Fisheries and Oceans Canada — Pêches et Océans Canada

Science — Sciences

CULTUS LAKE, BRITISH COLUMBIA: A REGIONAL BELLWETHER OF AQUATIC ECOSYSTEM RESPONSES TO ANTHROPOGENIC STRESSORS AND GLOBAL ENVIRONMENTAL CHANGE

Daniel T. Selbie, Ph.D.
Head, Lakes Research Program
Science Branch, Fisheries and Oceans Canada
Cultus Lake Salmon Research Laboratory

CULTUS LAKE IS A VALUED NATURAL RESOURCE

Situated near Chilliwack, British Columbia, 100 km east of Vancouver, in the traditional territory of the Sto:lo people and Soowahlie First Nation, Cultus Lake is a well-known, highly-valued peri-urban lake ecosystem, providing significant ecosystems services (i.e. recreation, water supplies, fisheries, local economy) to a wide array of interests (Robinson 2011, 2012). Given its azure blue summer waters, beautiful mountain vistas, extensive parks, and proximity to the British Columbia Lower Mainland, recreational values are particularly high both on the lake and within its watershed, attracting in excess of 2-3 million visitors each year, largely during the summer months (FVRD 2011; Delcan 2012).

Users of Cultus Lake do so for a variety of purposes. While most Cultus Lake experiences are seasonal (79%), many locals reside within the watershed, and very successful local businesses rely upon the lake and its ecosystem services, ranging from seasonal operations (i.e. waterslides, golf course, boat rentals, food suppliers, parks) to year-round enterprises (i.e. fuel station, convenience stores, restaurants; Robinson 2011). Many users of Cultus Lake identify with the area culturally, through long-formed memories and experiences, or even intrinsically, making the area a very cared-about space within the British Columbia Lower Mainland and beyond.

A user survey conducted in the summer, fall, and winter months of 2010-2011 revealed that most users value the environmental health of Cultus Lake highly, and desire greater environmental stewardship and care for the area (93%; Robinson 2011). The survey indicates most users (87%) are concerned about lake water quality, with a similar representation (87%) concerned about the excess nutrient loading, which threatens it (Robinson 2011). Similarly most users are concerned about the fate of species-at-risk within Cultus Lake, in particular the endangered Cultus Sockeye Salmon (*Oncorhynchus* nerka; 83%), while many (54%) know less about, but are concerned about the fate of the endangered Cultus Lake Pygmy Sculpin (*Cottus aleuticus*, Cultus Population; Robinson 2011). The results of this study indicate that there is broad societal desire to ensure the sustainable use of Cultus Lake, and to protect its ecosystem services and species at risk; central foci of a dedicated local lake stewardship group, the Cultus Lake Aquatic Stewardship Strategy (Robinson 2011, 2012).

Cultus Lake in a Watershed and Airshed Context

The Cultus Lake Watershed

Nestled within the northern Cascade Mountains of southwestern British Columbia, Cultus Lake is a relatively small, low elevation, coastal lake ecosystem, situated within a small, steep-sided, international watershed (18% USA (headwaters); 82% Canada; Putt et al. 2019; Table 1; Figure 1).

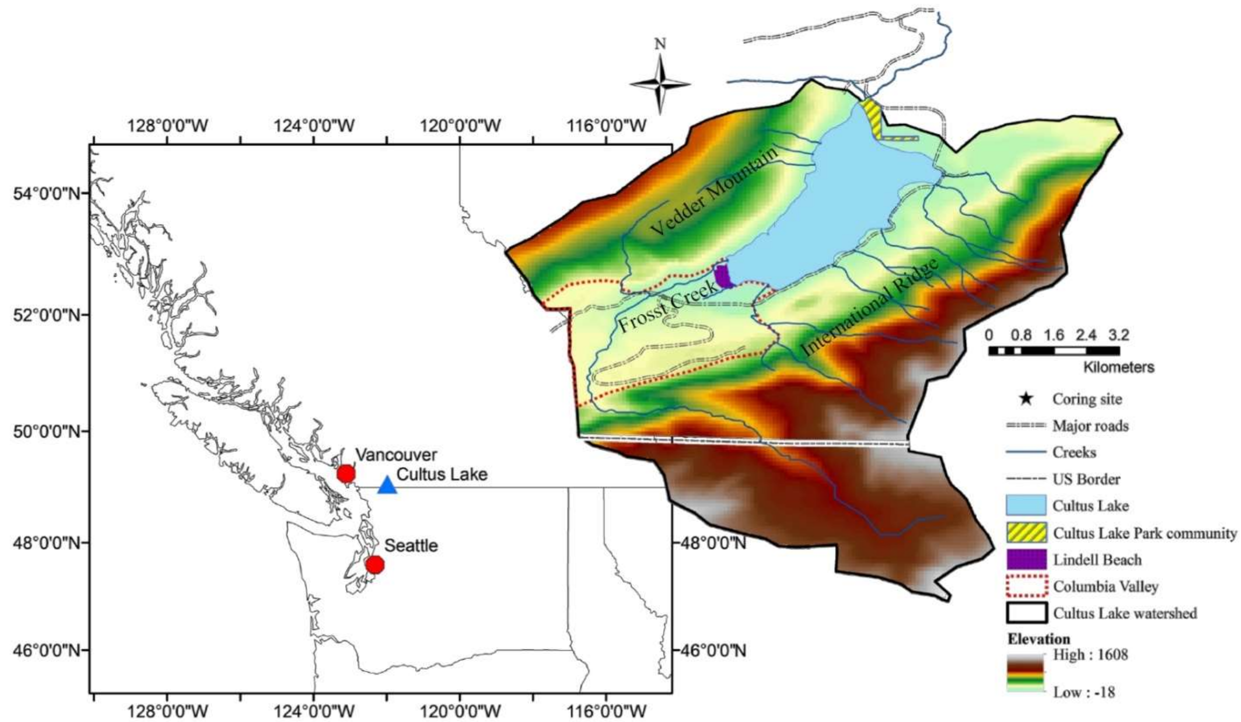

Figure 1: The Cultus Lake, BC international watershed in relation to the Canada-USA Pacific Northwest. Modified from Gauthier et al. (*accepted*).

Physiographically, the lake is bounded by Vedder Mountain Ridge to the northwest, separating the watershed from the Fraser Valley to the northwest, International Ridge to the east, and the Columbia Valley to the southwest (Figure 1). The latter is underlain by a large, unconstrained aquifer, hydrologically connected to Cultus Lake via both groundwater and surface inflows (Zubel 2000; Putt et al. 2019). Ultimately 11 primary creeks hydrologically feed 62 % of the annual lake water balance, ranging from high-gradient mountainside streams to ephemeral tributaries, with 30% arising from groundwater inputs, and ~ 8% from precipitation directly on the lake's surface (Figure 2). Sweltzer Creek, the only known outflow, accounts for the vast majority (~97%) of lake water effluxes (Putt et al. 2019).

