Management Options and Monitoring Programs for Persistent Blue-Green Algae Blooms in Quamichan Lake

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Cover photo: A panorama view of Quamichan Lake in the mist taken from the Kingsview neighborhood by the author on Mount Tzouhalem, 28 January 2019 from an elevation of 225m.

Photos above: Images taken on Quamichan Lake during water sampling events on 23 May 2018 (top 2 images), 20 June 2018 (bottom left image) and 13 August 2018 (bottom right image). These images show the various visual characteristics that Blue-Green Algae can have. The top left image is a colonial blob of Blue-Green Algae that was about 1m long. Many hundreds of these large colonies were observed in the southern half of the lake whereas in the northern half of the lake only smaller colonies, ~0.1m diameter, were observed, as shown in the top right photo. It may be that these differences in colony size reflect wind conditions in northern and southern portions of Quamichan Lake. The bottom left photo shows rafts of Blue-Green algae on the surface aggregated by wind action. The bottom right photo shows the degree of abundance of Blue-Green Algae in the lake as evidenced by the green tinge to water churned up by the survey boat and seen in its wake.

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Photo Above: A panorama view of Quamichan Lake in the mist taken from the Kingsview neighborhood by the author on Mount Tzouhalem, 28 January 2019 from an elevation of 225m.

Executive Summary

Quamichan Lake has been subject to undesirable blooms of Blue-Green Algae (Cyanobacteria) since at least the 1930s and possibly even before European settlement in the Cowichan Valley in the 1860s.

Blue-Green Algae blooms have become longer and more intense over the past two decades.

Blue-Green Algae are not the only group of algae causing conspicuous blooms in Quamichan Lake.

The root cause of these Blue-Green Algae blooms is the high concentration of phosphorus in the in the lake, especially during summer.

There are two potential overall management goals to choose from:

- remediate Quamichan Lake such that Blue Green Algae blooms are reduced to relatively short durations with fish kills recorded every few years (Goal A) OR
- remediate Quamichan Lake such that Blue-Green Algae blooms are almost entirely eradicated (Goal B).

The high concentration of phosphorus is largely due to phosphorus hat has been stored in the lake after 150 years of runoff from forested, farmed and developed lands in the Quamichan watershed.

Internal loading contributes between 80-85% of phosphorus in Quamichan Lake during the summer.

The intensity of Blue-Green Algae blooms has become sufficient to yield regular fish kills in the lake caused by a combination of effects from high temperature, low oxygen concentration and high pH.

Management of Blue-Green Algae in Quamichan Lake will require primarily establishing control over phosphorus in the lake.

Controlling phosphorus entering the lake will be important to the long-term management of Blue-Green Algae and programs to begin this are already in place, *e.g.*, treatment of stream and ditches with zeolite and limestone.

Results from monitoring work conducted in 2018 suggest that phosphorus in Quamichan Lake can not be remediated with any quick or cheap approach.

Several management options exist for mitigating phosphorus in Quamichan Lake but none of them carry any guarantee of success.

Control of phosphorus in Quamichan Lake is most likely to be achieved using one, or some combination of two or all five of the following five groups of options:

- **Aeration**, *e.g.*, hypolimnetic aeration, bubblers, nano-bubblers, upflow bubble aeration, and downflow bubble aeration,
- **Chemical Treatment**, *e.g.*, aluminum salts, calcium, iron salts, and lanthanum modified bentonite clay,
- **Dredging**
- **Flushing**, *e.g.*, stored water, well water, diverted water
- **Mitigation of inflow water**, *e.g.*, zeolite/limestone in creek beds, wetland enhancement

Selection of management options for controlling phosphorus and Blue-Green Algae will be contingent on results from monitoring, assessment, and outreach as described in the following section.

Recommendations

Experience in other watersheds suggests that successful mitigation of phosphorus in Quamichan Lake will require:

- Development of a multi-year plan for implementing a phosphorus mitigation and water quality monitoring program,
- Commitment of significant financial and human resources to mitigation and monitoring work,
- Partnering with federal and provincial agencies to offset financial and personnel costs,
- Development of a program to control phosphorus input to the lake by working with the agricultural community.

Assign responsibility for managing Blue-Green Algae bloom to a North Cowichan Municipal Staff member.

Develop a Municipally housed Quamichan Lake Water Quality Committee and collaborate with Ministry of Environment, Vancouver Island Heath Authority, Cowichan Tribes and local stewardship groups.

In order to most accurately assess the optimum treatment option, an analysis of Quamichan Lake sediment cores is recommended to fix the absolute level of internal versus external loading.

Initiate a study to accurately assess lake bathymetry, volume, ground water input, and flushing rate.

Install temperature and dissolved oxygen meters in the lake to track changes on an hourly basis, see appendix 1.

Monitor weekly with a multi-parameter sonde for pH, turbidity, conductivity, chlorophyll a and Blue-Green Algae.

Monitor monthly to track phosphorus and other nutrients.

Establish a study to investigate the scale and cost of hypolimnetic aeration with compressed air and downflow bubble contact aeration.

Establish a study to investigate the scale and cost of chemical treatments like aluminum salts, iron salts, and lanthanum modified bentonite clay.

Establish a study to investigate the scale and cost of water storage or diversion for the purpose of flushing the lake during the summer.

Establish a study to investigate the scale and cost of a lake dredging program.

Begin installation of zeolite and limestone stream treatments to remediate nutrients in small urban tributary streams and ditches.

Develop wetlands for phosphorus remediation in tributary streams and ditches draining agricultural lands, particularly McIntyre Creek, Stamps Road ditch, Martin Place ditch and Stanhope Road ditch.

Introduction

In order to develop an ecosystem baseline for managing Blue-Green Algae in Quamichan Lake the author was contacted by the Municipality of North Cowichan. The municipality had established the Quamichan Lake Water Quality Task Force in 2016. In 2017 that group provided a final report which made several general recommendations to begin the process of mitigating Blue-Green Algae blooms. One of these recommendations was to begin water quality sampling as soon as possible. The author of this paper was contracted by the Municipality to design a water quality sampling program and conduct water quality monitoring activities in order to establish baseline conditions for several water quality parameters. The results of this survey are used to formulate advice on the management policies and monitoring activities that will help mitigate persistent and noxious Blue-Green Algae blooms in Quamichan Lake.

Quamichan Lake is a relatively shallow body of water located in the southeast of the Municipality of North Cowichan, Figure 1. Quamichan Lake has a maximum depth of about 8m and a surface area of just over 300 Ha (BC Fish and Wildlife Branch 1973). Quamichan Lake has become subject to Blue-Green algae blooms of greater strength and duration during the last 20 years. These Blue-Green Algae blooms have caused significant declines in native populations of Cutthroat Trout (*Oncorhynchus clarkii*) in the lake. Blue-Green Algae is also associated with the release of toxins into the aquatic environment which pose a threat to human and animal health. These blooms compromise several functions and services that Quamichan Lake provides to the community including:

- rent from fishing opportunities,
- aesthetic enhancement of the area,
- enhancement of local property value,
- cultural value to Cowichan Tribes,
- pollution remediation, and
- provision of recreational opportunities.

This report is divided into five sections. The first will provide a brief discussion of the natural history of Quamichan Lake. The second will discuss the issue of Blue-Green Algae in terms of both its global pervasiveness and its local manifestation. The third section will describe the sampling program conducted by the author and a master's student, Katie Moore (British Columbia Institute of Technology) in 2018. The purpose of the sampling program being the establishment of a baseline of ecosystem conditions and determining the causes of Blue-Green Algae blooms in Quamichan Lake. The fourth section is a description of management options that are available for remediating Blue-Green Algae in Quamichan Lake. Section four will also have an assessment of costs benefits and limitations of available management options. The fifth section will provide a roadmap for management, monitoring and research actions necessary in the next two to three years to establish a program with the greatest possible chance of remediating Blue-Green Algae blooms in Quamichan Lake.

Mitigating Blue Green Algae blooms in Quamichan Lake will likely require collaboration among several levels of government and local stewardship groups. The problem is of sufficient magnitude and complexity that no management option can guarantee effective control of Blue Green Algae blooms within a predetermined time frame. A multi-year approach will be required with the expectation that more than one type of management policy may be required as well as dedication to monitoring changes in the baseline environmental conditions to measure the success of management actions.

This report *does not* promise any certainty of outcomes.

This report *does* provide a clear understanding of the status of the Quamichan Lake and the choices available to maximise the likelihood of reducing the influence of Blue-Green Algae blooms.

Quamichan Lake Natural History

Quamichan Lake is at an elevation of about 26m (British Columbia Lake Stewardship Society 2012), on a bench of land about 6m higher than the Somenos and Cowichan Watersheds to the west and south, Figure 3. The surface area of Quamichan Lake is about 314 hectares, with a mean depth of 4.4m and a maximum depth of 8.2m (BC Fish and Wildlife Branch 1973). The lake is bordered on the east by Mount Tzouhalem, and by gently rolling hills to the north and northwest, Figure 3. The Major axis of the lake is just over 3000m long and runs southwest to northeast. For most of this axis the lake is about 1000m wide. The Quamichan watershed is part of the Coastal Douglas Fir biogeoclimatic subzone of British Columbia (Ministry of Forests, Lands, Natural Resource Operations and Rural Development 2018). This area covers most of the coastal area of Southeast Vancouver Island from Race Rocks in the South to Denman and Hornby Islands in the North. The Coastal Douglas Fir subzone is characterised by long dry summers and dominated by Douglas Fir (*Pseudotsuga menziesii*) as the climax tree species, although stands of Garry Oak (*Quercus garryana*), Big Leaf Maple (*Acer macrophyllum*) and Western Red Cedar (*Thuja plicata*) are also common (Egan and Fergusson 1999). Since colonisation of the Cowichan Valley by European settlers in the 1860s, most of the land bordering the lake has been cleared of forest and it is now largely residential and agricultural, Figure 2. Many of the residential properties in the north and east are relatively large and built with septic systems to handle domestic waste, and there are over 150 agricultural properties Crawford (2008).

Because it is relatively shallow, Quamichan Lake has complex mixing processes which are the likely mechanism enhancing Blue-Green Algae blooms in the lake. Quamichan Lake only weakly stratifies in the summer so nutrient rich deep water is regularly mixed to the surface, thus feeding the summer Blue-Green Algae blooms. Deeper lakes in southeast BC have a permanent thermocline at about 10-15m in summer at which the temperature declines by about 10 °C over 1 or 2m, *e.g.* ~14m for Cowichan Lake (Epps and Phippen 2011) and ~10 m for Elk Lake (Nordin 2015). This thermocline creates a boundary between two layers of water across which there is limited mixing. In more shallow lakes, like Somenos and Quamichan Lakes, although there is a temperature gradient from the surface to the bottom, Exhibit 1, it is not of sufficient strength to create a barrier between the surface and deeper water.

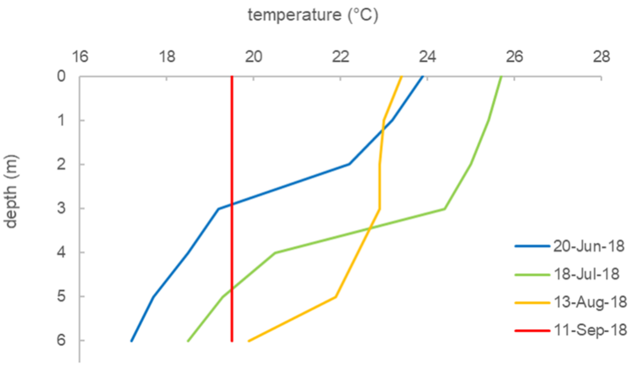


Exhibit 1: Temperature profiles for Quamichan Lake, summer 2018. Weak daily thermoclines can be seen in data collected on 18 July and 13 August. The lake temperature was completely uniform by 11 September.

Limnologists commonly refer to mixing processes in lakes as a useful way to understand their chemical and physical dynamics. The most common mixing types are:

- monomictic (mixes once per year): in summer the warm surface water is isolated from cool water at depth, in the fall the lake mixes as the surface temperature drops and increased wind promotes mixing,
- dimictic (mixes twice per year): fall mixing is followed by an ice-over, *i.e.*, surface water, <4°C, is less dense than deeper water, uniformly 4°C, which creates reverse stratification in winter, after the spring thaw, mixing occurs as surface water is heated to 4°C with summer stratification created as surface temperature rises above 4°C, and

- polymictic (mixes many times per year): insufficient gradient between temperature at the surface and at depth to prevent wind mixing, temporary and weak daily thermoclines may be established as near surface waters, *i.e.*, <5m are heated by solar radiation.

The weak summer stratification of Quamichan Lake allows nutrients to be supplied to the surface water where they are used by Blue-Green Algae. This phenomenon has been observed in hypereutrophic lakes in the Canadian Prairies of similar depth and size to Quamichan Lake (Orihel et al. 2015.)

As indicated by its persistent summer Blue-Green Algae blooms, Quamichan Lake can be classified as a eutrophic lake due to high concentrations of; chlorophyll a (> 7 µg/l), total phosphorus (>0.03 mg/l), total nitrogen (>0.5 mg/l) and Secchi disk depths less than 3m (Nordin 1985, Horne and Goldman 1994). Data from Quamichan Lake, reported in the British Columbia Environmental Monitoring System database (2019), shows that summer mean chlorophyll a concentration was 0.03 mg/l based on 15 samples collected between 2004 and 2018. Water quality data in this study shows that mean total phosphorus was about 0.3 mg/l, Figure 25, and mean total nitrogen was 1.5 mg/l, Figure 22. Secchi disk depth in Quamichan Lake was less than or equal to 3m for 10 out of 11 observations in the 2018 survey, Figure 17. Moore (2019) estimated chlorophyll a concentrations of 20-60 µg/l during blue-green algae blooms from June to August.

The increasing severity of Blue-Green Algae blooms in Quamichan Lake has put significant stress on fish populations in Quamichan Lake. In the summer, resident fish are confronted with a stark choice between near lethal temperatures and pH levels in surface waters versus hypoxia and anoxia in cooler waters at depth. Due to their ability to find refugia in shaded near shore waters, Quamichan Lake continues to support remnant populations of native fish. This phenomenon was observed by the author in summer 2015. Volunteers with the Western Bluebird Recovery Team working in the Garry Oak Preserve on the northeast shore of Quamichan Lake contacted me to inquire about fish observed in settling ponds for creeks draining Mount Tzouhalem. Upon visiting the site, I observed several dozen Cutthroat Trout in one of the small ponds about 200m from the lake. The trout apparently moved into the settling ponds during winter high water and presumably remained there after water levels had receded in the spring. The setting ponds were quite warm, T~20°C, but the fish appeared to survive and were observed on visits in subsequent weeks.

Quamichan Lake does not have any populations of anadromous salmon, but it does support a resident population of Cutthroat Trout (*Oncorhynchus clarkii*) (Burns 1999). These were known to have spawned in January in Quamichan Creek (Vernon 1951). Technicians from provincial agencies conducted general limnological surveys of the lake in 1951, 1972, 1985, and 2004. In the earliest survey (Vernon 1951) fish were sampled by gill and seine nets.

The 1951 survey identified Cutthroat Trout, Prickly Sculpin (*Cottus asper*), Threespined Stickleback (*Gasterosteus aculeatus*), and Steelhead [sic.] Trout (*Oncorhynchus mykiss*). The Steelhead Trout were more specifically identified as ‘Kamloops Trout’ and thus were likely hatchery-derived fish as described in Hayas (1942).

In the second survey (Klien and Heathman 1971) an overnight gillnet set yielded Cutthroat Trout and Brown Bullhead (*Ictalurus nebulosus*).

The third survey in 1985 (Yaworski 1986) found the same two species as the 1971 survey.

In the 2004 survey which used gillnets to sample fish, Cutthroat Trout, Sculpin and Brown Bullhead were all present in the lake (Fosker and Philp 2004). However, an invasive species, Pumpkinseed Sunfish (*Lepomis Gibbosus*) was also noted. The degree of stress on the fish community can be gauged by the relative abundances of fish species in the 2004 survey: 80% of all fish caught (700 of 871) were Pumpkinseed Sunfish. This situation matches observations made by Preikshot (2016) on the similar and nearby Somenos Lake, in which Pumpkinseed Sunfish Comprised over 80% of fish in a seine net survey.

Because Pumpkinseed Sunfish do well in relatively warm and low oxygen water, they may outcompete native species in environmentally compromised lakes (Jordan *et al.* 2009). Due to their effect as competitors for native fish, Pumpkinseed Sunfish are suspected of causing declines populations of trout and the extirpation of Threespined Sticklebacks in several lakes of Southern British Columbia (Jordan *et al.* 2009).

Another measure of the stress on the fish community of Quamichan lake can be seen in the record of hatchery enhancement. As mentioned above, hatchery trout were sporadically placed in Quamichan Lake through the 1930s and 1940s. Starting in the 1950s a regular program of enhancement with Rainbow Trout (*Oncorhynchus mykiss*) and Cutthroat Trout was started to support recreational fisheries on the lake. By the mid 1990s over 10,000 trout were being placed in the lake each year. However, by the year 2000 the number of trout annually placed in the lake began to decline. By 2017 fewer than 2000 trout were being put into the lake annually. An examination of the size of fish placed in the lake shows that during the peak of the early 1990s the fish were small yearlings intended to grow and contribute to the fishery over the course of the year. Trout placed in Quamichan lake in after 2015 tend to be larger fish (Freshwater Fisheries Society of BC 2019), presumably spent brood stock, which are not expected to survive the year in the lake. The decline in numbers of hatchery fish placed in the lake is suggests that hatchery management recognises the lack of value to anglers of enhancement efforts in Quamichan Lake.

Although Quamichan Lake is connected to the Somenos basin and the Cowichan River it does not support any populations of anadromous salmon, *i.e.*, those that migrating to the sea as juveniles (Burns 1999). The reason for this is that there is a significant waterfall on Quamichan Creek, approximately 1000 m downstream of where the creek drains the lake.

Photo 1: South shore of Quamichan Lake, 07 June 2018. An abundance of aquatic plants such as Yellow Water Lily and Cattail can be seen. Below the water surface was abundant Long-Stalked Pondweed.

Up to the 1990s Quamichan Lake supported an active year-round recreational fishery in addition to providing the region with access to other recreational aquatic activities like swimming, boating and water skiing. However, over the last 40 years the increasing frequency, duration and magnitude of Blue-Green Algae blooms have resulted in declining water quality in the lake such that a threat is now posed to both recreational activities and fish in the lake.

Several species of aquatic plant can be found in great abundance in and around Quamichan Lake including; Cattail (*Typha latifolia*), Yellow Water Lily (*Nymphaea mexicana*), Long-Stalked Pondweed (*Potamogeton praelongus*), Eurasian Water-Milfoil (*Myriophyllum spicatum*), and Duckweed (*Lemna minor*), Photo 1. All these species are recorded in early reports such as Waldichuk (1955) and Vernon (1951). The abundance of these plants gives a good indication of the high nutrient levels in the lake. Sampling of the Mouth of Quamichan Creek became increasingly difficult as the summer progressed in 2018 due to the increasing biomass of Long-Stalked Pondweed, Yellow Water Lily and Cattail.

Aquatic birds are also found in Quamichan Lake and are most numerous near the southern shore in wetland in and around Art Mann Park and the mouth of Quamichan Creek. Mallard Ducks (*Anas platyrhynchos*), American Coot (*Fulica americana*), and Canada Geese (*Branta canadensis*) are by far the most common and, depending on the availability of fish as prey, Great Blue Herons (*Ardea Herodias*), Osprey (*Pandion haliaetus*), and Bald Eagles (*Haliaeetus leucocephalus*) can also be common. In the winter, Trumpeter Swans (*Cygnus buccinator*) will forage in agricultural lands surrounding the lake. There is some concern regarding the potential role that ducks and geese may have in causing high Fecal coliform and *Escherichia coli* levels in Quamichan Lake (McPherson 2006).

The name of Quamichan Lake is derived from that of a significant Hul'q'umi'num' settlement nearby (Kwa'mutsun) (Cowichan Tribes 2008), see Photo 2. The Quamichan Somenos area supported thousands of people and the creeks, streams, lakes, wetlands and other waterways were important avenues of transportation and communication (Kulchyski pers. comm. 2019). Fish resources from the lake were important to the Cowichan people as well as aquatic and marsh plants used for medicine, food and clothing (August pers. comm. 2019). A search in Google for 'harvesting tules' (Bullrushes or Cattail) will yield several pictures, taken by the American photographer Edward Curtis, of Cowichan people harvesting, cutting and drying these aquatic plants for domestic use, see Photo 3 and 4.

