Lake and Watershed Management Options for the Control of Nuisance Blue-Green Algal Blooms in Pigeon Lake, Alberta

Alberta Government

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Executive Summary

Pigeon Lake is a large recreational lake located southwest of Edmonton. Due to natural soil characteristics and proximity to major urban centres, the Pigeon Lake watershed has undergone significant urban and rural development in the past decades. In recent years, occurrences of significant blue-green algae (cyanobacteria) blooms have been documented at Pigeon Lake. As a result of these blooms, stakeholders at Pigeon Lake have been seeking management options to assist with reducing the frequency and intensity of such events.

The following report includes an overview of cyanobacterial ecology and provides a list of in-lake and watershed management options for control of nuisance blue-green blooms and outlines the benefits, disadvantages and applicability to Pigeon Lake. While several options are available for stakeholders to pursue, it is important that a cost-benefit analysis be conducted beforehand and that stakeholders ensure that all applicable permits and approvals be obtained.

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Acknowledgements

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1.0 Introduction

Pigeon Lake is a large recreational lake located approximately 60km southwest of Edmonton. Due to its proximity to this large urban centre, the ease of access to the lake, and available amenities and recreational opportunities within the region, Pigeon Lake is one of Alberta's most popular recreational lakes. Land-uses within the Pigeon Lake watershed includes a mix of natural landscape, agriculture, and urban residential (both seasonal and permanent). Administratively, there are 10 summer villages surrounding the lake, two provincial parks and one first nations reserve (Mitchell and Prepas 1990). The population within the ten summer villages is estimated to be 747 (Statistics Canada 2012); however the number of transitory lake users far exceeds this, especially during the summer months. Pigeon Lake falls within two county boundaries; Leduc County on the northwest side, and the County of Wetaskiwin for the remainder of the watershed (Figure 1).

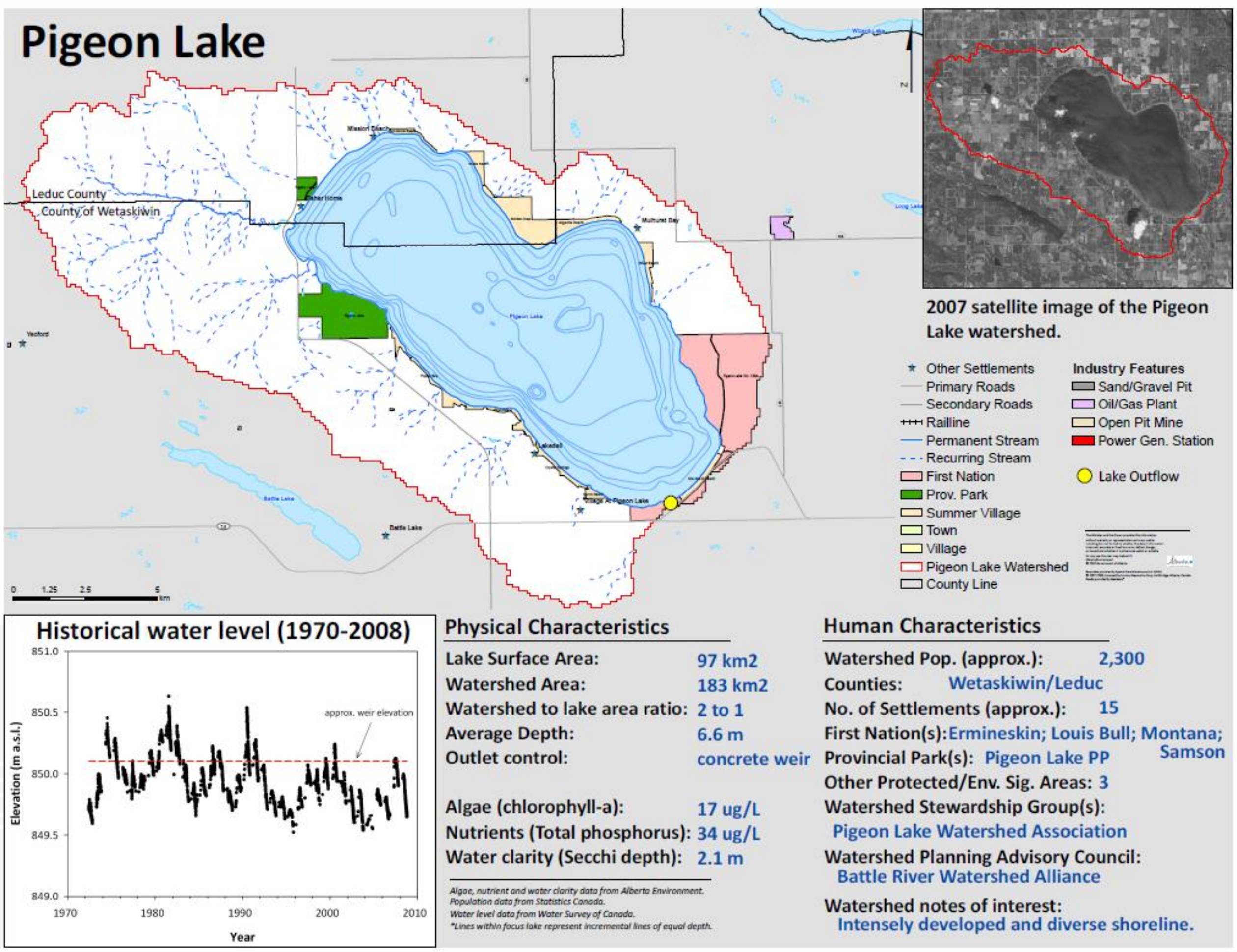

Figure 1. Overview of Pigeon Lake Watershed.

