ELK/BEAVER LAKE

Technical Report – Investigation of In-Lake Remediation Options

August 2018

Parks and Environmental Services
CRD

Executive Summary

The Elk/Beaver Lake watershed is located within the District of Saanich on Vancouver Island, BC, approximately 11 km north of Victoria. Elk/Beaver Lake is the headwaters for the Colquitz River system which flows from Beaver Lake through the District of Saanich, enters Cuthbert Holmes Park behind Tillicum Mall, and enters the ocean at Portage Inlet. The 2.24 km^2 combined lake area receives water from a 7.82 km^2 upstream drainage area. Like other coastal lakes, Elk/Beaver Lake is rain-fed, and relies heavily upon winter (October-March) recharge to maintain lake levels throughout the much drier summer months. The total filled lake volume is 18.8 million cubic metres. Water residence time is very long, approximately 7 years, thus it takes as many years for water and dissolved substances to exit the lake. The long water residence time is the primary reason that the lake is highly productive (eutrophic).

Given the small watershed to lake ratio (~3.5:1), and based on periodic water quality sampling, it has been determined that the primary source of (excess) phosphorus is internal loading from lake sediment. The low oxygen (anoxic) conditions at the sediment-water interface result in an internal phosphorus load 6-8 times higher than the estimated external load, or at least 86-89% of total phosphorus inputs.

The overall goals of the Elk/Beaver Initiative are: 1) to implement one or more actions that will lead to a reduction in the frequency and toxicity of cyanobacteria (a.k.a. blue-green algae 'BGA') blooms in Elk and Beaver Lakes, 2) improve fish habitat, and 3) manage weed growth to improve recreational use. The Initiative was established, and a part-time Coordinator hired by the Capital Regional District (CRD), in response to public demand for focus on the struggling lake ecosystem. In addition to annual toxic cyanobacteria blooms, there is concern over the sustainability of a healthy fishery under anoxic conditions, the proliferation of nuisance aquatic weeds, the presence of invasive aquatic and terrestrial species, and public health and safety during water contact recreation.

In-lake remediation options were evaluated to determine the most beneficial, cost-effective, and practical in-lake remedial action to reduce internal phosphorus loading, reduce the frequency and toxicity of cyanobacteria blooms, and to improve fish habitat. Potential options included hypolimnetic aeration ("full-lift Bernhardt"), downflow bubble contact hypolimnetic oxygenation (Speece Cone™), laminar flow aeration (mixing), the application of lanthanum-modified bentonite (Phoslock™), biomanipulation, and bioaugmentation.

Downflow bubble contact hypolimnetic oxygenation (DBHO) is the in-lake remedial option recommended for the reduction of cyanobacteria blooms and improvements to fish habitat in Elk Lake for the following reasons:

- DBHO results in highly concentrated (90-95%) oxygen saturation in the lake water as opposed to hypolimnetic aeration which can only achieve about 20%;
- Oxygen levels can be adjusted to meet the real-time oxygen demand of the hypolimnion and lake sediments;
- The addition of oxygen at the sediment-water interface will address the release of Fe/Mn-bound phosphorus (up to 41%), organic-bound phosphorus (up to 59%), and will meet the BC Ministry of Environment Water Quality Objective for dissolved oxygen (>5 mg/L at 1 m above the sediments).
- The DBHO and related infrastructure can be housed on the lake shore for easy maintenance, or can be submerged, and does not require any water surface obstruction;
- The system will not disrupt the thermocline of the lake, nor will it disturb lake sediments;

- The estimated cost of the system installation and 10-year operation is similar to hypolimnetic aeration and less than a one-time application of lanthanum-modified bentonite clay.

In-Lake Remediation Options Eliminated

Biomanipulation and bioaugmentation were eliminated because they have been shown to require extensive on-going effort for minimal guarantee of success. Other options were eliminated for the following reasons:

Dredging

- Based on estimates from a similar Burnaby Lake project, estimates of the cost of dredging Elk Lake would range from $66 to $120 million.
- Extensive land area (several hectares) would be needed to dewater the dredge material prior to transport, and securing such a location would be costly and likely involve environmental assessments before and after use.
- Newly exposed lake sediments would likely be very acidic and high in oxidizing iron, and additional treatment would likely be needed to protect water quality and aquatic biota following dredging.

Full-lift Hypolimnetic Aeration

- Full-lift hypolimnetic aeration systems require a separator box to be located on the lake surface. This structure would interfere with water recreation activities such as rowing and boating;
- If not properly sized or maintained, the underwater riser and exit tubes can stir up sediment and increase both phosphorus and hydrogen-sulfide in the water which can degrade water quality, and cause severe cyanobacteria blooms;
- There are better available technologies that will discharge a greater concentration of oxygen directly at the sediment-water interface without stirring up sediment.

Laminar-flow Oxygenation

- Laminar-flow oxygenation would disrupt the summer thermocline of the lake, and the lake would mix entirely every three days;
- This would result in an increase in deep water temperature from a fish-friendly 8°C to 19-22°C;
- This option was eliminated because it will raise summer water temperature above the MOE Water Quality Objective of 15°C, and would be detrimental to the cold-water fishery.

Lanthanum-modified Bentonite Clay

- Treatment can only prevent the release of iron/manganese-bound phosphorus, which accounts for only 41% of total sediment phosphorus, the remaining 59% of organic-bound phosphorus (e.g., in sediment bacteria and micro-organisms) would not be affected;
- Multiple dosing events (~once every 3 years) may be needed to maintain low internal phosphorus loading, and each event would cost an estimated $2.4 million;
- Treatment would have no effect on dissolved oxygen concentrations, and would thus not improve summer fish habitat or promote the decomposition of organic material on the lake sediment.

Table of Contents

List of Figures

List of Tables

Definitions and Useful Terminology	
Anoxic	the condition of very low oxygen
Benthivorous	aquatic biota that prey on biota that live in the lake sediments
Biochemical Oxygen Demand (BOD)	the consumption of oxygen by organisms during respiration
Conductivity	a measure of the amount of mineral ions present in the water, especially salts and dissolved inorganic substances
Diagenetic processes	chemical reactions, diffusion, advection, adsorption, burial, and compaction
Dissolved Organic Carbon (DOC)	a general description of the organic material dissolved in water; typically DOC is the organic matter able to pass through a 0.7-0.22 µm filter
Dissolved Oxygen (DO)	a measure of the amount of oxygen that is present in the water column
Epilimnion	the upper/surface layer of water in a stratified lake
Humic Acid	a complex mixture of different acids produced by the biodegradation of dead organic matter; see also D*issolved Organic Carbon (DOC)*
Hypolimnion	the deep water in a stratified lake that is separated from the surface by the thermocline
Metalimnion	the layer of water between the epilimnion and hypoliminon; the transitional layer or *thermocline*
Monomictic	refers to a lake that stratifies and re-mixes only one time per year
Organic Matter	composed of organic compounds from the remains of algae, plants, and fish
Oxic	the condition of high or sufficient oxygen
Oxidation-Reduction Potential (ORP or Eh)	decreases as oxygen decreases, due to microbial decomposition, may result in high hydrogen sulfide (H_2S)
pH	a measure of acidity or alkalinity of water (acidic 0, neutral 7, alkaline 14)
Phosphorus Sequestration	the retention or isolation of phosphorus such that it is not moving freely in the water, but is retained in the lake sediment or the tissues of organisms
Planktivorous	refers to fish or large biota that prey on zooplankton
Secchi transparency	a measure of the clarity or transparency of lake water as measured by the depth a "secchi disk" can be lowered into the water and still be visible; relates to *Total Suspended Solids*
Sediment-water interface	area at the lake bottom where the lake water and lake sediment meet; the upper few centimeters of lake sediment are saturated with lake water
Soluble Reactive Phosphorus (SRP or ortho-phosphorus)	proportion of total phosphorus available for use by aquatic life (e.g., bacteria and phytoplankton)
Stratification	the state of a lake when the temperature change through the water column is at least 1°C per metre depth; the epilimnion and hypolimnion are separated by the thermocline
Thermocline	distinct layer in which temperature changes more rapidly with depth than above or below; see also *stratification* and *metalimnion*
Total Dissolved Solids	amount of dissolved organic and inorganic particles in the water column; absorb heat from the sun and raise the water temperature and conductivity
Total Nitrogen (TN)	the total of all nitrogen in chemical forms (a.k.a. species) (NH_3, NO_3, etc.)
Total Phosphorus (TP)	the total of all phosphorus in chemical forms (a.k.a. species) (PO_4^{3-}, etc.)
Total Suspended Solids	organic (e.g., phytoplankton) and inorganic matter (e.g., sand) in the water column; absorb heat from the sun and raise the water temperature and conductivity
Turbidity	lack of water clarity due to total suspended solids (TSS) such as phytoplankton and soil particles; see also *Secchi transparency*

1.0 Introduction

1.1 Elk/Beaver Lake Initiative

The Elk/Beaver Lake Initiative (EBLI) was created by the Capital Regional District (CRD) in 2016 to implement one or more actions that will lead to a reduction in the frequency and toxicity of cyanobacteria (a.k.a. blue-green algae, 'BGA') blooms in Elk and Beaver Lakes, improve fish habitat, manage weed growth, and ensure continued recreational use. Prior to the creation of the EBLI, under coordination by the BC Ministry of Environment (MOE), an intergovernmental working group (IWG) consisting of representatives from MOE, the BC Ministry of Forests, Lands, and Natural Resources (FLNRO), Island Health, CRD, and the District of Saanich was meeting periodically to discuss the implications of 2014-2015 water quality monitoring (Nordin 2015) and potential in-lake remedial options (Nurnberg and LaZerte 2016). In 2016, CRD Parks and Environmental Services provided funding for one part-time coordinator, and a budget for continued water quality monitoring, the selection and implementation of an in-lake remediation option, and preparation of a watershed management plan. The EBLI was established in response to public demand for focus on the struggling lake ecosystem. In addition to annual toxic cyanobacteria blooms, there is concern over the sustainability of a healthy fishery under low oxygen (anoxic) conditions, the proliferation of nuisance aquatic weeds, the presence of invasive aquatic and terrestrial species, and public health and safety during water contact recreation. CRD agreed to fund the EBLI through 2019 (four years).

The EBLI has the following objectives:

- Coordinate the IWG;
- Liaise with and involve community stakeholders;
- Seek funding for and implement in-lake remedial action(s) for the reduction of internal phosphorus loading;
- Conduct pre- and post-remedial water quality and cyanobacteria monitoring;
- Implement other watershed management actions, such as stormwater control measures and riparian area enhancement, to reduce external phosphorus loading;
- Produce an integrated watershed management plan;
- Provide public education for watershed stewardship and cyanobacteria awareness.