In Quamichan Lake the foundation of the aquatic food web is phytoplankton. These single-celled organisms are photosynthetic and act as the food upon which small zooplankton feed which, in turn provide food for larger carnivorous zooplankton, which are preyed upon by fish. Blue-Green algae poses an obvious threat to humans in that one genus, *Microcystis sp*. can produce a liver damaging toxin. This was the cause of the mortality of dogs in Quamichan Lake in 2016 (Wilson 2016). In her thesis Moore (2019) identified 7 groups of phytoplankton in Quamichan Lake: Bacillariophyta, Charophyta, Chlorophyta Haptophyta, Cryptophyta, Cyanophyta and Dinophyta. Bacillariophyta, *i.e.*, diatoms, are usually unicellular but can also be colonial (Horne and Goldman 1994). Diatoms are the group that produces elegant silica structures within which they live and are often recognised by the lay person as 'microscopic algae'. Charophyta And Chrlorophyta are often collectively referred to as 'green algae' and a very diverse group which has many different forms including unicellular, colonial, filamentous, and flagellated (Horne and Goldman 1994). Haptophyta, commonly known as coccolithophores, are more often recognised as a marine group and have calcareous cells walls (Eikrem et al. 2017). Cryptophyta are common in lakes, typically unicellular with flagella and have cell walls made of cellulose (Hone and Goldman 1994). Cyanophyta, *i.e.* Blue-Green Algae, are very often filamentous and have a cell wall made of amino sugars and amino acids (Horne and Goldman 1994). Individual Blue-Green Algae cells are usually many times smaller than diatoms or dinoflagellates. Dinophyta, also known as Dinoflagellates, are the species commonly associated with red tides in marine areas, they always have flagella and can sometimes be found in chains. Their cell walls are often made of cellulose but can contain some silica (Horne and Goldman 1994).

In broad terms, Diatoms, Chlorophytes, and Dinoflagellates are regarded as the base of most healthy temperate lake fish ecosystems. Blue-Green algae, on the other hand have often been associated with less heathy lake ecosystems because they are hard for zooplankton to process. When in bloom, Blue-Green Algae interfere with the ability of fish predators to locate food and can clog their gills making respiration difficult. Because there are few zooplankton feeding on Blue-Green Algae they sink through the water column after they die and are consumed by heterotrophic bacteria in deeper water. The respiration by these heterotrophic bacteria can be a significant contributor to hypoxia and anoxia in deeper lake water.

Photo 2: ‘Qamūtsūn Village – Cowichan’ by the American photographer and ethnologist Edward Curtis in 1910. This photograph is in the public domain and was downloaded from the web page of the Library of Congress (2019a). The photograph shows some of the buildings in the village serving as the namesake for Quamichan Lake

Photo 3: ‘The Tule Gatherer’ by the American photographer and ethnologist Edward Curtis in 1910. This photograph is in the public domain and was downloaded from the web page of the Library of Congress (2019b). There are several pictures in this series of people engaged in the harvesting and processing of Cattail (Tule) which suggests its importance to the economy and society of the Cowichan people.

Photo 4: ‘Quamichan Lake’ by the American photographer and ethnologist Edward Curtis in 1910. This photograph is in the public domain and was downloaded from the web page of the Library of Congress (2019c). The person in the canoe appears to be near the mouth of Quamichan Creek with the picture looking northeast, along the main axis of the lake, with Mount Richards visible to the top left. The dense stands of Cattail in this image are similar to those of the present. Other photographs in this series show Yellow Water Lily growing in abundance.

Blue Green Algae Blooms

Blue Green Algae blooms are an increasing problem all over the world. As discussed above, the primary mechanism causing these blooms is excess phosphorus in aquatic environments. While many lakes are naturally high in nutrients, it is additions from agricultural fertilizers, eroded soil from deforested land, and runoff from urban areas that create the near universal high phosphorus levels around the world (Fink *et al.* 2017). Fink *et al.* (2017) reviewed phosphorus data from the 100 largest lakes in the world and found that human derived phosphorus accounted for more than 70% of all phosphorus going into lakes. Moreover, they observed that in most of these lakes' phosphorus loading had accelerated between the 1990s and 2000s.

In the Vicinity of Quamichan Lake phosphorus loading has coincided with Blue-Green Algae blooms on Elk Lake near Victoria (Nordin 2015), St Mary's Lake on Saltspring Island (Ashley 2007, Rieberger 1992), Somenos Lake (Preikshot 2016), and Burnaby Lake on the Lower Mainland.

High summer phosphorous concentrations in Quamichan Lake explains the now regular, severe, blooms of potentially toxic Blue-Green Algae. When phosphorous is at relatively high concentration relative to nitrogen, Blue-Green Algae, can outcompete other phytoplankton species for nutrients resulting in a Blue-Green Algae bloom. This 'classical' model of phosphate driven Blue-Green Algae blooms has been challenged by some research which indicates that in some cases Nitrogen may also be an important contributor to Blue Green Algae blooms (Dolman *et al.* 2012). The characteristic evidence of these blooms is thick mats of bright green biological material accumulating on the lake surface as well as greatly elevated surface water temperature and anoxia at depth.

This unpleasant combination of factors is a consequence of the inability of most organisms, *e.g.*, zooplankton, insects or benthic invertebrates, to exploit Blue-Green Algae as a food resource. The fast growing and dying Blue-Green Algae sink through the water column are chiefly consumed by heterotrophic bacteria. The resulting respiration by heterotrophic bacteria depletes oxygen in the lake often resulting in anoxia near the bottom. This anoxia near the sediment can release phosphorus that has been bound to metals such as iron (Orihel *et al.* 2017). In shallow lakes such as Quamichan Lake which are only weakly stratified in the summer this release of phosphorus from the sediment acts as a nutrient pump delivering phosphorus to the Blue-Green Algae at the lake surface (Orihel *et al.* 2015). When the lake is oxygenated, the phosphate becomes bound to metal ions in the water, which then settles on the bottom rendering the phosphate unavailable to Blue-Green Algae near the sunlit surface.

Thus, anoxia caused by bacterial consumption of dead Blue-Green Algae cells creates the chemical pathway that provides the nutrients to fuel the continuation of the Blue-Green Algae bloom. Extremely high concentrations of phosphate are created as phosphate accumulates in many urban and suburban lakes. This 'internal loading' is the chief source of fuel for the Blue-Green Algae blooms, not the relatively small incremental additions from outside the lake. This 'internal loading' phenomenon has been observed in several other low elevation lakes in and around Southeast Vancouver Island, *e.g.*, St. Mary Lake, Prospect, Langford, Swan, Florence, Glen, Quesnel, and Elk Lake (Nordin 2015) and at the nearby Somenos Lake (Preikshot 2016). The incidence of such Blue-Green Algae blooms is increasing in many lake environments near cities and farms (Fink *et al.* 2017).

As many high latitude areas, like Canada, experience longer and warmer summers associated with climate change, the strength, duration and frequency of Blue-Green Algae blooms are likely to increase (Jankowiak *et al.* 2019). There is ample evidence from data collected in and around the Cowichan Valley that over the last 50 years the area has experienced summers of increasing heat, and increasing length with less available water. Figure 6 shows that since the 1950s there has been about a 60% decline in discharge measured at Bings Creek in August from about 0.031 m^3/s to 0.013 m^3/s. This decline is not unique to Bings Creek and similar trends exist for the Cowichan, Nanaimo and Chemainus Rivers. An examination of temperature data collected at Nanaimo airport, Figure 7, shows that there has been a steady increase in mean July and August daily air temperature and that the average from 2010-2017 was

2ºC warmer than the period from 1950-1969. The longer period of the summer dry season can be seen in Figure 8 which shows annual changes in time between first significant rainfall in the fall and the last significant rainfall in the spring. The proxy for dry season was changes in discharge observed in the Cowichan River. In the mid 1980s there appears to have been an increase in the length dry seasons to three weeks longer than the historic mean. In the last eight years the length of the summer dry season is now four weeks longer than historic values. Given these trends in the Cowichan area it is likely that climate conditions for the foreseeable future will foster Blue-Green Algae blooms of greater strength and duration.

Although eutrophication and phosphorus loading in Quamichan Lake appear to have been increasing between the early 1990s and the present, (McPherson 2005 and Crawford 2008) Blue-Green Algae blooms appear to have occurred further back in history than previously thought. In her review of nutrient changes in Quamichan Lake between 1950 and 2005 McPherson (2005) reported that provincial reconnaissance surveys, *e.g.*, Vernon (1951), Klien and Heathman (1971), and Yaworski (1986) reported Blue-Green Algae blooms as being typical for the lake. However, a report from Waldichuk (1955) indicates that persistent and intense Blue-Green Algae blooms can be identified from even earlier research.

All information in the subsequent paragraph is derived from Waldichuk's 1955 report. Biologists at the Pacific Biological Station, then part of the Fisheries Research Board of Canada, were contacted by engineering staff from H.A. Simons, Ltd., who had been contracted to build the Crofton pulp mill. They were enquiring as to the suitability of Quamichan Lake to act as a settling pond for highly sedimented water pumped from the Cowichan River before being sent to the proposed mill. The opinion of Pacific Biological Station Staff was "…that profuse growths of blue-green algae would interfere with the water quality and probably clog the lines." Waldichuk also quotes M. Mottley and C. Carl who had surveyed Quamichan Lake in summer 1935 and reported that:

> At the time of the investigation a water bloom was present on Lake Quamichan. In the morning before the breeze disturbed the water the bloom appeared as a slimy yellow-green scum floating on the surface of the lake. Later in the day the organisms making up the bloom became distributed in the upper two-meter layer of water giving it a very turbid appearance. Examination of plankton samples showed that the dominant forms were two species of the blue-green alga, Microcystis.

The condition described above would be familiar to any observer of Quamichan Lake during recent summers. Waldichuk describes a fish kill in 1945 in which birds and mammals were also found to have succumbed. At the time of the 1945 mortality event surface temperature was about 27°C and the pH was 9.9, while at the bottom of the lake, the oxygen concentration was zero. Waldichuk notes that this was not an uncommon phenomenon because:

> …the artificial propagation of game fishes in the lake has not been too successful. Local anglers fishing in Quamichan Lake claimed, during the period of investigation in 1933 that they were not getting adequate returns from the plantings [of hatchery fish]."

Waldichuk concludes that the frequent blooms of Blue-Green Algae were the mechanism driving high hatchery fish mortality. Waldichuk inferred that nutrients from the agricultural land surrounding Quamichan Lake were the likely cause of the observed Blu-Green Algae blooms. The report suggests that, if Quamichan Lake was used as a settling pond for Cowichan River water destined for the pulp mill, flushing of the lake would likely significantly reduce phosphorus levels, by flushing and dilution and presumably help control algae blooms.

A few years after Waldichuk's report, another fish kill was noted by an anonymous representative from the British Columbia Game and Fish Culture Branch (Anon. 1958). In the report, dated 07 August 1958, the author notes a surface temperature of 23°C, and abundant algae making the water very turbid. Interestingly, the author reports that locals could not recall a similar such event in the past, a claim which appears to be gainsaid by evidence presented in Waldichuk (1955). It seems likely, therefore, that there was little or no communication between representatives of the federal and provincial agencies responsible for fish and aquatic ecosystems.

Exhibit 2: A comparison of surface (S) and deep (D) water quality parameters reported by Yaworski (1986) for 02 July 1985 versus averages for 20 June 2018 and 18 July 2018 from this study. Measurements that degraded over time are highlighted in yellow.

	(S) 1985	(S) 2018	(D) 1985	(D) 2018
T (ºC)	21.500	24.800	19.500	17.850
D.O (mg/l)	10.000	11.020	6.500	0.170
Conductance (µS/cm)	123.000	201.550	130.000	213.500
pH	8.000	9.445	7.400	7.635
total N (mg/l)	0.600	1.120	0.580	1.480
total NH3 (mg/l)	0.036	0.011	0.224	0.288
total NO2+NO3 (mg/l)	<0.020	0.000	<0.020	0.004
Total P (mg/l)	0.034	0.260	0.121	0.374

It is unfortunate that no representatives of any federal or provincial agency undertook a formal study of environmental conditions in Quamichan lake after these early indications of environmental stress. It would not be until the survey of 1985 (Yaworski 1986) that a serious attempt was made to measure water quality parameters in the lake. Yaworski (1986) made water quality observations at the lake surface and 6.5 m on 02 July 1985. Comparison of his observations with the mean of observations on 20 June 2018 and 18 July 2018, in this report, indicate that water quality has declined for most variables, see Exhibit 2. When comparing 2018 data to that collected in 1985, there has been a dramatic decline both at the surface and at depth for most water quality parameters. This overall trend is a continuation of degrading water quality, in general, and increasing nutrient concentrations reported by McPherson (2006).

The scarcity of quantitative water quality data before the 1980s makes it difficult to gauge how the lake has changed over the last 90 years. As discussed above, Waldichuk (1955) suggests that temperature, pH and Oxygen conditions at the surface and at depth were comparable to values observed today. What remains unreported are the nutrient concentrations that were associated with those conditions and the duration of the summer Blue-Green Algae bloom. This is a significant problem because any management plan to remediate nutrients and Blue-Green Algae blooms in Quamichan Lake needs to establish a target. If we were to use the available historic records for establishing an ecosystem baseline it may be difficult to argue that restoration of Quamichan Lake water quality necessarily equates to total elimination of Blue-Green Algae blooms if they are, in fact, a pre-existing condition of the Lake.

It can be logically inferred that agricultural practices and local urban development had already contributed sufficient nutrients to the lake to make Blue-Green Algae bloom an ecosystem management problem by the 1930s. By 1935 intensive agriculture had been underway in the watershed for more than 50 years and this was hypothesised by Waldichuk (1955) as a major source to nutrient enrichment for the lake. It is also likely that deforestation of the surrounding area liberated significant quantities of nutrients through erosion of exposed land into Quamichan Lake, see *e.g.*, Dittrich *et al.* (2013) and Evans *et al.* (1994) who discuss the combination of deforestation, agriculture, and urban development generated excess phosphorus in Lake Simcoe.

2018 Water Quality Sampling Program Design, Results, and Discussion

Sampling Program Design

The 2018 water quality sampling had two major components: sampling for physical parameters, *in situ*, and sampling for nutrients by sending samples to an environmental laboratory for analysis. Although it had been the desire of the Quamichan Lake Water Quality Task Force to sample input streams throughout the summer, a reconnaissance survey by the author in April 2018 suggested that few of the input streams were connected to the lake by overland flow by late spring. Indeed, it has been reported by other surveys that there is effectively no surface flow to the lake from its tributary creeks and streams through the summer (Crawford 2008, McPherson 2006, and Vernon 1951). This was observed to be the case during repeated visits to streams and creeks between May 2018 and September 2018 when the bulk of water quality sampling occurred. The outlet of the lake at the head of Quamichan Creek was also sampled but the creek ceased to flow in early June so that station effectively became a lake surface replicate.

Exhibit 3: Sampling stations for the Quamichan Lake Water Quality survey. An X indicates if the station was sampled on a given day.

	Creek Stations				**Lake Stations**			
	Aitken	**Deykin**	**Quamichan**	**Woodgrove**	**North 0M**	**North 5m**	**South 0m**	**South 5m**
11-Apr			X		X			
03-May			X		X			
09-May			X		X	X	X	X
23-May			X		X	X	X	X
07-Jun			X		X	X	X	X
20-Jun			X		X	X	X	X
18-Jul	X	X	X	X	X	X	X	X
25-Jul		X	X	X	X	X	X	X
13-Aug	X	X	X	X	X	X	X	X
23-Aug	X	X	X	X	X	X	X	X
11-Sep	X	X	X	X	X	X	X	X
24-Sep	X	X	X	X	X	X	X	X
09-Nov	X	X	X	X	X	X	X	X

In order to compare nutrient inputs from local streams, at present, to historic input, 9 local stream and ditches flowing to the lake were sampled in December 2018.The focus of this report will be results from 4 sampling locations on the lake and four sampling locations on streams (regardless of connectivity to the lake), see Exhibit 3.

For the stations noted in Exhibit 3 we collected physical data on temperature, dissolved oxygen, pH, and specific conductance. The physical measurements from creeks are not reported in detail here as they were all well within water quality guidelines. Data for physical parameters from creek sites can be seen in Table 12. For physical measurements we used a YSI multiparameter water quality meter. The device was provided, on loan, by the Somenos Marsh Wildlife Society. Stations when visited were sampled for the following nutrient data: total alkalinity, total ammonia, nitrate, nitrite, total nitrogen, dissolved orthophosphate, total dissolved phosphorus, and total phosphorus. Sample jars were put on ice and shipped overnight in a cooler. Nutrient analyses were provided by ALS Environmental Laboratory in Burnaby. Secchi Disk depths were also recorded at the north lake site to measure turbidity.

For the stream input sampling in December, data was collected for nutrients and was also analysed for 40 elements including metals, *e.g.*, iron, magnesium, calcium, sodium and aluminium, and non-metals, *e.g.*, silicon and sulfur. Sample jars were put on ice and shipped overnight in a cooler. Nutrient and metal analyses were provided by ALS Environmental Laboratory in Burnaby.

Physical Sampling Results

Temperature

As one might expect, the spring to fall cycle of lake temperatures starts low, peaks in mid-summer and declines with the approach of winter. The timing of peak temperatures does vary by depth, with peak temperature from the surface to 3m seen in mid July. Temperatures between 4m and 6m, however, peaked a month later in late August. These differences in heating suggest that the lake was developing weak daily thermoclines which are apparent in the separation of near surface water, ≤3m, temperatures from those at depths ≥4m near late June. Data collected earlier than 20 June show only small differences between temperature at the surface and temperature at depth, Figure 9. By September 11 the lake had returned to a state where there was little or no difference between surface temperature and that at depth causing the lake to enter a state of constant mixing. Peak temperature was just over 25 for both sites at the surface though the absolute highest temperature was 18 July 18 for the north site and 25 July for the south site. The difference in temperature at either site on both days was less than 0.5°C. A correlation analysis of all temperature data at all dates and depths at both sites suggests that there is very little difference in these two portions of the lake, Figure 10. When comparing temperature data for the two sites a derived linear relationship indicates that the north site was about 0.4°C warmer at all times (r^2=0.97) and depths on a given day. The exceptionally high correlation between the two suggests that almost all the variation in on can be explained by the other.

Dissolved Oxygen

Dissolved data from the two lake sites suggest that hypoxia at depth had already commenced by the end of May with a value of 0.5 mg/l observed at 5m at the north site on 23 May, Figure 11. Although oxygen concentration at the surface was initially high in the summer, by 11 September it had dropped to 5 mg/l. At both sites anoxia had shoaled to 4m depth by 25 July, coincidental with the timing of maximum surface temperature. Water shallower than 4m generally had dissolved oxygen concentrations of ≥5mg/l throughout the summer. From 11 September onwards oxygen was uniform through all depths as the lake was continuously mixing. The relationship between oxygen concentrations at the north and south lake sites was somewhat weaker than that for oxygen. However, the correlation between the two was still quite high, r^2=0.77, Figure 12.

Specific Conductivity

Specific conductivity measures ions dissolved in the water. On most sampling days specific conductivity was observed to have far less variation through the water column than other water quality parameters. The greatest variation occurred on 25 July, 13 August and 23 August when specific conductivity was much higher, more than 10% higher, at 6m than other depths, Figure 13. The peak value for specific conductivity, ~220 µS/cm, occurred on 18 July, as with the timing of the highest observed surface temperature. By the end of the time series, specific conductivity had returned to values like those observed in spring. As with temperature there was a tight relationship between specific conductivity measurements at north and south lake sites, r^2=0.97, Figure 14.

pH

Measurements of pH suggest a cycle at the surface similar to that of temperature over the progression of the year from spring to fall. Surface pH was uniformly higher than 9 for water shallower than 2m between 20 June and 13 August. An early spike in pH can be seen for the first sample on 09 May when the north lake surface and 5m samples both had a pH ≥10, Figure 15. For most samples, pH tended to be alkaline, *i.e.*, high, at the surface and declined with depth to near neutral, *i.e.*, pH=7 near the bottom. There were some days when the peak pH was at 1m or 2m depth. As with the other physical variables, once the lake became thermally uniform from top to bottom, on 11 September, pH was the same at all depths. The relationship between pH measured at the north and south sites was very close, r^2=0.93, Figure 16.

Secchi Disk

Secchi Disk depth was recorded only at the north lake station. Given the close relationship between other physical variables between north and south lake sites, it is unlikely significant differences would have been observed for water clarity between the two stations. Similar to pH, there was a noticeable difference between the Secchi Disk depth recorded on 09 May, 1.1m and the subsequent two sampling events, 23 May and 17 June when Secchi Disk depth was observed to be ≥3m. The minimum Secchi Disk depth was observed on 13 August at 0.3m. By the time of the last sample, 09 November Secchi Disk depth had increased to 1.5m, Figure 17.