Pigeon Lake lies within the dry mixedwood sub-region of the boreal region of Alberta (Mitchell and Prepas 1990, Natural Regions Committee 2006) and forms part of the Battle River watershed. While the surface area of Pigeon Lake is quite large at $97km^2$, its watershed is relatively small at only $187km^2$, resulting in a low annual inflow (17 million m^3) and long water residence time (exceeding 100 years; Mitchell and Prepas 1990). A long water residence time combined with shallow depths (maximum 9m, average 6m) means that nutrients entering the lake tend to remain available within the water column for extended periods of time. Not surprisingly then, Pigeon Lake is a productive (fertile) lake as measured by chlorophyll-*a* (a common photosynthetic plant/bacteria pigment) and total phosphorus (an essential nutrient required for plant growth). Average concentrations of chlorophyll-a and total phosphorus in Pigeon Lake are $17.2mg/m^3$ and 0.035mg/L respectively (Casey 2011) placing it in a mesotrophic to eutrophic category of lake productivity, typical of many lakes in Alberta.

Due to its productivity, Pigeon Lake is susceptible to nuisance blooms of algae and cyanobacteria (blue-green algae). Significant blooms have occurred in recent years, most notably in 2006 when Pigeon Lake experienced a severe *Gloeotrichia* and *Lyngbya* dominated bloom (Ron Zurawell, Alberta Environment and Water, pers. comm.). Observations have shown other nuisance bloom-forming cyanobacteria genera such as *Aphanizomenon* and *Anabaena* to be present in Pigeon Lake. Despite the apparent increase in nuisance bloom formation, both total phosphorus and chlorophyll-*a* concentrations, along with water clarity have remained relatively constant over time as evidenced by the lack of significant long-term trends in the data (Casey 2011). Of the parameters examined in Pigeon Lake by Casey, only total alkalinity and total dissolved solids showed significant increases from the 1980's to 2008.

While these results may, at first glance, appear to be in conflict with recent observations, they must be considered within the context of sampling, which focuses on whole-lake composites of the euphotic zone (*i.e.* from the surface to the greatest depth at which photosynthesis can occur). Nuisance blooms are often highly localized on a lake driven by wind and wave action and tend to accumulate near the surface along shorelines. This gives the appearance of much higher density compared to cyanobacteria distributed throughout the water column.

An increasing number of users/residents within the watershed and elevated property values has lead to a heightened awareness of changing conditions within the lake. This influences the property and recreational values within the watershed. As a result, residents and other stakeholders have requested recommendations on potential options to manage algal and cyanobacterial biomass within Pigeon Lake. The following sections provide an overview of blue-green algae ecology and potential lake and watershed management options for the control of nuisance blooms. Particular emphasis is placed on management options, which may be most suitable for Pigeon Lake. It should be noted that the options discussed are not necessarily endorsed by relevant regulatory agencies and thus should be used for information purposes only and as a basis for further discussion.

2.0 Cyanobacteria Ecology

Cyanobacteria or blue-green algae are photosynthetic bacteria found in a variety of moist and aquatic environments worldwide. They are widespread in both freshwater and marine environments with numerous species common in Alberta lakes. While similar to algae in habitat and appearance, cyanobacteria are not true plants and have several unique traits that differ from algae. The first is the capability of some species of blue-green algae to produce heterocysts, specialized cells capable of fixing atmospheric nitrogen when dissolved nitrogen in the water column is scarce (Wolk 1973). The second is the ability to develop akinetes, climate-resistant resting spores produced during unfavourable conditions (Elfgren 2003). Both of these adaptations give a competitive advantage over algae under appropriate conditions.

In addition to the above, cyanobacteria also have evolved a number of defence strategies against grazing by aquatic micro-invertebrates (zooplankton). These can include colony formation, mucilage production, or production of cyanotoxins (Dodds *et al.* 1995, Gliwicz 1990, Kirk and Gilbert 1992, Laybourn-Parry *et al.* 1987). Cyanotoxins are of greatest concern from a health perspective due to their ability to affect the liver or nervous system in a rapid manner (Codd *et al.* 1999, Zurawell 2010). As such, Alberta Environment and Water and Alberta Health Services routinely monitor for cyanotoxins in recreational lakes.

Cyanobacteria are most often associated with nuisance blooms occurring predominantly during the summer on Alberta lakes. Under favourable conditions (adequate nutrients, calm water, warm temperatures), explosive growth of blue-green algae can occur. Rapid growth combined with defence adaptations against grazing can result in massive accumulation of blue-green biomass within a short period. While this bloom is often distributed throughout the water column, wind mixing can stimulate the production of gas vacuoles within cells resulting in mass migration to the surface of the lake (Reynolds *et al.* 1987).

Once at the surface of the lake, high light intensity inhibits the downward migration of the cyanobacteria. Heat and intense UV-radiation cause the stranded cells/colonies to die and undergo autolysis releasing the characteristic blue-green pigment commonly found on shorelines during a bloom. Dead and dying blooms are decomposed through bacterial processes that consume dissolved oxygen in the process potentially resulting in anoxic conditions (often exacerbated by existing summer water conditions which holds less oxygen at warmer temperatures). Additionally, ammonia may be produced as a bi-product of this decomposition (Fallon and Brock 1979, Wetzel 1983). Unless invertebrates (snails, clams, zooplankton) and vertebrates (fish) are able to migrate to oxygenated water, death is likely.