1.2 Purpose and Scope of this Document

This document summarizes the in-lake remediation options which were evaluated to determine the most beneficial, cost-effective, and practical in-lake remedial action to reduce internal phosphorus loading, reduce the frequency and toxicity of cyanobacteria blooms, and to improve fish habitat. Potential options included hypolimnetic aeration ("full-lift Bernhardt"), downflow bubble contact hypolimnetic aeration (DBHO), laminar flow aeration (mixing), the application of lanthanum-modified bentonite (LMB), biomanipulation, and bioaugmentation.

The components of this document are as follows:
Section 1.0: Background and preliminary research conducted as part of the EBLI;
Section 2.0: Summary of lake and inflow water quality, and biota studies through Spring 2017;
Section 3.0: Descriptions of the in-lake remediation options considered and eliminated, and the benefits and description of the chosen option: downflow bubble contact hypolimnetic aeration.

1.3 Policy and Jurisdictional Context

The Elk/Beaver Lake watershed, along with Elk and Beaver Lakes, falls within multiple jurisdictions. Planning regulations and bylaw enforcement for residential properties in the watershed are within the jurisdiction of the District of Saanich. MOE is responsible for the lake water and lake sediments. Fish are managed and monitored by FLNRO. Water surface activities are regulated by Transport Canada. Elk/ Beaver Lake Regional Park is managed by the Regional Parks Division of the CRD. Island Health monitors fecal coliform near swimming beaches, and posts advisories when fecal coliform or cyanobacterial toxins are above recommended guidelines for water contact recreation. The CRD Integrated Watershed Management Program (IWMP) works with CRD Parks, Island Health, and MOE to facilitate lake water quality monitoring, and especially the detection of cyanobacterial toxins. Additional stakeholders include First Nations groups, non-governmental organizations, academic partners, funding contributors, scientific experts, and lake and park users as listed in **Table 1.1**.

Specific policy considerations include:

- Riparian Area enforcement, and stormwater control and management by the District of Saanich;
- Water Quality Objectives (WQOs) as established by the MOE;
- Fisheries management facilitated by FLNRO;
- Park upgrades, education, and lake vegetation maintenance by CRD Parks;
- Water quality monitoring and the coordination of the Elk/Beaver Lake Initiative by CRD-IWMP.

1.4 Community Stakeholders

The CRD acknowledges that Elk/Beaver Lakes and the surrounding park are located on the ancestral lands of the Esquimalt, Songhees, and WSANEC Nations. Numerous scientists have provided expertise that has led to the selection of a lake improvement option. Numerous volunteers and community groups have contributed to the assessment and planning of in-lake improvements. The enjoyment of recreation activities such as rowing, swimming, and fishing have driven the objectives of the EBLI. **Table 1.1** acknowledges these groups and individuals for their vital contribution to the health and enjoyment of Elk and Beaver Lakes.

Table 1.1 Elk/Beaver Lake Stakeholders

Government	First Nations
Capital Regional District, Parks and Environmental Services	Esquimalt Nation
District of Saanich	Songhees Nation
Vancouver Island Health Authority	WSANEC Nations
BC Ministry of Environment	Pauquachin
BC Ministry of Forests Lands and Natural Resource Operations	Tsartlip
Transport Canada	Tsawout
Fisheries and Oceans Canada	Tseycum
Non-Governmental Organizations	Academic Partners
Colquitz Watershed Stewardship Coalition	UVIC Engineering
Victoria Golden Rods and Reels Fishing and Social Club	UVIC Restoration of Natural Systems
Victoria Rowing Society, Rowing Canada, and Victoria City Rowing Club	Camosun College Environmental Tech Program
BC Lake Stewardship Society	
Habitat Acquisition Trust (turtles, species at risk)	
Haliburton Creek/Brook Stewardship Group	
Victoria Natural History Society (birding)	
Funding Contributors	Experts
Canadian Wildlife Federation	Richard Nordin PhD, Victoria, BC
BC Wildlife Federation	Purnima Govindarajulu, Amphibians, BC MOE
Habitat Conservation Trust Foundation	Ian Bruce, Peninsula Streams (agricultural outreach)
Freshwater Fisheries Society of BC	Christian Englestoft and
Peninsula Streams Society	Kristiina Ovaska, HAT contract biologists
Victoria Fish and Game Protective Association	Gertrude Nurnberg PhD, Freshwater Research, Baysville, ON
Recreation Groups	Agriculture
Equestrian Center	Haliburton Organic Farm
Retriever Club	Arabian Horse Farm
Flyfishing Group	Hobby farms
Boater Group	

2.0 Water Quality in Elk and Beaver Lakes

2.1 Location and Hydrology

The Elk/Beaver Lake watershed is located within the District of Saanich on Vancouver Island, BC, approximately 11 km north of Victoria. Elk and Beaver Lakes are the headwaters for the Colquitz River system which flows from Beaver Lake through the District of Saanich, enters Cuthbert Holmes Park behind Tillicum Mall, and enters the ocean at Portage Inlet. Water from Elk Lake flows into Beaver Lake where a dam controls downstream flows to the Colquitz River. In 1872, Elk Lake was the water source for Greater Victoria. Elk and Beaver Lakes were joined when Colquitz Creek was dammed at the south end of Beaver Lake. The lake area and depth was expanded between 1873 and 1879 in order to supply drinking water to the growing population of the City of Victoria. The lake surface area was expanded by 21% (from 1.84 to 2.24 km^2). This effort also expanded the shoreline perimeter by 19%. In 1896, filter beds were constructed after Victoria residents complained of fish and tadpoles in their drinking water. The lake provided water to the residents of Victoria until 1914, and remained a water source for some areas of the region until 1977.

The 2.24 km^2 combined lake area receives water from a 7.82 km^2 upstream drainage area. Like other coastal lakes, Elk/Beaver Lake is rain-fed, and relies heavily upon winter (October-March) recharge to maintain lake levels throughout the much drier summer months. The total filled lake volume is 18.8 million cubic metres. Water residence time is very long, approximately 7 years, thus it takes as many years for water and dissolved substances to exit the lake. The long water residence time is the primary reason that the lake is highly productive (eutrophic). The low oxygen conditions at the sediment-water interface result in an internal phosphorus load 6-8 times higher than the estimated external load, or at least 86-89% of total phosphorus inputs (Nurnberg and LaZerte 2016). A low nitrogen to phosphorus ratio (<15:1) for much of the year results in a prevalence of nitrogen-fixing cyanobacteria due to a shortage of nitrogen compared to phosphorus for biological activity. Given the small watershed to lake ratio (~3.5:1), and based on periodic water quality sampling, it has been determined that the primary source of excess phosphorus is internal loading from lake sediment.

Although conjoined by a channel, the bathymetry and ecological patterns of the two lakes are different. Elk Lake has a maximum depth of 19 m, and an average depth of 7.7 m. Elk Lake stratifies once per year in the summer when surface water temperatures are much higher than deep water temperatures. Winter water temperatures rarely fall below 5°C, and are relatively consistent throughout the water column. Elk Lake is subject to winter (Dec.-Feb.) cyanobacteria blooms that can be toxic.

Beaver Lake has a maximum depth of 8 m, and an average depth of about 4 m. Temperature data showed that Beaver Lake is not thermally stratified in the summer, but dissolved oxygen levels are very high at the surface, and decline to near zero below 4 m. Beaver Lake experienced toxic cyanobacteria blooms in August, September, and October-November 2016, which persisted until air temperatures were near 0°C in December 2016.

Tables 2.1 and 2.2 summarize the watershed characteristics. **Figure 2.1** shows the watershed land cover, and **Figure 2.2** shows the lake's bathymetry.

Table 2.1 Elk and Beaver Lake Watershed Characteristics

Latitude (dec. deg.)	48.524	Elk Lake Area	1.82 km^2
Longitude (dec. deg.)	-123.396	Beaver Lake Area	0.42 km^2
Elk Watershed size (excluding lake)	5.63 km^2	Total Lake Area	2.24 km^2
Beaver Watershed (km^2) (excluding lake)	2.19 km^2	Elk Lake Depth	19.4 m (maximum) 7.7 m (mean)
Total Watershed (km^2) (excluding lakes)	7.82 km^2	Beaver Lake Depth	8.0 m (maximum) 4.0 m (mean)
Relief (m)	220-70 m	Total Volume	18.8 x 10^6 m^3
Elk Lake Hypolimnetic Volume (below 9 m)			3.9 x 10^6 m^3

Table 2.2 Elk and Beaver Lake Watershed Land Cover

Forest	45.0%	Disturbed	1.3%
Pasture	9.2%	Low Density Res. (<30% imperv.)	24.5%
Cropland	4.2%	Med. Density Res. (30-75% imperv.)	5.0%
Open/Herbaceous	5.3%	Other 30-75% imperv.	4.0%
Wetland	1.5%		
Ponds	0.001%		