Nutrient Sampling

Alkalinity

Alkalinity as indicated by calcium carbonate was higher at creek sites than lake sites, Figure 18 but this was not reflective of higher pH, Table 12. The highest Calcium carbonate measurements were in Woodgrove Creek. For all nutrients examined, the data from Quamichan Creek was more similar to data from the lake north and lake south surface stations than it was to data from tributary creeks.

Ammonia

Ammonia was higher in lake stations than it was in the creek, Figure 19. At lake sites the ammonia was almost always greater at the 5m depth station than it was at the surface. Peak values for ammonia were at the 5m stations on 23 August.

Nitrate

Nitrate tended to be higher at inflow creek sites than lake sites, Figure 20. The highest value for Nitrate in the lake was at the start of sampling on 09 May. For most of the lake samples the measured nitrate was below the detection limit of the lab equipment. Nitrate measured in Aitken Creek was uniformly high through the summer

Nitrite

Nitrite was usually higher in tributary stream sites than lake sites for all sampling dates, Figure 21. In the lake, nitrite was observed to rapidly decline at the start of the summer and was below detection limit from 18 July to 23 August.

Total Nitrogen

This is a measure of all nitrogen in the water, including non biologically available nitrogen. Total nitrogen in the lake tended to be higher than values observed from creek sites, Figure 22. Total nitrogen in the lake tended to increase through the summer and then dropped in the last sample taken on 09 November.

Dissolved Orthophosphate

Throughout the samples, dissolved orthophosphate, *i.e.*, the organically available form of phosphorus, was higher in lake samples than those from tributary creeks. Dissolved orthophosphate in the lake appears to gradually increase through the summer at all stations. Over the summer, orthophosphate at lake surface stations began at about 0.1mg/l in May and was over 0.2mg/l by the end of August. At deep stations dissolved orthophosphate was about 0.2 mg/l at the start of June and over 0.3 mg/l in mid August. At tributary streams values ranged from 0.007 to 0.04 mg/l, Figure 23. During stream sampling in December, concentrations of dissolved orthophosphate were quite high in Stamps Road ditch (0.64 mg/l), McIntyre Creek (0.28 mg/l), and Martin Place ditch (0.06 mg/l), Table 12.

Dissolved Phosphorus

Patterns of seasonal change for dissolved phosphorus were very similar to those for dissolved orthophosphate and Lake stations were always higher than tributary creek stations, Figure 24. Dissolved phosphorus was usually about 10-25% larger than dissolved orthophosphate and the correlation between the two variables in lake samples was very high, r^2=0.93, Figure 26.

Total Phosphorus

Total phosphorus accounts for bioavailable and non-bioavailable phosphorus whether dissolved or suspended. Therefore, total phosphorus numbers were always higher than observations for dissolved phosphorus or dissolved orthophosphate at all stations, Figure 25. The correlation between total phosphorus and total dissolved orthophosphate was quite high, r^2=0.71, Figure 25. The sample on 13 August was anomalously higher than any other samples and was a clear outlier from the relationship suggested by the correlation. Removal of the 13 August data point from the correlation improves the estimated r^2 from 0.05 to 0.71 As with other forms of phosphorus sampled at lake sites, values measured at 5m were consistently higher than values observed at the surface. Concentration of total phosphorus in the lake increased during the summer and declined after late August. Total phosphorus measured in tributary streams was quite variable in the summer. Total phosphorus measured in streams in December was an order of magnitude higher at the Stamps Road Ditch and Mcintyre Creek than it was at any other site, Table 12

Discussion

General Observations

The decision to sample Quamichan Lake at two sites was made in order to discount the possibility of divergent physical and nutrient dynamics in different parts of the lake. Results from both the physical and nutrient sampling in this study indicate that there was little difference between data from the two sites. The tendency for temperature to be about 0.4°C at the north lake site, may simply be a consequence of the sampling schedule. On most days the south lake site was visited first, usually 45-60 minutes prior to the north lake site. During this time delay it is likely that solar radiation had simply heated the water by the observed difference. For future monitoring work it will only be necessary to have one lake sampling station. Results from future monitoring activities at one station will be congruent with results from this, and previous, surveys which have occurred at both the north and south lake sites. For analysing data sets in future, it should be possible to pool data from both sites to generate a more robust data set.

Temperature data demonstrates that deeper water is prevented from creating a trout refuge during the summer due to hypoxia and anoxia at depth. Hypoxia and anoxia below 4m for much of the summer would preclude trout from using deeper lake water as habitat when high pH and temperature at the surface would preclude the use of shallow water as habitat (Carter 2005a and 2005b). Even at the surface, dissolved oxygen had declined to 5 mg/l by the end of the summer, the lower limit for trout and salmon. The low dissolved oxygen at the end of summer appears to be a product of mixing hypoxic water from ≥5m with weakly oxygenated water closed to the surface.

Although algae appeared to be in abundance as early as 09 May, as evidenced by the high observed pH, ~9, and shallow Secchi Disk depth, ~1 m, the largest biomass of phytoplankton at the time was actually a Green Algae-Charophyta, not Blue-Green Algae (Moore 2019). Persistent and high pH, ≥ 9, was also associated with the longer bloom observed first in sampling on 20 June and last in sampling on 13 August. This longer bloom was associated with relatively larger numbers and biomass of Blue-Green Algae than other groups of Algae (Moore 2019). High environmental pH of 9-10 causes ammonium (NH_4^+), which is harmless to most aquatic organisms, to be converted to unionised ammonia (NH_3) which is quite harmful to many aquatic organisms. At temperature and pH conditions observed between 20 June and 13 August more than 50% of ammonia near the surface would be in the unionised form (Emmerson et al. 1975).

While Blue-Green Algae were almost always the numerically dominant group in the phytoplankton community during the 2018 sampling period (Moore 2019) it was not necessarily the dominant species by volume or mass. For example, the first observed algae bloom on 09 May was made up of mostly of Blue-Green Algae by number, but in terms of volume, Chlorophytes were a far larger portion of the phytoplankton community biomass (Moore 2019). In the samples take on 20 June, 18 July, 25 July, and 13 August, Blue-Green Algae were dominant both numerically and by biomass (Moore 2019). In the sample from 13 August, Moore (2019) estimated more than a billion Blue-Green Algae cells per liter. Note that there are also abundant coliforms found in Quamichan Lake (Preikshot 2018) so the number of bacterial particles in the water was likely even larger. Given the previously stated dire physical and chemical characteristics of the lake it is easy to see how fish were placed in a precarious state when forced to respire water with such density of bacterial particles.

The fish kill on 13 August was associated with the shallowest observed Secchi Disk depth. For fish in near surface water, ≤ 4 m, the tremendous number of Blue-Green Algae cells suspended in the near surface water combined with high temperature, ≥ 23°C, and high pH, ≥ 9, likely acted together to yield the fish mortality event. The suspended Blue-Green Algae cells would have made respiration difficult for fish by clogging their gills and reducing their capacity to locate and process prey items. Fish attempting to escape these near surface water, ≤ 4 m, conditions by moving to deeper water would have been confronted with anoxia below 4 m.

Exhibit 4: Estimated volume of Quamichan Lake and Quamichan Lake depth intervals. The area of each lake depth interval was estimated by using SketchAndCalc^{tm} (2019) to estimate perimeters and areas. Data for depth intervals was derived from the 1972 bathymetry chart (BC Fish and Wildlife Branch 1973).

interval	**depth (m)**	**area (ha)**	**vol (m^3)**	**CuVol (m^3)**	**vol (l)**	**CuVol (l)**	**CuVol (ft^3)**
0m-2.5m	2.5	276.9	6.923E+06	6.923E+06	6.923E+09	6.923E+09	244,364,250
2.5m-5m	2.5	207.8	5.195E+06	1.212E+07	5.195E+09	1.212E+10	427,747,750
5.0m-7.0m	2	182.9	3.658E+06	1.578E+07	3.658E+09	1.578E+10	556,875,150
7.0m-8.5m	1.5	137.9	2.069E+06	1.784E+07	2.069E+09	1.784E+10	629,893,200
8.5m-9.5m	1	40.9	4.090E+05	1.825E+07	4.090E+08	1.825E+10	644,330,900

The overall similarity of physical and nutrient data collected at the Quamichan Creek site to data collected at the surface at the north and south lake sites, suggests the Quamichan 'Creek' data is more appropriately understood as a lake surface station. It was well known before this study that Quamichan Creek ceased to flow in the summer, (Crawford, 2008, Burns 1999, Vernon 1951). Given the climate change effects observed elsewhere in the Cowichan Valley, Figures 6, 7, and 8, it is very likely that the duration of the dry period in Quamichan Lake has extended to a longer period than was true even 10 years ago. Given estimated surface water input, Crawford (2008) calculated that Quamichan Lake is flushed about once every 1.02 years. Waldichuk (1955) suggested that a benefit of using Quamichan Lake as a sediment setting area would be that given an estimated inflow of 39.6 ft^3/s, 1.12 m^3/s that the flushing rate of the lake could be improved to once every 146 days, *i.e.*, 2.5 times per year.

Both estimations, of flushing and potential flushing, were made with a very rough derivation of lake volume. Waldichuk (1955) simply multiplied area by average depth and calculated a volume of 497 million cubic feet, ~14 million cubic meters. The value used by Crawford (2008) was similar, 13.8 million cubic meters. However, using a bathymetric chart I estimate Quamichan lake volume to be about 18.3 million cubic meters, *i.e.*, about 30% more water than the original estimate. If the volume estimate in this study is correct there will need to be a reassessment of the rate at which Quamichan Lake is flushed. If the volume calculated here is correct, its is likely that the rate of lake flushing may be about one third longer than previously estimated. If it is also true that there is more evaporation from the lake and less inflow of water due to climate change effects, the flushing rate may be slower still.

Nutrient Dynamics

Most of the nitrogen available to plants and algae during summer 2018 in Quamichan Lake appears to have been in the form of ammonium/ammonia. Concentrations at the surface during the height of the bloom were always lower indicating consumption by Blue-Green Algae. However, mixing of nutrient rich deeper water throughout the summer was likely pumping nitrogen and phosphorus into near surface water allowing blooms to continue. The shallow Secchi Disk depths during the height of the Blue-Green Algae bloom suggests that photosynthesis and growth was probably restricted to the upper two meters of the water column which is coincidental with the timing and depth of the high pH levels in the lake

When examining whether the nutrient of concern is Nitrogen, Phosphorus or both we must answer the question of which is more likely to be a limiting factor in the lake. Classically this is done by examining the ratio of one to the other in near surface waters. Nordin (1985) suggest that a nitrogen to phosphorus ratio of less than 5 to one, *i.e.*, N:P < 5 is indicative of nitrogen limitation, whereas N:P >15 suggests phosphorus limitation. This can be done either by measuring the total nitrogen to total phosphorus ratio of the ratio of bioavailable nitrogen (nitrate NO_3, nitriteNO_2 and ammonia NH_3) to bioavailable phosphorus (phosphate PO_4). In her review of water quality from the 1980s to the 2000s in Quamichan Lake, McPherson (2006) found phosphorus to be the limiting nutrient in 80% of all samples. When her analysis was restricted to bioavailable forms of nitrogen, 93% of samples showed that nitrogen was the limiting nutrient. This is crucial to determining the make up of the phytoplankton community because Blue-Green Algae can fix nitrogen from atmospheric nitrogen and so they have a competitive advantage over other phytoplankton species in Nitrogen limited environments (Shatwell and Köhler 2019,). There is also evidence that some cases low N:P ratios may also be associated with higher concentrations of hepatotoxic *Myocystis sp.* (Orihel et al. 2015). Data from the monitoring work in 2018 shows that Quamichan Lake was nitrogen limited less than half the time when comparing total nitrogen to total phosphorus. In 24 samples taken from the north and south lake surface stations the mean total N: total P ratio was 5.6 with a maximum of 14.4 and a minimum of 3.9. When only bio-available forms of nitrogen and phosphorus were considered, a different conclusion is suggested. In 24 samples taken from the north and south lake surface stations the mean bio-available N: bio-available P ratio was 0.9 with a maximum of 2.9 and a minimum of 0. The latter conclusion is more likely to be representative of the situation in Quamichan Lake given the dominance of Blue-Green Algae in the phytoplankton community and was also the conclusion of an analysis of this data by Moore (2019).

Exhibit 5: Estimated phosphorus loading based on data collected in 2018. Base phosphorus was estimated using total phosphorus on 11 April at the north lake site. The low loading estimate is derived from data collected at the Lake North site and the high loading estimate from lake south site data on 23 August. The total phosphorus measured in the surface sample was used to estimate phosphorus mass in 0-5m strata and the 5m sample was used to estimate phosphorus mass for water deeper than 5m.

interval	vol (l)	CuVol (l)	P mg/l early	mass P (kg) spring	P (mg/l) late low	P Summer (low)	P mg/l high	P Summer (high)
0m-2.5m	6.923E+09	6.923E+09	0.222	1,536.80	0.301	2,083.67	0.296	2,049.06
2.5m-5m	5.195E+09	1.212E+10	0.222	1,153.29	0.301	1,563.70	0.296	1,537.72
5.0m-7.0m	3.658E+09	1.578E+10	0.222	812.08	0.372	1,360.78	0.523	1,913.13
7.0m-8.5m	2.069E+09	1.784E+10	0.222	459.21	0.372	769.48	0.523	1,081.83
8.5m-9.5m	4.090E+08	1.825E+10	0.222	90.80	0.372	152.15	0.523	213.91
			total	4,052.17		5,929.77		6,795.65
			loading			**1,878**		**2,743**

Given that nitrogen appears to be the limiting nutrient the controlling Blue-Green Algae blooms will likely require controlling phosphorus in the lake. There are two potential sources of phosphorus:

- built-up reserves in the lake sediment which get resuspended during deep water anoxia in the summer (see above) and
- run-off from land surrounding the lake (see above)

A determination of the relative contribution of each of these sources is critical in formulating a realistic management program. While there can be no doubt that controlling phosphorus moving to the lake from surrounding lands will be an important part of a long-term management program, this study suggests that internal loading is by far the largest source of phosphorus available to Blue-Green Algae in the lake. Although previous work by Crawford (2006) suggested that internal loading was responsible for only 20%-50% of all phosphorus in Quamichan Lake, estimations based on data from the 2018 survey show that internal loading likely contributes more than 90% of phosphorus entering the lake in the summer. Using methodology described by Nordin (2015) and McKean (1992), I estimated the mass of internally loaded phosphorus in Quamichan Lake as the difference between mass of phosphorus at the end of summer versus the mass of phosphorus in the lake at the start of before summer, see Exhibit 5.

Exhibit 6: Estimated phosphorus budget for Quamichan Lake by Crawford (2006)

	min (kg)	mean (kg)	max (kg)
Agricultural/Rural	43.9	133.4	299.5
Residential	20.8	55.3	120
Atmosphere	49.8	49.8	49.8
Total Inflow	114.5	238.5	469.3
Internal Loading Crawford (2006)	121.1		121.1
Internal Loading Preikshot (2018)	1877.6		2743.5

Crawford (2006) estimated that internal loading contributed only about 121 kg of phosphorus to the lake and did not estimate a low or high range. She further estimated agricultural run-off at 44-300 kg per year, residential as 21-120 kg per year and atmospheric input as 50 kg per year, Exhibit 6. Using these values, internal load only accounts for about 25% to 50% of phosphorus in the lake. A closer look at assumptions underlying those internal loading estimates suggests that the volume of water used to estimate phosphorus in the lake was too small, see discussion above. The low estimate of lake volume at deeper strata would explain the relatively modest estimate for internal loading by Crawford (2006). Given that the total phosphorus measured in the streams and ditches in December 2018, Table 12, was very similar to values measured by Crawford (2006), see her Figure 2, and that her estimates of discharge were derived from provincial data, I assume that her estimates for total phosphorus input remain applicable today. Note that Crawford (2006) does not account for ground water, although this may be a significant source of both nutrients and water in the lake over the summer. Thus, in order to estimate the contribution of internal loading to total phosphorus loading I used:

- the low and high range estimates for internal loading of phosphorus from lake sediments in Exhibit 5 and
- the high range of phosphorus input estimated by Crawford (2006), Exhibit 6.

Using this range for low and high internal loading I estimate that between 80% and 85% of total phosphorus in Quamichan Lake is internally derived during the summer. Therefore, controlling phosphorus in Quamichan Lake will not be possible without first addressing the massive and significant storehouse of phosphorus in the lakebed. This issue is even more proximate given that there is no detectable movement of surface water into or out of the lake between May and September.

Assessing Management Options

Exhibit 7: Cost estimates for water quality monitoring options in Quamichan Lake. Estimates are based on costs incurred by this monitoring program and from costs incurred in monitoring Water Quality on Somenos Lake (Preikshot 2016).

item	details	cost estimate
temperature data logger array	hourly monitor temperature at 0,3 and 6m two loggers at each depth	$ 2,600.00
dissolved oxygen data logger array	hourly monitor oxygen at 0,3 and 6m one logger at each depth	$ 6,000.00
water quality multi parameter sonde (A)	weekly monitor T, D.O. pH, conductivity, turbidity	$ 5,000.00
water quality multi parameter sonde (B)	weekly monitor T, D.O. pH, turbidity, option available for nitrogen species, chlorophyll a and Blue-Green Algae	$ 10,000.00
lake/ stream nutrient monitoring	monthly at one lake station (0m, 3m, 6m), and at first flush and late spring on late spring at ~12 ditch/stream sites	$ 10,000.00

Understanding how and when phosphorus accumulated in Quamichan Lake is crucial to establishing a management goals for controlling phosphorus and Blue-Green Algae blooms. Given our present knowledge of baseline ecosystem conditions, *i.e.*, before European settlement, it is impossible to state whether Quamichan lake was susceptible to Blue-Green Algae blooms in its natural state. This knowledge is important for credibly defining management targets because stake holders will want to know if the natural state of Quamichan Lake is:

- more like conditions described by Waldichuk (1955) (Scenario A) OR,
- before colonisation, there was no significant Blue-Green Algae blooms (Scenario B).

There are two potential overall management goals to choose from:

- remediate Quamichan Lake such that Blue Green Algae blooms are reduced to relatively short durations with fish kills recorded every few years (Goal A) OR
- remediate Quamichan Lake such that Blue-Green Algae blooms are almost entirely eradicated (Goal B).

Upon establishment of a Quamichan Lake Water Quality Management Committee there will be an immediate requirement to decide whether it wants to adopt Goal A or B. The choice of whether Goal B is even attainable is contingent on establishing whether Scenario A or B is the actual pre-existing condition of Quamichan Lake. Therefore, in order establish an achievable and realistic management goal for mitigating Blue Green Algae blooms in Quamichan Lake there should be a survey with sediment coring of lake sediments to determine the historic timing and scale of nutrient additions. Sediment cores will also be crucial in determining the exact amount of phosphorus loading to the water column that needs to me mitigated. Many of the proposed management options will cost hundreds of thousands to millions of dollars. Establishing a higher degree of certainty of the total phosphorus present will likely save hundreds of thousands of dollars versus adopting risk-averse management actions which may be overly robust for actual requirements.

Despite this gap in knowledge about Quamichan Lake sediments, a high probability exists that management actions can be implemented that will limit, or curtail, Blue-Green Algae blooms in Quamichan Lake. Developing the best chance of success in choosing management policies will rely on high quality field data on which to judge choices open for consideration. An informative management program would be similar (but augmented) to the plan used for assessing water quality and fish habitat at Somenos Lake (Preikshot 2016). Monitoring the nutrient and physical parameters analysed in this report should continue. Data logger arrays should be installed in the lake in order to monitor hourly changes in temperature and dissolved oxygen. Once management options are enacted lake sensors will allow for a high-resolution image of the success or failure of those policies. Monthly monitoring of nutrients needs to be conducted on the lake in order to determine progress in controlling nutrients in general and phosphorus, in particular, both as inputs to the lake and in terms of absolute amount in the lake itself. Cost estimates for the monitoring work are seen in Exhibit 7.