Blue-green blooms are natural phenomena of many Alberta lakes and paleolimnological records indicate they have been occurring prior to human settlement in the region. Human disturbance has, in many cases, worsened the situation by increasing the delivery of excess nutrients to the lake from overfertilization of land or improper disposal of human and animal faeces (Köster *et al.* 2008). Blue-green algae require light and nutrients to grow. Water temperature influences reproductive rate. Hence, it is imperative that methods for controlling blue-green algae focus on reducing available nutrients since physical factors (light and temperature) are difficult or impossible to alter, especially for large lakes like Pigeon Lake.

3.0 Management Options for Control of Nuisance Blooms

Table 1 provides an overview of various management options for the control of nuisance blooms in lakes. This list was derived from an overview by Wagner (2004) listing options for controlling nuisance blooms in lakes in Massachusetts. It should be noted that some options listed may have legal implications or other approval requirements not discussed here. Before pursuing any option, it is incumbent that the proponent ensures that all proper applications and requirements are fulfilled.

Table 1 splits management options into two major categories; watershed control and in-lake controls (further split into physical, chemical and biological options). Table 2 provides a broad overview of how watershed and in-lake controls compare with each other. In general, where feasible a number of options, both watershed and in-lake controls, should be explored. In reality however, many options are not cost effective or have minimal desired effect. Thus it is very important that any group pursue a cost-benefit analysis which examines the environmental, social and economic impacts prior to proceeding with a planned management option.

Table 1: Management Options for Control of Nuisance Blue-Green Cyanobacteria and Algae Blooms (Adapted from Wagner 2004)

Option	Mode of Action	Advantages	Disadvantages	Applicability in Alberta	Applicable to Pigeon Lake?
Watershed Controls					
1) Management for nutrient input reduction	• Includes wide range of watershed and lake edge activities intended to eliminate nutrient sources or reduce delivery to lake • Essential component of algal control strategy	• Acts against the original source of algal nutrition. • Creates sustainable limitation on algal growth. • May control delivery of other unwanted pollutants to lake. • Facilitates ecosystem management approach which considers more than just algal control	• May involve considerable lag time before improvement observed • May not be sufficient to achieve goals without some form of in-lake management • Reduction of overall system fertility may impact fisheries • May cause shift in nutrient ratios which favor less desirable algae	• Essential component of addressing problem blooms on lakes in Alberta • Requires commitment from all residents around a lake (both urban and rural) • Without this component, the source of the issue is never truly addressed (i.e., change in attitude does not occur)	• Yes • Essential component of addressing blooms on Pigeon Lake • Requires commitment from residents in the watershed • Without this component, source of nutrients is never addressed
1a) Point source controls	• More stringent discharge requirements • May involve diversion • May involve technological or operational adjustments • May involve pollution prevention plans	• Often provides major input reduction • Highly efficient approach in most cases • Success easily monitored	• May be very expensive in terms of capital and operational costs • May transfer problems to another watershed • Variability in results may be high in some cases	• Applied extensively in lake watersheds in Alberta • Examples include development of regional wastewater lines, and regulatory control of stormwater and other inputs into lake	• Yes • Currently developing regional wastewater line which will eliminate wastewater from entering Pigeon Lake • Previous actions have included elimination of land spreading of septage
1b) Non-point source controls	• Reduction of sources of nutrients • May involve elimination of land uses or activities that release nutrients • May involve alternative product use, as with no phosphate fertilizer	• Removes source • Limited or no ongoing costs	• May require purchase of land or activity • May be viewed as limitation of “quality of life” • Usually requires education and gradual implementation • May impact other land-uses (agriculture, development)	• Applied through numerous programs through provincial government, municipalities, stewardship groups • Basis of "Respect our Lakes" related programs • Within Alberta, has included riparian restoration/maintenance, low or no phosphorus use, low/no till agricultural practices and many more	• Yes • Applied through "Respect our Lakes" and other educational campaigns • Applied through home site visits on a regular basis around Pigeon Lake

1c) Non-point source pollutant trapping	• Capture of pollutants between source and lake • May involve drainage system alteration • Often involves wetland treatments (detention/infiltration) • May involve stormwater collection and treatment as with point sources	• Minimizes interference with land uses and activities • Allows diffuse and phased implementation throughout watershed • Highly flexible approach • Tends to address wide range of pollutant loads	• Does not address actual sources • May require substantial maintenance • May be viewed as limitation of "quality of life" • May have impacts on other land-uses (agriculture, development)	• Applied through ESRD approvals with stormwater treatment requirements above and beyond basic standards for new developments around lakes • Also used extensively in agriculture to divert water coming from high nutrient areas (e.g., livestock feeding areas) away from lakes	• Yes • Stormwater regulations for new developments around Pigeon Lake requiring higher standard of treatment