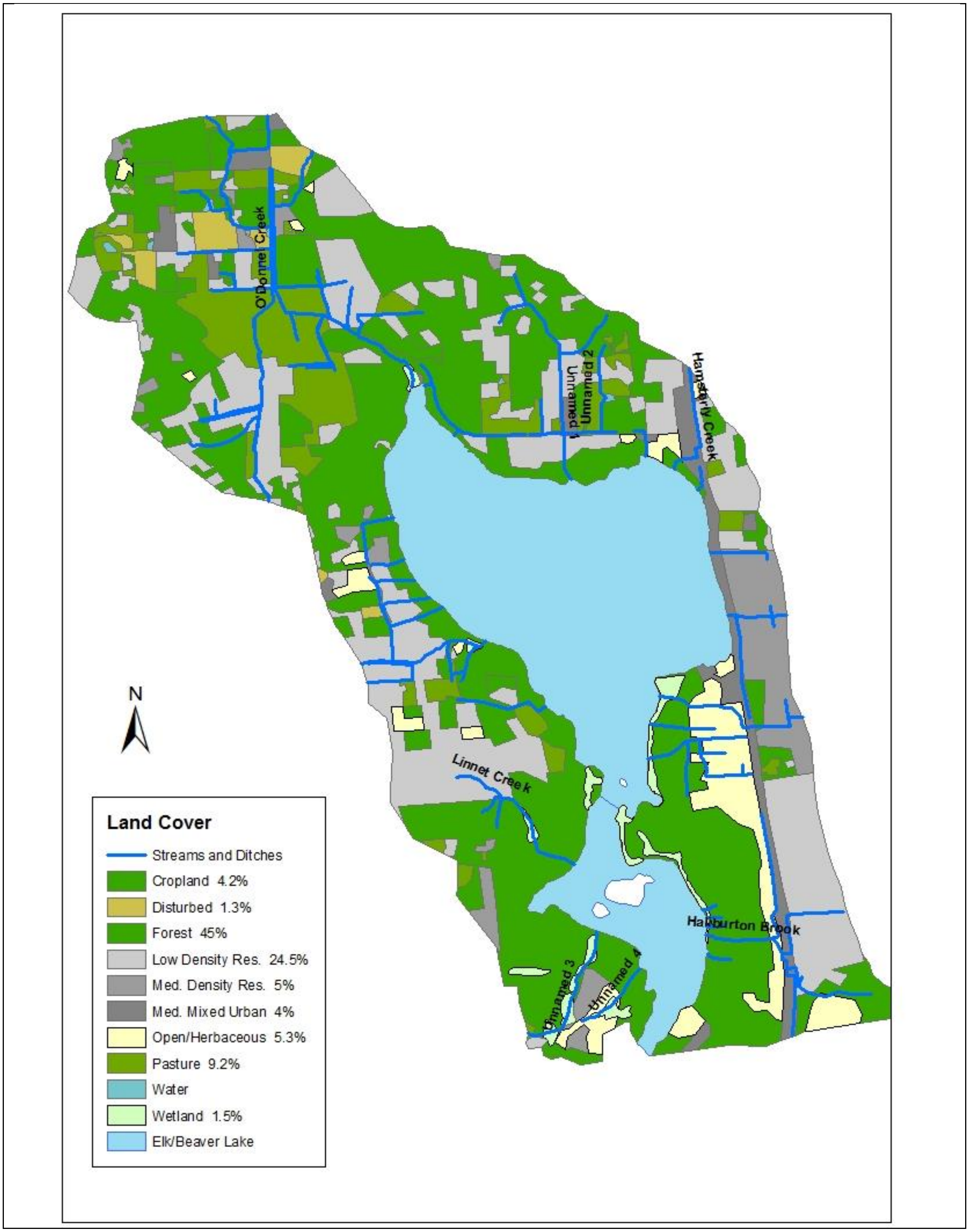
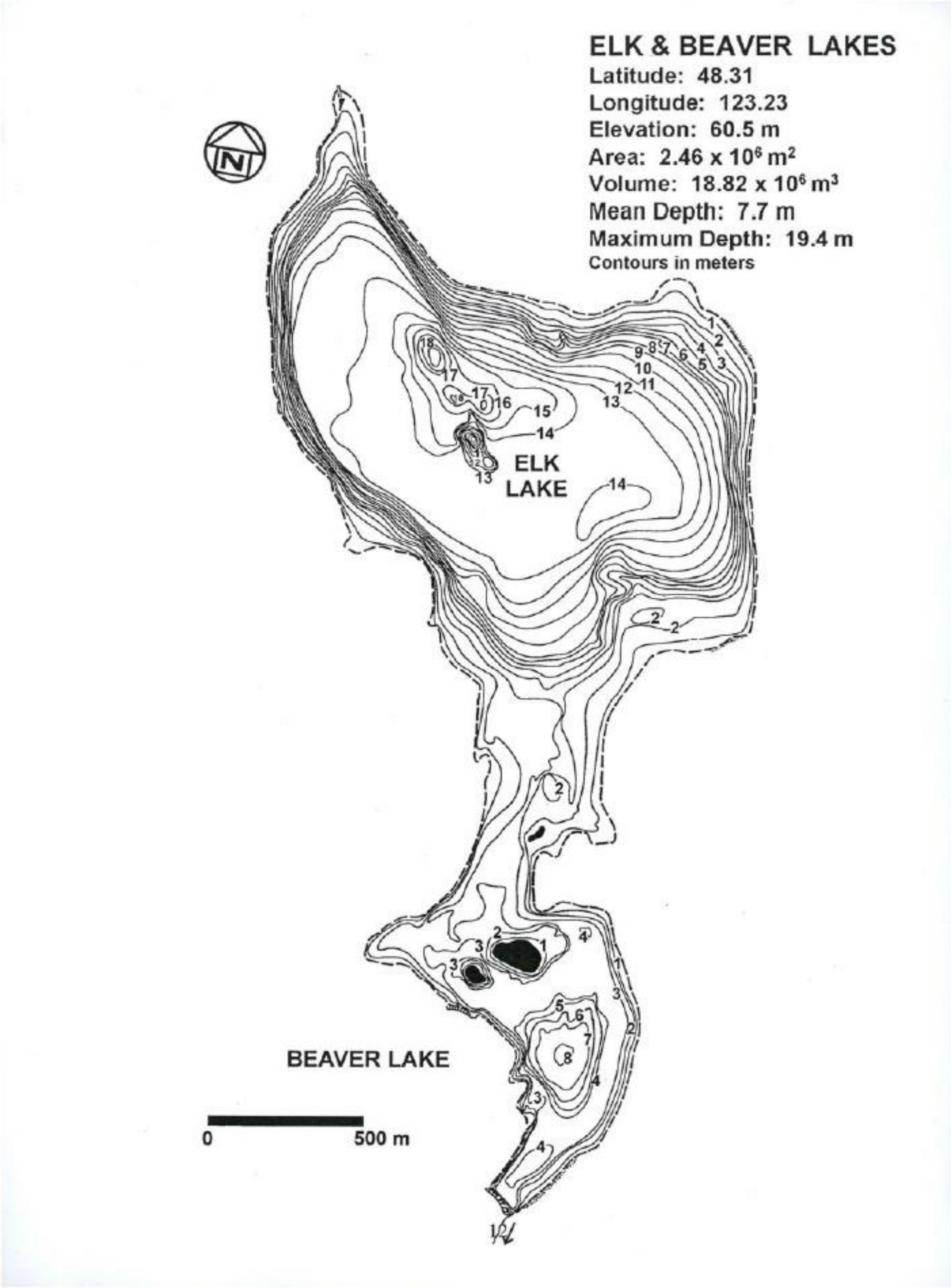


Figure 2.1 Land Cover Map of Elk/Beaver Lake Watershed



Bathymetric map from Spafard et al 2002

Figure 2.2 Bathymetry of Elk/Beaver Lake

2.2 History

Groeneveld (2002) analyzed lake sediment cores to evaluate water quality changes in Elk Lake over the past 500 years. Nordin (2014) summarized the results of Groenveld's paleolimnological analysis which most notably showed that annual sediment accumulation in Elk Lake increased significantly after about 1960, and the sediment accumulation rate continued to increase exponentially through 2002 when the study was completed. Sediment phosphorus may have increased as well, from 800-900 µg/g to over 1600 µg/g. In support of the sediment phosphorus estimated by Groeneveld (2002), Nowak (2016) found Elk Lake sediment phosphorus ranged from 1230-2500 µg/g. However, it should be noted that Carey and Rydin (2011) found similar phosphorus sequestration trends among eutrophic lakes, such that all eutrophic lakes have a higher concentration of phosphorus in the upper part of the sediment which decreases predictably with sediment depth. In contrast, mesotrophic lakes have relatively uniform soil phosphorus throughout the upper 30 cm, and in oligotrophic lakes phosphorus increases with depth, indicating sediment sequestration and burial (Carey and Rydin 2011). Thus, the presence of phosphorus in higher concentrations near the sediment-water interface may not represent an increase over time, rather it may demonstrate the trend of phosphorus sequestration typical of eutrophic lakes.

Water quality data were obtained in 1988 for the MOE Water Quality Objectives established in 1992 (McKean 1992). The 1988 deep water (hypolimnetic) samples showed that total phosphorus (TP) concentrations in Elk Lake increased from 15 µg/L in the spring to 880 µg/L by October, indicating that lake sediments were the source of substantial phosphorus loading. Beaver Lake total hypolimnetic phosphorus concentrations increased from 28 µg/L in May, to 80 µg/L in August, and decreased to 23 µg/L by November 1988.

Following additional monitoring from 1993-1995, the 1997 WQO Attainment Report showed that Elk Lake was not meeting the WQOs for dissolved oxygen, Chlorophyll-a (Chl-a), and phytoplankton community. Future monitoring was determined to be a low priority until action is taken to improve water quality.

2.3 Factors Influencing Lake Water Quality

Lake trophic state refers to lake productivity (i.e., the extent to which the growth of organisms is supported by available nutrients), and is most commonly characterized based on total phosphorus (TP) concentration[1] or the total nitrogen (TN) to total phosphorus ratio (TN:TP) of lake water. Nurnberg (1996) concluded that both TP and TN concentrations, as well as, transparency (Secchi) depth are most strongly correlated with trophic status. The study also found a significant relationship between TP and Chl-a (indicates phytoplankton biomass) which also makes Chl-a levels a significant metric. **Table 2.3** shows the parameters by which lake productivity is classified, and illustrates the trophic status of Elk Lake.

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[1] Measurements of TP include the phosphorus content of both live and dead cyanobacterial cells, along with other live or decomposing biota which will sink to the bottom of the lake at the end of their life cycle.

Table 2.3 Lake Trophic Status

Metric	Oligotrophic	Mesotrophic	Eutrophic	Elk Lake
TP concentration	< 10 µg/L	10-30 µg/L	30-100 µg/L	73 µg/L
TN concentration	<350 µg/L	350-650 µg/L	650-1200 µg/L	840 µg/L
N:P Ratio	25:1	---	<15:1	11:1
Chl-a	<3.5 µg/L	3.5-9 µg/L	9-25 µg/L	>2.5 µg/L
Transparency (Secchi depth)	>4 m	3-4 m	1-2 m	3 m

2.3.1 Water Residence Time

Elk/Beaver Lake has a relatively long water residence time of approximately 7 years, compared to oligotrophic lakes such as Sooke and Shawnigan Lakes with water residence times of 1-2 years. Water residence time is dependent on inflow-outflow, and fluctuates both seasonally and inter-annually. Drought-years and the significant reduction in precipitation during the summer months result in longer residence times, especially for small, hydrologically isolated lakes like Elk/Beaver Lake, which is entirely dependent on rain for water inflow[2]. Water residence time is very positively correlated with the retention of both nitrogen and phosphorus by lakes (Saunders and Kalff 2001; Brett and Benjamin 2008).

