range USD 11–USD 260 per square metre.[9]

Biohaven™ FTW installation in St. Gabriel, LA (2.1 hectare pond, 0.7 per cent surface area coverage)

Installation, plants (70 plants) and monitoring for one year: USD 40,000.



Biological Treatment 3: Removal of Macrophytes

DESCRIPTION

Removing macrophyte biomass from lakes removes nutrients, which for some lakes can be a significant contribution to internal loading. Macrophyte removal can alleviate oxygen deficiency and sediment phosphorus release attributed to thick overstory and decomposition of organic matter

BENEFITS

- Extracts nutrients from both the sediment and the water column.
- Over the long term, harvesting macrophytes can affect nutrient cycling between the water column and the sediment.
- Increase waterbody aesthetics.

SHORTFALLS

- Immediate physical, and prolonged physical and chemical effects on biota and ecosystem processes.
- Directly and indirectly removes fish, invertebrates and other species from the ecosystem.
- Loss of habitat for grazers.
- Fish common in the littoral zone are often considered desirable for fishing.
- Reducing macrophytes decreases competition with algae and may even promote algal blooms.

SUITABLE LAKE CONDITIONS

Parameters involved to calculate the potential for removing nutrients:

- Area of the lake covered with macrophytes (m^2).
- The average biomass of the plants in the area (g m^{-2} per year).
- The nutrient concentration of the plants (g nutrient/g dry weight of plant).

Successful implementation of hypolimnetic withdrawal as reviewed in the literature.

Lake size: 10–5,300 hectares.

Depth: 2.4–5 metres (shallow lakes).

Phosphorus load: 1,890 tonnes of nitrogen and 296 tonnes of phosphorus were removed by harvesting 6.0 x 10^5 tonnes of macrophytes, which corresponded to 28 per cent and 57 per cent, respectively, of total external loading.[10]

Longevity: Harvesting is continuous and a multi-year obligation for maximum affect in the long term.

Cost is variable and dependent upon width of cut and harvesting method, area harvested, plant species and density, water depth and bottom obstructions.

- USD 42,000 per year or USD 728 per hectare (2015) to harvest 60 hectares.[11]
- USD 550,000 per year: Chautauqua Lake, New York to harvest 5,300 hectares, 2,348 tonnes removed in 2014.[12]
- Range in the literature USD 650–USD 1,000 per hectare.[13]
- Cost of a large system harvester USD 50,000–USD 200,000.
- Smaller harvesters attached to a boat are significantly less expensive.

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Physical, Engineering Treatment 1: Hypolimnetic Withdrawal

DESCRIPTION

Lakes tend to stratify or form layers based on temperature, density and other characteristics. The lowest layer that comes into contact with the sediment, or the hypolimnion, often contains higher phosphorus concentrations when the lake is stratified. This remediation technique involves selectively removing the nutrient-enriched layers of water from the lake through siphoning, pumping or selective discharge. Consequently, hypolimnetic withdrawal shortens hypolimnetic retention time, decreases the chance for anaerobic conditions to develop, accelerates phosphorus export, reduces surface phosphorus concentrations, and improves hypolimnetic oxygen content.

BENEFITS

- Relatively low capital and operational costs.
- Potentially long-term effectiveness.
- Hypolimnetic dissolved oxygen increase, which can result in a decrease in the anoxic volume and days of anoxia.
- Reduce the accessibility of cyanobacteria to Fe(II), now thought to be a precursor to the development of blue-green algal blooms.
- Increase in hypolimnetic DO can improve fish habitat.

SHORTFALLS

- Potential for water-quality issues downstream if hypolimnetic water contains high concentrations of P, ammonia, hydrogen sulfide and low oxygen.
- Withdrawal followed by treatment and discharge back to the lake is inefficient in removing phosphorus compared to in-lake treatment.
- Potential warming of the lake as bottom waters are exposed to surface temperatures.
- Destabilization of the thermocline (distinct layer of water in which temperature changes rapidly with depth) and enable nutrients from the hypolimnion to become available for phytoplankton growth in the epilimnion (upper layer of water in a stratified lake).
- Water removed may have strong odour.