The ways in which we can manage Blue-Green Algae blooms all are associated with attacking their ability to access phosphate, by creating a chemical or physical barrier between the two. There are several management options that are being implemented, sometimes with surprising success (positive and negative), to isolate phosphate from Blue-Green Algae including;

- treatment with lanthanum modified bentonite (Epe *et al*. 2017, Spears *et al*. 2016, Copetti *et al.* 2016, and Spears *et al*. 2013)
- manipulation of nitrogen: phosphorous ratios (Harris *et al.* 2014, Stockner and Shortreed 1988),
- mixing of the water column (Lehman 2014),
- iron enrichment (Orihel *et al.* 2016),
- downflow bubble aeration (CRD 2018, CH2M Hill 2018, Barber et al. 2015, and Ashley 2007)
- upflow bubble aeration (CRD 2018, Nordin 2015, Ashley 2007, and Ashley 1983),
- nano-bubble aeration, and
- dredging (Ashley 2007)

The situation on Quamichan Lake can very likely be remediated by using one or more of the above strategies. The sections below provides brief assessments of the potential of management options to be suitable for mitigating phosphorus in Quamichan Lake. Management options are grouped into 4 categories; aeration, chemical treatment, flushing, and dredging. Other options that have been mentioned for managing phosphorus in Quamichan Lake are:

- laminar circulation using SolarBee^{tm} technology,
- Hay bales,
- Biochar
- Nutrient manipulation
- Plant removal.

Multiple trials of SolarBee^{tm} technology in the United states have yielded equivocal results for significant investments. For example, Fitzsimon (2016) describes how a $US 2.8 million investment in several SolarBees for Jordan Lake in North Carolina, which was subject to algae control problems, failed to yield any improvement after 3 years. Spreadsheet models by the author of this paper show that while biochar plant removal and hay bales have been used in small scale applications, when scaled to a project the size of Quamichan Lake would balloon to unmanageable volumes of treatment material and waste material. For example, based on recommended biochar application rates online I estimate that Quamichan Lake would require at minimum 200,000 bags, of material each weighing 20 kg. Treatment with barley straw is estimated to involve the use of over 1200 bales each weighing over 200 kg. Nutrient manipulation attempts to leverage the competitive advantage that Blue-Green Algae has in nitrogen limited situations by simply adding nitrogen to the lake. Such work has been done in Kennedy Lake (Stockner and Shortreed 1988) but it is oligotrophic and thus nutrient poor. This approach would not be prudent for Quamichan Lake which would simply have nuisance level Blue-Green Algae blooms replace by nuisance Green Algae blooms. Removal phosphate in plant material would necessitate the removal of tens of thousands of tons of plant material from the lake in order to significantly reduce phosphate. Locating a place to move that plant material for decomposition, as well as establishing a trucking infrastructure to move that material, would be a daunting, long-term and expensive task.

Algaecides are not regarded as a serious management option because the use of such chemicals will only temporarily treat the symptom of the problem, *i.e.*, kill Blue-Green Algae for a short period of time, rather than acting as a permanent cure, *i.e.*, removing phosphorus from the water column and improving overall water quality

Aeration

Bubblers are the longest studied method of mitigating phosphorus in lakes. Compressed air is pumped into the lake, which oxygenates deeper water by reducing or eliminating the thermocline (Ashley 2007). Metal ions in the oxygenated water can bond to phosphate and precipitate to the bottom removing it from the water column. Experience has shown, however that bubble aeration is best suited to lakes with an established thermocline and for a time this was the preferred method for dealing with Blue-Green Algae in Elk Lake. (Nordin 2015). The use of bubblers and compressed air in shallow lakes is not generally recommended in situations where the removal of any thermal structure could bring warmer water to lake depths. In a destratified Quamichan Lake, the deeper water would be aerated but at the cost of being warmed to temperatures harmful or lethal to trout (Ashley 2007). A small-scale bubbler was placed in the Woodmere property on the southeast shore of Quamichan Lake but, given observed fish kills and hatchery stocking trends, it seems unlikely that the bubbler has had the intended effect of remediating trout habitat.

Nano-bubble technology is a relatively new approach which injects oxygen into deep anoxic water as very small bubbles. These small bubbles are neutrally buoyant and, therefore stay at depth preserving thermal structure in the lake. Nano-bubbler appear to be moderately expensive as an option and would have an ongoing expense of operating air pumps. A nano-bubble installation is being installed in an 8 acre lake in Lee County Florida at a cost of $750,000 US and has resulted in significant improvement in appearance, though no peer-reviewed studies are yet available (National Centre for Coastal Ocean Science 2018). Also, if this is scaled up to a project the size of Quamichan Lake, installation cost may be several millions to tens of millions of dollars.

Upflow bubble aeration has had widespread adaptation since the 1970s (Ashley 2007). However, most applications have been in deeper lakes. In St Mary’s Lake, mean depth 8m, upflow bubble aeration was meeting with limited success but operations were stopped when it was discovered that it may actually have increased the magnitude of Bleu-Green Algae blooms between 2011 and 2013 (North Salt Spring Waterworks District (2015). Another limitation is that an upflow aeration system, similar to that installed on St. Mary’s Lake would require a separator box on the lake which could create a navigational issue for recreational users of the lake.

Downflow bubble aeration is a technology that has increased in attention in recent years and is now the preferred option for mitigating phosphorus in Elk Lake (CRD 2018). This approach uses a pump to extract water from the hypolimnion to a ‘Speece Cone’ where it is supersaturated with oxygenated and pumped back into the lake, at depth. Operation of the pump is relatively cost effective compared to pumping air because there is no need to pressurise the water. In applications of this technology in Newman Lake, Washington and Camanche Reservoir, California downflow bubble aeration has remediated deep water anoxia (Ashley 2007). Newman Lake is quite similar to Quamichan Lake (490 Ha, mean depth ~ 5.8m). The installation there involved use of Speece Cone 2.8m diameter and 5.5m tall with a 45kW pump to move lake water, with oxygen supplied by two 37 kW air compressors. In their recommendation to install downflow bubble aeration in Elk Lake CRD technical staff suggest a:

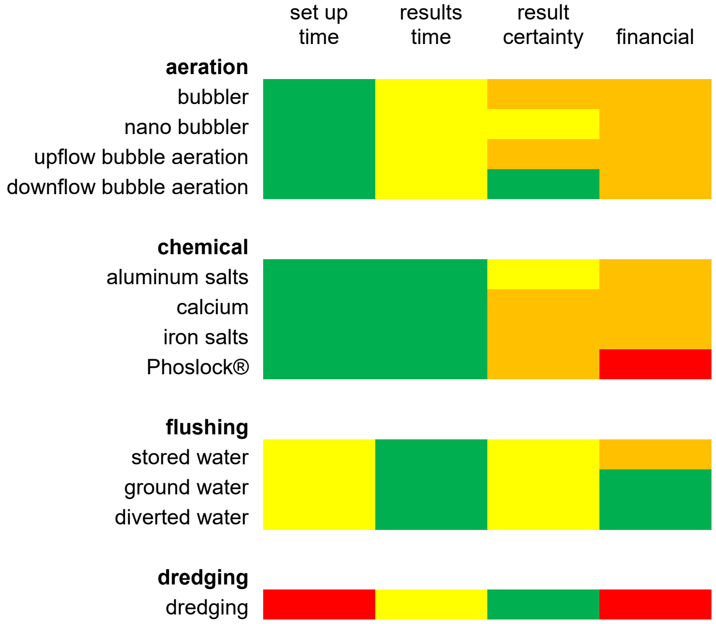
> preliminary design for a shore-based DBHO (downflow bubble hypolimnetic oxygenation) system, guaranteed to deliver the 435 kg O2 per day estimated to meet the oxygen demand needed to achieve the MOE 1992 Water Quality Objective for DO in Elk Lake (*i.e.*, >5 mg/L at 1m above the lake bottom), would 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.

It would be expected that a device of similar or even smaller magnitude may be suitable for Quamichan Lake. Downflow bubble aeration would appear to be the aeration approach with the highest probability of remediating phosphorus while lowering risks of adverse effects from destratification.

Chemical Treatment

Calcium, aluminum salts and iron salts have all been used to precipitate phosphorus from the water column. There has been widespread use of aluminum salts in several European lakes with high internal loading. One drawback can be sensitivity of lake chemistry to pH changes after treatment with aluminum salts which can result in resuspension of phosphate (Ashley 2007). Ferric chloride was used to mitigate phosphorus by Orihel et al. (2016) in a hypereutrophic prairie lake. However, it is also cautioned that the chemistry of individual lakes and the pre-existing concentration of iron in the lake sediment can confound the use of iron (Orihel et al 2016 and Orihel et al. 2015).

Exhibit 8: Stoplight diagram of costs for management options to mitigate phosphate in Somenos lake. Green items are more likely favourable, red ones are more likely unfavourable.



	set up time	results time	result certainty	financial
aeration				
bubbler	🟩	🟨	🟧	🟧
nano bubbler	🟩	🟨	🟨	🟧
upflow bubble aeration	🟩	🟨	🟧	🟧
downflow bubble aeration	🟩	🟨	🟩	🟧
chemical				
aluminum salts	🟩	🟩	🟨	🟧
calcium	🟩	🟩	🟧	🟧
iron salts	🟩	🟩	🟧	🟧
Phoslock®	🟩	🟩	🟧	🟥
flushing				
stored water	🟨	🟩	🟨	🟧
ground water	🟨	🟩	🟨	🟩
diverted water	🟨	🟩	🟨	🟩
dredging				
dredging	🟥	🟨	🟩	🟥

Lanthanum modified bentonite clay, commercially known as Phoslock®, has received a large amount of attention and has been employed to mitigate phosphate levels in many small lakes around the world, (Epe at al 2017 and Spears et al. 2013). Phoslock has the benefit of being relatively benign to fish and aquatic invertebrates (Finsterle 2014) and has the effect of increasing the diversity and biomass of aquatic vascular plants and Secchi Disk depths very soon after application (Spears et al. 2016). Phoslock is generally recommended for use in lakes with significant and re-application may be required if phosphorus inputs are not controlled (Finsterle 2014). Applications of Phoslock to lakes of similar Scale to Quamichan Lake have been rare, however (Copetti et al. 2015 and Dithmer et al. 2015). Bromont Lake in Quebec is a 45 Ha lake which was treated with Phoslock in 2017 at a cost of $CDN 615,000 (CBC News 2018). Initial anecdotal results have been favourable as to water quality, but no scientific or technical reports were available at the time this report was written. Assuming direct of lake size to treatment cost a Phoslock® application in Quamichan Lake may cost almost $CDN4 million. Other potential drawbacks are that there are limitations placed on the efficacy of Phoslock® by sediment chemistry and a better understanding of Quamichan Lake sediments would be required before moving forward with this approach. Lastly there are limitations on the timing of Phoslock® application which should not coincide with; stratification, wind mixing, fish breeding, spawning, or stocking, high algal mass, high total phosphorus in water column and recreational peak times (CRD 2018). It is difficult to imagine a time window on Quamichan like in which one or more of these restrictions is not violated.

Flushing

Flushing Quamichan Lake with stored water, well water, or diverted water would be an ecologically benign way to improve water quality by both diluting phosphates and by flushing them out of the lake in the summer. As described above, there is little to no flow of water into Quamichan Lake during the summer. By moving water through the lake phosphorus could be exported during the time is becomes suspended in the water column. The most difficult aspect of this approach is locating a source of low nutrient water that could supply the lake in the summer. Stored water, such as is done in Crofton Lake could be used to dilute Quamichan Lake, however the amount stored would have to be significantly larger. For example, in order to flush out the lake once, in a five month dry period of the summer, an inflow of $1.3 m^3/s$ would be required, *i.e.*, an amount comparable to the water consumption of the Crofton pulp mill. If the issue of water supply can be overcome, flushing would be a relatively cost-effective policy in the long-term. Pumping water at this scale would likely incur costs in the tens of thousands of dollars.

Dredging

Dredging has proven to be a relatively successful way to remove phosphorus, but it comes at a tremendous cost in money and time. A dredging program in Burnaby Lake, which is similar in area to Quamichan Lake, was lauded across the province but cost more than 20 million dollars to bring the project to completion in 2012 after many years of planning and several years of operations. In the CRD's analysis of dredging as an option for Elk lake they estimated the 2018 cost at between $CDN 66-120 million (CRD 2018). Based on cost estimates for dredging in Ashley (2007), dredging 0.5m from the bottom of Quamichan Lake would cost on the order of $CDN80-110 Million (2.7 million m^2 * 0.5m depth * 60-79 $\$/m^2$). Other factors to consider are:

- finding a place to place to store removed dredgeate,
- dealing with potentially contaminated dredgeate,
- closing significant portions of the lake while dredging, and
- completing environmental assessments of the lake before dredging

Treatment of Inflow water

Treatment of phosphate entering Quamichan Lake from its watershed is crucial to long-term success in controlling Blue-Green Algae Blooms. Proposals have already been enacted to begin treatment of certain streams and ditches leading to the lake with a mixture of limestone and zeolite. Moore (2019) provides a useful suggestion in rebuilding wetlands for streams and creeks before they enter Quamichan Lake. Using the example of a wetland constructed near the intersection of Beverly Street and the Island Highway, we should expect that it would cost approximately $10,000 - $20,000 per hectare of wetland remediated or installed. It would be most useful to work with the agricultural community to establish wetlands in and around the mouth of McIntyre Creek and the areas where ditches from Stamps Road, Martin Place and Stanhope Road enter the Lake. However, such an undertaking would require a significant degree of collaboration with the agricultural and residential communities in order to acquire land for wetland adaptation. It may be more efficacious to develop phosphorus reduction strategies with farm operators. The data collected in December 2018 suggests that the magnitude of phosphorus entering the lake from rural properties is far greater tan that from residential lands. Ideally the community will collaborate to develop a combination policy of in-stream mitigation with wetland remediation that combines with reduced phosphorus use in both the residential and farming properties.

Road Map for the Next 4 Years

Year	Task	Group(s)
1	Create Quamichan Lake Phosphorus Management Committee	Municipality, Cowichan Tribes, Ministry of Environment, Ministry of Agriculture, Quamichan Stewards
1	Develop outreach and education program	Municipality, Cowichan Tribes, Ministry of Environment, Ministry of Agriculture, Quamichan Stewards
1	Install zeolite and limestone in creeks	Municipality, Ministry of Environment, Quamichan Stewards
1	Implement studies on lake physics and chemistry	Municipality (staff)
1	Install water quality monitoring equipment	Municipality (staff), Quamichan Stewards
1	complete sediment study	Ministry of Environment
1	detailed report on top 3 management options	Municipality (staff)
1	report on 1st year operations	Municipality (staff)
2	report on preferred management option(s)	Municipality (staff)
2	Selection of preferred management option(s)	Municipality, Cowichan Tribes, Ministry of Environment, Ministry of Agriculture, Quamichan Stewards
2	Explore selection of wetland sites	Municipality, community, Quamichan Stewards
2	continue monitoring operations	Municipality (staff), Quamichan Stewards
2	report on 2nd year operations	Municipality (staff)
3	Implement preferred management option(s)	Municipality, Cowichan Tribes, Ministry of Environment, Ministry of Agriculture, Quamichan Stewards
3	continue monitoring operations	Municipality (staff), Quamichan Stewards
3	report on 3rd year operations	Municipality (staff)
4	report on progress of management options make adjustments	Municipality, Cowichan Tribes, Ministry of Environment, Ministry of Agriculture, Quamichan Stewards
4	continue monitoring operations	Municipality (staff), Quamichan Stewards
4	report on 4th year operations	Municipality (staff)

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Figures

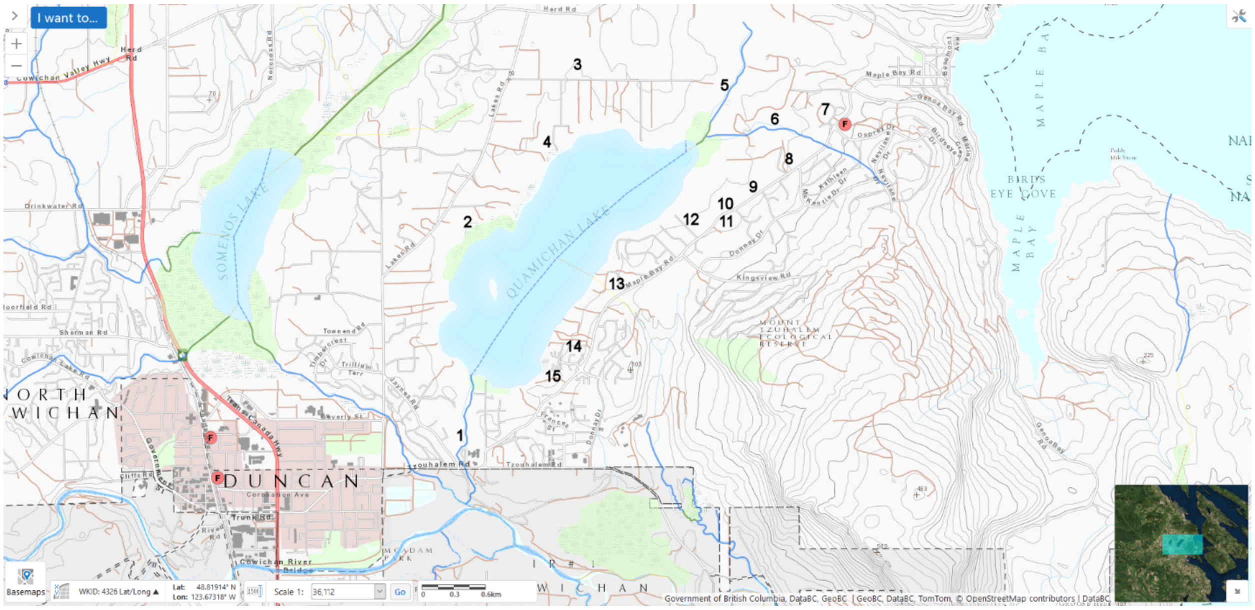

Figure 1: Geographic Situation of Quamichan Lake in the Cowichan Valley. Streams and ditches draining and tributary to the lake are numbered: Quamichan Creek (1), Stanhope Road ditch (2), Stamps Road ditch (3), Martin Place ditch (4), MacIntyre Creek (5), Elkington Creek (6), Osprey Creek (7), Aitken Creek (8), Highwood Creek (9), Woodgrove Creek (10), South Woodgrove Creek (11), Deykin Creek (12), Churchill Creek (13), Sterling Creek (14) Woodmere ditch (15). This map was generated using online GIS resources from the Province of British Columbia at www2.gov.bc.ca/gov/content/data/geographic-data-services/web-based-mapping/imapbc.

Figure 2: Land cover in the Quamichan watershed. Wetlands are in light green and open water in blue. Note forested land on Mount Tzouhalem in dark green and cleared land for residences and agriculture surrounding Quamichan Lake in brown. This map was generated using online GIS resources from the Province of British Columbia at www2.gov.bc.ca/gov/content/data/geographic-data-services/web-based-mapping/imapbc.

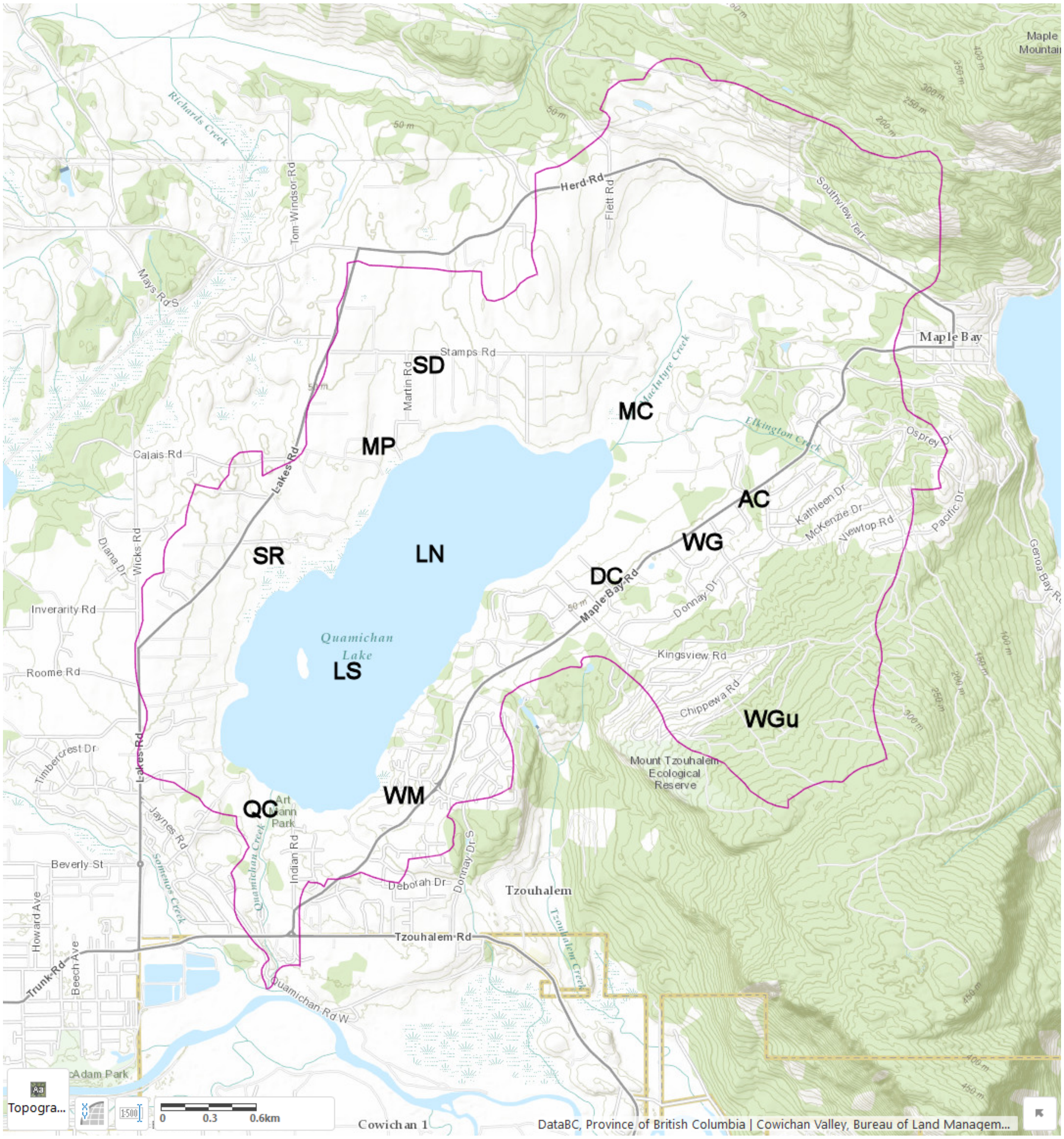

Figure 3: The Quamichan watershed (outlined in purple) and sample sites referred to in this report. Quamichan Creek (QC), Stanhope Road ditch (SR), Martin Place ditch (MP), Stamps Road ditch (SD), McIntyre Creek (MC), Aitken Creek (AC), Woodgrove Creek (WG) upper Woodgrove Creek (WGu), Deykin Creek (DC), Quamichan Lake South (LS) and Quamichan Lake North (LN). This map was generated using online GIS resources from the Province of British Columbia at www2.gov.bc.ca/gov/content/data/geographic-data-services/web-based-mapping/imapbc.