Option	Mode of Action	Advantages	Disadvantages	Applicability in Alberta	Applicable to Pigeon Lake?
In-Lake Physical Controls					
2) Circulation and destratification	• Use of water or air to keep water in motion • Intended to prevent or break stratification • Generally driven by mechanical or pneumatic force	• Reduces surface buildup of algal scums • May disrupt growth of blue-green algae • Counteraction of anoxia improves habitat for fish/invertebrates • May reduce internal loading of phosphorus	• May spread localized impacts • May lower oxygen levels in shallow water • May promote downstream impacts • Does not address the source of nutrients in most cases	• Within Alberta, most common technology has been the use of solar bees • While the principle behind the technology is sound, solar bees have a limited area of impact (on a lake the size of Pigeon Lake, it was estimated 200 units would be required) • In addition, solar bees pose a potential boating hazard, target for vandalism, require maintenance, and may not be considered cost effective • May be useful for small ponds/in-city lakes or localized areas	• Maybe • May work in localized areas • Requires assessment of cost in terms of maintenance and operations • Needs to examine potential boating hazards (may require permits under Navigable Waters Act)
3) Dilution and flushing	• Addition of water of better quality can dilute nutrients • Addition of water of similar or poorer quality flushes system to minimize algal buildup • May have continuous or periodic additions	• Dilution reduces nutrient concentrations without altering load • Flushing minimizes detention; response to pollutants may be reduced	• Diverts water from other uses • Flushing may wash desirable zooplankton from lake • Use of poorer quality water increases loads • Potential erosion of shoreline areas increasing nutrient loads • Introduction of exotic or non-native species • Possible downstream impacts	• In use at Gull and Buffalo lakes, but primarily to improve/stabilize water levels (no noticeable change in water quality) • If lake does not "top over" there will be no flushing and additional nutrients from diversion water may enhance nuisance blooms • ESRD has indicated future diversions would require treatment to prevent introduction of exotic/non-native species	• Maybe • Will require approvals process through ESRD • Need to ensure transferred water does not cause further decline in water quality of Pigeon Lake • ESRD has indicated requirement to treat to prevent exotic/non-native species from entering the lake

4) Drawdown	• Lowering of water over autumn period allows oxidation, desiccation and compaction of sediments • Duration of exposure and degree of dewatering of exposed areas are important • Algae are affected mainly by reduction in available nutrients.	• May reduce available nutrients or nutrient ratios, affecting algal biomass and composition • Opportunity for shoreline cleanup/structure repair • Flood control utility • May provide rooted plant control as well	• Possible impacts on non-target resources • Possible impairment of water supply • Alteration of downstream flows and winter water level • May result in greater nutrient availability if flushing inadequate • Impact to other lake uses	• Not used on recreational lakes in Alberta due to impracticality of drawing down large lakes • Drawing down lake may result in long-term low lake levels	• No • Risk of drawing down Pigeon Lake too high • Likely not permitted under Fisheries Act
5) Dredging	• Sediment is physically removed by wet or dry excavation, with deposition in a containment area for dewatering • Dredging can be applied on a limited basis, but is most often a major restructuring of a severely impacted system • Nutrient reserves are removed and algal growth can be limited by nutrient availability	• Can control algae if internal recycling is main nutrient source • Increases water depth • Can reduce pollutant reserves • Can reduce sediment oxygen demand • Can improve spawning habitat for many fish species • Allows complete renovation of aquatic ecosystem	• Temporarily removes benthic invertebrates • May create turbidity • May eliminate fish community (complete dry dredging only) • Possible impacts from containment area discharge • Possible impacts from dredged material disposal • Interference with recreation or other uses during dredging • Cost and disposal issues	• Dredging used on a limited basis in Alberta, primarily to provide access for recreational purposes • Quite expensive and time consuming and likely to impact other lake uses	• Maybe • Limited area dredging may remove accumulated sediments and associated sediments • Need to ensure no hazard to recreational users • Need to mitigate impacts to fisheries habitat
5a) "Dry" excavation	• Lake drained or lowered to maximum extent practical • Target material dried to maximum extent possible • Conventional excavation equipment used to remove sediments	• Tends to facilitate a very thorough effort • May allow drying of sediments prior to removal • Allows use of less specialized equipment	• Rarely truly a dry operation; tends to be messy • Eliminates most aquatic biota unless a portion left undrained • Eliminates lake use during dredging • Disturbed sediment may release additional nutrients to the lake • Recovery of lake from low levels may take several years or more	• Not used in Alberta due to expense, time and potential impact to the lake	• No • Drawing down lake levels in Pigeon Lake may exacerbate existing problems • Likely not permitted under Fisheries Act due to impact to fish habitat

5b) "Wet" excavation	• Lake level may be lowered, but sediments not substantially exposed • Draglines, bucket dredges, or long-reach backhoes used to remove sediment	• Requires least preparation time or effort, tends to be least cost dredging approach • May allow use of easily acquired equipment • May preserve aquatic biota	• Usually creates extreme turbidity • Normally requires intermediate containment area to dry sediments prior to hauling • May disrupt ecological function • Disrupts many uses • Disturbed sediments may release additional nutrients to the lake	• Used on a small scale, primarily to provide access for boating through development of marinas • Requires careful monitoring of turbidity levels and no use of the area during dredging • Has not been shown to improve nuisance blooms on the scale conducted in Alberta	• Maybe • Localized dredging may remove accumulated sediment and nutrients • Need to consider disposal issues, mitigation of other impacts (turbidity, fisheries habitat, recreation)
5c) Hydraulic removal	• Lake level not reduced • Suction or cutterhead dredges create slurry which is hydraulically pumped to containment area • Slurry is dewatered; sediment retained, water discharged	• Creates minimal turbidity and impact on biota • Can allow some lake uses during dredging • Allows removal with limited access or shoreline disturbance	• Often leaves some sediment behind • Cannot handle coarse or debris-laden materials • Requires sophisticated and more expensive containment area • Disturbed sediments may release additional nutrients to the lake	• As with wet excavation, used in small areas on lakes, large scale would be cost prohibitive	• Maybe • Localized dredging may remove accumulated sediment and nutrients • Need to consider disposal issues, mitigation of other impacts (turbidity, fisheries habitat, recreation)
6) Light-limiting dyes and surface covers	• Creates light limitation	• Creates light limit on algal growth without high turbidity or great depth • May achieve some control of rooted plants as well	• May cause thermal stratification in shallow ponds • May facilitate anoxia at sediment interface with water	• Not utilized in Alberta to date • While typically harmless, would likely generate public concern without prior notification	• Maybe • Effectiveness uncertain • Would need to ensure public is notified to prevent concerns being generated when adding dyes
6.a) Dyes	• Water-soluble dye is mixed with lake water, thereby limiting light penetration and inhibiting algal growth • Dyes remain in solution until washed out of system.	• Produces appealing color • Creates illusion of greater depth	• May not control surface bloom-forming species • May not control growth of shallow water algal mats • Alters thermal regime	• Not used in Alberta to date • As it may not control surface blooms of algae, may not be appropriate for addressing these issues	• Maybe • Effectiveness uncertain • Would need to ensure public is notified to prevent concerns being generated when adding dyes
6.b) Surface covers	• Opaque sheet material applied to water surface	• Minimizes atmospheric and wildlife pollutant inputs	• Minimizes atmospheric gas exchange • Limits recreational use	• Not applied in Alberta lakes to date • Surface covers for large recreational lakes would be cost prohibitive and prevent recreational use of the lake	• Maybe • Surface covers would need to be restricted to areas where they would not interfere with recreational activities