SUITABLE LAKE CONDITIONS

There is evidence of the effectiveness of hypolimnetic withdrawal in a number of cases; however, successful implementation of this method is restricted to deeper, stratified lakes with considerable internal loading or phosphorus release from sediments at the bottom of the lake.

Successful implementation of hypolimnetic withdrawal as reviewed in the literature.

Lake size: 1.5–400 hectares.

Depth (mean): 3.0–48 metres.

Depth (max.): 6.8–56 metres.

Residence time: 0.26–9.0 years.

Longevity: Effectiveness of treatment depends on magnitude and duration of TP transport from the hypolimnion, and it is important to exchange the hypolimnion volume as frequently as possible. A low rate of replacement may limit the effectiveness and longevity of treatment.

Important to understand natural refilling rate and whether or not it is high enough to reduce lake drawdown resulting from hypolimnion discharge. Smaller lakes may refill too slowly to be effective.

COST

Relatively low capital and annual operation cost are advantages of hypolimnetic withdrawal.

Cost range from literature: USD 80,000–USD 600,000 (lake size ranged from 1.5 to 400 hectares in the review).

Twin Lake, MN (8 hectares in size):[14]

Construction cost: USD 400,000.

Annual operation USD 40,000.

Total cost (20-year treatment lifespan): USD 1.3 million.

Physical, Engineering Treatment 2: Dilution and Flushing

DESCRIPTION

Dilution involves the addition of low-nutrient water to reduce lake nutrient concentration and has been effective where external or internal sources are not controlled. Flushing refers to the removal of algal biomass. Dilution and flushing can improve quality in eutrophic lakes by reducing the concentration of the limiting nutrient (dilution) and by increasing the water exchange rate (flushing).

BENEFITS

- Relatively low cost if water is available in high quantity.
- Immediate and proven effectiveness if the limiting nutrient can be decreased.
- Moderate success even if only moderate-to high-nutrient water is available.

SHORTFALLS

- If dilution water is derived from a source outside of the catchment, there may be a risk of introducing undesirable taxa.
- Potential impacts on the diverted water source.

SUITABLE LAKE CONDITIONS

Successful implementation of dilution and flushing as reviewed in the literature.[15]

Lake size: 104–490 hectares. Generally limited to relatively small lakes where there is sufficiently large amounts of low-nutrient water to effect a decrease in nutrient concentration. However, Moses Lake (WA) successful decreased TP concentration with the application of dilution/flushing and the lake is 2,753 hectares in size.

Depth (mean): 3.8–5.6 metres. .

Phosphorus load: In-lake nutrient conc. are usually lower than inflow conc. because sedimentation is greater than internal loading. Nutrient load is usually increased with this strategy, however, nutrient loss through sedimentation is potentially decreased.

Chlorophyll-*a*: 71–102 $\mu g\ L^{-1}$.

Flushing rate: 5.8 - 17 per cent per day, large enough initially to reduce in-lake concentration.

The amount of water needed to achieve a given reduction in inflow concentration is a function of the concentration difference between the normal inflow and dilution water source.

COST

High variability and dependence on the presence of a facility to deliver water, and the quantity and proximity of available water.

Cost range from literature: USD 100,000–USD 800,000.

Moses Lake, WA (2,753 hectares): Primary cost was the pumping facility USD 750,000 (2015).