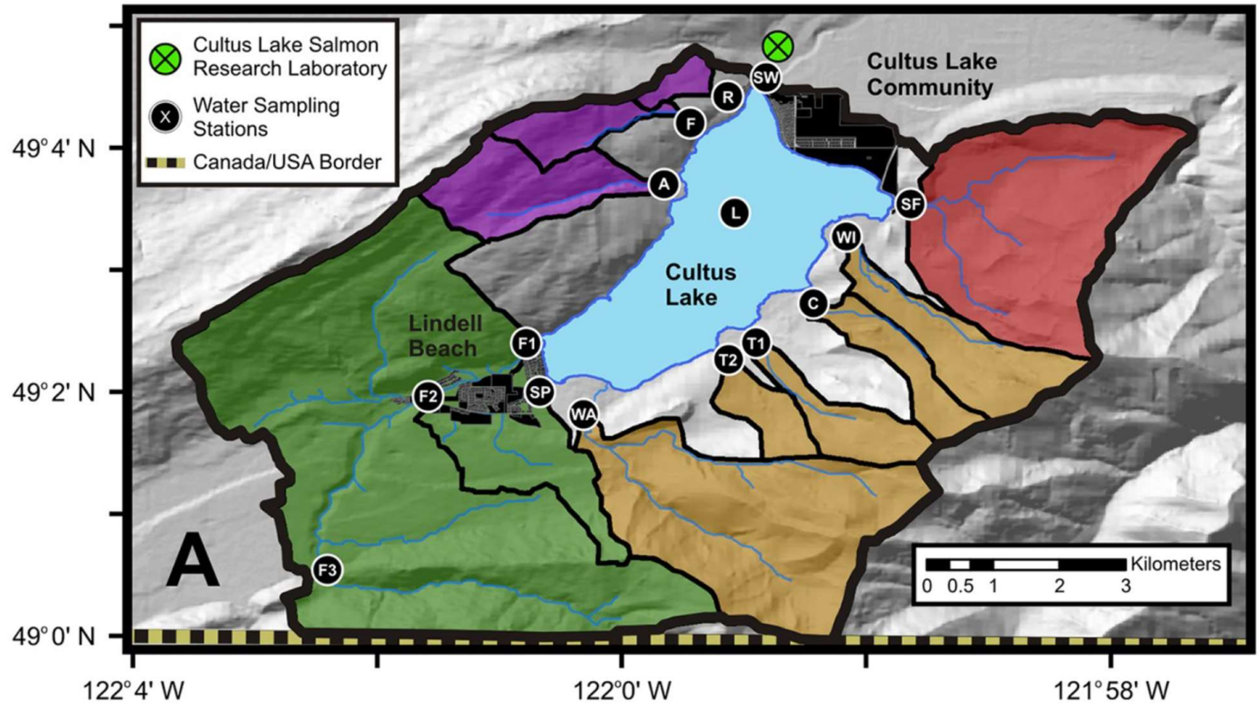

Figure 2. Map of the Cultus Lake, BC watershed (Canadian portion shown). Locations of the Putt et al. (2019) study water sampling stations are shown (R-Reservoir Creek; F-Fin Creek; A-Ascaphus Creek; F1-Frosst Creek Station 1; F2-Frosst Creek Station 2; F3-Frosst Creek Station 3; SP-Spring Creek, WA- Watt Creek; T1-Teapot Creek braid 1; T2-Teapot Creek braid 2; C-Clear Creek; WI-Windfall Creek; SF-Smith Falls Creek; SW-Sweltzer Creek (lake outlet); L-Fisheries and Oceans Canada limnological monitoring station), as is the location of the local atmospheric sampling station at the Fisheries and Oceans Canada's Cultus Lake Salmon Research Laboratory. Cultus Lake sub-catchment boundaries are coloured to reflect sub-catchments derived from clustering analysis as presented in Putt et al. (2019), Vedder Mountain (purple), Columbia Valley (green), International Ridge (orange), and Smith Falls Creek (red). The outflow Sweltzer Creek subwatershed, largely encompassing the community of Cultus Lake is not coloured. Modified from Putt et al. (2019).

The Cultus Lake watershed is largely within the Coastal Western-Hemlock Biogeoclimatic Zone, characterized by a temperate maritime climate with mild winters and warm, dry summers (Meidinger and Pojar 1991; Kottek et al. 2006). The annual daily average temperature is 10.8 ^{o}C ± 2.0 ^{o}C (1SD), ranging from mean daily minima in December and January (3.3^{o}C ± 1.9 ^{o}C (1SD), to a mean daily maximum in July (18.8 ^{o}C ± 0.9 ^{o}C (1SD) (1981-2010 Canadian Climate Normals – Stn # 1101530; Environment and Climate Change Canada 2019). Significant precipitation (1.67 m) occurs within this temperate rainforest setting, largely falling as rain, and concentrated between the months of October and April (1981-2010 Canadian Climate Normals – Stn # 1101530; Environment and Climate Change Canada 2019). Consequently, Cultus Lake has a relatively short estimated water residence time (1.8 yr; Table 1; Shortreed 2007), likely seasonally characterized by higher winter and lower summer flushing (Putt et al. 2019).

Much of the Cultus Lake shoreline and near-lake catchment are within the bounds of municipal and provincial parks. As such, overall shoreline development is somewhat limited, and watershed occupancy rather diffuse, with more concentrated communities situated to the northeast (i.e. Cultus Lake Parks Board) and southwest ends of the lake (i.e. Lindell Beach; Figure 1,2).

The Cultus Lake watershed can be divided into 5 distinct inflowing sub-catchments, based upon similar geomorphological, land use, and hydrological properties (Figure 2; Putt et al. 2019). To the northwest, the Vedder Mountain sub-catchment is largely forested, with some forest harvesting and recreational trails in its upper reaches. The sub-catchment encompasses all northwestern lake tributaries (Ascaphus, Fin, and Reservoir creeks), and at lower elevations is within Cultus Lake Provincial Park, with localized group campsites accessed seasonally (Figure 2). To the southeast, the International Ridge sub-catchment, which drains Windfall, Clear, Teapot, and Watt creeks, is primarily densely forested (>80%; Putt et al. 2019). This sub-catchment is largely devoid of private development, as it lies within Cultus Lake Provincial Park, but is characterized by extensive provincial campgrounds and day use areas along the shoreline and nearshore upland areas, receiving more than an estimated 800,000 visitors annually (BC Parks 2018).

The Columbia Valley to the southwest, is the largest sub-catchment within the Cultus Lake watershed. It is primarily drained by Frosst Creek, the largest inflowing tributary to the lake, which originates from the USA, but also by Spring Creek, which emerges directly from the Columbia Valley aquifer near the lake (Zubel 2000; Putt et al. 2019). The slopes bounding the Columbia Valley are predominantly forested, while agriculture and other developments (20% of the total sub-catchment area) occur along the central valley floor (Putt et al. 2019). The Smith Falls Creek and Sweltzer Creek sub-catchments, drain the northern portion of the Cultus Lake catchment. The Smith Falls Creek sub-catchment partially lies within the densely forested Cultus Lake Provincial Park, while its north-eastern portion is sparsely covered and contains meadows and wetlands (Putt et al. 2019). The Sweltzer Creek sub-catchment encompasses the community of Cultus Lake (population ~990; ISL 2014) and the outlet of the lake, Sweltzer Creek, which flows northward along a shallow gradient to the Chilliwack River (Shortreed 2007; Putt et al. 2019).