7) Mechanical removal	• Filtering of pumped water for water supply purposes • Collection of floating scums or mats with booms, nets, or other devices • Continuous or multiple applications per year usually needed	• Algae and associated nutrients can be removed from system • Surface collection can be applied as needed • May remove floating debris • Collected algae dry to minimal volume	• Filtration requires high backwash and sludge handling capability for use with high algal densities • Labor and/or capital intensive • Variable collection efficiency • Possible impacts on non-target aquatic life • Disposal of harvested algae may be an issue	• Within Alberta, this technology has been used primarily to address excessive macrophyte (lake weed) growth • Principle is sound (removes biomass and associated nutrients) • Cost may be prohibitive and disposal of removed material may be problematic	• Yes • Removal of accumulated algal biomass removes associated nutrients although effectiveness may be limited • Need to consider disposal issues
8) Selective withdrawal	• Discharge of bottom water which may contain (or be susceptible to) low oxygen and higher nutrient levels • May be pumped or utilize passive head differential	• Removes targeted water from lake efficiently • Complements other techniques such as drawdown or aeration • May prevent anoxia and phosphorus build up in bottom water • May remove initial phase of algal blooms which start in deep water	• Possible downstream impacts of poor water quality • May eliminate colder thermal layer that supports certain fish • May promote mixing of remaining poor quality bottom water with surface waters • May cause unintended drawdown if inflows do not match withdrawal	• Used at Pine Lake • Only works on lakes which thermally stratify and have sufficient water inputs to replace water pumped out (most recreational lakes in Alberta do not fit this profile) • Despite use at Pine Lake, significant surface blooms still occur	• No • Pigeon Lake does not thermally stratify, hence hypolimnetic withdrawal is not an option
9) Sonication	• Sound waves disrupt algal cells	• Supposedly affects only algae • Applicable in localized areas	• Uncertain effects on non-target organisms • May release cellular toxins or other undesirable contents into water column	• Relatively new technique, not in use at Alberta lakes	• Maybe • Technology is new and effectiveness/effects unknown

Option	Mode of Action	Advantages	Disadvantages	Applicability in Alberta	Applicable to Pigeon Lake?
In-Lake Chemical Controls					
10) Hypolimnetic aeration or oxygenation	• Addition of air or oxygen at varying depth provides oxic conditions • May maintain or break stratification • Can also withdraw water, oxygenate, then replace	• Oxic conditions promote binding/sedimentation of phosphorus • Counteraction of anoxia improves habitat for fish/invertebrates • Build-up of dissolved iron, manganese, sulphide, ammonia and phosphorus reduced	• May accidentally disrupt thermal layers important to fish community • Biota may become dependent on continued aeration	• Aeration has been used on small lakes and ponds primarily to prevent summer or winterkill of fish, but with added benefit of improving water quality to an extent • Most larger recreational lakes in Alberta do not exhibit anoxic conditions during the summer due to shallow depths and continuous wind mixing, so additional aeration may have very little effect	• No • Previous sampling has shown Pigeon Lake to be well oxygenated throughout the year • Additional oxygen unlikely to have much or any benefit
11) Algaecides	• Liquid or pelletized algaecides applied to target area • Algae killed by direct toxicity or metabolic interference • Typically requires application at least once/yr, often more frequently	• Rapid elimination of algae from water column, normally with increased water clarity • May result in net movement of nutrients to bottom of lake	• Possible toxicity to non-target species • Restrictions on water use for varying time after treatment • Increased oxygen demand and possible toxicity • Possible recycling of nutrients	• Typically very effective at killing nuisance blue-green cyanobacteria and algae • Potential effect on non-target species, including fish, has lead to use of algaecides being prohibited in fish bearing waters	• No • Application of chemicals for the control of algae prohibited in fish bearing lakes such as Pigeon Lake
11a) Forms of copper	• Cellular toxicant, suggested disruption of photosynthesis, nitrogen metabolism, and membrane transport • Applied as wide variety of liquid or granular formulations, often in conjunction with chelators, polymers, surfactants or herbicides	• Effective and rapid control of many algae species	• Possible toxicity to aquatic fauna • Ineffective at colder temperatures • Accumulation of copper in system • Resistance by certain green and blue-green nuisance species • Rupturing of cells releases nutrients and toxins	• Used frequently on dugouts in the form of "bluestone" • Prohibited from use in fish bearing waterbodies • Not always effective as some species of blue-green cyanobacteria are copper resistant	• No • Application of chemicals for the control of algae prohibited in fish bearing lakes such as Pigeon Lake