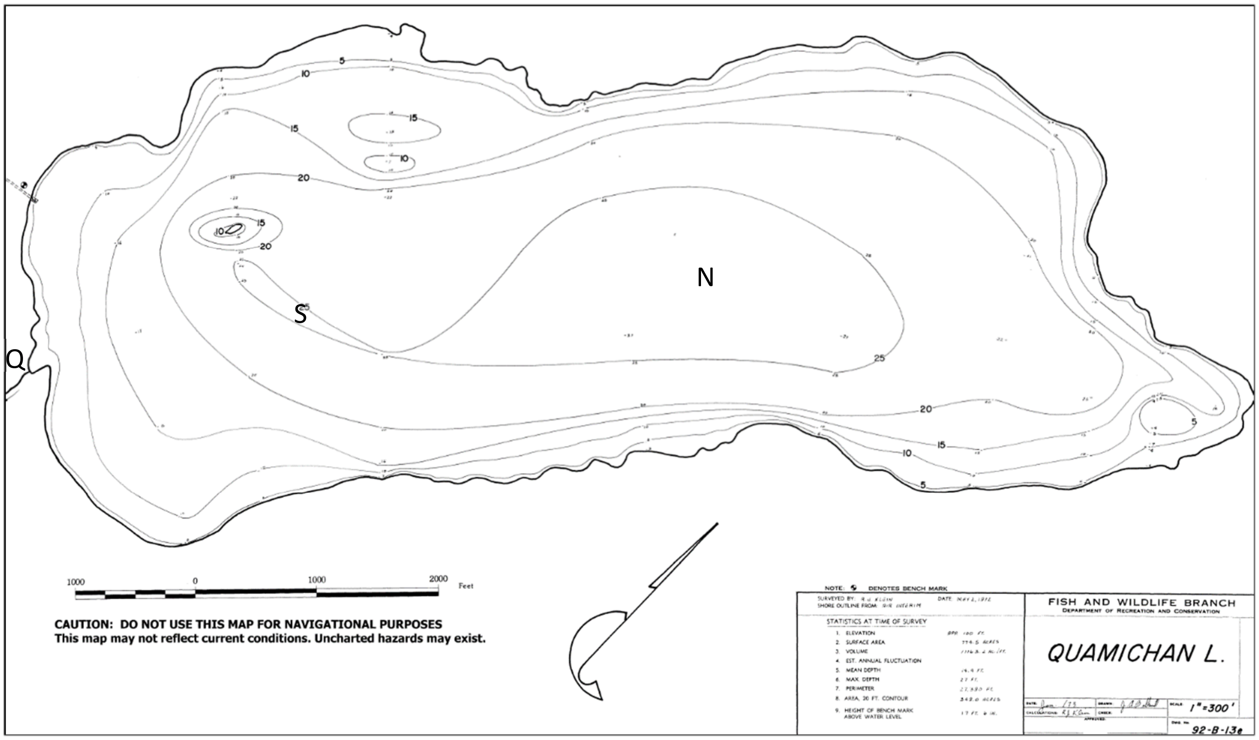

Figure 4: Bathymetric chart of Quamichan prepared in May 1972. Note that the depth contours are in feet and that north is oriented at the upper right of the chart. To approximate depths in meters, divide by three. Quamichan Creek can be seen at the left of the chart. The positions of the north (N) and south (S) sampling stations can be seen within the deepest contour. The Quamichan Creek station (Q) is at the tail of the Q. The north station is near the deepest part of the lake (27 ft, 8.2m). This chart can be accessed from the government of British Columbia online at catalogue.data.gov.bc.ca/dataset/bathymetric-maps

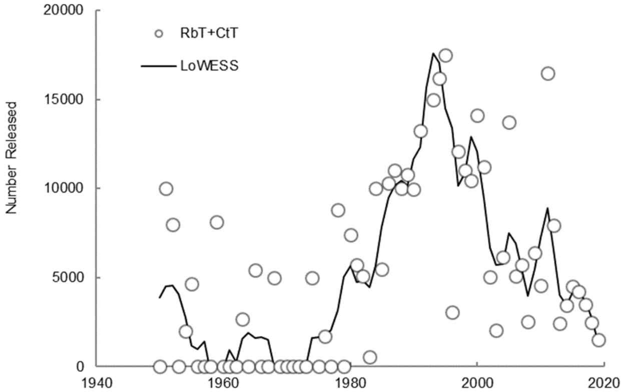

Figure 5: Combined releases of hatchery origin Rainbow Trout (RbT) and Cutthroat Trout (CtT) into Quamichan Lake, 1950-2019. Data is from the Freshwater Society of British Columbia. Locally weighted scatterplot smoothing (LoWESS), using a second degree polynomial and 10 year window, is shown to indicate interannual trends.

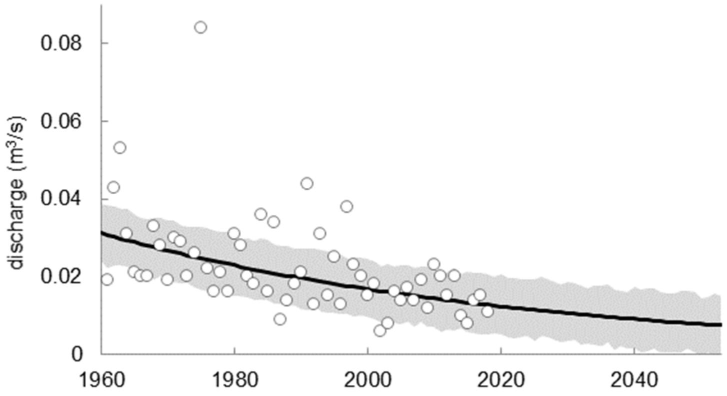

Figure 6: Bing’s Creek Mean August discharge, 1960-2018 (circles), Environment Canada data. The line shows a model of the historic trend and forecasted monthly discharge to 2050. The grey area shows the ±50% confidence interval of 1000 simulations. This model suggests that by the year 2040 Bing’s Creek may run dry in August about one in every 4 years.

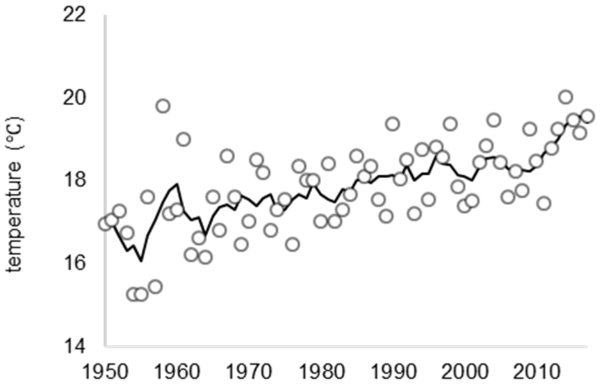

Figure 7: Mean July/August air temperature, 1950-2017 (circles) and 5 year running average (line) at Nanaimo Airport. The mean for the 20-year period from 1950-1969 was 17.0 ℃ and the mean for the period from 2010-2017 was 19.0 ℃. Data from Environment Canada

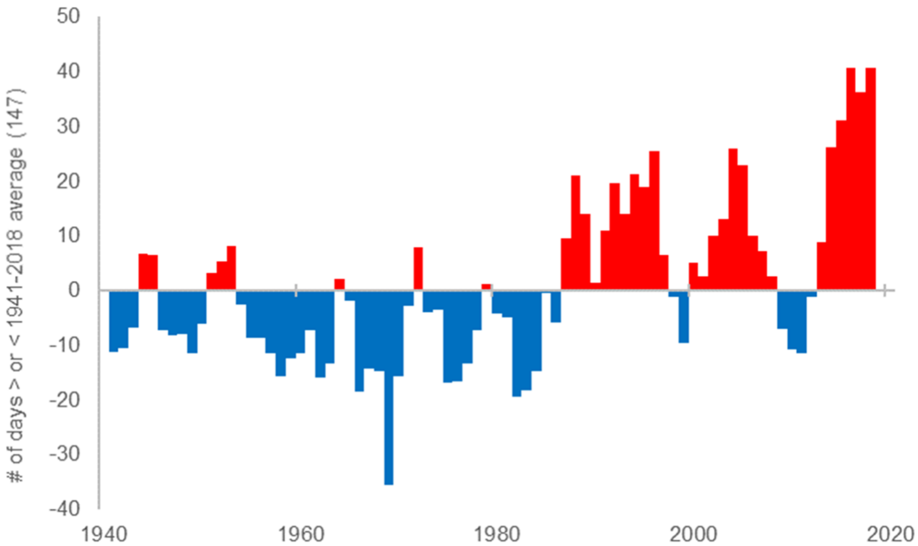

Figure 8: Annual anomaly of length of summer dry season in the Cowichan Valley, 1941-2018. The dry season is inferred from Cowichan River discharge reflecting the difference between the date of the first significant fall rain of a given year versus the date of the last significant winter rain of each year, data from Environment Canada. Over the 78 years of the time series the average length of the dry season was 147 days. There appears to be a shift to longer dry seasons in the mid 1980s. the average length of dry season from 1941 to 1983 was 139 days, whereas the average length of dry season from 1984-2018 was 158 days. The mean length of dry season from 2010-2018 was 165 days.

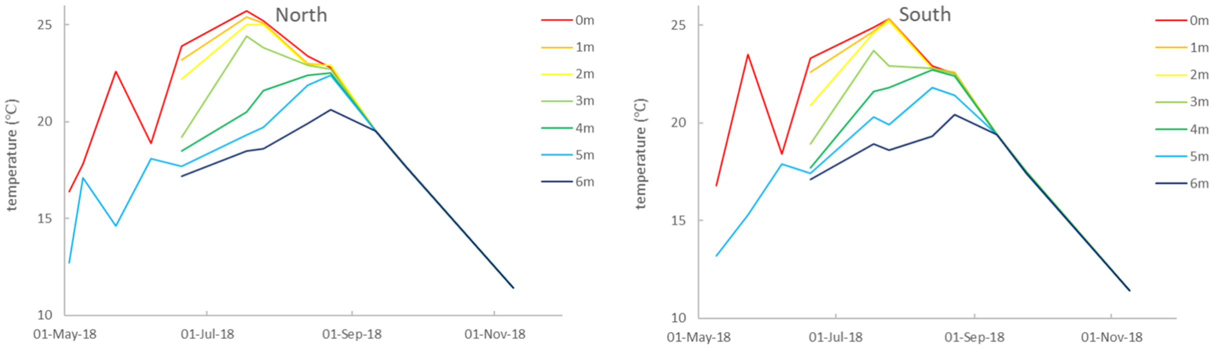

Figure 9: Seasonal trends in temperature measured at the south and north Quamichan Lake stations at 0, 1, 2, 3, 4, 5, and 6m. Peak temperature for the south station was 25.2℃ at the surface on 25 July, 2018 and for the north station 25.7℃ at the surface on 18 July 2018. Both stations show that the lake had turned over by 11 September 2019.

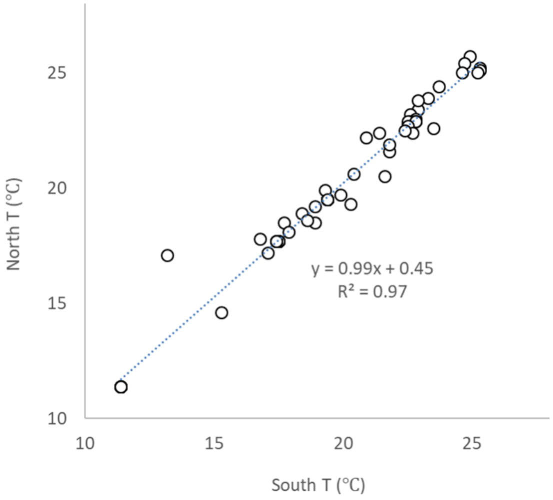

Figure 10: Correlation of temperatures measured at the same depth and date at the south and north lake stations.

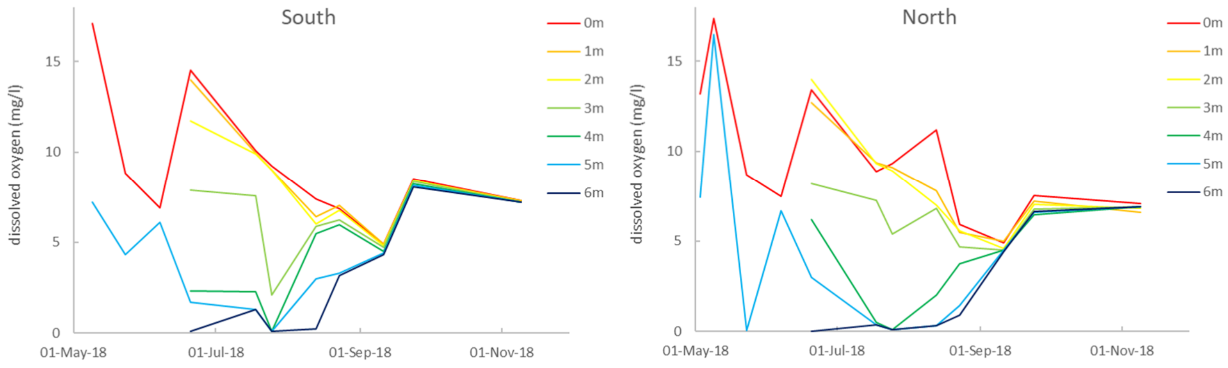

Figure 11: Seasonal trends in dissolved oxygen measured at the south and north Quamichan Lake Stations at 0, 1, 2, 3, 4, 5, and 6m. Anoxia was first observed at 5m on 26 may, 2019 at the north station and on 20 June 2018 at 6m at the south station. The lake turnover removed anoxic conditions at depth by 11 September 2018.

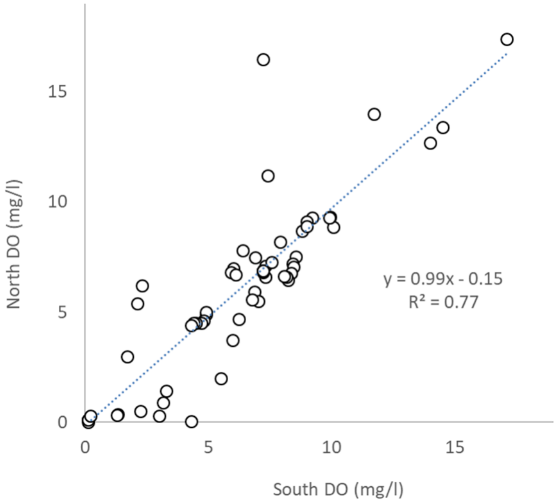

Figure 12: Correlation of dissolved oxygen measured at the same depth and date at the south and north lake stations.

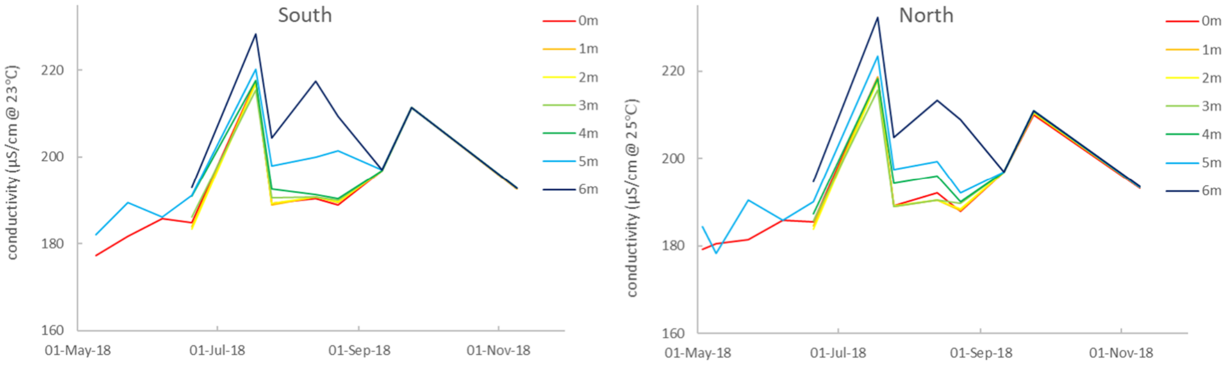

Figure 13: Seasonal trends in specific conductivity measured at the south and north Quamichan Lake stations at 0, 1, 2, 3, 4, 5, and 6m. Peak conductivity for both the south and north stations was ~230 µS/cm on 18 July 2018. Both stations show that the lake had turned over by 11 September 2019.

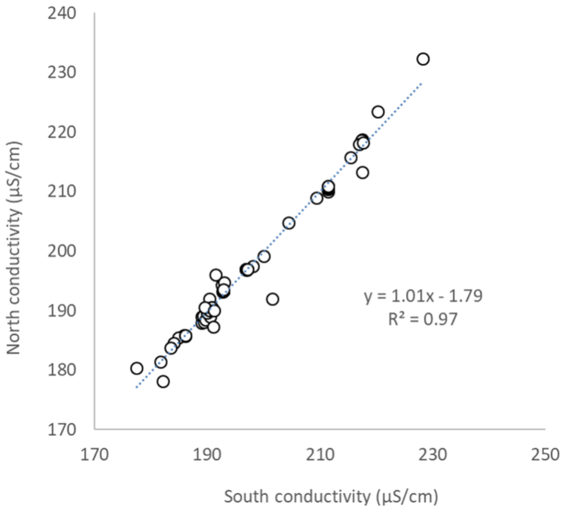

Figure 14: Correlation of conductivity measured at the same depth and date at the south and north lake stations.

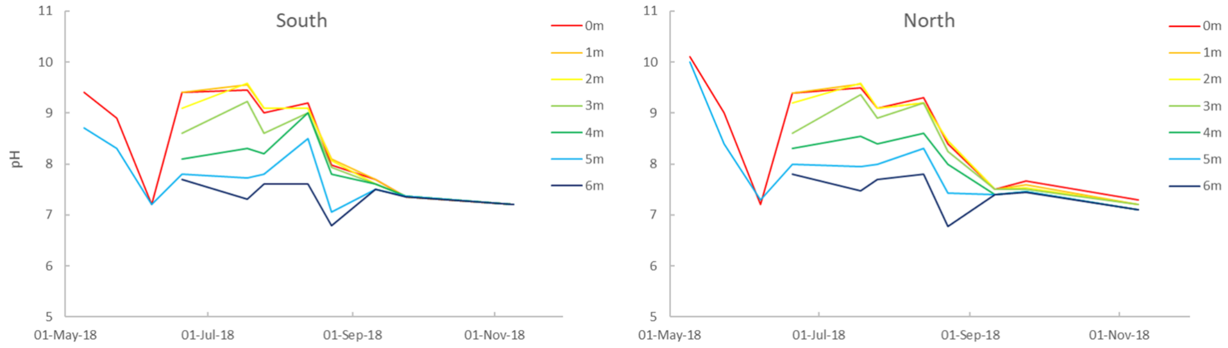

Figure 15: Seasonal trends in pH measured at the south and north Quamichan Lake stations at 0, 1, 2, 3, 4, 5, and 6m. Peak pH for both the south station was 9.6 at 2m on 18 July 2018 and 10.1 for the north station at the surface on 09 May 2018. Both stations show that the lake had turned over by 11 September 2019.