Physical, Engineering Treatment 3: Hypolimnetic Aeration and Oxygenation

DESCRIPTION

Hypolimnetic aeration is usually accomplished by the injection of pure oxygen or air into the hypolimnion (lower layer of water, which comes into contact with sediment), without disturbing stratification or the separation of water layers based on depth and temperature. The specific objectives of hypolimnetic aeration are:

- To raise the oxygen content of the hypolimnion without destratifying the water column or warming the hypolimnion.
- To provide an increased habitat and food supply for coldwater fish species (dependent on the previous objective).
- If sediment-to-water exchange of phosphorus is controlled by iron redox, to reduce sediment phosphorus release by establishing undesirable conditions at the sediment–water interface.

BENEFITS

- Anoxic hypolimnia can switch to an oxic state while still maintaining a coldwater environment.
- Potentially decrease internal loading of phosphorus (P), iron (Fe), manganese (Mn), ammonium, hydrogen sulfide and methyl mercury.
- Aeration may improve habitat quality for coldwater fish, even if improvements in epilimnetic water quality are not achieved

SHORTFALLS

- Interactions between Fe and P primarily affect only the short-term cycling of P, and do not result in the permanent storage of P in lake sediment.
- Phosphorus improvements do not always occur with aeration.
- Lakes where internal P recycling is driven by processes unrelated to Fe-P interactions may not show any positive effects on nutrient loading.
- Potential supersaturation hypolimnetic water with N_2 can lead to gas bubble disease in fish.
- Potential to increase eddy diffusion of nutrients into the epilimnion, even though stratification is maintained.
- Slow circulation conditions and destratification may result in low dissolved oxygen throughout the water column and introduce toxic chemicals (for example, hydrogen sulfide) into the epilimnion.

SUITABLE LAKE CONDITIONS

Hypolimnetic aeration will not be effective if the waterbody is too shallow. Although stratification may exist, the density gradient may not be sufficient to resist thermocline erosion. While hypolimnetic aeration may restore oxygen conditions for fish and other biota, other toxic elements may not be sufficiently reduced to allow survival. Successful implementation conditions reviewed in the literature:[16]

Lake size: 5.3–3,000 hectares.

Depth (mean): 3.5–28.4 metres and lake must be stratified.

Depth (max.): 5.7–85 metres. Not recommended if max. depth is less than 12–15 m and/or hypolimnetic volume is relatively small.

Device depth: 5.2–33 metres.

Longevity: Continual treatment. For example, Lake Steven and Lake Tegel 10 years of operation.

COST

Less cost effective than other treatments for phosphorus control, such as alum; however, there are other reasons for aeration, such as creating an aerobic environment.

USD 4,000 per hectare per year (based on mean areas of 15 lakes).

Lake Steven (operating 160 days per year): USD 340,000 (\$0.27/kg O_2 or \$1,610 per hectare)..

Physical, Engineering Treatment 4: Artificial Circulation

DESCRIPTION

Artificial circulation involves using pumps and diffused air to circulate water in an entire lake, which can be differentiated from hypolimnetic aeration that focuses on circulation in a select region or depth. Unlike with hypolimnetic aeration, the temperature of the whole lake will increase with complete circulation if mixing includes water that was previously part of the cooler hypolimnion. The principal improvements in water quality caused by complete circulation are oxygenation and chemical oxidation of substances in the entire water column, as well as enlarging the suitable habitat for aerobic warm-water species. Circulation improves dissolved oxygen and reduces iron and manganese: it also causes light to limit algal growth in environments where nutrients are uncontrollable and neutralize the factors favouring the dominance of blue-green algae.

BENEFITS

- Circulation can reduce phytoplankton biomass by increased depth of mixing of plankton cells and increased light limitations.
- Increased circulation usually results in the complexation and precipitation of iron (Fe) and manganese (Mn), reducing trace elements and phosphorus (P) internal loading, therefore algal biomass.
- If sediments are distributed by mixing, algal biomass may also decrease due to decreased light availability.
- Improvement of warm-water fisheries.

SHORTFALLS

- If circulation increases the suspension of particulate material, associated P may mineralize and become available to phytoplankton.
- Mixing of sediment may increase inorganic turbidity.
- Whole lake circulation will result in the loss of deep coldwater habitat for fish in stratified lakes.
- Overall lake temperatures typically increase following treatment.