Ultimately, Cultus Lake and its watershed (Figure 1) can be viewed as a connected network of terrestrial (i.e. riparian, forest, montane) and aquatic ecosystems (i.e. wetlands, streams, lake), interdependent upon one another. Water and air movements connect these ecosystems through numerous ecological processes (Figure 3), which in turn link them to other ecosystems (i.e. Fraser River Valley, Strait of Georgia/Salish Sea),

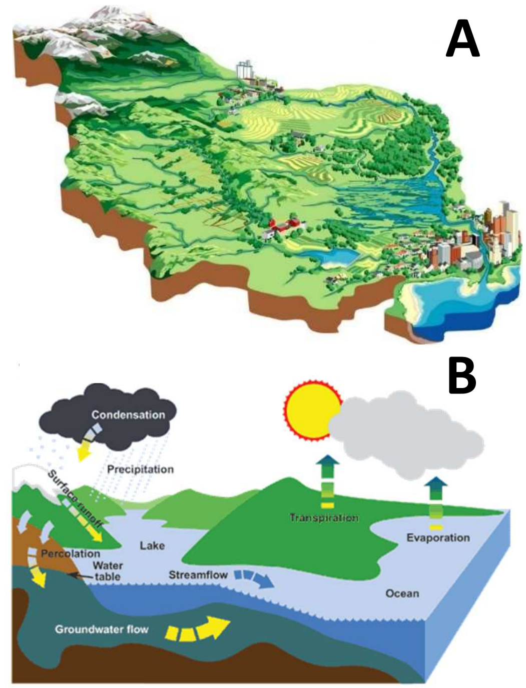

Figure 3: Aquatic and terrestrial ecosystems are connected and to the atmosphere (i.e. hydrologic, nutrient, energy flows), largely through actions of the hydrologic (water) cycle, but also other mechanisms such as atmospheric transport and chemical transformations. Panel A) shows a pictorial watershed schematic illustrating down-gradient linkages between landscapes, human activities and recipient aquatic ecosystems. Modified from USDA Natural Resources Conservation Service. Panel B) illustrates the hydrologic cycle, highlighting the major movements and phase transformations of water in the environment, including atmospheric-landscape-aquatic interchanges. Modified from Environment and Climate Change Canada (2020).

transporting biologically-essential resources (e.g. nitrogen, phosphorus, carbon) that, in part, sustain them. These ecological processes, which have been ongoing for millennia, are heavily relied upon as beneficial ecosystem services to society, but are being impacted by human activities. Thus, activities in the water, on the land, and within the air, have the potential to alter the ecology of Cultus Lake, as they do other regional aquatic ecosystems.

The Fraser Valley Airshed

Landscapes and aquatic ecosystems are inextricably linked to the atmosphere through various interactive processes and feedbacks, such as weather controls on landscape hydrology (i.e. precipitation, evaporation), and landscape effects on atmospheric properties and processes (i.e. smog, acid rain, climate change; Smol 2008). Air mass movements, the hydrological cycle (i.e. precipitation, evaporation), environmental chemistry, and solar energy are key connections between these domains.

Figure 3: Schematic of Metro Vancouver, the Fraser Valley, Whatcom County, and the shared "Fraser Valley Airshed", as viewed aerially from the west. The topographical features of the Coast and Cascade mountains funnel predominantly westerly air masses across a landscape dominated by multiple urban centers and extensive agriculture, with connectivity to the peripheral valleys. Cultus Lake is indicated by the red star. Modified from Metro Vancouver (2018).

In a similar way we view watersheds, the airshed for any geographical area can be given physical boundaries. Typically, an airshed is considered the area where the movement of air, and its constituents (e.g. particulate, pollutants), can be hindered by local geographical features, such as mountains, and by weather conditions (Government of British Columbia 2020). The Fraser Valley Airshed is international, encompassing Metro Vancouver and the Fraser Valley Regional District in Canada, and Whatcom County in the USA (Figure 3; Metro Vancouver 2018). The region can generally be considered the area bounded by the Pacific Ocean to the west, the Cascade mountains to the south, and the Coast Mountains to the North, including the lower elevations of adjacent mountain valleys (Figure 3; Metro Vancouver 2018).

The Fraser Valley Airshed is considered, by virtue of its mountainous orographic constraints, abundant and increasing population, and various pollutant emissions sources, a sensitive and constrained airshed (McKendry 2010). Landscape and marine influences on the airshed include the emissions and effects of dense urbanization and industrialization in Vancouver and surrounding areas, marine and land-based transport emissions, and emissions and from extensive agriculture in the Fraser Valley and Whatcom County (EC-USEPA 2014; Metro Vancouver 2018). Prevailing westerly atmospheric flows generally transport air masses and their pollutants eastward through the increasingly narrowing Fraser Valley and adjacent montane valleys, largely constrained by the peripheral mountains (Figure 3). More broadly, the Fraser Valley Airshed lies within the broader

Georgia Basin-Puget Sound Airshed, encompassing the Strait of Georgia, Puget Sound, the Strait of Juan de Fuca, and the populations, land uses, and emissions therein (EC-USEPA 2014).

Owing to the low altitude of Cultus Lake, the mountainous nature and physiographic aspects of its watershed, and its close proximity to the Fraser Valley, local atmospheric conditions within the watershed are strongly influenced by the dynamics and properties of the Fraser Valley Airshed, as are the physical, chemical, and biological attributes Cultus Lake itself (Figure 3; Sumka 2017; Putt et al. 2019; DFO 2020). Fortunately due to its well-known Sockeye Salmon (*Oncorhynchus nerka*) run, Cultus Lake has been studied intermittently since the 1920's, with a particularly intensive effort over the two decades by DFO's Lakes Research Program (Cultus Lake Salmon Research Laboratory), focused on understanding mechanisms of imperilment for species-at-risk and their critical habitat (Shortreed 2007; Putt 2014; Chiang et al. 2015; Sumka 2017; Loudon 2019; Putt et al. 2019; DFO 2020; Gauthier et al. *accepted*). Given the insights from this work, and connectivity to the regional airshed, Cultus Lake can be considered a model ecosystem, and a valuable indicator of the drivers and mechanisms of aquatic ecosystem changes occurring throughout southern British Columbia and Northwest Washington (Putt et al. 2019).