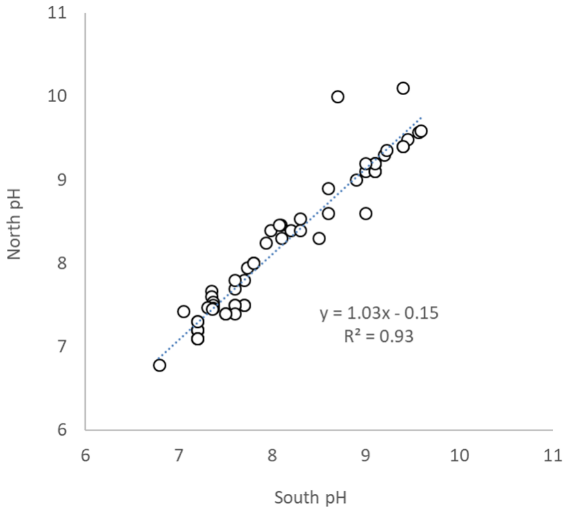

Figure 16: Correlation of pH measured at the same depth and date at the south and north lake stations.

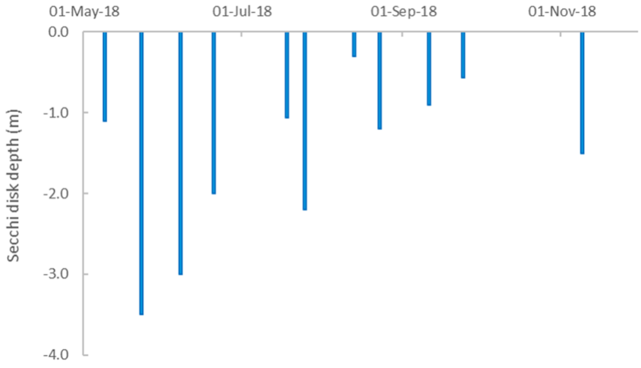

Figure 17: Secchi disk depths recorded at the Quamichan Lake north station during the 2018 survey.

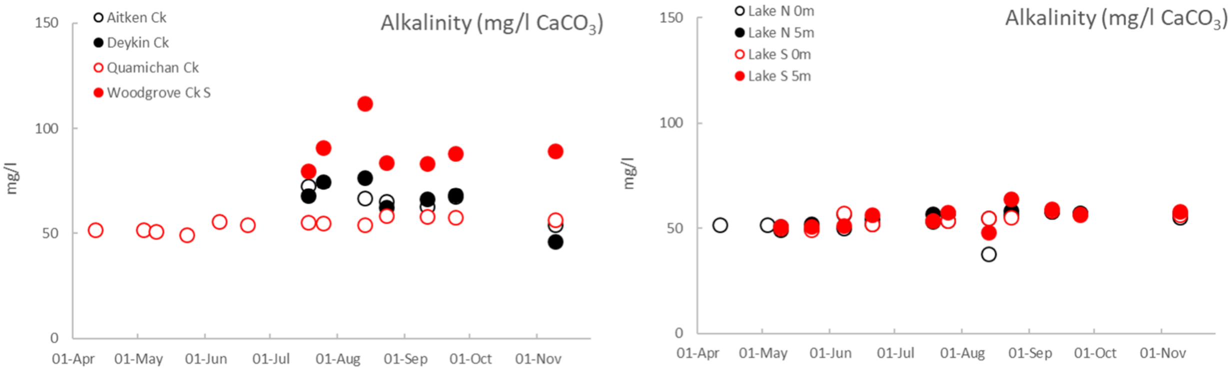

Figure 18: Seasonal trends in alkalinity measured at creek and lake stations. Variation in alkalinity was much higher at creek stations as well as the maximum observed values.

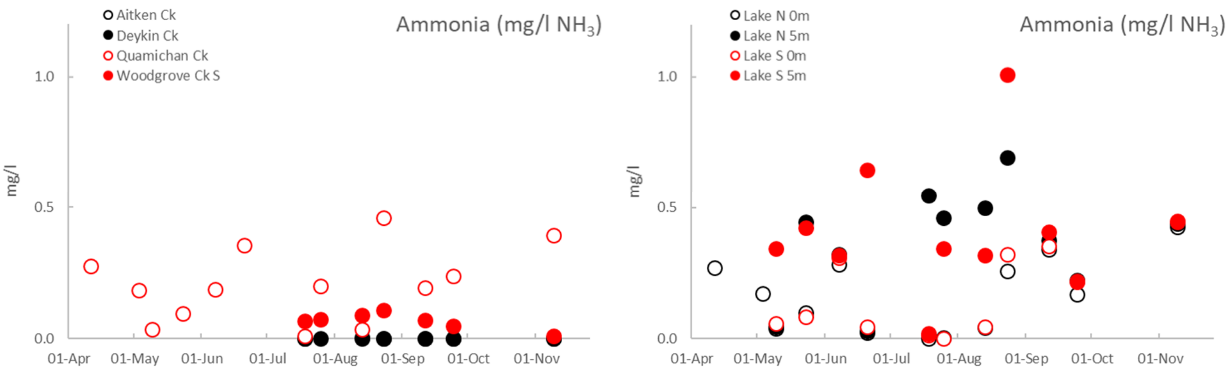

Figure 19: Seasonal trends in ammonia measured at creek and lake stations. Variation in ammonia was much higher at lake stations as well as the maximum observed values.

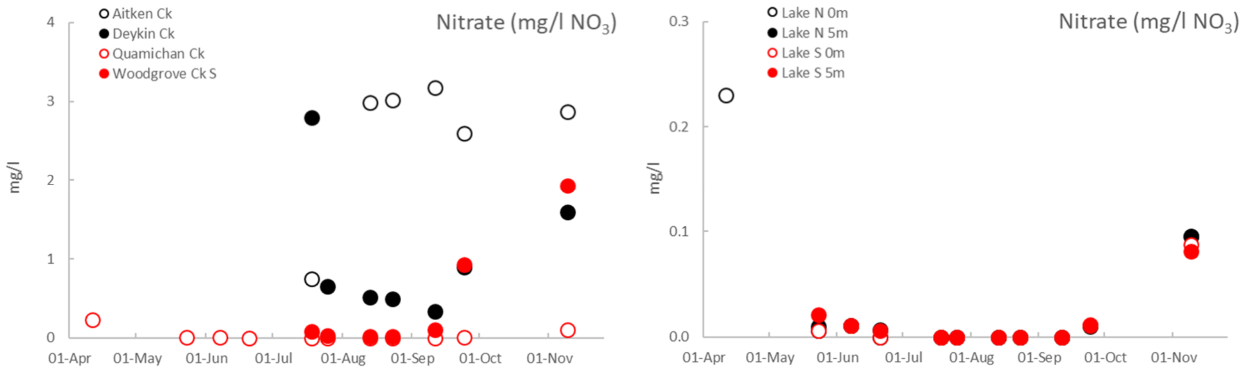

Figure 20: Seasonal trends in nitrate measured at creek and lake stations. Variation in nitrate was much higher at creek stations as well as the maximum observed values. Peak values for most stations were in November.

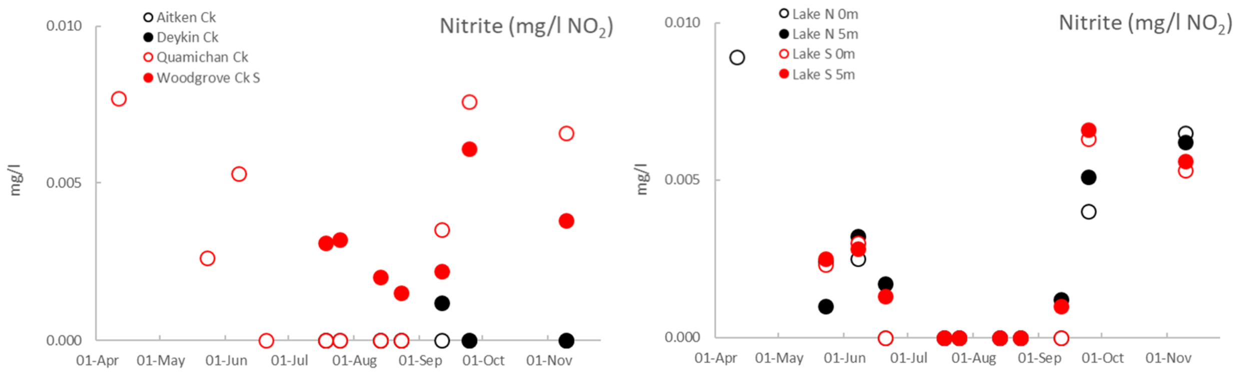

Figure 21: Seasonal trends in nitrite measured at creek and lake stations. Variation in nitrite was much higher at creek stations. Values increased at most stations towards the end of summer.

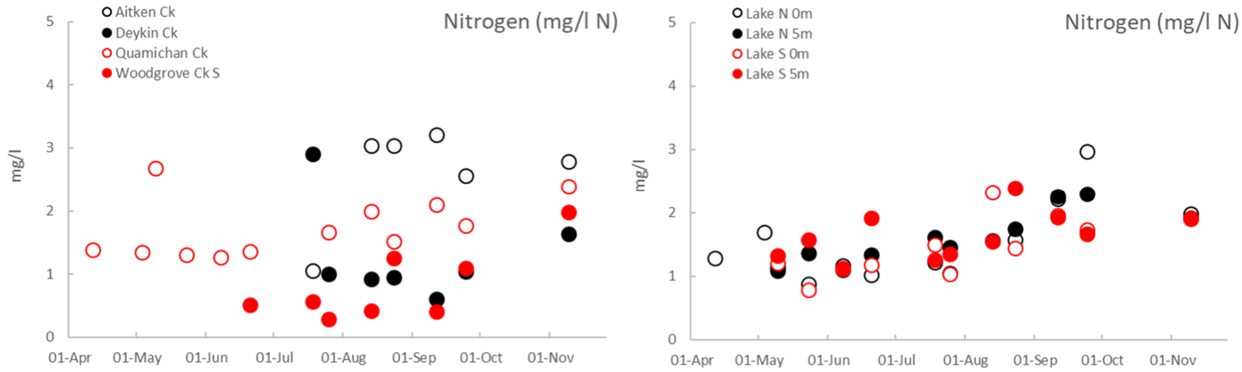

Figure 22: Seasonal trends in nitrogen measured at creek and lake stations. Variation in nitrogen was much higher at creek stations as well as the maximum observed values. Values at most stations increased through the summer.

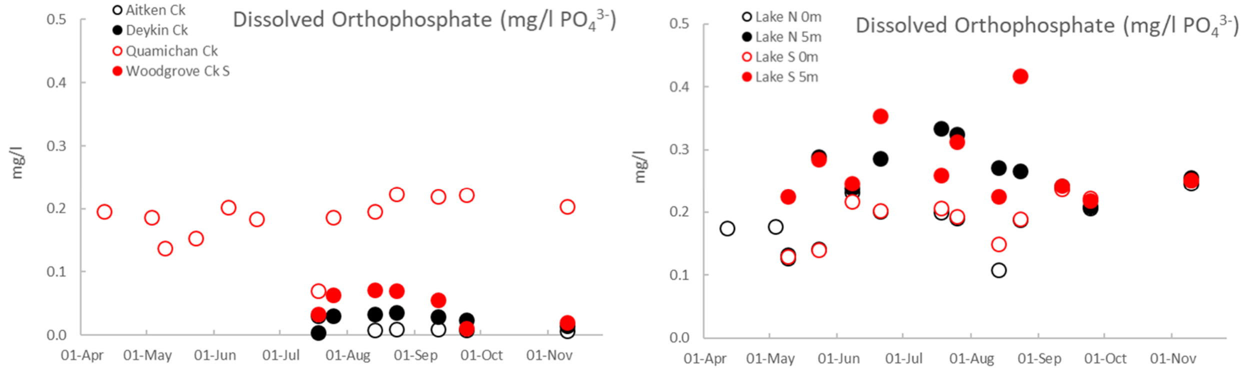

Figure 23: Seasonal trends in dissolved orthophosphate measured at creek and lake stations. Variation in dissolved orthophosphate was much higher at lake stations as well as the maximum observed values. Values observed at the lake stations were highest in mid summer.

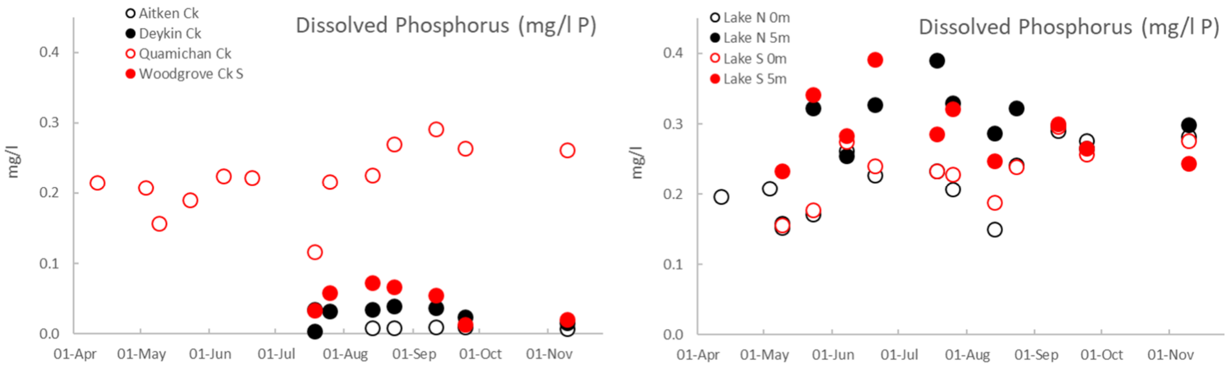

Figure 24: Seasonal trends in dissolved phosphorus measured at creek and lake stations. Variation in dissolved phosphorus was much higher at lake stations as well as the maximum observed values. Values observed at the lake stations were highest in mid summer.

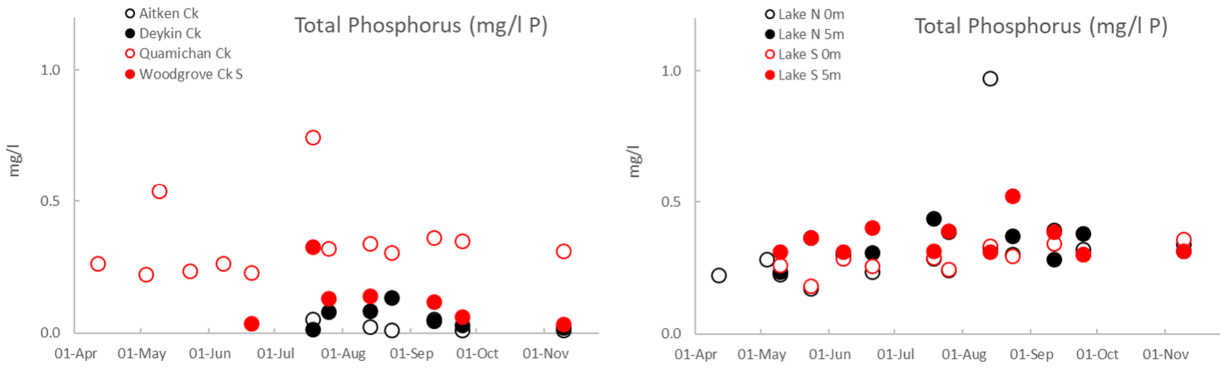

Figure 25: Seasonal trends in total phosphorus measured at creek and lake stations. Both observed values and variation were much higher at lake stations. Values observed at the lake stations were highest in mid to late summer.

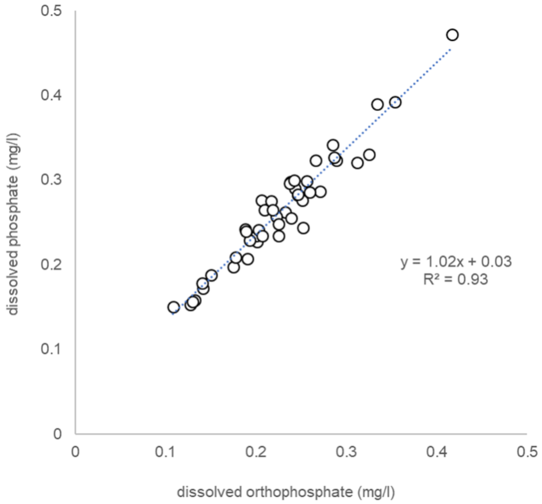

Figure 26: Correlation between dissolved orthophosphate and total dissolved phosphate at the same date station and depth.

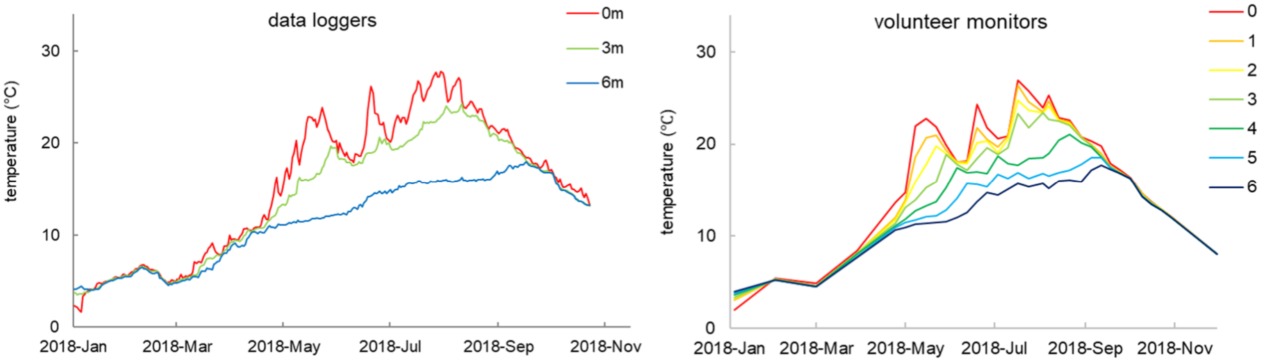

Figure 27: Seasonal trends in temperature in Somenos Lake measured hourly by temperature data loggers (data shown is daily mean temperature) and weekly by volunteers. The data loggers were installed by the Somenos marsh Wildlife Society in 2014. Weekly monitoring is by volunteers from the Salmon Habitat Restoration Program of the Somenos Marsh Wildlife Society which has been ongoing since 2014.

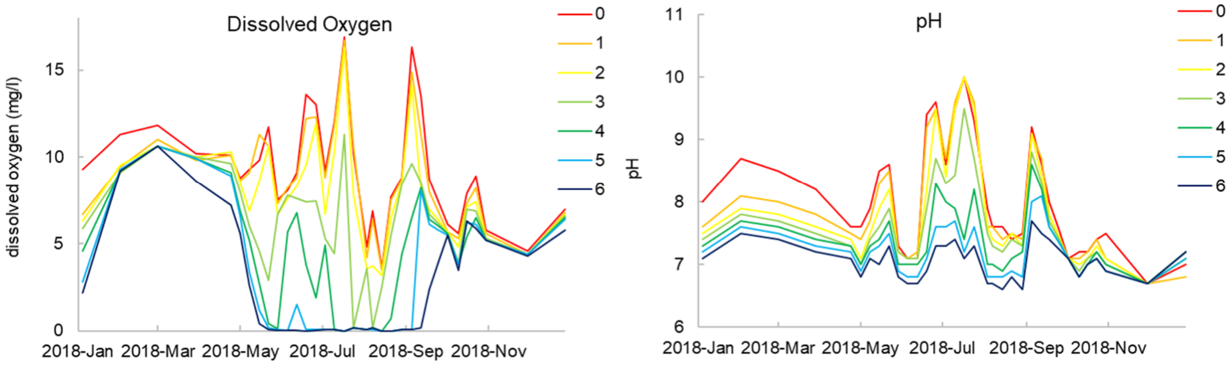

Figure 28: Seasonal trends in dissolved oxygen and pH in Somenos Lake measured weekly by volunteers from the Salmon Habitat Restoration Program of the Somenos Marsh Wildlife Society since 2014.