11b) Synthetic organic herbicides	• Absorbed or membrane-active chemicals which disrupt metabolism • Causes structural deterioration	• Used where copper is ineffective • Limited toxicity to fish at recommended dosages • Rapid action	• Non-selective in treated area • Possible toxicity to aquatic fauna (varying degrees by dose and formulation) • Time delays on water use	• Not used on water bodies in Alberta (potentially prohibited) • The potential impact to non-target species makes use of herbicides on recreational lakes risky	• No • Application of chemicals for the control of algae prohibited in fish bearing lake such as Pigeon Lake
11c) Oxidants	• Disrupts most cellular functions, tends to attack membranes • Applied most often as a liquid.	• Potential selectivity against blue-greens • Moderate control of thick algal mats, used where copper alone is ineffective • Rapid action	• Older formulations tended to have high toxicity to some aquatic fauna • New formulations not well tested in the field yet	• Not used in Alberta • Potential treatment of blue-green cyanobacteria, but would require additional testing to ensure safety • Re-application would be necessary • Does not address source of nutrient issues resulting in nuisance blooms	• Maybe • Effects on biota unknown, would require further testing before being allowed for use in Pigeon Lake
12) Phosphorus inactivation	• Typically salts of aluminum, iron or calcium are added to the lake or injected into the sediments, as liquid or powder • Phosphorus in water column is complexed and settled to the bottom of the lake • Phosphorus in upper sediment layer is complexed, reducing release from sediment • Permanence of binding varies by binder in relation to redox potential and pH	• Can provide rapid, major decrease in phosphorus concentration in water column • Can minimize release of phosphorus from sediment • May remove other nutrients and contaminants as well as phosphorus • Flexible with regard to depth of application and speed of improvement	• Possible toxicity to fish and invertebrates, mainly by aluminum at low or high pH • Possible release of phosphorus under anoxia (with Fe) or extreme pH (with Ca) • May cause fluctuations in water chemistry, especially pH, during treatment • Possible resuspension of floc in shallow areas • Adds to bottom sediment, but typically an insignificant amount	• Currently being researched as a potential treatment to remove available phosphorus from the water column in recreational lakes • May be cost prohibitive at large scale and would require ongoing applications • Does not remove phosphorus, just makes it unavailable for uptake by algae (i.e., does not address source)	• Maybe • Currently, research being done into the injection of iron at the sediment water interface to bind phosphorus and sink into the sediment • When results known, Pigeon Lake could be a candidate for treatment if considered appropriate
13) Sediment oxidation	• Addition of oxidants, binders and pH adjusters to oxidize sediment • Binding of phosphorus is enhanced • Denitrification is stimulated	• Can reduce phosphorus supply to algae • Can alter N:P ratios in water column • May decrease sediment oxygen demand	• Possible impacts on benthic biota • Longevity of effects not well known • Possible source of nitrogen for blue-green algae	• Not currently used in Alberta lakes	• Maybe • Depending on technology, would require experimentation to ensure safety in Pigeon Lake

14) Settling agents	• Closely aligned with phosphorus inactivation, but can be used to reduce algae directly too • Lime, alum or polymers applied, usually as a liquid or slurry • Creates a floc with algae and other suspended particles • Floc settles to bottom • Re-application typically necessary at least once/yr	• Removes algae and increases water clarity without lysing most cells • Reduces nutrient recycling if floc sufficient • Removes non-algal particles as well as algae • May reduce dissolved phosphorus levels at the same time	• Possible impacts on aquatic fauna • Possible fluctuations in water chemistry during treatment • Resuspension of floc possible in shallow, well-mixed waters • Promotes increased sediment accumulation	• Used in small urban lakes and ponds • Alum is typically safe for use, but requires ongoing application and does not remove nutrients • Use on larger fish bearing lakes would require permits from ESRD/DFO and potential testing on smaller scale level to determine impacts to the aquatic biota • At larger scale, may be cost prohibitive	• Maybe • Treatment with chemically and biologically inert flocculents could be used in Pigeon Lake • Would require consultation with ESRD and DFO to ensure no harmful effects to fish biota
15) Selective nutrient addition	• Ratio of nutrients changed by additions of selected nutrients • Addition of non-limiting nutrients can change composition of algal community • Processes such as settling and grazing can then reduce algal biomass	• Can reduce algal levels where control of limiting nutrient not feasible • Can promote non-nuisance forms of algae • Can improve productivity of system without increased standing crop of algae	• May result in greater algal abundance through uncertain biological response • May require frequent application to maintain desired ratios • Possible downstream effects	• Not used in Alberta lakes to date • Adding nutrients to lakes which have changing dynamics would require careful continous monitoring	• No • Given the constantly changing phytoplankton community in Pigeon Lake, addition of nutrients would be too unpredictable to recommend