In addition, water residence time greatly influences both the growth of cyanobacteria and the concentrations of cyanotoxins (Saunders and Kalff 2001; Brett and Benjamin 2008). Toxic cyanobacteria blooms in Elk Lake are typically dominated by the cyanobacteria genera *Aphanizomenon*. The 2016 Beaver Lake toxic cyanobacteria blooms were dominated by *Microcystis* and *Anabaena*. The growth of *Anabaena* and *Aphanizomenon* has been strongly correlated to water residence time and increases in lake water temperature (Elliot 2010; Romo et al. 2013; Davis et al. 2009). Elliot (2010) found that *Anabaena* and *Aphanizomenon* were generally the dominant cyanobacteria in lakes with longer residence times. The abundance of these cyanobacteria increased even under cooler water temperatures, indicating that elevated cyanobacteria concentrations correspond with low-flows more than temperature (Elliott 2010).

Climate change researchers predict longer summer droughts and more intense winter rainstorms for the Pacific Coast in the future (IPCC 2013). In the absence of effective, consistent, on-going in-lake treatment, the prevalence of toxic cyanobacteria blooms is likely to increase because more intense precipitation during winter months will contribute to higher nutrient loading from the watershed into the lake, and longer summer retention times coupled with higher water temperature will promote the internal loading of phosphorus, and the resultant abundance of cyanobacteria.

2.3.2 Chemical Phosphorus Release/Sequestration

The concentration of dissolved oxygen (DO) near the lake bottom is the primary driver of internal phosphorus loading in Elk and Beaver Lakes. The use of oxygen by bacteria for the decomposition of organic material (e.g., dead plants and micro-organisms) depletes the oxygen supply, especially at the sediment-water interface where the bacteria are most active. Lake water gains oxygen from the air above the lake surface. During the summer when surface water temperatures average 22°C and deep water temperatures are around 7°C a thermal barrier (thermocline) is formed which isolates the deep

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[2] In contrast, higher elevation interior lakes receive water (inflow) from snowmelt, often throughout the summer dry season.

water from atmospheric oxygen exchange (stratification). Phosphorus sequestration in lake sediments requires chemical bonding of phosphorus with minerals such as iron (Fe) and manganese (Mn). Under low DO conditions (<2 mg/L) Fe and Mn, along with the previously bonded phosphorus, are released into the lake water. After several (2-3) months of very low oxygen, phosphorus has been shown to diffuse upward through lake sediments and into the overlying water from at least 10 cm deep (Wetzel 2001). When surface waters cool the lake water mixes, and the released phosphorus is available near the water surface where cyanobacteria photosynthesize and reproduce.

Data from 2014 showed that Elk Lake can begin to thermally stratify as early as February, is fully stratified by early June, and re-mixes in early November. In summer months, the lake consists of an epilimnion to about 5 m depth, a mesolimnion between 5 m and 10 m, and a hypolimnion below 9-10 m. Summer epilimnetic water temperatures average 22°C when hypolimnetic temperatures are around 8°C. During stratification, DO concentrations below 10 m decrease from about 10 mg/L in April, to 3 mg/L by the end of May, and are less than 1.0 mg/L throughout the summer (Nordin 2015).

2.3.3 Biological Phosphorus Release/Sequestration

Gachter, Meyer and Mares (1988) investigated the role of sediment bacteria in phosphorus release and sequestration. The study showed that sedimentary bacteria grown in oxygenated conditions depleted bioavailable phosphorus concentrations from 150 to 0.05 µmol/L. When the bacteria were exposed to very low oxygen, 14-25% of the bioavailable phosphorus was released within 70 hours of anoxia. When oxygen was again provided to the bacteria, all of the bioavailable phosphorus was re-sequestered within 4 hours. Results also showed that the amount of phosphorus sequestered in bacteria is highest at the sediment surface where up to 80% is contained within bacterial cells. Bacteria can outcompete cyanobacteria in the uptake of phosphorus, and will release significant amounts of phosphorus under low oxygen conditions (Gachter, Meyer and Mares 1988).

Phosphorus-mobilizing bacteria have been shown to be abundant to at least 15 cm deep in lake sediment, and are most abundant in sediments containing moderate to high quantities of organic matter. The ability of these organisms to transport phosphorus from the water into the sediment is governed by the amount of oxygen at the sediment-water interface. With sufficient oxygen, bacteria significantly increase the movement of phosphorus from the water and into the sediment (i.e., sequestration). When oxygen levels are very low, bacteria have been shown to facilitate less than 5% of phosphorus sequestration (Wetzel 2001), and also contribute to the release of phosphorus from the sediments (Gachter, Meyer and Mares 1988). Sediments with low oxygen also promote the formation of sulfate which, facilitated by sulfate-reducing bacteria, bonds with iron to form iron sulfides. This leads to greater release of phosphorus that was previously bonded to iron (Wetzel 2001).

2.3.4 Cyanobacteria (a.k.a. blue-green algae)

Cyanobacteria (a.k.a. blue-green algae) are always present in freshwater lakes, but not all species produce toxic compounds, and toxin release by potentially toxic species is very unpredictable. Many lakes on Vancouver Island experience cyanobacteria blooms in late summer due to low flows and high water temperatures, and/or in the late fall/early winter after the temperature of the surface water has cooled, and the phosphorus released from the sediment mixes into the whole water column. Under certain conditions some cyanobacteria produce secondary metabolites that inhibit the growth of other organisms. This phenomenon is called allelopathy, and is a competitive mechanism used by many organisms. For instance *Anabaena* is known to produce the cyanotoxin “microcystin” which can be detected in water samples. Other species of *Anabaena*, as well as, *Aphanizomenon, Woronichinia*, and *Microcystis* are also known allelopaths (Graneli, Weberg and Salomon 2008). Toxin production by cyanobacteria is thought to vary as a result of imbalances in nitrogen and phosphorus where severe nitrogen limitations (i.e., shortages) are compounded when a sudden increase in phosphorus occurs. This results in sudden rapid growth or a “bloom” of nitrogen-fixing cyanobacteria, which have a competitive advantage over other micro-organisms because they can transform atmospheric nitrogen into bioavailable nitrogen, thus creating an appropriate N:P ratio for optimum growth. As the population density increases cyanotoxin production in harmful quantities becomes more likely. When the cyanobacteria reach the end of their life cycle, a blue-green or neon green “scum” may appear on the surface of the water, the cell walls disintegrate, and cyanotoxins are released into the water.

2.4 Elk/Beaver Lake Water Quality 2014-2015

In cooperation with the MOE, Nordin (2015) conducted a year-long sampling program at the Elk Lake deep water sampling point from February 2014 to February 2015. Water quality samples were obtained for Beaver Lake in February, May, and August 2015.

2.4.1 Elk Lake Water Quality

Low oxygen conditions at the sediment-water interface were estimated to result in an internal phosphorus load 6-8 times higher than the estimated external load, or about 86-89% of TP inputs (Nurnberg and LaZerte 2016). Spring TP levels show a general trend of increased values from around 20 µg/L prior to 2000 to more than 30 µg/L up to 2014 (Nordin 2014). In 2014, hypolimnetic TP ranged from about 30 µg/L in February to nearly 700 µg/L in July. The phosphorus released from chemical bonds and sedimentary bacteria under anoxic conditions is mostly in the biologically available form (i.e. phosphate, PO_4^-). Up to a 93% reduction in summer internal phosphorus loading may be required to reduce the fall TP concentration to the non-stratified (Nov.-Apr.) seasonal average, or approximately 50 µg/L.

Measurements of TP include the phosphorus content of both live and dead cyanobacterial cells, along with other live or decomposing biota which will sink to the bottom of the lake at the end of their life cycle. It is interesting to note that TP concentrations can vary throughout the water column in the winter when the lake does not exhibit a significant thermocline. This is likely due to a combination of residual phosphorus from summer internal loading, some external loading from heavy rains, minor stratification, and biological uptake. For instance, in January 2015, water temperatures were uniform throughout the water column (5.7°C). By February, surface waters had warmed to 6.4°C while deep water remained cooler at 5.7°C. TP concentrations in the epilimnion, mesolimnion, and hypolimnion were 8, 28, and 72 µg/L respectively (Nordin 2015). The low TP concentration in the epilimnion can be explained by the availability of light near the water surface which enables the growth of phytoplankton when sufficient nutrients are available. Phytoplankton growth would consume the available phosphorus in the range of sufficient light availability. The expiration and sinking of phytoplankton would result in a transfer of phosphorus from the surface to the bottom of the lake. The moderate TP concentration in the mesolimnion is equal to the total water column average of about 30 µg/L which, in the absence of excessive internal loading, would likely be the approximate equilibrium concentration of phosphorus, and is to be expected given the lake’s natural meso- to eutrophic state (see **Table 2.3**). This supports the conclusion that external loading does not contribute significant phosphorus to the lake system. Instead, several factors may be influencing the phosphorus concentrations in the different strata. The high TP concentration in the hypolimnion is likely residual from summer internal loading, and coincided with the severe cyanobacteria bloom that occurred in January 2015.

Further, a comparison of data from the 1988 (McKean 1992) and the 2014/2015 (Nordin 2015) sample periods showed no difference in water clarity, but did show a spike in Chl-a in late 2014 through January 2015. High concentrations of Chl-a indicate high photosynthetic primary production by phytoplankton. As discussed previously, the phytoplankton community is typically dominated by cyanobacteria with the potential to produce toxic compounds.

Sources of external phosphorus loading include incoming drainages, the atmosphere, and wildlife fecal matter. Septic inputs have been estimated using several models; however, due to the strong tendency of phosphorus to bond with soil particles, along with the required lake and drainage set-back requirements, and low *E. coli* and fecal coliform counts in the in-coming streams, septic systems are not likely contributing significantly to phosphorus loads. When septic system estimates were included, external phosphorus loading was estimated to account for up to 12.6 µg/L of TP in the water column, which is on average 12% of the total annual phosphorus load (Nurnberg and LaZerte 2016); however, general septic system models tend to overestimate the actual phosphorus contribution (Hodgins 2015).

2.4.2 Beaver Lake Water Quality

Water quality samples obtained for Beaver Lake in February, May, and August 2015. February samples showed surface water TP concentrations of 15 µg/L, compared to 24 µg/L in May, and 32 µg/L in August. Deep water TP concentrations were 21 µg/L in February, but rose to 225 µg/L in May, and 650 µg/L in August. Total rainfall in June and July 2015 was only 15 cm, thus runoff would not account for the increase in TP. Temperature data from August 2016 showed that Beaver Lake was not thermally stratified in the late summer, but DO levels were very high at the surface, and declined to near zero below 4 m due to high biological activity at the sediment-water interface. The low oxygen in the deep water resulted in internal phosphorus loading in Beaver Lake.