The Cultus Lake Ecosystem

Cultus Lake is a simple, steep-sided basin with limited nearshore area (littoral zone; 12% of the total lake surface area (Figure 2)). The lake is currently categorized as oligo-mesotrophic in nutrient status (i.e. moderate nutrient levels; Table 1; Putt et al. 2019), and as a consequence is quite biologically productive, particularly relative to the other Sockeye Salmon nursery lakes within the Fraser River drainage (Selbie et al. 2010). Coupled with high light penetration, and a general lack of ice formation, nutrients delivered to the lake fuel elevated and sustained primary production (e.g. algal growth) from the spring through fall, and moderate productivity throughout the winter period (Table 1; Shortreed et al. 2007; Gauthier et al. *accepted*, *in review*). Cultus Lake algal production supports a very productive food web, with abundant zooplankton (Table 1), that feed plankton-eating fish (e.g. juvenile Sockeye Salmon, *Oncorhynchus nerka*; Cultus Lake Pygmy Sculpin, *Cottus aleuticus*, Cultus population; threespine stickleback, *Gasterosteus aculeatus*; larval forms of various fish species) and in turn their predators (i.e. Cutthroat Trout, *O. clarkii*; Bull Trout, *Salvelinus confluentus* Northern Pikeminnow, *Ptychocheilus oregonensis*).

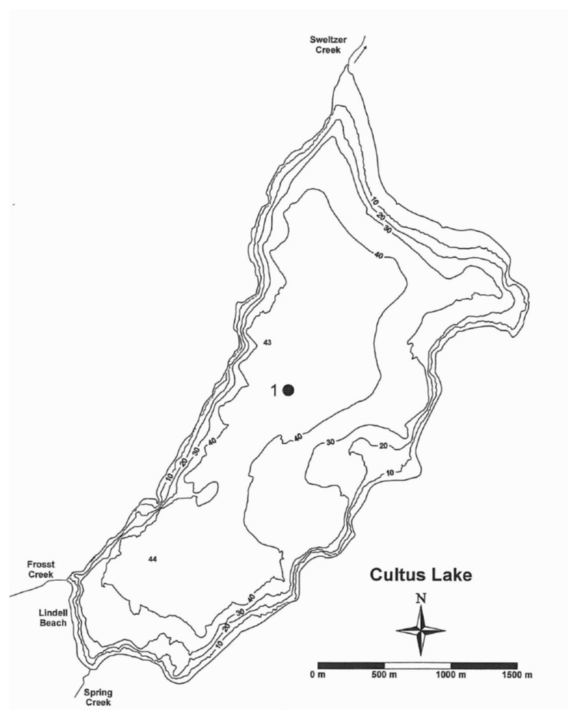

Figure 3: Bathymetric map of Cultus Lake, BC. The DFO Lakes Research Program limnological monitoring station is indicated (1).

Table 1: Biogeographical & aquatic ecological characteristics of Cultus Lake BC & its watershed

Characteristic	Value
Elevation (m asl.) [1]	46
Watershed Area (km^2) [1]	75
Surface Area (km^2) [1]	6.3
Mean Depth (m) [1]	31
Max Depth (m) [1]	44
Est. Lake Residence Time (years) [1]	1.8
Euphotic Zone Depth (m) [2]	16.3
pH [2]	7.8
Conductivity (µS/cm)[2]	155
Total Phosphorus (µg/L) [2, †]	7.4
Total Nitrogen (µg/L) [2, †]	226
Photosynthetic Rate (µg/L) [2, †]	376
Chlorophyll *a* (µg/L) [2, †]	2.6
Total Zooplankton Biomass (mg d.wt/m^2) [2]	2434

[1] Shortreed 2007; [2] DFO Lakes Research Program multi-year data;
† Values are euphotic zone April-November averages 2009-2017

Lake Thermal Stratification & the Seasonal Cycle

Lake physical dynamics (i.e. heating, mixing) are very important controls on seasonal ecosystem development, with cascading ecological effects on water chemistry and biology (Wetzel 2001; DFO 2020). Lake water temperatures and water column mixing are influenced by prevailing weather patterns and climate (i.e. insolation, wind, air temperature, precipitation; Wetzel 2001), a particularly strong coupling in Cultus Lake (Sumka 2017; DFO 2020). In spring, increasing solar intensity and duration increase air temperatures, cumulatively disproportionately warming the lake's surface, creating a density separation or 'stratification' between warmer, less dense surface waters (~ 0-15 m in Cultus Lake; the epilimnion) and colder, more dense, deeper waters (the hypolimnion; Figure 4; Wetzel 2001). These two lake 'strata' are separated by the thermocline, or metalimnion, which in Cultus Lake becomes apparent by April, and is strongly reinforced by increasing summer epilimnion temperatures, which can exceed 24.5 °C in August (DFO 2020), requiring significant fall cooling and wind action to induce lake turnover and subsequent mixing through the winter period (Sumka 2017). Owing to its proximity to the coastal Pacific Ocean, Cultus Lake is classified as a warm monomictic lake system ('once mixing'), meaning it undergoes this annual process of thermal stratification only once, through the spring to fall months, with one complete and ongoing mixing period occurring from fall through spring. Seasonal water column

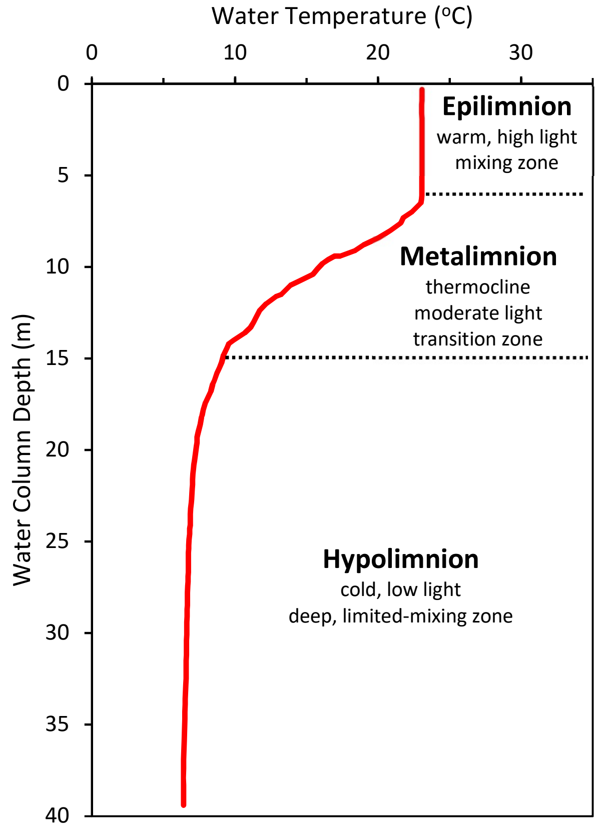

Figure 4: Example Cultus Lake summer water column temperature profile (August 2015), illustrating the physical density separation of warmer surface waters (epilimnion) and colder deeper waters (hypolimnion) during lake thermal stratification. The zone of rapid temperature change between these lake zones is known as the metalimnion or thermocline. DFO Lakes Research Program data.