Option	Mode of Action	Advantages	Disadvantages	Applicability in Alberta	Applicable to Pigeon Lake?
In-Lake Biological Controls					
16) Enhanced grazing	• Manipulation of biological components of system to achieve grazing control over algae • Typically involves alteration of fish community to promote growth of large herbivorous zooplankton, or stocking with phytophagous fish	• May increase water clarity by changes in algal biomass or cell size distribution without reduction of nutrient levels • Can convert unwanted biomass into desirable form (fish) • Harnesses natural processes to produce desired conditions	• May involve introduction of exotic species • Effects may not be controllable or lasting • May foster shifts in algal composition to even less desirable forms	• May have been applied to small ponds for control of nuisance algae and weeds (e.g., introduction of Tilapia sp.) • Unlikely to be approved for use in larger fish bearing lakes where introduction of exotic species may impact fisheries	• Maybe • Pigeon Lake fish populations have previously been manipulated through stocking • Would require approvals through ESRD and DFO • Unknown what impact may be
16.a) Herbivorous fish	• Stocking of fish that eat algae	• Converts algae directly into potentially harvestable fish • Grazing pressure can be adjusted through stocking rate	• Typically requires introduction of non-native species • Difficult to control over long term • Smaller algal forms may be benefited and bloom	• May have been applied to small, non-fish bearing isolated ponds/lakes where control of introduced fish is possible • Unlikely to be approved for use in larger recreational lakes due to risk of impact to native fisheries	• Maybe • Would require approvals through ESRD and DFO • Unknown what impact may be to other biota
16.b) Herbivorous zooplankton	• Reduction in planktivorous fish to promote grazing pressure by zooplankton • May involve stocking piscivores or removing planktivores • May also involve stocking zooplankton or establishing refugia	• Converts algae indirectly into harvestable fish • Zooplankton response to increasing algae can be rapid • May be accomplished without introduction of non-native species • Generally compatible with most fishery management goals	• Highly variable response expected; temporal and spatial variability may be high • Requires careful monitoring and management action on 1-5 yr basis • Larger or toxic algal forms may be benefited and bloom	• Not currently done in Alberta, although ESRD does stock lakes (not for algal control purposes) • Highly variable response • Nuisance blue-green algae unlikely to be affected given natural strategies to avoid grazing by zooplankton	• Maybe • Would require approvals through ESRD and DFO • Unknown what impact may be to other biota

17) Bottom-feeding fish removal	• Removes fish that browse among bottom deposits, releasing nutrients to the water column by physical agitation and excretion	• Reduces turbidity and nutrient additions from this source • May restructure fish community in more desirable manner	• Targeted fish species are difficult to eradicate or control • Reduction in fish populations valued by some lake users (human/non-human)	• Not currently used in Alberta • Within most recreational lakes, would involve removal of species such as suckers and whitefish, considered valuable to recreational fisheries • Difficult to predict effects of removing fish	• No • Removal of bottom feeding fish (whitefish and suckers) would not be allowed by ESRD
18) Pathogens	• Addition of inoculum to initiate attack on algal cells • May involve fungi, bacteria or viruses	• May create lakewide "epidemic" and reduction of algal biomass • May provide sustained control through cycles • Can be highly specific to algal group or genera	• Largely experimental approach at this time • May promote resistant nuisance forms • May cause high oxygen demand or release of toxins by lysed algal cells • Effects on non-target organisms uncertain	• Not currently used in Alberta lakes • Experimental approach and would likely result in high public concerns over introduction of bacteria or viruses to a recreational lake	• Maybe • Requires more direct research to determine effects in Pigeon Lake • Likely would result in significant public concern
19) Competition and allelopathy	• Plants may tie up sufficient nutrients to limit algal growth • Plants may create a light limitation on algal growth • Chemical inhibition of algae may occur through substances released by other organisms	• Harnesses power of natural biological interactions • May provide responsive and prolonged control	• Some algal forms appear resistant • Use of plants may lead to problems with vascular plants • Use of plant material may cause depression of oxygen levels	• Not currently used in Alberta • Introduction of competitive plants may cause issues for recreational users due to increased lake weed growth • May not be effective against nuisance blue-green algae	• No • Introduction of aquatic plants to Pigeon Lake would create issues with recreational use • Effect on blue-green blooms would be minimal
19a) Plantings for nutrient control	• Plant growths of sufficient density may limit algal access to nutrients • Plants can exude allelopathic substances which inhibit algal growth • Portable plant "pods" , floating islands, or other structures can be installed	• Productivity and associated habitat value can remain high without algal blooms • Can be managed to limit interference with recreation and provide habitat • Wetland cells in or adjacent to the lake can minimize nutrient inputs	• Vascular plants may achieve nuisance densities • Vascular plant senescence may release nutrients and cause algal blooms • The switch from algae to vascular plant domination of a lake may cause unexpected or undesirable changes	• Not currently pursued for Alberta lakes • Experiments have shown that growth of plant on "floating islands" in wastewater treatment plants did not remove a significant amount of nutrients in cooler climates similar to Alberta due to short growth season • Floating islands would represent a potential boating hazard, target for vandalism, would likely require ongoing maintenance and at a larger scale, be cost prohibitive	• No • Experiments conducted in cold climates, such as at Pigeon Lake, have shown "floating islands" to be ineffective in uptake of nutrients due to short growing season • Floating islands may also impede recreational activities and would be a target for vandalism

19b) Plantings for light control	• Plant species with floating leaves can shade out many algal growths at elevated densities	• Vascular plants can be more easily harvested than most algae • Many floating species provide valuable waterfowl food	• At the necessary density, floating plants likely to be a recreational nuisance • Low surface mixing and atmospheric contact promote anoxia	• Not currently used in Alberta lakes • Potential nuisance for other recreational used on lakes (boating, swimming)	• No • Pigeon Lake characteristics and chemistry not favourable for growth of floating leaved aquatic plants
19c) Addition of barley straw	• Input of barely straw can set off a series of chemical reactions which limit algal growth • Release of allelopathic chemicals can kill algae • Release of humic substances may bind phosphorus	• Materials and application are relatively inexpensive • Decline in algal abundance is more gradual than with algaecides, limiting oxygen demand and the release of cell contents	• Success appears linked to uncertain and potentially uncontrollable water chemistry factors • Depression of oxygen levels may result • Water chemistry may be altered in other ways unsuitable for non-target organisms • Decomposition of bales can result in increased turbidity	• Used on small city ponds within Alberta with varying success at controlling nuisance algae • Principle is sound, but application at larger scale may be unfeasible	• Maybe • Addition of straw bales would need to ensure that the straw does not decompose and further pollute the water • Need to ensure bales are clean (no residual pesticides or other chemicals)