2.4.3 Status of Water Quality Objective Attainment in Elk Lake

Table 2.4 shows the water quality status as it relates to 1992 BC Water Quality Parameters and Elk Lake WQOs (McKean 1992).

Table 2.4 Water Quality Attainment in Elk Lake

Parameter	BC WQ	Elk Lake Objectives (McKean 1992)	2014/2015 Average (Nordin 2015)	Performance Comments
Temperature	+/-1°C from natural	15°C	<15°C below 10 m	Set for fish habitat
pH	6.5-9.0	---	7.5	pH attained
DO	8-15 mg/L	5 mg/L 1 m above bottom	<5 mg/L 6 months May-October	Low DO in summer
Nitrite	2 mg/L	---	0.1-0.2 mg N/L	Nitrogen levels are very low
Nitrate	40 mg/L	---		

Parameter	BC WQ	Elk Lake Objectives (McKean 1992)	2014/2015 Average (Nordin 2015)	Performance Comments
Spring total phosphorus	15 µg/L	---	33-44 µg/L	Low end of eutrophic scale
Chlorophyll-a	---	1.5-2.5 µg/L summer	6.2 µg/L	Typical range = 2.5-10 µg/L; Early January peak of 33 µg/L
Phytoplankton	---	<50% cyanobacteria	66%	Cyanobacteria typically dominate

2.4.4 Elk Lake Cyanobacteria Blooms

Elk Lake experienced toxic cyanobacterial blooms from December to February from 2011-2015. In 2014 and 2015, the toxicity of these blooms required that the New Year Polar Bear Swims be moved to Thetis Lake due to testing that confirmed the presence of Anatoxin in concentrations exceeding guidelines for water contact. Ten different genera of potentially hazardous cyanobacteria were dominant in Elk Lake in 2014. Of these, *Anabaena* and *Woronichinia* have the potential to produce cyanotoxins, and when dominant, represented 53-97% of all cyanobacteria in the samples. *Aphanizomenon* is responsible for the toxic blooms that occurred between December 2014 and February 2015, as it was the sole dominant genera representing 64-99% of all cyanobacteria in the samples.

Water near Hamsterly Beach at the north end of Elk Lake was tested for cyanotoxins in August and September 2016. These samples did not exceed cyanotoxin thresholds. At that time, cyanobacteria comprised approximately 40% overall relative abundance, with species belonging to the chrysophyte (golden-brown algae) genus *Dinobryon*, comprising another 40%. Filamentous, colonial, and single-celled species of green algae (chlorophytes) accounted for the remaining 20% (Kline 2016).

2.4.5 2016 Beaver Lake Cyanobacteria Blooms

On August 3, 2016 CRD Parks staff alerted CRD Environmental Protection that a green “scum” could be seen on the water near Beaver Beach at the south end of Beaver Lake. Samples were taken, and microbiological analyses determined that the scum contained the cyanotoxin Microcystin in high amounts. At that time, cyanobacteria of the genus *Microcystis* comprised 90-95% of the sample and *Anabaena* the remaining 5-10% (100% cyanobacteria).

On August 5, 2016 *Microcystis* colonies were detected in the Colquitz River just south of the Beaver Lake dam but cyanotoxins did not exceed the detection threshold.

On August 10, 2016, cyanotoxins in Beaver Lake no longer exceeded the established threshold, but *Microcystis* still composed 60% of the algal abundance, *Anabaena* 39%, and 1% were *Aphanizomenon* and *Woronichinia.* All of these genera belong to the cyanobacteria group and all have potential for cyanotoxin production.

By August 19, scum and shallow water samples containing cyanobacteria tested negative for cyanotoxins. Once the cyanobacteria had consumed the excess phosphorus, the bloom peaked, and then died-off.

An additional bloom was identified on September 9, 2016. This bloom contained 80% *Microcystis* and 20% *Anabaena*, but did not exceed the toxicity threshold. It is likely that this bloom was caused by lake mixing from 18 mm of rainfall that occurred between 31 August and 7 September 2016.

A third bloom was identified on September 24, 2016. This bloom consisted of 50% *Microcystis* and 50% *Anabaena*. This bloom contained cyanotoxins greater than 20 ppb, which exceeds the threshold for recreation.

Cyanobacteria surface scum were observed weekly from September 24, 2016 to early December 2016.

Figure 2.3 shows the August 2016 cyanobacteria upon detection and after expiration. **Figure 2.4** is a photograph of the cyanobacteria under the microscope.

3 August 2016

18 August 2016

Figure 2.3 August 2016 Microcystis bloom in Beaver Lake

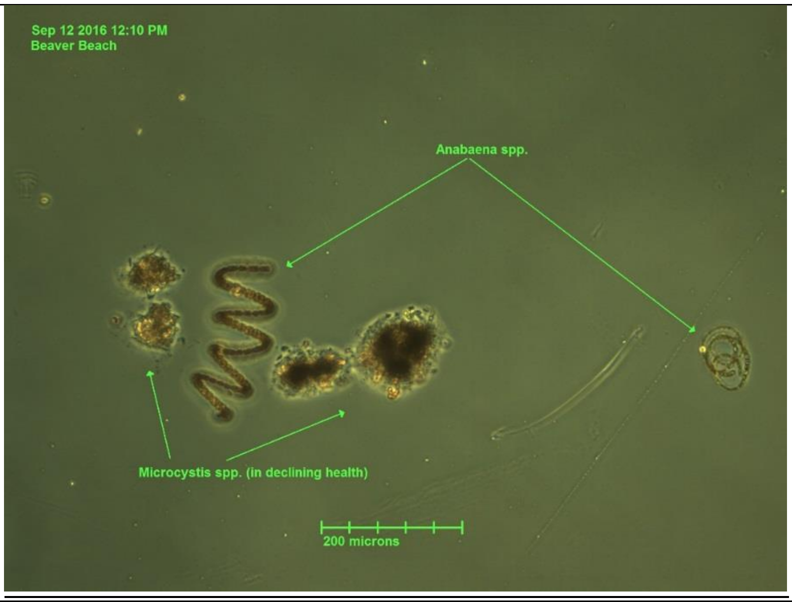

Figure 2.4 Microscope photo of Anabaena spp. and Microcystis spp. found in Beaver Lake

3.0 Evaluation of In-Lake Remediation Options

In-lake remediation options evaluated for Elk Lake included dredging, biological augmentation, bio-manipulation, lanthanum-modified bentonite clay treatment (LMB), full-lift "Bernhardt" hypolimnetic aeration, laminar-flow (a.k.a. bubbler) oxygenation, and downflow bubble contact hypolimnetic oxygenation (DBHO). The following section reviews each option, summarizes the reasons each was eliminated, and clearly outlines why downflow bubble contact hypolimnetic aeration was chosen as the preferred treatment. Finally, the implications of taking no action are also summarized.

3.1 Dredging

Dredging lake sediments has been performed in lakes to remove the phosphorus or other chemicals from the lake sediment surface. Dredging is a complex effort which requires significant land area to dewater the sediment-slurry that is extracted from the lake bottom. Ashley (2008) summarized the dredging program at Burnaby Lake (Burnaby, BC). Four options were considered, and included the removal of between 262,000 m^3 and 563,000 m^3 of contaminated material at costs ranging from $18.6-$34.5 million. If dredging is conducted in 50% (1.1 million m^3) or 75% (1.7 million m^3) of the Elk and Beaver Lakes area, and total costs are similar to the Burnaby Lake project at $60-$71 per cubic meter, approximate costs for dredging would be between $66 million and $120 million. Extensive land area (several hectares) would be needed to dewater the dredge material prior to transport. Following dredging, newly exposed lake sediments would likely be very acidic and high in oxidizing iron, and additional treatment would be needed to protect water quality and aquatic biota.

This option was eliminated for the following reasons:

- According to estimates from a Burnaby Lake project, the cost of dredging Elk Lake would range from $66 to $120 million;
- Extensive land area (several hectares) would be needed to dewater the dredge material prior to transport, and securing such a location would be costly and likely involve environmental assessments before and after use;
- Newly exposed sediments would likely be very acidic and high in oxidizing iron, and additional treatment would likely be needed to protect water quality and aquatic biota following dredging.

3.2 Biological Augmentation

The rate of organic material decomposition in lake sediments, and the subsequent nutrient release have a major influence on trophic status and water quality. Organic material decomposition rates depend on oxygen availability and bacterial abundance which simultaneously act as sources and sinks for nutrients. Eutrophication occurs as a result of excess nutrients which drive lake productivity, and when nutrients are not sequestered in living biota, they are a source of nutrients for cyanobacteria. When the amount of available organic matter decreases, fewer nutrients are readily available, and this facilitates lake recovery (Schultz and Urban 2008).

Biological augmentation involves the application of customized beneficial microbes, including diatoms and aerobic bacteria, to clean the water and decompose organic material. Used in concert with an aeration or oxygenation system, the diatoms absorb excess nutrients from the water and provide food for fish, while beneficial bacteria decompose organic matter, and as a result reduce hydrogen sulfide (H_2S) and carbon dioxide (CO_2) (Clean-Flo 2016). Theoretically, phosphorus previously bound in organic material would be released into the water column, but would be sequestered in diatoms, zooplankton, and fish. The oxygenation of the lake water, coupled with the addition of diatoms and beneficial bacteria are claimed to shift the phytoplankton community from cyanobacterial dominance to a more diverse biotic system.

This option was eliminated due to a lack of scientific evidence of the effectiveness of this practice. The existing natural bacteria within the lake sediments are sufficient for decomposition, and the low oxygen levels at the sediment-water interface in both Elk and Beaver Lakes during the summer indicate high bacterial decomposition rates because oxygen is being consumed for biological processes. Following oxygenation of Langford Lake (Victoria, BC), and without artificial bacterial augmentation, the phytoplankton community shifted from cyanobacteria to diatom dominance (Ashley and Nordin 1999).

3.3 Biomanipulation: Fish Removal

Although not likely to improve water quality as a single, independent action, fish-removal has been shown to improve water clarity by shifting the food-web dynamics and reducing cyanobacterial abundance (Hansson, et al. 1998; Meijer et al. 1999; Houser, Carter and Cole 2000; Mehner, et al. 2002) The purpose of biomanipulation as fish removal is to deliberately reduce planktivorous fish in order to increase the abundance and size of zooplankton which are the primary predator of cyanobacteria. Studies agree that improved water clarity can be achieved by a rapid reduction (within 1-3 years) of at least 75% of planktivorous fish species (Hansson et al. 1998; Meijer et al. 1999) such as yellow perch, pumpkinseed, and prickly sculpin found in Elk Lake. The reduction of benthivorous fish, such as carp, may also increase water clarity (Meijer, et al. 1999). Zooplankton size has been related to the reduction of TP in the water column. The exact fate of the phosphorus is predicted to be due to the assimilation of phosphorus within the zooplankton and losses to sedimentation due to sinking zooplankton (Houser, Carter and Cole 2000).