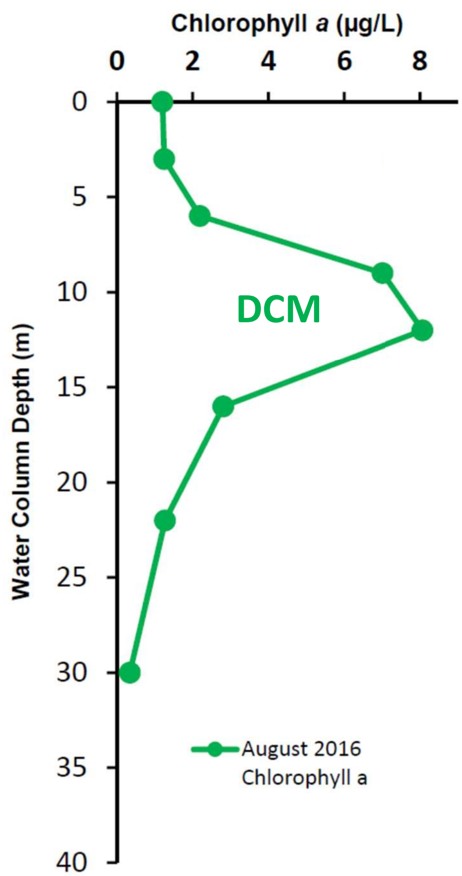

Figure 5: Example Cultus Lake summer water column chlorophyll *a* profile (indicator of algal biomass), illustrating annual deep chlorophyll maximum (DCM) formation, indicative of abundant primary production at depth, owing to rich deep lake nutrient pools, and high surface light penetration. Modified from DFO (2020).

mixing is critically important for the distribution and redistribution of nutrients and oxygen within Cultus Lake, and to the organisms that rely upon them (Wetzel 2001; Shortreed 2007; DFO 2020).

With the seasonal physical development of thermal stratification in Cultus Lake, comes tightly coupled chemical and biological responses in the open water zone (DFO 2020; Gauthier, *accepted*). Abundant nutrients in the surface waters, and high light penetration, stimulate an intensive spring blooming in algal production, typically from March-May (although sometimes as early as February). Seasonal algal production begins within the surface waters (epilimnion), but as surface nitrogen (i.e. nitrate; NO_3) is depleted, algal production transitions deeper in the water column, forming a layer at the metalimnion (thermocline) and upper hypolimnion, called a deep chlorophyll maximum (DCM; Figure 5). Elevated algal production largely continues at depth throughout the summer and fall until lake overturn (DFO 2020). Resultant algal biomass is grazed upon by abundant zooplankton (e.g. *Daphnia, Bosmina*, copepods; Table 1), small free swimming invertebrates that are an important link in the food web for energy transfers to fish in the lake, including the endangered Cultus Lake Sockeye Salmon and Cultus Lake Pygmy Sculpin (Shortreed 2007; DFO 2017, 2020). In contrast to many lakes in British Columbia, Cultus Lake maintains a low to moderate level of biological productivity through the winter mixing period, although reduced from the summer period (Shortreed 2007; DFO 2020).

Two key fish species at risk inhabit Cultus Lake. The Coastrange Sculpin (*Cottus aleuticus*, Cultus population; Cultus Pygmy Sculpin; DFO 2017) is listed under Schedule 1 of the federal Species at Risk Act (SARA 2002) as threatened, but was recently up-listed to endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC), based upon threats degrading its critical habitat, Cultus Lake (SARA 2020). Cultus Lake also supports the long-imperiled, endangered Cultus Lake Sockeye Salmon (*Oncorhynchus nerka*; COSEWIC 2017), currently undergoing reconsideration for federal listing under SARA (DFO 2020). Species at risk, and other species in Cultus Lake, rely upon the natural structure and functioning of the lake ecosystem to carry out critical life functions that sustain their persistence and unique evolutionary histories, and thus are directly and indirectly threatened by human pressures on water quality in their critical habitat (Chiang et al. 2015; DFO 2017, 2020). Similarly, although less intuitive for many, the various ecosystem services that society derives from

Cultus Lake and other aquatic ecosystems (i.e. recreation, water quality and access, cultural connections, economies), often highly-valued, but rarely-considered, are tied to lake water quality, and thus are threatened by its declines.

CULTUS LAKE IS AN ECOSYSTEM UNDER STRESS

Cultus Lake has a relatively lengthy development history for western Canada. In the mid-1800's, mining trails and camps were first established within the Cultus Lake watershed, followed by logging in the early 1900's (peaking in the 1920's; Cramer 2005; Gauthier et al. *accepted*). Agriculture, focused within the Columbia Valley, closely followed forestry by the 1930's, as did rural residential development (Soutar 2005; Gauthier et al. *accepted*). Recreational values have long been important at Cultus Lake, exemplified by the establishment of the Cultus Park in 1924 and Park Board in 1932. Summer cottages and other recreational facilities (i.e. golf course) expanded as the number of permanent residents and visitors increased through the 1940's and 1950's (Soutar 2005; Gauthier et al. *accepted*). By the mid-1950's the lake received over 167,000 visitors annually (Gauthier et al. *accepted*). Amazingly, despite a limited overall full time residential population within the Cultus Lake watershed (Urban Systems 2012), development has continued, as has recreational attraction, yielding contemporary estimates of 2-3 million visitors to the Cultus Lake annually (FVRD 2011; Putt et al. 2019). Given this modern context, Cultus Lake is now considered peri-urban (Putt et al. 2019; Gauthier et al. *accepted*), indicating that while local development is still diffuse, the lake receives undue anthropogenic (human-induced) stresses from rapidly-expanding nearby populations (i.e. BC Lower Mainland; NW Washington State).

Peri-urban lakes increasingly experience greater and more varied watershed uses, modifications, and developments as commercial, recreational, and residential uses increase, commensurate with suburban population expansion (Paul and Meyer 2001; Alberti et al. 2007; Putt et al. 2019). Ecosystem services provided by such lakes (e.g., fisheries, recreation, drinking water, irrigation) can be of significant cultural and socioeconomic value, with the conservation of water quality and ecosystem structure and functioning important for sustainable use (Wilson and Carpenter 1999; Baron et al. 2002; Putt et al. 2019).

Multiple Stressors Threaten Cultus Lake

Cultus Lake, has not been immune to the demands society has placed upon the regional landscape, and the ecology of the system is changing as a result of human development and land-uses, both within and outside of the lake's watershed (Shortreed 2007; Putt et al. 2019; DFO 2020; Gauthier et al. *accepted*). Excess nutrient loading is a key threat to the preservation of lake water quality, species at risk, and numerous lake ecosystem services important to society (Chiang et al. 2015; Putt et al. 2019; DFO 2020; Gauthier et al. *accepted*). Additionally, climate variability and climate change, pervasive and complex influences on lake ecosystems globally (Adrian et al. 2009; O'Reilly et al. 2015), are strong controls on the annual physics of Cultus Lake (Sumka 2017; DFO 2020). Multiple concurrent stresses on aquatic ecosystems can be interactive, induce cumulative stresses, and tend to lead to unexpected ecological outcomes, which in turn affect lake ecosystem services that society relies upon (Christensen et al. 2006; Moss et al. 2011; Selbie et al. 2011; Putt et al. 2019).