SUITABLE LAKE CONDITIONS

Four indicators of the effects of artificial circulation are dissolved oxygen (DO), ammonium, epilimnetic pH (upper layer of water in a stratified lake) and the trace metals iron and manganese. The lake conditions for successful implementation of artificial circulation, as reviewed in the literature, are as follows:[17]

Lake size: 9.1–18 hectares. However, successful implementation in a large lake, Lake Nieuwe Meer (Netherlands).
132 hectares in size.

Depth (mean): 2.6–3 metres.

Longevity: Artificial circulation requires continual treatment and management.

COST

Cost increases with lake size, although costs per hectare decline, demonstrating economies of scale.[18]

Lakes > 53 hectares: USD 760 $ha^{-1.}$

Lakes 23–25 hectares: USD 1,680 $ha^{-1.}$

Lakes <10 hectares: USD 7,743 $ha^{-1.}$

Twin Lake, MN (8 hectares):

20-year lifetime cost: USD 935,000 (2013).

Maintenance cost: USD 35,000 per year.

Initial cost: USD 520–USD 6,100 per hectare

Annual cost: USD 150–USD 2940 per hectare.

Physical, Engineering Treatment 5: Dredging and Removal of Sediment

DESCRIPTION

For lakes where significant nutrient loading from sediment occurs, removal of nutrient-rich surficial sediments can reduce the rate of internal nutrient recycling, improving overall lake water quality. In addition to removing nutrients in bottom sediments, removal may also decrease cyanobacterial innocula.

BENEFITS

- Lake deepening.
- Expand habitat.
- Limit nutrient recycling.
- Reduce macrophyte nuisance.
- Remove toxic sediment.

SHORTFALLS

- Resuspension of sediments on aquatic organisms including clogging filtering apparatus of benthos and zooplankton, and reduction of light.
- Many fish species cannot tolerate high sediment loads.
- Nutrient liberation from disturbed sediments and porewaters.
- Potential release of toxic substances associated with fine particulars (polluted).
- Destruction of benthic fish-food organisms and its effect on a lake's food web.
- Lake draining will result in the mortality of most native aquatic biota.

SUITABLE LAKE CONDITIONS

Dredging is generally limited to shallow lakes (depth of less than 3 metres), but lake area is not a constraint. Depth, size, disposal area, watershed area and sedimentation rates are important physical variables that affect treatment feasibility. Successful implementation of dredging as reviewed in the literature.[19]

Lake size: Area is not a constraint. Successful implementation reviewed in the literature ranges from 2–1,000 hectares.

Lake Depth: Highest success in lakes shallower than 3 m. Depth as reviewed in the literature: 0.5–9.75 m (max. depth).

Sediment depth: Dredging will only be effective in lakes with high-nutrient-enriched surface sediments relative to underlying sediment. Sediments are the source of internal loading and the bulk of nutrients are located in the top 0.3–0.5 m of a sediment core: removal of that layer by dredging should provide a reliable and permanent solution, although costly.[20]

Sedimentation rate: Low

Water-to-surface ratio: Small, approx. 10:1.

Hydraulic retention time: Long.

Watershed sourced loading: Requirement of a reduction in external nutrient load of at least 50 per cent.

Longevity: Long-term benefit of removing the nutrient source.

COST

The main objection to dredging is the high cost. Project-to-project cost comparison for sediment removal is difficult due to the large number of variables that affect dredging cost, such as equipment, volume of material removed, and density of material.

Removal of contaminated sediments: USD 34–USD 1,409 per m^3.[21]

Literature review: USD 1–USD 30 per m^3; or USD 3,200–USD 60,000 per hectare.