Legend:

Blue highlighted are applicable to Pigeon Lake
Yellow highlighted may be beneficial to Pigeon Lake
Orange highlighted are not applicable to Pigeon Lake for technical or legal reasons

Table 2: Comparison of Watershed and In-Lake Controls of Nuisance Blooms

Watershed Controls	In-Lake Controls
Examples: Riparian restoration, fertilizer restriction, wastewater management	Examples: Chemicals/binding agents, dredging, addition/removal of water
Treats the source by preventing nutrients from entering lake	Treats internal source of nutrients and/or treats the issue (nuisance bloom)
Generally requires change in behaviour of watershed users	Generally does not require change in behaviour of users
Stakeholders are involved and engaged	Level of stakeholder involvement usually lower
Cost/benefit ratio usually low	Cost/benefit ration usually higher
Long-term strategy	Can be a long-term strategy or short-term response to nuisance bloom

3.1 Watershed Controls

As the name implies, watershed controls are strategies intended to prevent the delivery of nutrients to a lake. Incorporation of a variety of these options is essential to a program aimed at reducing frequency and intensity of nuisance blooms in lakes as this eliminates an external source of nutrients to the lake. Given that the turnover time (time in which it takes to replace the water in a lake through inflowing surface and groundwater) for Pigeon Lake exceeds 100 years, eliminating nutrient inputs to the lake prevents the risk of nutrients accumulating over a longer period. Even if the residence time was short, if the level of nutrients entering a lake basin continues to be elevated, the lake will be susceptible to nuisance blooms (as seen in Baptiste Lake).

Examples of watershed controls include fertilizer restrictions, enhanced stormwater treatment, development of regional wastewater lines, riparian restoration, agricultural bmp's (best management practises) and use of communal wastewater tanks. A number of watershed initiatives have either been incorporated or are underway at Pigeon Lake. Along with these initiatives is the need for a strong education and awareness campaign to encourage uptake and help lower the input of nutrients to the lake.

3.2 In-Lake Controls

In-lake controls for the management of nuisance blooms are broken-down into three major categories; physical, chemical and biological. Physical controls involve the physical modification of in-lake elements to remove accumulated nutrients or disrupt conditions favourable for algal or cyanobacterial growth. These can include such strategies as increased circulation, dilution and flushing, dredging, light-limiting dyes, surface covers and mechanical removal of blooms. While effective at smaller scales, large scale applications as would be needed at Pigeon Lake may prove too costly and interfere with recreational opportunities. In addition, several potential controls may have additional impacts to fish habitat or other beneficial species, which must be considered before pursuing. However, methods such as removing accumulated bloom material may provide some benefit if applied in local areas such as swimming beaches, removing both the biomass and the associated nutrients. In these cases, it must be ensured that removed material be deposited as far away from the lake as possible to ensure nutrients do not re-enter the lake in the future.

Chemical control involves the application of chemicals to kill nuisance algae or cyanobacteria or bind with the nuisance species and nutrients to prevent growth. Examples of chemical options include application of algaecides, binding agents, aeration/oxygenation of the water column, and phosphorus inactivation. Many chemical options are illegal to use in fish bearing waterbodies such as Pigeon Lake due to their potential impact to non-target organisms. Studies have shown that these chemicals may persist in the environment and impact lake ecosystems long after initial application (Schindler and Vallentyne 2008). Phosphorus inactivation through the application of ferric salts near the sediment water interface may be a potential option for Pigeon Lake, although current research needs to be fully evaluated to determine its effectiveness in well aerated systems like Pigeon Lake.

Biological controls involve modifying the biological components of a lake ecosystem to produce a less favourable environment for the growth of nuisance algae or cyanobacteria. Examples of biological control include enhanced grazing by stocking zooplankton species, bottom-feeding fish removal and pathogens. Biological control is based on the principle of modifying food webs to favour enhanced grazing and the growth of non-nuisance species of algae (see Carpenter and Kitchell 1993 for an overview of trophic cascade effects). It does require an excellent understanding of food web dynamics within a particular lake and would be strongly cautioned against in Pigeon Lake due to the potential disruption or alteration of a highly desirable fishery.

4.0 Summary

Overall, there are several options that can be pursued at Pigeon Lake. Each option should be examined carefully from a cost-benefit analysis and ensure that environmental impacts to Pigeon Lake are minimized. It should also be kept in mind that many options do not provide immediate results, but rather are longer term strategies for the management of nutrients. Given the long turnover time, natural productivity of the lake and the fact that development has been ongoing at Pigeon Lake for the past 60 years, successes in the management of nuisance blooms should be viewed as a long-term ongoing strategy.

It is also important to note that the response of Pigeon Lake to the various options in terms of frequency and intensity of blooms will likely vary from year to year. While cyanobacterial ecology is relatively well understood, variations in population composition, food web dynamics and climatic variability make predicting the occurrence of nuisance blooms an inexact science. However, if strategies for the reduction of nutrients in Pigeon Lake are not incorporated, it will continue to be susceptible to nuisance blue-green blooms in the future.

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