In a study of 18 shallow lakes in the Netherlands, Meijer et al. (1999) found that fish removal resulted in a decrease in TP and Chl-a. The associated increase in Secchi transparency was significant compared to lakes where only the phosphorus load was reduced. *Daphnia* spp. (zooplankton) grazing on cyanobacteria seemed to affect spring-time water clarity, but had almost no effect on summertime cyanobacteria blooms. In most lakes the summer TP concentration remained too high to reduce cyanobacteria growth, and several lakes experienced a decline in water clarity within four years following planktivorous fish removal (Meijer, et al. 1999), indicating that a significant number of fish would need to be removed every 3-4 years to maintain the water quality improvements over the long-term.

This option has been eliminated because Elk Lake is dominated by planktivorous fish species, and a 75% reduction in planktivorous fish species is not a feasible undertaking. As presented above, Meijer et al. (1999) found no effect on summertime cyanobacteria blooms, and a likely decline in water quality after four years indicates that fish removal approximately every three years would be required. It is likely that improved water quality (i.e., phosphorus reduction), and the resulting shift in lake food web dynamics (e.g., from cyanobacteria dominance to an increase in green and brown algae and diatoms) will have a positive effect on the species composition of the Elk Lake fishery.

3.4 Lanthanum-modified Bentonite

LMB is a commercial product consisting of 95% bentonite and 5% lanthanum (La^{3+}), a rare earth mineral that binds readily to phosphate (PO_4^{3-}). Lanthanum-modified bentonite is applied from the lake surface either in a solid granular form or as a slurry. In the water column, La^{3+} bonds with PO_4^{3-} and water to form rhabdophane ($LaPO_4$+H_2O). Once settled into the lake sediment, the $LaPO_4$ stabilizes as solid "monazite", and has low water solubility (Dithmer, et al. 2015; Copetti, et al. 2016). At the correct dosage, the La^{3+} should permanently bind PO_4^{3-} such that it would not be released into the lake water even under very low DO conditions.

Bentonite clay is commonly used to cap and seal contaminated soils or leaking ponds and reservoirs. Naturally occurring bentonite contains sodium ions that cause the clay to swell and form a putty-like seal when saturated. In LMB, the sodium ions have been replaced with La^{3+}, and the bentonite does not swell, and does not form a physical barrier. Instead, the LMB particles have similar density and consistency to most sediments, and will mix with the sediments to provide additional bonding sites for phosphate that are not influenced by oxygen concentrations (Traill 2016b).

Nowak et al. (2016) produced a sediment phosphorus fractionation analysis of the upper 5 cm of seven, and upper 10 cm of two, sediment core samples extracted in June 2016 throughout Elk Lake. The study was conducted to determine the appropriate dose of LMB needed to permanently sequester phosphorus from: (1) loosely-bound and immediately available phosphorus (water labile phosphorus), (2) phosphorus bound by Fe and Mn (reductive releasable organic phosphorus), and (3) phosphorus bound in organic structures such as microorganisms, detritus, and humic substances (organic-bound phosphorus). Water labile phosphorus is immediately available, Fe- and Mn-bound phosphorus is released under anoxic conditions, and organic-bound phosphorus is released both under anoxic conditions and during bacterial degradation.

Sediments were relatively homogenous among all nine core samples except that the deep sample contained significantly more phosphorus, and two samples near the west shore contained significantly more hydrogen sulfide (H_2S). On average, water labile phosphorus was very low (1.8 mgP/kg dry weight (DW)), while Fe/Mn-bound and reductive releasable phosphorus averaged 343 mgP/kg DW (41%), and organic-bound phosphorus averaged 488 mgP/kg DW (59%).

The reported success of LMB varies, but a study of 18 lakes showed average summer, fall, and winter reductions in phosphorus of 56%, 63%, and 71% respectively (Spears, et al. 2016). The effectiveness of LMB depends on the amount of Fe/Mn-bound phosphorus in each specific lake, and the implications for Elk Lake are discussed in the next paragraph. Multiple dosing events (~once every 3 years) are often needed to maintain low internal phosphorus loading. Laboratory trials have shown greater phosphorus sequestration than lake-scale applications, and field studies have found that laboratory-based dosages tend to underestimate the quantity of material needed to effectively reduce phosphorus at the full-scale of lake applications (Meis et al. 2012; Spears et al. 2016; Dithmer et al. 2016). Studies agree that this is largely due to vertical translocation of La^{3+} from 5 cm to up to 10 cm deep in the lake sediments. LMB dosage recommendations are based on a ratio of 1 kg LMB per 10 g of phosphorus (100:1); however, several studies have indicated that the field application of LMB at this ratio was too low (Meis, et al. 2012; Spears, et al. 2016; Dithmer et al. 2015), and that a ratio of 220:1 may be more effective (Lurling, Waajen and vanOosterhout 2014). At the correct dosage, LMB should permanently bind releasable (i.e., chemical) phosphorus such that it would not separate from Fe and Mn even under very low DO conditions. LMB cannot, however, sequester phosphorus that is organic-bound (i.e., sequestered in microorganisms, detritus, and humic substances) unless it is transformed to water labile phosphorus and exposed to La^{3+} bonding sites in the lake sediment (Traill 2016a).

According to the sediment phosphorus fractionation analysis (Nowak et al. 2016), organic-bound phosphorus constituted 59%, and Fe/Mn-bound phosphorus constituted 41% of total sediment phosphorus. As discussed previously, sediment bacteria require oxygen for the decomposition of organic material, and DO concentrations affect the sequestration and release of phosphorus by sedimentary bacteria and from chemical bonds. During the summer when deep water DO is low, the presence of La^{3+} in the lake sediment could prevent the release of 41% of sediment phosphorus (Fe/Mn-bound). Because sediment bacteria also release phosphorus under low DO conditions, it is possible that the previously organic-bound phosphorus may become water labile, and could potentially bond with available La^{3+} such that some percentage of organic-bound phosphorus may also be permanently sequestered. However, sediment samples were collected from Elk Lake in June 2016 when the lake was already stratified and DO concentrations were likely 0-2 mg/L (based on 2014 measurements; Nordin 2015). This indicates that the amount of organic-bound phosphorus found in the June 2016 samples may represent the summer-time organic-bound phosphorus fraction which cannot be sequestered by LMB. In addition, low oxygen at the sediment-water interface during stratification restricts decomposition by bacteria, and organic material may stay intact so phosphorus from this source would not become water labile. Once mixed with the sediment, the extent to which La^{3+} can capture water labile phosphorus before it is consumed by floating or benthic microorganisms is not known, and the potential of organic-bound phosphorus to release and eventually bond with La^{3+} in the sediment is likewise uncertain. Therefore, as much as 59% of sediment phosphorus may not be permanently sequestered by LMB.

The timing of a LMB application must be considered carefully. LMB cannot be applied during the following conditions (Hickey and Gibbs 2009; Copetti et al. 2016):

- Stratification
- Wind mixing
- Fish breeding, spawning, or stocking
- High algal mass
- High total phosphorus in water column
- Recreational peak times

Temporary fish mortalities (~2 weeks) and zooplankton reduction (~7 weeks) can be expected due to the increase in total suspended solids in the water column. La^{3+} has been shown to accumulate in fish gills and organs, but is typically eliminated after about 7 weeks (Copetti, et al. 2016).

This option was eliminated for the following reasons:

- Lanthanum-modified bentonite clay treatment can only prevent the release of Fe/Mn-bound phosphorus, which accounts for only 41% of total sediment phosphorus, the remaining 59% of organic-bound phosphorus (e.g., in sediment bacteria and micro-organisms) may not be affected;

- Multiple dosing events (~once every 3 years) may be needed to maintain low internal phosphorus loading, and each event would cost an estimated $2.4 million;
- Treatment would have no effect on DO concentrations, and would thus not improve summer fish habitat nor promote the decomposition of organic material on the lake sediment.

3.5 Aeration and Oxygenation Systems

Nordin (2015) observed that summer DO levels have decreased by depth when compared to the results of McKean (1992). DO levels less than 2 mg/L at shallower depths for more of the summer result in increased internal phosphorus loading, reduced benthic productivity, and greater risk to the fishery due to loss of habitat. Thus, in addition to the increased risk of toxic cyanobacteria blooms following low DO conditions, another major concern is that fish cannot inhabit areas with low DO. DO concentrations <2 mg/L below 10 m depth means fish are unable to occupy the majority of the lake from June to October. This is detrimental to the fishery because at shallow depths fish are subjected to higher water temperatures, light exposure, and greater predation risk. Nordin (2015) calculated the summer oxygen demand based on the rate of oxygen depletion between 27 May and 10 June 2014. He found an oxygen deficit of 2432 kg, which means 174 kg of oxygen per day is needed to maintain DO above 2 mg/L. The MOE 1992 Water Quality Objective for DO in Elk Lake is >5 mg/L at 1 m above the lake bottom. Assuming at least 2.5x the oxygen (mass) is needed to meet the DO Objective, at least 435 kgO_2/day is needed to compensate for the oxygen demand of decomposing bacteria. In addition to the DO in the bottom 1 m of the water column, bacterial decomposition and biological transformation in the lake sediments also requires oxygen (i.e., sediment-oxygen demand), and this additional demand should be considered when calculating the daily oxygen deficit.

In the past, the main challenge of various aeration system types was configuring systems to be powerful enough to meet the actual sediment oxygen demand of the lake, which is increased by the addition of oxygen. The sediment oxygen demand is the rate of oxygen removal from the overlying water column due to the decomposition of settled organic matter in the lake sediment. The oxygen demand is difficult to estimate because it includes both the deep water demand and the sediment demand, and due to the increased decomposition enabled by higher oxygen saturation, the demand will increase significantly at the onset of aeration (Ashley and Nordin 1999). However, once the systems are properly configured, they do decrease the release of phosphorus from the lake sediments. Following the installation of a destratification system in Langford Lake (Langford, BC) in the mid-1980s, and once the diffuser had been calibrated to meet the actual oxygen demand, data showed that internal phosphorus loading was reduced. Fish habitat was expanded due to increased DO levels, aquatic macrophyte species abundance increased, zooplankton populations increased, and the phytoplankton community shifted from cyanobacteria to diatom dominance (Ashley and Nordin 1999). Following an upgrade from 3,175 µm diameter diffusers to 140 µm diffusers in 1988, the daily oxygen input to St. Mary Lake (Salt Spring Island, BC) increased from 311 kg/day to 512 kg/day with no corresponding increase in operational costs (Ashley et al. 1990). As a result, late summer oxygen saturation increased by 30%, and the lake was able to support both warm-water species in the epilimnion and cold-water species in the hypolimnion (Ashley and Nordin 1999). **Figure 3.1** shows that hypolimnetic phosphorus was notably lower in St. Mary Lake during years that the aeration system (full-lift “Bernhardt”) was maintained and operated (1987-1990 and 2009-2011) (North Salt Spring Waterworks 2014; Rodgers 2015).