Twin Lake, MN (8 hectares): Total cost USD 2,570,000.[22]

Chemical Treatment 1: Phosphorus Inactivation

DESCRIPTION

Phosphorus in lakes can be inactivated using techniques such as capping, which involves covering contaminated sediments with a stable layer of material. Many different methods of sediment capping and P inactivation have been used in lake restoration projects, including physical (mechanical or passive) capping and active capping using alum, calcium, zeolite, Phoslock™, iron and modified clays. Passive capping with sand, gravel, or clay is used to decrease diffusion of nutrients and contaminants to the overlying water column and bury them deeper in the sediments.

BENEFITS

Alum

- Proven effective control.

Calcium

- Extensively used in hard-water lakes.
- Calcium additions to hard-water lakes have fewer toxic impacts than alum.

Phoslock™

- Proven effective control, non-toxic under a wide range of environmental conditions; effective under a wide range of pH values and alkalinities; does not affect pH levels following treatment (advantages over alum).

SHORTFALLS

Alum

- Restricted to a narrow pH range; additions to low-alkalinity lakes can result in acidification.
- Toxicity bioaccumulates in fish tissue.

Calcium

- With increased turbidity, potential smothering of benthos by $CaCO_3$.

Phoslock™

- Potential toxicity of La.
- Long-term negative ecological impacts not well understood.

SUITABLE LAKE CONDITIONS

Capping thickness usually exceeds 5 cm, which limits the approach to small lakes or reservoirs due to the large volume of material required and difficulties depositing a uniform layer. Successful implementation of phosphorus inactivation as reviewed in the literature[23]:

Alum	Calcium	Phoslock™
Lake size: 9–600 hectares. Mean depth: 1.8–8.4 m Max depth: 3.5–23.7 m pH: 6–8 throughout treatment Alkalinity: <50 mg $CaCO_3$/L; will lower pH if lake has low alkalinity	Lake size: 58–240 hectares. Mean depth: 10–18 m Max. depth: 30–42 m. Hydraulic res. time: 4.4 yrs. (Lake Schmaler). Chl-*a*: 4.0 Secchi depth: 5 m pH: 8.5	Lake size: 0.9–64 hectares. Mean depth: 1.6–8.8 m. Max depth: 2.5–34 m.

Longevity: P inactivation longevity does not typically exceed 15 years and will depend on phosphate release rates and application dose. Alum longevity typically 4–21 years (stratified); 1–11 years (shallow lakes).

Lake characteristic	Alum	Phoslock™
Wind-exposed lakes	N	R
Deep lakes	R	R
Highly turbid lakes	NR	R
High sedimentation	R	NR
Low alkalinity and poor buffering capacity	NR	R
Long period of stratification and anoxia	NR	R
High ammonium concentration	NR	NR

NR = not recommended; R = recommended.

COST

Alum: Twin Lake, MN (8 hectares): USD 148,000 (2013).

Jessie Lake, MN: alum (40 per cent) USD 508,000; alum (60 per cent) USD 754, 000.

Phoslock™: USD 440–USD 880 per kg for biologically available P immobilized[24]

If 50 mg mobile P/kg in top 10 cm: USD 0.75; if 400 mg mobile P/kg in top 10 cm: USD 6.02[25]

Chemical Treatment 2: Sediment Oxidation

DESCRIPTION

This technique involves injecting chemical solutions, such as calcium nitrate [$Ca(NO_3)_2$], iron (as ferric chloride, $FeCl_3$) or lime ($CaCO_3$), into lake sediments. The method reduces internal loading in lakes where iron redox reactions control phosphorus fluxes between sediment and overlying water. Nitrate acts as an alternate electron acceptor to oxygen, preventing the development of ferrous iron and subsequent phosphorus release.

BENEFITS

- Although greater in cost, treatment is an effective alternative to alum to inactivate sediment phosphorus.
- Chemicals added are found in high concentrations naturally in unpolluted sediments.
- Toxicity to animals is perceived as a lesser issue than for other phosphorus inactivation methods.
- Potentially more permanent than alum due to direct injection into the sediment column.