Cultural Eutrophication: A Cumulative Effects Problem Driving Ecological Change in Cultus Lake

Cultural eutrophication, or human-induced nutrient enrichment of freshwater ecosystems is a globally-pervasive, population-related problem, driven by excess external and internal nutrient loadings (i.e. phosphorus (P), nitrogen (N)) that can degrade water quality and threaten the ecology of affected lakes (Carpenter et al. 1998; Smith et al. 1999; Schindler et al. 2001; Moss et al. 2011; Putt et al. 2019). Consistently cited the most common water quality problem in the world (Schindler 2006; Smol 2008), eutrophication can lead to many undesirable lake symptoms, including, but not limited to unsightly algal blooms, extensive growth of aquatic plants, excessive accumulations of decaying organic matter, water taste and odour problems, decreased deep-water oxygen levels, and fundamental changes to lake ecology, such as reorganization of food webs, and loss of fish species and other organisms (Wetzel 2001; Smol 2008). Put simply, cultural eutrophication is a very strong and interactive driver of ecological change in affected lakes, ultimately resulting in habitats degraded from their natural states, and if left unchecked, can result in reductions or losses of highly –valued lake ecosystem services, estimated at tens to hundreds of millions of dollars to regional economies for popular lakes (Mueller et al. 2016; Rhodes et al. 2017; Janmaat and Cebry 2019).

Cultural eutrophication, in most cases, is not an immediate phenomenon, but rather a lake-specific manifestation of responses over time to varied and cumulative nutrient sources and loadings (Smith and Schindler 2009). The eutrophication of lakes can go unnoticed during its early phases or under certain lake settings (i.e. deep algal blooming). For many impacted lakes, long receiving excess nutrients, significant eutrophication may have occurred prior to modern monitoring and record keeping (i.e. over a century or more), resulting in an unknown natural lake state, yet a degraded lake ecosystem (Smol 2008; Gauthier et al. *accepted*). Moreover, novel nutrient loadings (e.g. septic leachate with recreational/residential development) may initially stimulate lake food webs, increasing the productivity and attraction of ecosystem services, such as fisheries, but as loading continues and/or intensifies, structural and functional ecosystem transformations can occur that fundamentally alter the lake state (e.g. physics, chemistry, and biology; trophic status). Such ecosystem transformations may alter or even eliminate reliant ecosystem services (e.g. recreation, fisheries, potable water supply; Putt et al. 2019; Gauthier et al. *accepted*).

Cultus Lake is undergoing cultural eutrophication as a result of nutrient loadings to the lake from diffuse and point sources, both within and outside of the watershed (Putt et al. 2019; DFO 2020; Gauthier et al. *accepted*). Shortreed (2007) first speculated, based upon comparison of limnological (lake ecosystem) data collected in the 1920's-1930's (Ricker 1937) and early-2000's, that the productivity of the lake may have increased. This inference was supported by an integrated watershed-lake model, calibrated to conditions in Cultus Lake, which was used to hind-cast water quality prior to the onset of Euro-American influence in the region (Putt et al. 2019). The model indicated that Cultus Lake was naturally nutrient-poor, and of considerably lower algal productivity in the past (Putt et al. 2019), which is consistent with the limnology of most nursery lakes colonized by Sockeye Salmon in the region (Shortreed et al. 2001; Selbie et al. 2010). Moreover, a recent multi-indicator paleolimnological study of Cultus Lake, which reconstructed lake, watershed, and climatic conditions over the past ~200 years from indicators archived in the sediment record, verified that

Cultus Lake has been undergoing cultural eutrophication for some time, with symptoms evident as early as ca. 1940 C.E., and large increases in lake algal production evident by ca. 1970 C.E., commensurate with regional population increases, landscape development and agricultural expansion in the Fraser Valley (Gauthier et al. *accepted*).

Putt et al. (2019) studied Cultus Lake, its watershed, and its airshed, to determine the primary sources and loadings of nitrogen (N) and phosphorus (P) to the system, in support of watershed and airshed management that promotes lake sustainability and preservation of species-at-risk. Watershed hydrological and nutrient mass balance modeling highlighted that the nutrient loads to Cultus Lake arise from multiple sources both within and outside of the watershed. Local nutrient sources were important to the eutrophication of Cultus Lake, with substantial local (i.e. within-watershed) nitrogen loadings from the agricultural Columbia Valley (41% of total N load), and significant local P loadings arising from septic leachate (19%) and guano deposited from fall through spring by migratory gulls (22%; Putt et al. 2019). Watershed runoff contributes the majority of total P (53%) and N (73%) loads to Cultus Lake, however, as noted previously, the Fraser Valley Airshed has strong influence on the properties of the atmosphere overlying the Cultus Lake watershed, and it is estimated that up to 66% of N and 70% of P contained in watershed runoff, is ultimately sourced via atmospheric deposition from the nutrient-contaminated regional airshed (Putt et al. 2019). With direct atmospheric deposition on the lake surface contributing an additional 17% of N and 5% of P loads, atmospheric deposition is the largest single source of nutrient loading to Cultus Lake annually, responsible for 63% and 42% of total N and P loadings, respectively (Putt et al. 2019). Primary nitrogen and phosphorus sources to the regional atmosphere arise from intensive agricultural practices in the adjacent Fraser Valley and Whatcom County, WA USA, and to some extent upwind urban and transportation activities (Vingarzan et al. 2002; Metro Vancouver 2018).

A Eutrophication x Lake Physics Interaction: Enhanced Deep Water Oxygen Declines

The nature and trajectory of declining lake water quality and ecological changes associated with nutrient loading, will be specific to the nutrient loading, limnological, landscape, climatic, and atmospheric context of any given lake (Smol 2008; Selbie et al. 2009). Across lakes, however, it can be generalized that increased nutrient loading stimulates elevated in-lake organic matter production (i.e. algal, aquatic plant, invertebrate biomasses; Wetzel 2001; Smol 2008). Ultimately much of this excess organic matter settles to deeper waters and the lake sediments (Wetzel 2001; Smith and Schindler 2009; Moss et al. 2011), where it is decomposed along with organic matter delivered from the watershed and airshed (Selbie et al. 2009; DFO 2020). In most temperate lakes, decomposition is largely sustained by aerobic microbial activity (Wetzel 2001), which ultimately increases biological and chemical oxygen demands below the lake thermocline (i.e. hypolimnion; Figure 4; Müller et al. 2012; DFO 2020). Due to strong physical density separation of the water column under lake stratification, the lake hypolimnion is effectively isolated from the atmosphere, inhibiting re-oxygenation of deeper lake waters during this period (Figure 4; Wetzel 2001; Moss et al. 2011), and resulting in dissolved oxygen depletion at depth, until lake overturn re-oxygenates the water column in fall (Wetzel 2001). In lakes experiencing cultural eutrophication, organic matter loads to the hypolimnion are enhanced, resulting in more rapid and greater oxygen depletion seasonally within this deep lake zone (Wetzel 2001; Shortreed 2007; Smol 2008; Putt et al. 2019).