Tables

Table 1: Raw data from the 2018 Quamichan water sampling program, lake north site. Note that where results are prefixed by a < sign, the sample was below the detection limit of the test. Samples were analysed by ALS Environmental laboratory in Burnaby.

Sample ID	Date	Time	Total Alkalinity (mg/l CaCO3)	Total Ammonia, (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Total Nitrogen (mg/l)	Dissolved Orthophosphate (mg/l)	Total Dissolved Phosphorus (mg/l)	Total Phosphorus (mg/l)
Lake N 0m	11-Apr-2018	12:12	51.5	0.269	0.230	0.0089	1.29	0.175	0.197	0.222
Lake N 0m	3-May-2018	10:10	51.6	0.173			1.69	0.177	0.209	0.284
Lake N 0m	9-May-2018	12:04	49.3	0.0378			1.14	0.127	0.153	0.226
Lake N 0m	23-May-2018	11:58	49.7	0.0991	0.0061	0.0024	0.878	0.141	0.172	0.173
Lake N 0m	7-Jun-2018	12:00	50.2	0.283	0.0108	0.0025	1.17	0.232	0.262	0.299
Lake N 0m	20-Jun-2018	11:21	52.2	0.0219	<0.0050	<0.0010	1.02	0.201	0.227	0.235
Lake N 0m	18-Jul-2018	11:25	53.2	<0.0050	<0.0050	<0.0010	1.22	0.200	0.234	0.285
Lake N 0m	25-Jul-2018	9:15	53.7	0.0051	<0.0050	<0.0010	1.05	0.190	0.207	0.242
Lake N 0m	13-Aug-2018	10:40	37.8	0.0428	<0.0050	<0.0010	14.0	0.108	0.150	0.973
Lake N 0m	23-Aug-2018	11:04	56.6	0.257	<0.0050	<0.0010	1.58	0.188	0.242	0.301
Lake N 0m	11-Sep-2018	10:40	57.9	0.340	<0.0050	<0.0010	2.22	0.243	0.290	0.394
Lake N 0m	24-Sep-2018	10:45	57.4	0.168	0.0102	0.0040	2.97	0.206	0.276	0.320
Lake N 0m	9-Nov-2018	10:45	55.2	0.427	0.0959	0.0065	1.98	0.246	0.282	0.339
Lake N 5m	9-May-2018	12:04	50.7	0.0466			1.09	0.132	0.158	0.235
Lake N 5m	23-May-2018	12:05	52.2	0.446	0.0104	0.0010	1.36	0.289	0.323	0.365
Lake N 5m	7-Jun-2018	12:00	56.7	0.320	0.0108	0.0032	1.10	0.239	0.255	0.305
Lake N 5m	20-Jun-2018	11:22	54.4	0.0308	0.0071	0.0017	1.34	0.286	0.327	0.310
Lake N 5m	18-Jul-2018	11:40	56.9	0.546	<0.0050	<0.0010	1.62	0.334	0.390	0.437
Lake N 5m	25-Jul-2018	9:15	57.3	0.462	<0.0050	<0.0010	1.45	0.325	0.330	0.388
Lake N 5m	13-Aug-2018	10:40	54.7	0.498	<0.0050	<0.0010	1.56	0.271	0.287	0.327
Lake N 5m	23-Aug-2018	11:15	58.3	0.691	<0.0050	<0.0010	1.75	0.266	0.323	0.372
Lake N 5m	11-Sep-2018	10:40	58.0	0.376	<0.0050	0.0012	2.26	0.238	0.298	0.284
Lake N 5m	24-Sep-2018	10:52	57.3	0.222	0.0112	0.0051	2.30	0.209	0.265	0.382
Lake N 5m	9-Nov-2018	10:45	57.1	0.439	0.0952	0.0062	1.91	0.256	0.299	0.316

Table 2: Raw data from the 2018 Quamichan water sampling program, lake south site. Note that where results are prefixed by a < sign, the sample was below the detection limit of the test. Samples were analysed by ALS Environmental laboratory in Burnaby.

Sample ID	Date	Time	Total Alkalinity (mg/l CaCO3)	Total Ammonia, (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Total Nitrogen (mg/l)	Dissolved Orthophosphate (mg/l)	Total Dissolved Phosphorus (mg/l)	Total Phosphorus (mg/l)
Lake S 0m	9-May-2018	11:06	50.0	0.0576			1.20	0.130	0.156	0.262
Lake S 0m	23-May-2018	11:32	49.1	0.0834	0.0059	0.0023	0.783	0.140	0.178	0.183
Lake S 0m	7-Jun-2018	11:30	57.1	0.308	0.0106	0.0030	1.13	0.217	0.275	0.286
Lake S 0m	20-Jun-2018	10:33	52.2	0.0443	<0.0050	<0.0010	1.18	0.203	0.241	0.259
Lake S 0m	18-Jul-2018	10:45	53.6	0.0137	<0.0050	<0.0010	1.49	0.207	0.234	0.291
Lake S 0m	25-Jul-2018	8:45	53.7	<0.0050	<0.0050	<0.0010	1.03	0.193	0.229	0.246
Lake S 0m	13-Aug-2018	9:50	55.0	0.0453	<0.0050	<0.0010	2.33	0.150	0.188	0.335
Lake S 0m	23-Aug-2018	10:15	55.4	0.322	<0.0050	<0.0010	1.44	0.189	0.239	0.296
Lake S 0m	11-Sep-2018	10:10	58.3	0.352	<0.0050	<0.0010	1.95	0.237	0.296	0.344
Lake S 0m	24-Sep-2018	10:08	56.9	0.220	0.0109	0.0063	1.73	0.222	0.257	0.301
Lake S 0m	9-Nov-2018	11:45	56.4	0.449	0.0876	0.0053	1.90	0.251	0.276	0.358
Lake S 5m	9-May-2018	11:06	50.9	0.343			1.32	0.225	0.234	0.311
Lake S 5m	23-May-2018	11:36	50.9	0.421	0.0212	0.0025	1.58	0.285	0.342	0.364
Lake S 5m	7-Jun-2018	11:30	51.2	0.318	0.0108	0.0028	1.11	0.246	0.283	0.313
Lake S 5m	20-Jun-2018	10:35	56.4	0.643	0.0058	0.0013	1.92	0.354	0.392	0.404
Lake S 5m	18-Jul-2018	11:05	53.6	0.0211	<0.0050	<0.0010	1.26	0.259	0.286	0.315
Lake S 5m	25-Jul-2018	8:45	57.5	0.342	<0.0050	<0.0010	1.35	0.312	0.321	0.391
Lake S 5m	13-Aug-2018	9:50	48.2	0.318	<0.0050	<0.0010	1.55	0.225	0.248	0.312
Lake S 5m	23-Aug-2018	10:25	63.8	1.01	<0.0050	<0.0010	2.39	0.417	0.472	0.523
Lake S 5m	11-Sep-2018	10:10	59.0	0.408	<0.0050	0.0010	1.93	0.242	0.300	0.388
Lake S 5m	24-Sep-2018	10:17	56.6	0.215	0.0117	0.0066	1.67	0.218	0.265	0.303
Lake S 5m	9-Nov-2018	11:45	57.9	0.444	0.0814	0.0056	1.91	0.252	0.244	0.314

Table 3: Raw data from the 2018 Quamichan water sampling program, creek and ditch sites. Note that where results are prefixed by a < sign, the sample was below the detection limit of the test. Samples were analysed by ALS Environmental laboratory in Burnaby.

Sample ID	Date	Time	Total Alkalinity (mg/l CaCO3)	Total Ammonia, (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)	Total Nitrogen (mg/l)	Dissolved Orthophosphate (mg/l)	Total Dissolved Phosphorus (mg/l)	Total Phosphorus (mg/l)
Aitken Ck	18-Jul-2018	12:15	72.7	<0.0050	0.751	<0.0010	1.05	0.0310	0.0342	0.0536
Aitken Ck	13-Aug-2018	12:45	66.9	<0.0050	2.98	<0.0010	3.04	0.0086	0.0085	0.0240
Aitken Ck	23-Aug-2018	0:00	65.4	<0.0050	3.02	<0.0010	3.04	0.0091	0.0089	0.0106
Aitken Ck	11-Sep-2018	12:10	62.7	<0.0050	3.17	<0.0010	3.21	0.0095	0.0097	0.0526
Aitken Ck	24-Sep-2018	13:00	67.7	<0.0050	2.60	<0.0010	2.56	0.0085	0.0101	0.0119
Aitken Ck	9-Nov-2018	13:15	54.1	<0.0050	2.87	<0.0010	2.79	0.0067	0.0078	0.0124
Deykin Ck	18-Jul-2018	13:50	68.0	0.0083	2.80	<0.0010	2.91	0.0036	0.0041	0.0137
Deykin Ck	25-Jul-2018	9:55	74.9	<0.0050	0.651	<0.0010	1.00	0.0303	0.0327	0.0823
Deykin Ck	13-Aug-2018	11:45	76.7	0.0053	0.520	<0.0010	0.924	0.0332	0.0347	0.0847
Deykin Ck	23-Aug-2018	11:56	62.5	<0.0050	0.491	<0.0010	0.952	0.0356	0.0388	0.134
Deykin Ck	11-Sep-2018	11:15	66.2	<0.0050	0.334	0.0012	0.605	0.0299	0.0367	0.0455
Deykin Ck	24-Sep-2018	11:36	68.5	<0.0050	0.901	<0.0010	1.04	0.0236	0.0239	0.0294
Deykin Ck	9-Nov-2018	12:30	46.1	<0.0050	1.59	<0.0010	1.64	0.0143	0.0156	0.0215
Quamichan Ck	11-Apr-2018	13:00	51.9	0.277	0.227	0.0077	1.39	0.196	0.215	0.266
Quamichan Ck	3-May-2018	10:40	51.9	0.185			1.34	0.187	0.208	0.224
Quamichan Ck	9-May-2018	10:24	50.8	0.0346			2.68	0.137	0.157	0.540
Quamichan Ck	23-May-2018	10:58	49.3	0.0959	0.0072	0.0026	1.30	0.154	0.190	0.236
Quamichan Ck	7-Jun-2018	11:00	55.6	0.189	0.0112	0.0053	1.27	0.202	0.225	0.263
Quamichan Ck	20-Jun-2018	9:35	54.3	0.356	<0.0050	<0.0010	1.36	0.184	0.222	0.230
Quamichan Ck	18-Jul-2018	10:15	55.5	0.0089	<0.0050	<0.0010	14.7	0.0702	0.117	0.744
Quamichan Ck	25-Jul-2018	8:15	54.9	0.201	<0.0050	<0.0010	1.66	0.187	0.216	0.321
Quamichan Ck	13-Aug-2018	9:30	54.1	0.0354	<0.0050	<0.0010	1.99	0.196	0.226	0.339
Quamichan Ck	23-Aug-2018	9:45	58.6	0.461	<0.0050	<0.0010	1.52	0.224	0.270	0.307
Quamichan Ck	11-Sep-2018	9:50	58.2	0.194	<0.0050	0.0035	2.10	0.219	0.292	0.362
Quamichan Ck	24-Sep-2018	9:45	57.6	0.238	0.0097	0.0076	1.77	0.222	0.264	0.350
Quamichan Ck	9-Nov-2018	11:43	56.6	0.394	0.103	0.0066	2.39	0.204	0.262	0.311
Stamps Ditch	11-Apr-2018	15:00	120	0.0434	0.527	0.0061	1.46	0.291	0.304	0.424
Stamps Ditch	3-May-2018	12:30	150	0.0393			1.10	0.159	0.166	0.554
Stamps Ditch	9-Nov-2018	13:45	64.0	0.0491	0.255	0.0048	1.23	0.228	0.259	0.350
Woodgrove Pond	18-Jul-2018	13:15	76.5	0.0053	<0.0050	<0.0010	2.61	0.0189	0.0453	0.236
Woodgrove Ck S	20-Jun-2018	12:20					0.509			0.0378
Woodgrove Ck S	18-Jul-2018	13:00	79.8	0.0676	0.0850	0.0031	0.563	0.0327	0.0338	0.328
Woodgrove Ck S	25-Jul-2018	10:25	91.0	0.0725	0.0262	0.0032	0.290	0.0631	0.0579	0.133
Woodgrove Ck S	13-Aug-2018	12:15	112	0.0893	0.0169	0.0020	0.425	0.0713	0.0728	0.142
Woodgrove Ck S	23-Aug-2018	12:10	83.8	0.108	0.0153	0.0015	1.25	0.0698	0.0671	2.91
Woodgrove Ck S	11-Sep-2018	11:45	83.6	0.0707	0.0993	0.0022	0.410	0.0559	0.0545	0.120
Woodgrove Ck S	24-Sep-2018	11:56	88.2	0.0492	0.930	0.0061	1.09	0.0113	0.0132	0.0629
Woodgrove Ck S	9-Nov-2018	12:50	89.5	0.0093	1.93	0.0038	1.98	0.0195	0.0201	0.0329
Woodmere Ditch	9-Nov-2018	13:30	66.7	0.0159	0.929	0.0065	1.15	0.0263	0.0298	0.0449

Table 4: Nutrient concentration (mg/l) during winter high discharge sampling of tributary streams (Dec 2019). Samples exceeding provincial water quality guidelines for freshwater habitat are in **bold and outlined**. Cells are colour coded to indicate relative concentration of each site compared to the other sites in the sample set (red – relatively high, white – relatively low).

	Hardness	Ammonia, Dissolved	Total Nitrogen	Orthophosphate, Dissolved	Phosphorus dissolved	Phosphorus total
Stamps Rd	96.4	0.0599	3.96	0.642	0.690	**0.678**
Martin Pl	43.7	0.0101	1.49	0.0569	0.0808	**0.0976**
Stanhope Rd	50.5	0	1.98	0.0250	0.0379	**0.0572**
Woodmere ditch	72.8	0.0179	2.32	0.0183	0.0262	**0.0396**
Woodgrove U	24.2	0	0.157	0.0228	0.0284	**0.0395**
Woodgrove L	90.8	0.0119	1.15	0.0040	0.0063	**0.0072**
Deykin Ck	84.6	0	1.98	0.0072	0.0085	**0.0201**
Aitken Ck	115	0	2.93	0.0087	0.0119	**0.0159**
McIntyre Ck	58.7	0.173	3.00	0.279	0.280	**0.89**
WQ Standard		2				0.015

Table 5: Alkali metal concentration (mg/l) during winter high discharge sampling of tributary streams (Dec 2019). Samples exceeding provincial water quality guidelines for freshwater habitat are in **bold and outlined**. Cells are colour coded to indicate relative concentration of each site compared to the other sites in the sample set (red – relatively high, white – relatively low).

	Lithium	Sodium	Potassium	Rubidium	Cesium
Stamps Rd	0	7.17	2.72	0.00123	0.000019
Martin Pl	0	6.48	2.23	0.00179	0.000028
Stanhope Rd	0.0015	10.0	0.660	0.00081	0.000058
Woodmere ditch	0	9.38	1.07	0.00067	0
Woodgrove U	0.0017	3.36	0.480	0.00079	0.000047
Woodgrove L	0	7.09	0.377	0.00025	0
Deykin Ck	0	12.5	0.538	0.00046	0.000010
Aitken Ck	0.0022	11.0	0.494	0.00039	0.000024
McIntyre Ck	0	7.87	3.62	0.00469	0.000040
WQ Standard					

Table 6: Alkaline earth metal concentration (mg/l) during winter high discharge sampling of tributary streams (Dec 2019). Samples exceeding provincial water quality guidelines for freshwater habitat are in **bold and outlined**. Cells are colour coded to indicate relative concentration of each site compared to the other sites in the sample set (red – relatively high, white – relatively low).

	Beryllium	Magnesium	Calcium	Strontium	Barium
Stamps Rd	0	7.80	25.7	0.144	0.0120
Martin Pl	0	4.23	10.5	0.0633	0.0141
Stanhope Rd	0	3.99	13.6	0.113	0.0133
Woodmere ditch	0	4.85	21.1	0.113	0.0133
Woodgrove U	0	1.97	6.45	0.0399	0.00789
Woodgrove L	0	5.59	27.2	0.195	0.00791
Deykin Ck	0	4.46	26.5	0.143	0.0107
Aitken Ck	0	8.07	32.6	0.263	0.0140
McIntyre Ck	0	4.75	15.7	0.102	0.0157
WQ Standard					

Table 7: Metal concentration (mg/l) during winter high discharge sampling of tributary streams (Dec 2019). Samples exceeding provincial water quality guidelines for freshwater habitat are in **bold and outlined**. Cells are colour coded to indicate relative concentration of each site compared to the other sites in the sample set (red – relatively high, white – relatively low).

	Titanium	Vanadium	Chromium	Manganese	Iron	Cobalt
Stamps Rd	0.0201	0.00243	0.00073	**0.00583**	0.280	0.00021
Martin Pl	0.0333	0.00222	0.00118	**0.00895**	0.586	0.00026
Stanhope Rd	0.0369	0.00253	0.00136	**0.0129**	0.772	0.00033
Woodmere ditch	0.00714	0.00081	0.00043	**0.0228**	0.151	0.00018
Woodgrove U	0.0479	0.00278	0.00158	**0.0304**	**1.30**	0.00081
Woodgrove L	0.00288	0	0.00016	**0.00183**	0.068	0
Deykin Ck	0.00481	0.00053	0.00026	**0.0105**	0.110	0.00016
Aitken Ck	0.00300	0.00057	0.00035	**0.00641**	0.168	0.00018
McIntyre Ck	0.0198	0.00403	0.00106	**0.195**	**1.30**	0.00190
WQ Standard				0.001	1	0.004

Table 8: Metal (continued) concentration (mg/l) during winter high discharge sampling of tributary streams (Dec 2019). Samples exceeding provincial water quality guidelines for freshwater habitat are in **bold and outlined**. Cells are colour coded to indicate relative concentration of each site compared to the other sites in the sample set (red – relatively high, white – relatively low).

	Nickel	Copper	Zirconium	Molybdenum	Tungsten	Silver
Stamps Rd	0.00121	0.00390	0.000217	0.000354	0	0
Martin Pl	0.00123	0.00337	0.000244	0.000083	0	0.000011
Stanhope Rd	0.00138	0.00270	0.000184	0	0	0.000020
Woodmere ditch	0.00057	**0.00382**	0.000092	0.000077	0	0
Woodgrove U	0.00122	0.00281	0.000107	0	0	0
Woodgrove L	0	0.00117	0	0	0	0
Deykin Ck	0.00068	0.00194	0.000094	0	0	0
Aitken Ck	0.00064	0.00071	0	0.000054	0	0
McIntyre Ck	0.00270	**0.00819**	0.000128	0.000790	0	0.000014
WQ Standard		0.004		0.002		0.00005

Table 9: Post-transition metal concentration (mg/l) during winter high discharge sampling of tributary streams (Dec 2019). Samples exceeding provincial water quality guidelines for freshwater habitat are in **bold and outlined**. Cells are colour coded to indicate relative concentration of each site compared to the other sites in the sample set (red – relatively high, white – relatively low).

	Aluminum	Zinc	Cadmium	Tin	Mercury	Thallium	Lead	Bismuth
Stamps Rd	**0.420**	0.0064	0.0000059	0	0	0	0.000097	0
Martin Pl	**0.725**	0.0037	0.0000081	0	0.0000052	0	0.000149	0
Stanhope Rd	**0.855**	0.0084	0.0000116	0	0	0	0.000221	0
Woodmere ditch	**0.138**	0.0066	0.0000078	0	0	0	0.000084	0
Woodgrove U	**0.919**	0.0037	0.0000062	0	0	0	0.000190	0
Woodgrove L	0.0613	0.0034	0.0000051	0	0	0	0	0
Deykin Ck	**0.106**	**0.0146**	0.0000085	0	0	0	0.000067	0
Aitken Ck	**0.147**	0	0.0000054	0	0	0	0.000086	0
McIntyre Ck	**0.553**	**0.0231**	0.0000394	0	0	0.000016	0.000389	0
WQ Standard	0.1	0.015	0.0001		0.00001		0.003	

Table 10: Metalloid concentration (mg/l) during winter high discharge sampling of tributary streams (Dec 2019). Samples exceeding provincial water quality guidelines for freshwater habitat are in **bold and outlined**. Cells are colour coded to indicate relative concentration of each site compared to the other sites in the sample set (red – relatively high, white – relatively low).