SHORTFALLS

- Expected to succeed only if internal loading of phosphorus is controlled by iron redox reaction.
- Concerns over the lack of documented successful applications.

SUITABLE LAKE CONDITIONS

Because the method requires direct injection of chemicals into sediments, it can typically be used in shallow lakes with relatively flat bottoms. Successful implementation of hypolimnetic withdrawal as reviewed in the literature:[26]

Lake size: 4.2–49 hectares.

Depth: Suitable for shallow lakes; 0.7–2.3 metres.

Injection depth: 0.2–3.0 metres.

pH: Ferric chloride and lime additions have been determined as unnecessary in some cases, where pH may be sufficiently high to promote denitrification and sediment iron content adequate (30–50 mg per gram) for phosphorus binding.

Longevity: Continued low sediment phosphorus release 10 years following treatment was observed for Lake Lillesjön, Sweden.

COST

Sediment oxidation is a comparatively expensive remediation method.

Lake Lillesjön, Sweden (applied to 1.2 hectares lake area):

USD 232,500 (2015).

Lake Trekanten, Sweden (87 hectares):

USD 609,000 (2015).

White Lough, Ireland:

Nitrate: USD 43,000; USD 9,350 per hectare (2015).

Iron/alum: USD 11,500; USD 2,500 per hectare (2015).

Chemical Treatment 3: Algicide

DESCRIPTION

This technique was more commonly used in earlier lake remediation management strategies and water supply reservoirs suffering from algal biomass. However, algicide is not frequently practiced due to the significant detrimental aspects associated with the technique on the lake's biological community. It is important to note that dose application concentrations for copper sulfate (*Chara* and *Nitella* require a dose of 1.5 mg/L or higher) greatly exceed existing Canadian limits for the protection of aquatic life[27] and consequently cannot be legally added to lakes in most jurisdictions.

BENEFITS

- Copper sulfate application used to be standard treatment for algal problems for many decades due to its short-term effectiveness.
- Short-term beneficial effects include suppression of algae; however, the negative effects outweigh this positive.

SHORTFALLS

- Ineffective for long-term treatment.
- Potential human health problems.
- Mortality of toxic algae from copper sulfate may result in the release of cellular toxins such as microcystin.
- Resistance may develop in target algae.
- Dissolved oxygen depletion can occur when large volumes of dead algal cells decompose.
- Reduce potential binding capacity of lake sediment.
- Negatively impacts aquatic communities.
- Copper stress impairs food-web functions.
- Accelerated phosphorus recycling from lake bed.
- Copper accumulation in the sediment.
- Disappearance of macrophytes.
- Reductions in benthic macroinvertebrates.

SUITABLE LAKE CONDITIONS

Successful implementation of algicide as reviewed in the literature:[28]

Lake size: 84–224 hectares.

Depth: Depth: For lakes with a methyl orange alkalinity > 40 mg/L as $CaCO_3$, the dose for planktonic algae is 1.0 mg $CuSO4 \cdot 5\ H_2O$ per litre, as copper sulfate crystals, for the upper 0.3 m depth, regardless of actual depth.

Temperature: More effective >15 °C.

Alkalinity: For lakes with a methyl orange alkalinity >40 mg/L ($CaCO_3$), dose is 1.0 mg $CuSO_4 \cdot 5\ H_2O$ per litre. If alkalinity is < 40 mg/L, the dose is 0.3 mg $CuSO_4 \cdot 5\ H_2O$ per litre.

Longevity: Applications of algicides provide only temporary relief for algal problems and will require continued reapplication. Copper sulfate additions in the Fairmont Lakes, MN, occurred for 58 years.

COST

Single treatment costs for Casitas Reservoir, CA.[29]

$CuSO_4$ solution: USD 220–USD 650.

$CuSO_4$ crystals: USD 197–USD 1,185.