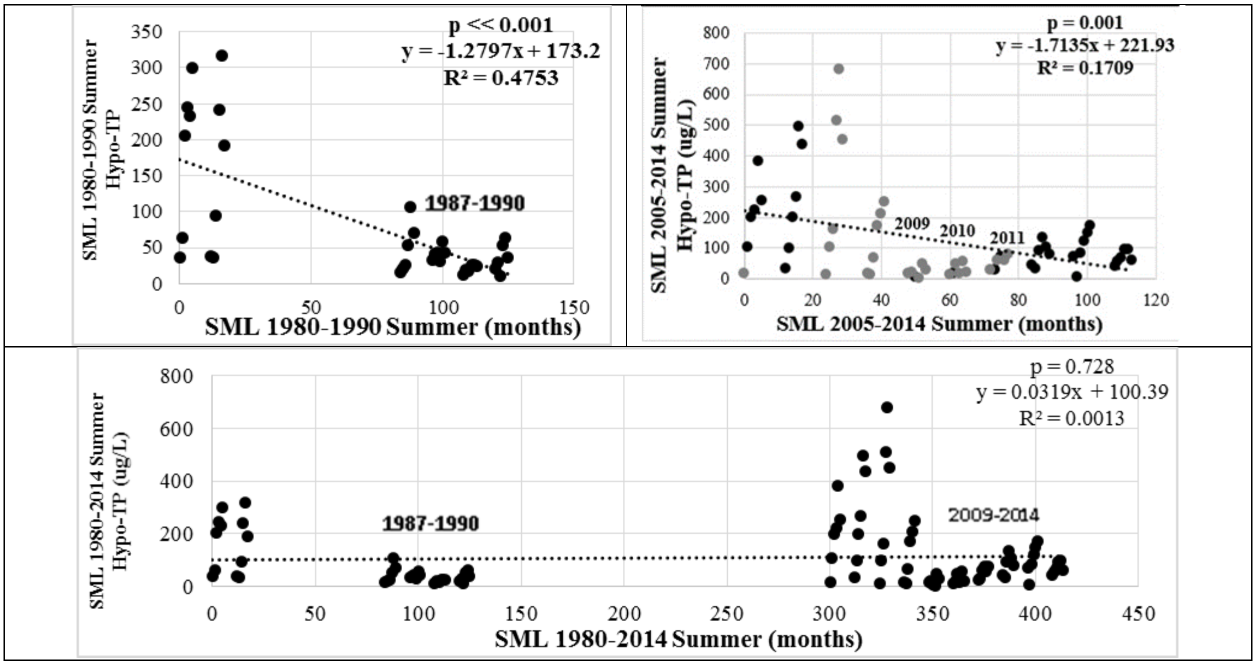

Figure 3.1 St. Mary Lake (Salt Spring Island, BC) Hypolimnetic Phosphorus 1980-2014

As summarized in **Figure 3.2**, Liboriussen et al. (2009) also demonstrated that hypolimnetic oxygenation: "… resulted in considerably lower accumulation of phosphorus in the bottom water (during stratification) of all five (Danish) lakes."

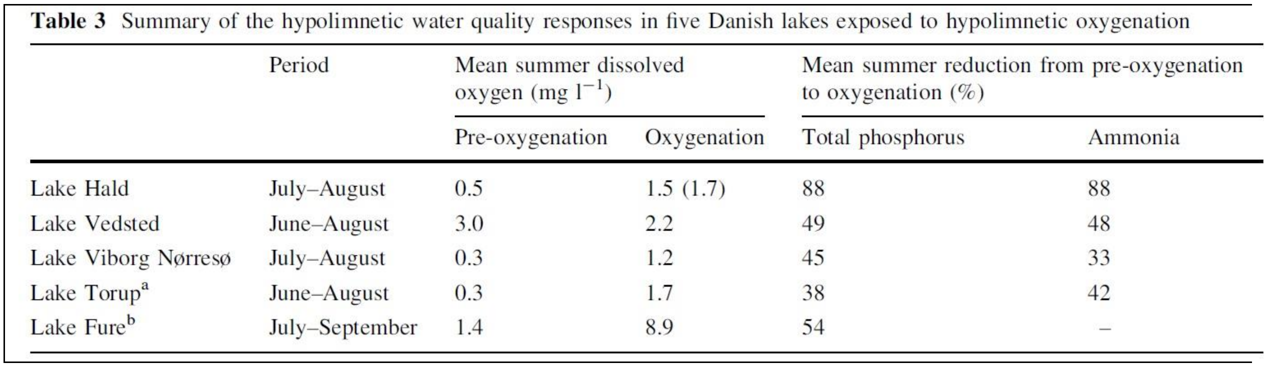

Table 3 Summary of the hypolimnetic water quality responses in five Danish lakes exposed to hypolimnetic oxygenation

	Period	Mean summer dissolved oxygen ($mg\ l^{-1}$)		Mean summer reduction from pre-oxygenation to oxygenation (%)	
		Pre-oxygenation	Oxygenation	Total phosphorus	Ammonia
Lake Hald	July–August	0.5	1.5 (1.7)	88	88
Lake Vedsted	June–August	3.0	2.2	49	48
Lake Viborg Nørresø	July–August	0.3	1.2	45	33
Lake Torup[a]	June–August	0.3	1.7	38	42
Lake Fure[b]	July–September	1.4	8.9	54	–

Figure 3.2 Change in mean summer DO and percent total phosphorus reduction in the hypolimnion of five Danish Lakes (Liboriussen, et al. 2009)

3.5.1 Full-Lift "Bernhardt" Hypolimnetic Aerator

In the past, full-lift "Bernhardt" hypolimnetic aerators have been the common choice among lake managers who wish to provide oxygen to the lake hypolimnion without disrupting the lake thermocline. This type of system was used in St. Mary Lake, and did reduce hypolimnetic phosphorus during summer stratification (**Figure 3.1**). Full-lift aeration systems must be designed with careful consideration of the diffuser orifice diameter, and the distance from the riser and exit tube orifices to any mucky or loose organic materials near the lake bottom (Ashley, Hall and Mavinic 1990) (**Figure 3.3**).

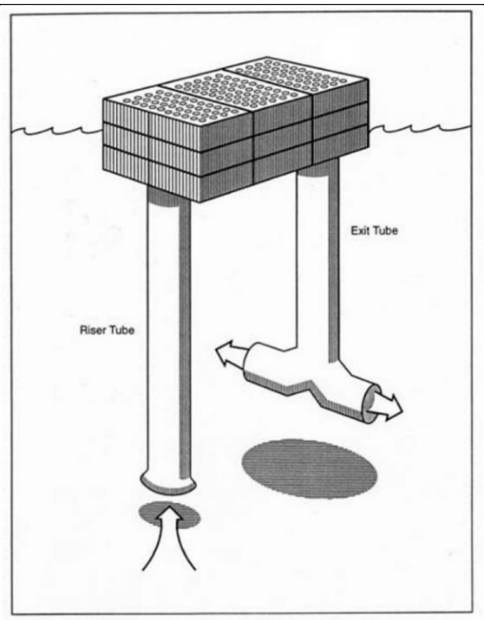

Figure 3.3 Full-lift "Bernhardt" Hypolimnetic Aeration System (Ashley 1990)

These systems require a separator box on the lake surface which must be sized appropriately to provide the desired amount of oxygen. A full-lift system would not be ideal for Elk Lake primarily due to the necessity of the lake surface obstruction, but also because of the low oxygen delivery rate (~20%), and risk of sediment disturbances associated with the riser and exit tubes. The lake hosts rowers and boaters on a daily basis, and the floating separator box would be a hazard and a nuisance for these and other lake users. Accessibility for maintenance would require underwater divers. Systems that are not sized or maintained properly can stir up lake sediments causing phosphorus and hydrogen sulfide (H_2S) to be released into the water column, and triggering severe cyanobacteria blooms.

This option was eliminated for the following reasons:

- Full-lift hypolimnetic aeration systems require a separator box to be located on the lake surface. This structure would interfere with water recreation activities such as rowing and boating;
- If not properly sized or maintained, the underwater riser and exit tubes can stir up sediment and increase both phosphorus and hydrogen sulfide in the water which can degrade water quality, and cause severe cyanobacteria blooms;
- There are better technologies that will discharge a greater concentration of oxygen directly at the sediment-water interface without stirring up sediment.

3.5.2 Laminar Flow Aeration

Laminar flow aeration systems have successfully reduced aquatic plant cover and phosphorus loading in numerous lakes, including lakes over 500 acres (2 km^2). Laminar flow technology consists of a small compressor on the lake shore, and self-sinking air lines that connect from the compressor to diffusers on the lake bottom. Laminar flow aeration systems work by drawing oxygen from a lake shore compressor and diffusing it outward into the lake sediments and upward toward the lake surface.

These systems do disrupt the thermocline, and as a result, hypolimnetic water temperatures may increase significantly in the summer. Elk Lake would mix entirely every three days. Based on the temperature profile from 2015 (Nordin 2015), a distributor of laminar flow aeration systems estimated that summer surface water temperatures would decrease by 2-4°C, and deep lake temperatures would be 2-5°C colder than surface temperatures. This means that during operation of a laminar flow aeration system, summer surface temperatures of 20-22°C would be expected. Deep water temperatures would raise from approximately 8°C to 19-22°C. The 1992 MOE Water Quality Objective for Elk Lake is <15°C, and under mixing conditions this objective would not likely be met between June and September.

This option was eliminated for the following reasons:

- Laminar-flow oxygenation would disrupt the summer thermocline of the lake, and the lake would mix entirely every three days;
- Mixing would result in an increase in deep water temperature from a fish-friendly 8°C to 19-22°C;
- This option was eliminated because it will raise summer water temperature above the MOE Water Quality Objective of 15°C, and would be detrimental to the cold-water fishery.