	Boron	Silicon	Arsenic	Antimony	Tellurium
Stamps Rd	0.013	5.16	0.00052	0	0
Martin Pl	0.012	5.31	0.00042	0	0
Stanhope Rd	0.017	6.32	0.00038	0	0
Woodmere ditch	0.018	5.58	0.00023	0.00015	0
Woodgrove U	0	4.23	0.00031	0	0
Woodgrove L	0.019	3.77	0.00011	0	0
Deykin Ck	0.021	3.49	0.00016	0	0
Aitken Ck	0.031	4.77	0.00014	0	0
McIntyre Ck	0.068	5.03	0.00077	0.00012	0
WQ Standard	1.2		0.005		

Table 11: Actinide, thorium+uranium, and reactive non-metal concentrations (mg/l) during winter high discharge sampling of tributary streams (Dec 2019). Samples exceeding provincial water quality guidelines for freshwater habitat are in **bold and outlined**. Cells are colour coded to indicate relative concentration of each site compared to the other sites in the sample set (red – relatively high, white – relatively low).

	Thorium	Uranium	Phosphorus	Sulfur	Selenium
Stamps Rd	0	0.000031	0.653	5.23	0.000141
Martin Pl	0	0.000019	0.080	2.61	0.000106
Stanhope Rd	0	0.000015	0.056	2.58	0.000183
Woodmere ditch	0	0	0	6.85	0.000087
Woodgrove U	0	0.000011	0.060	1.91	0
Woodgrove L	0	0	0	23.1	0.000791
Deykin Ck	0	0	0	17.6	0.000062
Aitken Ck	0	0	0	22.0	**0.00290**
McIntyre Ck	0	0.000044	1.61	6.62	0.000212
WQ Standard					0.002

Table 12: Physical water quality parameter collected at creek sites

	Deykin Ck	Woodgrove Ck	Aitken Ck
T (°C)			
18-Jul-18	15.7	16.6	12.9
25-Jul-18	16	16.6	
13-Aug-18	16	17	12.6
11-Sep-18	14.3	15.1	12.7
24-Sep-18	13.2	13.2	12.5
09-Nov-18	10.4	10.2	10.7
DO (mg/l)			
18-Jul-18	7.54	3.9	7.57
25-Jul-18	10.4	4.1	
13-Aug-18	8.6	3.8	9.5
11-Sep-18	9.5	4.7	8.9
24-Sep-18	7.87	5.3	6.62
09-Nov-18	10.7	9	9.9
SPC (µS/cm)			
18-Jul-18	435.4	428.7	
25-Jul-18	380.9	370.5	
13-Aug-18	380.4	396.3	282.2
11-Sep-18	282.4	348.4	268
24-Sep-18	211.3	516.7	326.6
09-Nov-18	311.1	491.8	334.6
pH			
18-Jul-18	8.31	7.47	7.84
25-Jul-18	7.7	7.7	
13-Aug-18	8.3	8	8.1
11-Sep-18	7.5	7.4	7.4
24-Sep-18	7.5	6.83	7.15
09-Nov-18	7.4	7.3	7.5

Appendix 1:

Installation of a Temperature Data Logger Array in Quamichan Lake

Somenos Marsh
WILDLIFE SOCIETY
Stewards of the Somenos Marsh Conservation Area

Prepared For:
The Quamichan Stewards

Prepared By
Dave Preikshot, PhD, RPBio
Staff Ecosystems Scientist
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Summary

As part of the Somenos marsh Wildlife Society’s ongoing research and monitoring of water Quality in the Somenos basin and adjacent waterways we propose to install up to two temperature data logger arrays in Quamichan Lake to monitor lake dynamics on time scales ranging from hours to years. Monitoring temperature is a simple and cost-effective means to understand the physical, chemical, and biological processes in an aquatic environment. In Quamichan lake temperature will be a useful index to the status of water circulation, oxygen concentration, fish physiology, fish distribution, water chemistry and undesirable algal blooms. Understanding changes in these types of lake processes will be invaluable in guiding management decisions on habitat remediation and trout enhancement activities given recent episodes of anoxia in Quamichan Lake.

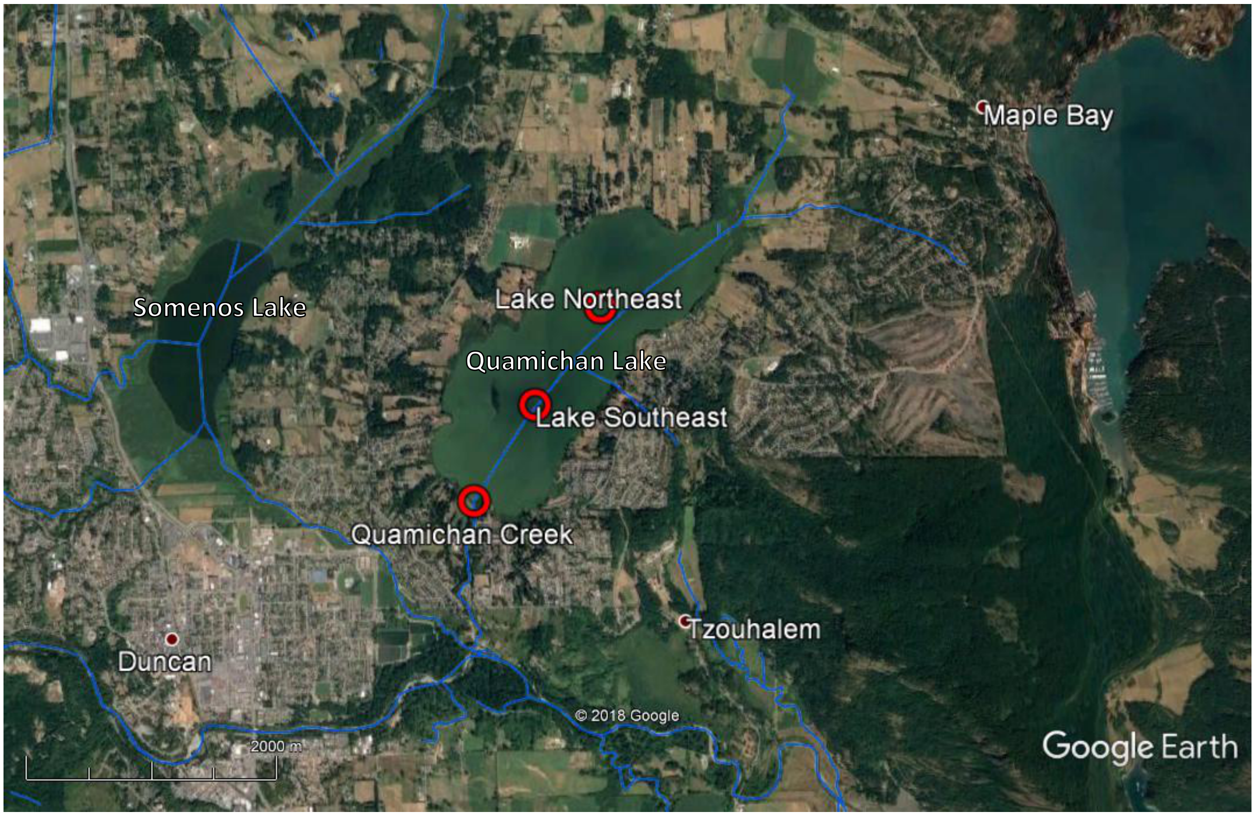

Figure 1: Quamichan Lake and sample sites (red circles) used in water quality monitoring. Creeks, stream, and lake center lines are shown as blue.

Introduction

Quamichan Lake is both relatively shallow and eutrophic with a maximum depth of about 9m (McPherson 2006) in a suburban/rural area in the Municipality of North Cowichan, Figure 1. Its setting has made it increasingly susceptible to Blue-Green Algae algal blooms resulting from high concentrations of phosphate. These Blue-Green Algae blooms begin in the late spring and peak in the summer. During the peak of these blooms in the summer the decomposition of dying Blue-Green Algae sinking through the water column creates anoxia in lake habitat below three meters depth. This phenomenon has been well documented in nearby Somenos Lake (Preikshot 2016). In recent years there has been increasing anecdotal evidence that these anoxia events have been associated with significant fish kills in Quamichan Lake. In order to help ameliorate this situation, an aeration unit was installed in the lake in 2014 to create refuge habitat for trout. Funding for this aeration habitat improvement exercise was a joint effort by Quamichan Stewards, the Municipality of North Cowichan, the Duncan Rotary Club, TimberWest (which owns the lake bottom), Woodmere Strata Corporation and Aquatech Environmental Systems.

Agricultural activities and suburban development in the Quamichan watershed have resulted in the lake being subjected to nutrient loading, particularly by phosphorous. In recent years this phosphorous loading has resulted in Blue-Green Algae blooms. Studies of similar issues in the nearby Somenos Lake (Preikshot et al. 2015 and Preikshot 2016) demonstrate that such algae blooms can set up a cascade of effects on the lake causing harm to fish habitat and fish populations:

- Blue-Green Algae is at the bottom of a food chain that does not result in the secondary production of zooplankton suitable as prey for fish,
- production of Blue-Green Algae excludes other phytoplankton that would be consumed by zooplankton allowing energy transfer to fish,
- Blue-Green Algae traps light energy near the waster surface and heats the lake water more than would otherwise occur creating a very steep thermocline,
- oxygen in the lower part of the water column is consumed by heterotrophic bacteria feeding upon dead and sinking Blue-Green Algae.
- A positive feedback loop can thus be created as the very warm surface water will not mix with water below the thermocline leading to anoxia below the thermocline.

By determining the timing and duration of high temperature summer periods in Quamichan Lake it may be possible to better time use of devices such as aerators to minimise operating cost and maximise their effect. The temperature data can also be combined with periodic monitoring of other physical and chemical variables, *e.g.*, pH, conductivity, dissolved organic matter and dissolved oxygen to provide a more detailed understanding of the range and dynamics of lake processes that create or remove habitat suitable for trout. Such augmentation could be possible by collaboration with the Somenos Wildlife Conservation Society which is in possession of limnological sampling gear.

Quamichan Lake is known to have supported small wild breeding populations of Cutthroat Trout (*Oncorhynchus clarki*) and Rainbow Trout (*O. mykiss*) (Burns 1999). However, in the past 20 years it is likely that populations of both trout species in Quamichan Lake have been severely reduced by a combination of high summer temperatures and anoxia events resulting from increasingly persistent and pervasive summer Blue-Green Algae blooms. Annual stocking by the Freshwater Fisheries Society of British Columbia (FWFSBC) hatchery program has allowed fisheries to persist in a limited form on the lake, but stocking has declined in the last twenty years, Figure 2. Stocking reports from the FWFSBC webpage (www.gofishbc.com/fish-stocking-reports.aspx) indicate that over the last decade 1,000 to 5,000 Cutthroat Trout and Rainbow Trout are released into the lake in most years.

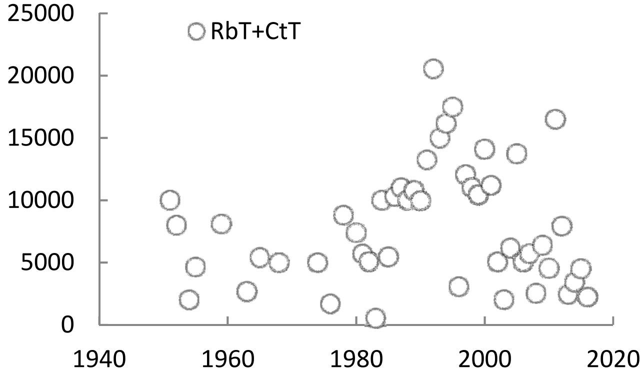

Figure 2: Annual total numbers of hatchery Rainbow Trout (RbT) and Cutthroat Trout (CtT) placed in Quamichan Lake, 1950-2016.

One goal for fish management in Quamichan Lake could be the reestablishment of wild breeding populations of Cutthroat Trout and Rainbow Trout. In order to achieve this, and remove the requirement, for continual hatchery augmentation it will be necessary to remediate the lake habitat. Two important parameters to measure habitat suitability for fish are water temperature and oxygen concentration. Monitoring water temperature will provide a useful baseline for comparison as management actions are taken in the future to improve Quamichan Lake habitat for fish. Oxygen solubility in water declines as temperature rises so monitoring temperature also can be a guide to maximum potential oxygen concentration throughout the water column.

Laboratory trials suggest that Cutthroat Trout survival is negatively influenced by long-term (~60 days) exposure to temperatures over 19.6ºC, whereas Rainbow Trout experience increased mortality when long-term temperatures were over 24.3ºC (Bear et al. 2007). Data reported by McPherson (2006) suggests that such temperatures are regularly exceeded in the near surface waters of Quamichan Lake during the months of June to September, which is much longer than the 60 days in the lab study referenced above. Although a summer temperature refuge exists in deeper waters of the lake, >7m, this portion of the water column almost always exhibits dissolved oxygen concentrations below 5mg/l and is often even anoxic (McPherson 2006). For most salmonid species dissolved oxygen concentration below 5mg/l will impose moderate limitations on survival and levels lower than 3 are likely to lead to ‘acute mortality’ (Carter 2005).

Monitoring temperature will thus allow the identification of the timing of thermal limits to salmonid habitat. Understanding seasonal changes in temperature will thus determine whether it is possible to sustain salmonids in Quamichan Lake under current conditions. Once a baseline is established management options can then be examined as to whether to protect suitable habitat or enhance degraded habitat in the lake.

It is generally understood by local long-term residents that significant blue-green algae blooms did not occur in Quamichan Lake before the 1970s. It is also held that anoxia events and fish kills were also very rare historically. Indeed, a field report on a broad and extensive fish kill in Quamichan Lake (Anon. 1958) states that local residents could not recall a similar event during the decades up to that time. Monitoring temperature in the water column will be a cost-effective and informative way to measure how habitat characteristics respond to management efforts designed to reduce total phosphorus in the lake and phosphorus entering the lake input. Given this information, concerned local residents and government agencies can share a common frame of reference to measure the success of habitat remediation in Quamichan Lake and the potential rejuvenation of wild stocks of Cutthroat Trout and Rainbow Trout.

This project would complement ongoing research and monitoring in Somenos Lake which is facing similar issues with Blue-Green Algae blooms and loss of salmonid habitat. The waters of the Somenos and Quamichan basins mingle at the confluence of Somenos and Quamichan Creek near the Cowichan River. It is therefore logical to study both systems together so that appropriate research and management approaches can be adopted that leverage economies of scale while addressing differences in these linked aquatic ecosystems.

Methodolgy

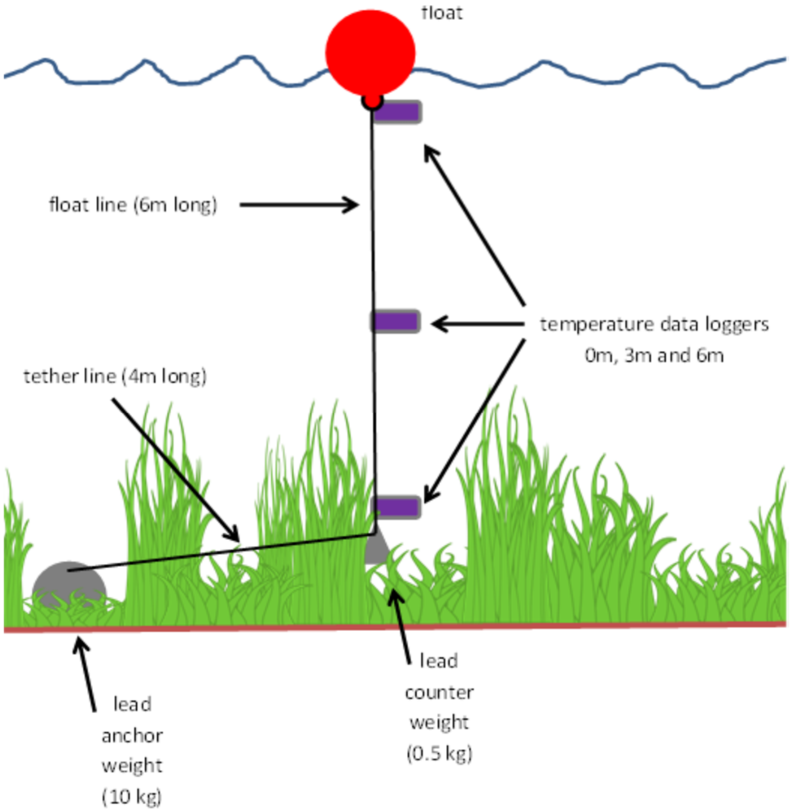

Figure 3: Design of temperature data logger array.

Temperature data logger array(s), see Figure 3 will be installed in Quamichan Lake at location(s) to be determined by reconnaissance and liaising with local residents and the Quamichan Stewards. Data logger array(s) will be set up such that temperature data loggers are placed in pairs at 0, 3, and 6m (maximum winter depth is ~9m). It is proposed that two data loggers be placed at each depth in case of failure of one. Each array would therefore have 6 data loggers. Arrays will be suspended from a large float at the surface and anchored to the bottom with a ~10 kg weight. The data loggers will be attached, by zip ties, to a polypropylene line suspended from the float. The float is held vertical in the water column by a small weight ~0.5kg attached to the polypropylene line just below the 6m temperature loggers. The array will be able to move up and down with changes in the surface elevation of the lake because the small weight is separated from the anchor weight by approximately 4m of polypropylene line.

A similar data logger array has been installed in Somenos Lake and has been in operation for over 4 years, see Figure 4. In the author’s experience, these devices will last for about 5 years when measuring temperature at a frequency of once per hour. This temperature data has proven invaluable to understanding when the lake becomes unsuitable for trout and salmonids and helping to define research programs and management options too target specific aspects of juvenile and adult life history that the lake regulates.

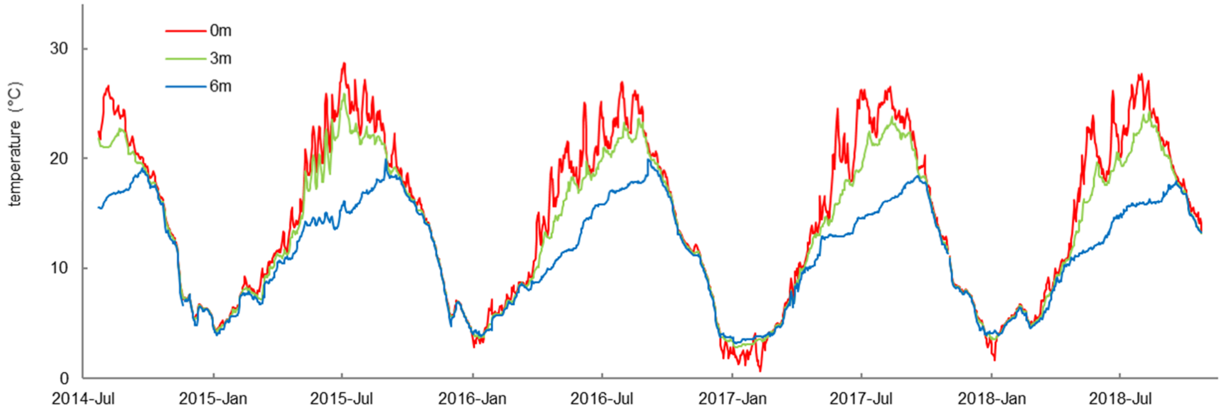

Figure 4: Daily mean temperature in Somenos Lake at 0, 3, and 6m, July 2014 to May 2018.

Work will be done Dave Preikshot (PhD, RPBio), the Somenos marsh Wildlife Society ecosystems scientist, at a rate of $CDN 60 per hour ($40 per hour plus 50% overhead for field equipment, administrative support and office space). It is anticipated that there will be 4 hours of reconnaissance and site selection, 8 hours for data array construction and installation and 16 hours of data collection and analysis for presentation to the Quamichan Stewards. It is anticipated that support for site reconnaissance temperature data array installation will be provided by Quamichan Stewards volunteers.

A formal report could be prepared for the Quamichan Stewards at the end of year one with an option to continue monitoring and reporting work on an annual basis. The cost of such a report is not included in the budget below but would be at the quoted bill out rate for 40 hours, *i.e.*, a cost of $CDN2,400.

Budget

Materials (option1: 2 data logger arrays)			
Item	*Unit Cost ($CDN)*	*Number*	*Total ($CDN)*
Data logger	100	14	1,400
Polypropylene Line	2 per meter	20m	40
Lead Weight	20	4	80
Float	30	2	60
Sub Total			**1,580**
Materials (option2: 1 data logger array)			
Item	*Unit Cost ($CDN)*	*Number*	*Total ($CDN)*
Data logger	100	8	800
Polypropylene Line	2 per meter	10m	20
Lead Weight	20	2	40
Float	30	1	30
Sub Total			**890**

Personnel			
Crew	*Rate ($CDN/hour)*	*Hours*	*Total ($CDN)*
Field Biologist	60	28	1680
Sub Total			**1,680**

Total Cost Option1	**3,260**
Total Cost Option2	**2,570**

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