$CuSO_4$ citric acid solution: USD 127–USD 1,50.

Copper-ethanolamine granular: USD 710–USD 3,000.

Application costs vary greatly: granular copper sulfate ~USD 2 kg^{-1}; liquid Cutrine Plus ~USD 10 $litre^{-1}$.

Endnotes

[1] Art, 1993.

[2] van Donk Gulati, & Grimm, 1990; Hosper & Jagtman, 1990; Hansson et al., 1998; Hobbs et al., 2012; Lathrop et al., 2002; Søndergaard et al., 2007; Barr Engineering Company, 2013.

[3] Olin et al., 2006

[4] Lathrop et al., 2002

[5] Hansson et al., 1998

[6] Barr Engineering Company, 2013.

[7] MCWD, 2013.

[8] Stanley, 2015.

[9] Virginia State University, 2013.

[10] Wu Chen, & Gao, 1995.

[11] Korth, Engel, & Helsel, 1997.

[12] Chautauqua Lake Association, 2015.

[13] Aquamarine, 2014.

[14] Barr Engineering Company, 2013.

[15] Perkins, 1983; Sas et al., 1989; Cooke, Welch, Peterson, & Newroth, 1993; Cooke, Welch, Peterson, & Nichols, 2005.

[16] Fast, Lorenzen, & Glenn, 1976; Soltero et al., 1994; Gachter & Muller, 2003; Cooke et al., 2005; Katsev, Tsandev, L'Heureux & Rancourt, 2006.

[17] Lorenzen & Fast, 1977; Pastorak, Ginn, & Lorenzen, 1981; Spencer & King, 1987; Osgood & Stiegler, 1990; Shapiro, 1997; Nurnberg & LaZerta, 2003; Cooke et al., 2005; ICLEI, 2006; Barr Engineering Company , 2013.

[18] Cooke et al., 2005.

[19] Andersson, Berggren, & Hambrin, 1975; Worth, 1981; Peterson, 1981; Garrison, 1989; Garrison & Ihm, 1991; Kleeberg & Kohl, 1999; Cooke et al., 2005; Barr Engineering Company, 2013.

[20] Cooke et al., 1993.

[21] Blazquez, Adams, & Keillor, 2001.

[22] Barr Engineering Company, 2013.

[23] Wang, Wilkie, Heigenhauser, & Wood, 1994; Hupfer, Gachter, & Giovanoli, 1995; Cooke, 1995; Welch & Cooke, 1999; Lewandowski Schauser, & Hupfer, 2003; Cooke et al., 2005; Pan, Zou, Chen, & Yuan, 2006; Zou et al., 2006; Landman, Brijs, Glover, & Ling, 2007; Hickey & Gibbs, 2009; Gibbs, Hickey, & Ozkundakci, 2011; Itasca Soil and Water Conservation District, 2011; Dittrich, Gabriel, Rutzen, & Koschel, 2011; Morrison, 2012; Barr Engineering Company, 2013; Spears, Sebastian, Anderson, & Kellou, 2013; Huser & Pilgrim, 2014; Zamparas & Zacharias, 2014; Ackerman & Cicek, 2014.

[24] Morrison, 2012.

[25] Ackerman & Cicek, 2014.

[26] Ripl, 1981; Ripl, 1986; Foy, 1986; Noonan, 1986; Cooke et al., 2005; Hickey & Gibbs, 2009.

[27] Canadian Council of Ministers of the Environment, 2003.

[28] Benoit, 1975; McKnight, Chisholm, & Morel, 1981; Hanson & Stefan, 1984; Ellgaard & Guillot, 1988; Havens, 1994; Lam, Prepas, Spink, & Hrudey, 1995; Erikson et al., 1996; Haughey et al., 2000; Anderson, Giusti, & Taylor, 2001; McComas, 2003; Cooke et al., 2005

[29] Cooke et al., 2005.

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