3.5.3 Recommended Option: Downflow bubble contact hypolimnetic oxygenation (DBHO)

Compared to hypolimnetic aeration (e.g., full lift “Bernhardt” hypolimnetic aerator) DBHO results in higher dissolved oxygen, lower induced oxygen demand, and maintenance of more stable thermal stratification. Hypolimnetic oxygenation provides pure oxygen (90-95%) to the hypolimnion at five times the solubility of pure aeration because air is only about 20% oxygen (Beutel and Horne 1999). DBHO systems work by drawing water from the hypolimnion through a pipe, pumping it through the top of the cone, and then releasing highly oxygenated water horizontally across the lake sediment. DBHO systems create an aerobic cap above the lake sediment, and do not disrupt the thermocline nor lake sediments.

The DBHO system consists of a pressure-rated, hollow, stainless steel cone with no internal mixers, baffles, or moving parts. The influent and effluent pipes have wide openings to prevent clogging, and the dish-shaped bottom of the cone with the discharge pipe at the low point provides for a self-cleaning device with no need for maintenance. The system has a life expectancy of 20+ years. The oxygen feed is fully automated, and the only moving part is the side stream pump that requires standard maintenance (**Figure 3.4**) (ECO2 Technologies 2016).

The DBHO traps pure oxygen bubbles which are circulated inside the cone until they are fully dissolved for an average oxygen transfer efficiency of 90-95%, and an exceptionally large oxygen/water ratio. The system can be installed on the shore or can be submerged in the lake.

A preliminary design for a shore-based DBHO system, guaranteed to deliver the 435 kg O_2 per day estimated to meet the oxygen demand needed to achieve the MOE 1992 Water Quality Objective for DO in Elk Lake (i.e., >5 mg/L at 1m above the lake bottom), would consist of a 12-foot tall, 4-foot diameter Speece cone™ designed to discharge DO at 78 mg/L. The system would be equipped with oxygen flow controls that can be adjusted to add a specific amount of oxygen to the lake. Thus, when the oxygen demand is lower (e.g., March-May), the operating costs will also be lower. Pure oxygen can be brought in by a local gas supplier, or it can be generated on site and on demand with a vacuum swing adsorption

(VSA) system. The total footprint of housing for the system would be approximately 27 m^2 (300 ft^2) of shoreline.

Due to the bathymetric separation between the Elk Lake basin and the Beaver Lake basin, tertiary effects of downflow bubble contact hypolimnetic aeration are not expected to be significant in Beaver Lake. Beaver Lake was formerly a shallow submerged wetland, and the lake sediments are overlain by a significant amount of organic matter, which as evidenced by year-round low oxygen at the lake bottom. The depth to mineral lake-bed is unknown, but is likely several meters deep. A separate oxygenation system is recommended to address weed growth and late summer cyanobacteria blooms in Beaver Lake.

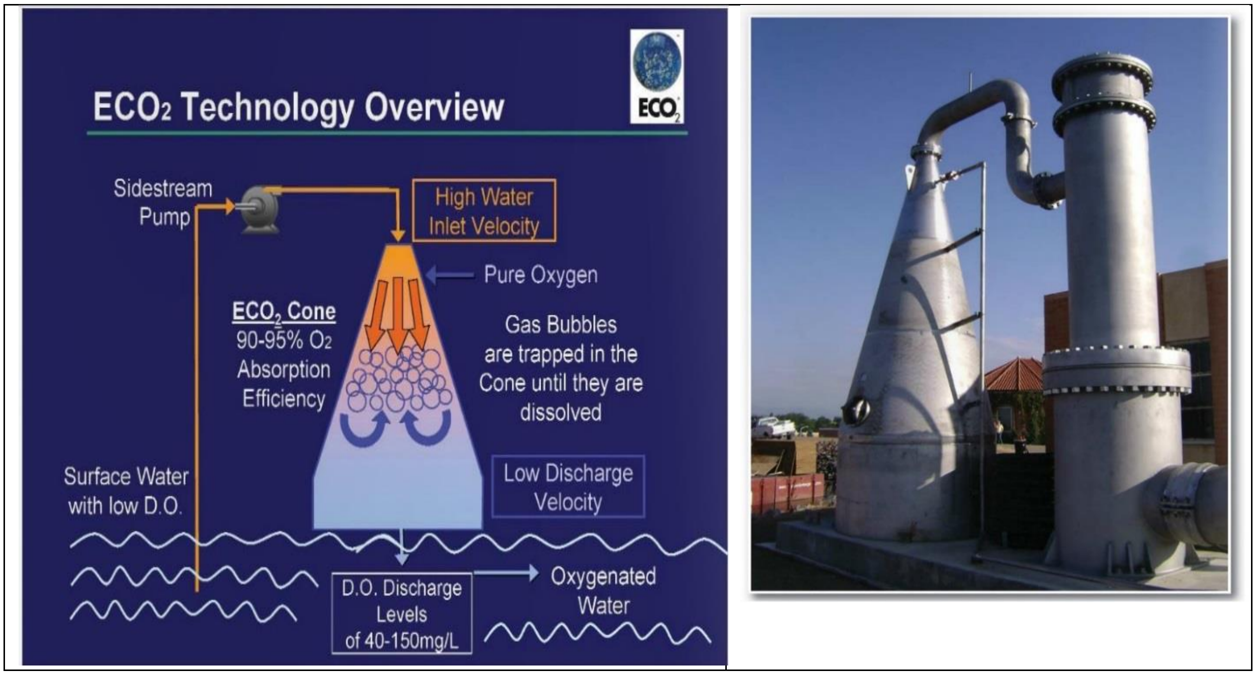

Figure 3.4 Speece Cone™ Downflow Bubble Contact Hypolimnetic Oxygenation (ECO2 Technologies 2016)

DBHO is the in-lake remediation option recommended for the reduction of cyanobacteria blooms and improvements to fish habitat in Elk Lake for the following reasons:

- DBHO technology results in highly concentrated (90-95%) oxygen saturation at the sediment-water interface as opposed to full-lift hypolimnetic aeration which can only achieve about 20%;
- Oxygen levels can be adjusted to meet the real-time oxygen demand of the hypolimnion and lake sediments;
- The addition of highly concentrated oxygen at the sediment-water interface will address both the release of Fe/Mn-bound phosphorus (up to 41%) and organic-bound phosphorus (up to 59%), and will meet the MOE WQO for DO (>5 mg/L at 1 m above the sediments).
- The cone and related infrastructure can be housed on the lake shore for easy maintenance and does not require any water surface obstruction;
- The system will not disrupt the thermocline of the lake, nor will it disturb lake sediments;
- The estimated cost of the system installation and 10-year operation is similar to hypolimnetic aeration, and about half that of a one-time application of lanthanum-modified bentonite clay.

3.6 No Action Alternative

In the absence of effective, consistent, on-going in-lake treatment, the prevalence of toxic cyanobacteria blooms is likely to increase over time because more intense precipitation during winter months will contribute to higher nutrient loading from the watershed into the lake, and longer summer retention times coupled with higher water temperatures will promote the internal loading of phosphorus, and the resultant abundance of cyanobacteria. In addition, if oxygen is not provided to the hypolimnion during summer months, fish habitat will continue to be restricted to the upper 7-9 m of the lake where predation risk is high and water temperatures are too warm.

4.0 Conclusion

The EBLI was created by the CRD in 2016 to implement one or more actions that will lead to a reduction in the frequency and toxicity of cyanobacteria (a.k.a. blue-green algae, 'BGA') blooms in Elk and Beaver Lakes, improve fish habitat, manage weed growth, and ensure continued recreational use. In 2016, CRD Parks and Environmental Services provided funding for one part-time coordinator, and a budget for continued water quality monitoring, the selection and implementation of an in-lake remediation option, and preparation of a watershed management plan. The EBLI was established in response to public demand for focus on the struggling lake ecosystem. In addition to annual toxic cyanobacteria blooms, there is concern over the sustainability of a healthy fishery under low oxygen (anoxic) conditions, the proliferation of nuisance aquatic weeds, the presence of invasive aquatic and terrestrial species, and public health and safety during water contact recreation.

Elk Lake has a maximum depth of 19 m, and an average depth of 7.7 m. Elk Lake stratifies once per year in the summer when surface water temperatures are much higher than deep water temperatures. Winter water temperatures rarely fall below 5°C, and are relatively consistent throughout the water column. Elk Lake is subject to winter (Dec.-Feb.) cyanobacteria blooms that can be toxic. The low oxygen conditions at the sediment-water interface result in an internal phosphorus load 6-8 times higher than the estimated external load, or at least 86-89% of total phosphorus inputs. A low nitrogen to phosphorus ratio (<15:1) for much of the year results in a prevalence of nitrogen-fixing cyanobacteria due to a shortage of nitrogen compared to phosphorus for biological activity. Given the small watershed to lake ratio (~3.5:1), and based on periodic water quality sampling, it has been determined that the primary source of excess phosphorus is internal loading from lake sediment.

Although conjoined by a channel, the bathymetry and ecological patterns of the two lakes are different. Beaver Lake has a maximum depth of 8 m, and an average depth of about 4 m. Temperature data showed that Beaver Lake is not thermally stratified in the summer, but dissolved oxygen levels are very high at the surface, and decline to near zero below 4 m. Beaver Lake experienced toxic cyanobacteria blooms in August, September, and October-November 2016, which persisted until air temperatures were near 0°C in December 2016.

In-lake remediation options evaluated for Elk Lake included dredging, biological augmentation, bio-manipulation, lanthanum-modified bentonite clay treatment (LMB), full-lift "Bernhardt" hypolimnetic aeration, laminar-flow (a.k.a. bubbler) oxygenation, and downflow bubble contact hypolimnetic oxygenation (DBHO). The DBHO system is recommended because compared to hypolimnetic aeration (e.g., full lift "Bernhardt" hypolimnetic aerator) DBHO aeration results in higher dissolved oxygen, lower induced oxygen demand, and maintenance of more stable thermal stratification. Hypolimnetic oxygenation provides pure oxygen (90-95%) to the hypolimnion at five times the solubility of pure aeration because air is only about 20% oxygen. DBHO oxygenation systems work by pumping water from the hypolimnion through a pipe through the top of the cone, and then releasing highly oxygenated water horizontally across the lake sediment. DBHO systems create an aerobic cap above the lake sediment, and do not disrupt the thermocline nor lake sediments. The addition of highly concentrated oxygen at the sediment-water interface will address both the release of Fe/Mn-bound phosphorus (up to 41%) and organic-bound phosphorus (up to 59%), and will meet the MOE WQO for DO (>5 mg/L at 1 m above the sediments).

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