The length of time that a lake is thermally stratified also influences the magnitude and extent of seasonal deep water oxygen depletion, particularly in lakes experiencing cultural eutrophication (Smol 2008; Moss et al. 2011). As noted, prolonged temperature-density separation of the water column (i.e. thermal stratification) largely isolates the hypolimnion from diffusive atmospheric oxygen regeneration at the lake surface (Figure 4) This physical separation also prolongs organic matter production and aerobic decomposition at depth, cumulatively increasing seasonal hypolimnetic oxygen demands and deficits (Wetzel 2001; Smith and Schindler 2009; Moss et al. 2011; Müller et al 2012; Sumka 2017). Under moderate to heavy nutrient loadings, hypoxic (< 6 mg/L dissolved oxygen) to anoxic (0 mg/L dissolved oxygen) conditions can be induced in deep water and benthic habitats, creating stressful conditions for biota (e.g. invertebrates, salmonids, benthic fishes; Ruggerone 2000; Smith and Schindler 2009; Putt et al. 2019). Moreover, low dissolved oxygen at the sediment-water interface in lakes can facilitate oxidation-reduction (redox) reactions that release nutrients and other toxicants, originally bound within the lake sediments, into the overlying water column. This process, known as lake internal loading, effectively reverses the lake sediments function in storage of nutrients, becoming a novel source of nutrients to the overlying water column, a process that can lead to runaway lake eutrophication if not closely managed (Pettersson 1998; Wetzel 2001).

Cultus Lake now experiences concerning annual deep water hypoxia and anoxia events, a direct consequence of human-induced lake eutrophication (Figure 6; Putt et al. 2019; Loudon 2020; DFO 2020). Oxygen deficits are most severe in the deepest waters (bottom 5-10 m), towards the end of the stratified period and fall precipitation (~ October), but moderate oxygen depletion occurs throughout much of the hypolimnion during the mid- to late-stratified period (Shortreed 2007; Loudon 2020; DFO 2020). This worsening problem is deep and hidden within Cultus Lake (Figure 6), much like the algal blooming that sustains it (Figure 5). It threatens overall lake water quality, the persistence of species at risk which rely upon these habitats (i.e. Cultus Lake Sockeye Salmon and Pygmy Sculpin; Chiang et al. 2015; Putt et al. 2019; Loudon 2020; DFO 2020), and the many highly-valued lake ecosystem services (i.e. water supply, recreation, fishing, property values; Janmaat and Cebry 2019; Putt et al. 2019; Gauthier et al. *accepted*).

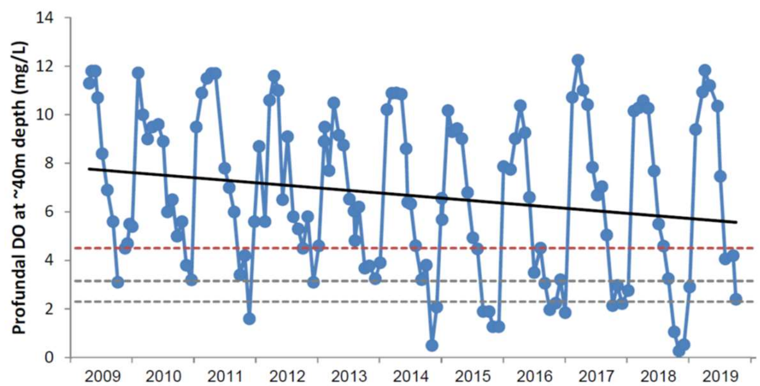

Figure 6: Long-term monthly time series of deep water oxygen concentrations (~40m depth) in Cultus Lake, BC, at the long-term limnological sampling station maintained by Fisheries and Oceans Canada's Lakes Research Program. Note the annual cycle of oxygen depletion during stratification and regeneration during annual fall lake turnover, but overall declining annual trend (black line). The red dashed line indicates the hypoxic threshold for effects on juvenile Sockeye Salmon survival (4.5 mg/L; Ruggerone 2000). The grey dashed lines indicate 24 hr juvenile sockeye salmon survival thresholds for 45% survival (upper; 3.15 mg/L) and 0% survival (lower; 2.3 mg/L) from Ruggerone (2000). As summarized in DFO (2020).

Current seasonal deep water oxygen deficits in Cultus Lake are causing internal loading of nutrients and likely other redox-sensitive compounds from the lake sediments, which are exacerbated by increases in air and water temperatures (Figure 7: DFO 2020; Loudon 2020). Internal loading, once

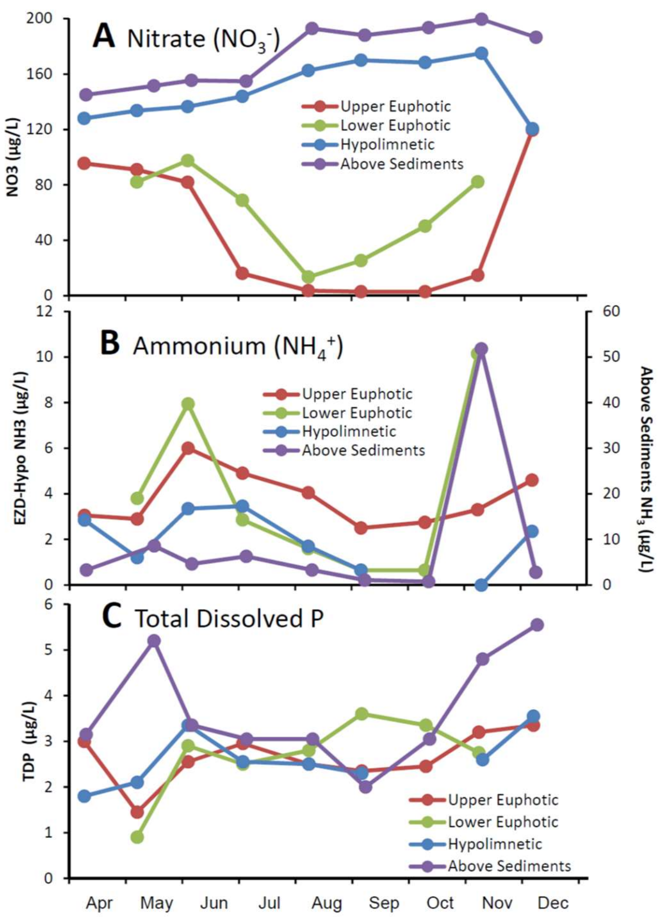

Figure 7: 2014 time series of redox-sensitive nutrients A) nitrate (NO_3^--N); B) ammonium (NH_4^+-N); and C) total dissolved phosphorus (TDP) in the Cultus Lake water column. Note the buildup of hypolimnetic nitrate through the stratified period (April-Nov) in A) and pulses of ammonium and phosphorus from the sediments during the spring bloom (April-May) and lake senescence (Oct-Nov) in B,C) relative to concentrations in the overlying water column. As summarized in DFO (2020).

substantial, serves as a positive feedback on lake eutrophication, reinforcing and accelerating the process (Pettersson 1998; Wetzel 2001; Smol 2008). In Cultus Lake, continued eutrophication is likely to lead to an unanticipated increase in symptoms of declining water quality, experienced at the surface of the lake (i.e. algal blooming and matting, water taste and odour problems), as have been observed in a limited way in Cultus Lake to date (Putt et al. 2018), with more pronounced in other British Columbia Lakes experiencing eutrophication (i.e. Shuswap Lake, SLIPP 2014; Osoyoos Lake; Simmatis et al. 2018).

As cultural eutrophication is a cumulative loading problem, largely tied to human actions, it is inherently reversible through targeted watershed to airshed management that identifies, quantifies, and mitigates nutrient sources and loads to recipient lakes (Smol 2008; Putt et al. 2019). Many highly successful lake management examples exist, leading to the reversal of eutrophication (Smol 2008), such as the recovery of nearby Lake Washington, WA, which had significantly degraded as a result of Seattle sewage loadings from the 1940's to the 1960's (Edmondson and Lehman 1981). Lake management is most likely to be successful in reversing eutrophication in Cultus Lake, and preserving its water quality, if actioned directly and early, before internal lake responses (e.g. lake sediment internal nutrient loading) and/or interactive lake stressors (e.g. climate warming) inhibit recovery actions, and reinforce permanence (Wetzel 2001; Smol 2008; Moss et al. 2011; Putt et al. 2019; DFO 2020).

Climate Change and Climate Variability: Compounding Lake Influences Enhancing the Impacts of Lake Eutrophication on Cultus Lake

Lakes are highly influenced by and responsive to the state of their atmospheres (i.e. weather, climate, atmospheric constituents) and the sun (Wetzel 2001; Vincent 2009; Moss et al. 2011; Selbie et al. 2009, 2011). Atmospheric processes (i.e. air heating, precipitation, winds) and the intensity of solar irradiance largely dictate the seasonal physical cycle of lakes (i.e. thermal stratification, mixing), which is very important to their annual chemical and biological development (Wetzel 2001; Sumka 2017). Similarly both shorter-term atmospheric dynamics (i.e. weather) and longer-lived changes in the climate system, such as regional climate variability (i.e. El Niño) and global climate warming can be interactive, and have great influences on regional lake ecosystems (Smol 2008; O'Reilly et al. 2015; BC MoE 2016).

The weather and the climate dynamics of British Columbia can be described as highly variable (BC MoE 2016). A diverse topography creates numerous "micro-climates" and Biogeoclimatic Zones (Pojar et al. 1987), and prevailing meteorological conditions are strongly influenced by large-scale, coupled ocean-atmospheric processes (i.e. Pacific Decadal Oscillation, El Niño-Southern Oscillation), which induce large-scale fluctuations in air temperatures and precipitation, on sub-annual to decadal scales (Mantua et al. 1997; Stahl et al. 2006). Moreover, climate change has significantly warmed southern British Columbia for over a century (annual +0.8^{o}C; 1900-2013), particularly in winter (+1.2^{o}C; 1900-2013), with minimum temperatures increasing the greatest (spring +1.2^{o}C; summer +1.5^{o}C; fall +0.8^{o}C; winter +1.2^{o}C; 1900-2013; BC MoE 2016). Regional warming has been associated with a +14% increase in annual precipitation, particularly in spring (+23%; 1900-2013; BC MoE 2016). Cumulatively such climate forcings have altered the seasonal processes of British Columbia lakes (Selbie et al. 2011; BC MoE 2016; Sumka 2017; DFO 2020; Gauthier et al. *accepted*), shortening the period of ice cover in those that freeze (Duguay et al. 2006) , and increasing the annual strength and duration of thermal stratification across many lakes (Selbie et al. 2011; BC MoE 2016; DFO 2020). The most pronounced lake responses to climate change have been observed in warm, deep lakes, like Cultus Lake (Kraemer et al. 2015; Sumka 2017).

Sumka (2017) developed a hydrodynamic model for Cultus lake, calibrated to ambient wind, temperature, precipitation, and solar irradiance, to characterize the seasonal thermal dynamics of the lake, past and present. The model hind-cast lake conditions over the period of recorded meteorological data (1923-2016), highlighting that Cultus Lake has experienced pronounced warming and physical changes over the past century (total heat content increases of 0.80 $MJ/m^2/yr$) in response to climate change, lengthening the stratified period by ~ 0.18 days/yr, and advancing the onset of annual stratification by ~2 weeks over the same period. Cultus Lake seasonal physical dynamics (i.e. heating, mixing, thermal stratification, stability) are now very tightly coupled to regional climate (Sumka 2017; DFO 2020; Gauthier et al. *accepted*). Monthly upper water column (0-5 m) temperatures in Cultus Lake strongly track monthly mean air temperatures, with a one month thermal lag in water heating (Figure 6; Gauthier et al. *accepted*; DFO 2020), as does monthly lake stability, the resistance of the water column to turnover by surface wind stresses, a measure of the strength of lake thermal stratification (DFO 2020).

Such strong air-water temperature relationships permitted reconstruction of past water temperatures in Cultus Lake from the long-term air temperature record at Agassiz, BC (Figure 7; ECC 2017; Stn ID:1100120). This analysis suggests that upper water column temperatures within Cultus Lake have likely fluctuated for some time, associated known with regional climate variability (Figure 7; DFO 2020; Gauthier et al. *accepted*). However, pronounced increases in inferred summer temperatures are evident following the ca. 1970's (Figure 7 A), a period of known regional warming associated with a shift to the warm phase of the Pacific Decadal Oscillation (Mantua et al. 1997; BC MoE 2016), rapid change in the limnology and ecology of Cultus Lake (Gauthier et al. *accepted*;

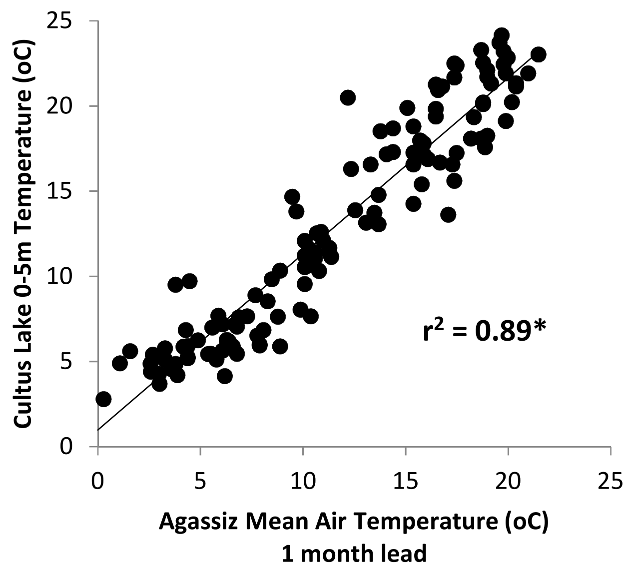

Figure 6: Atmospheric-upper water column (0-5m) temperature coupling within Cultus Lake, BC. Evidence of strong modern climatic control of Cultus Lake surface heating, leading to enhanced and protracted water column stratification (DFO 2020; Gauthier et al. *accepted*).

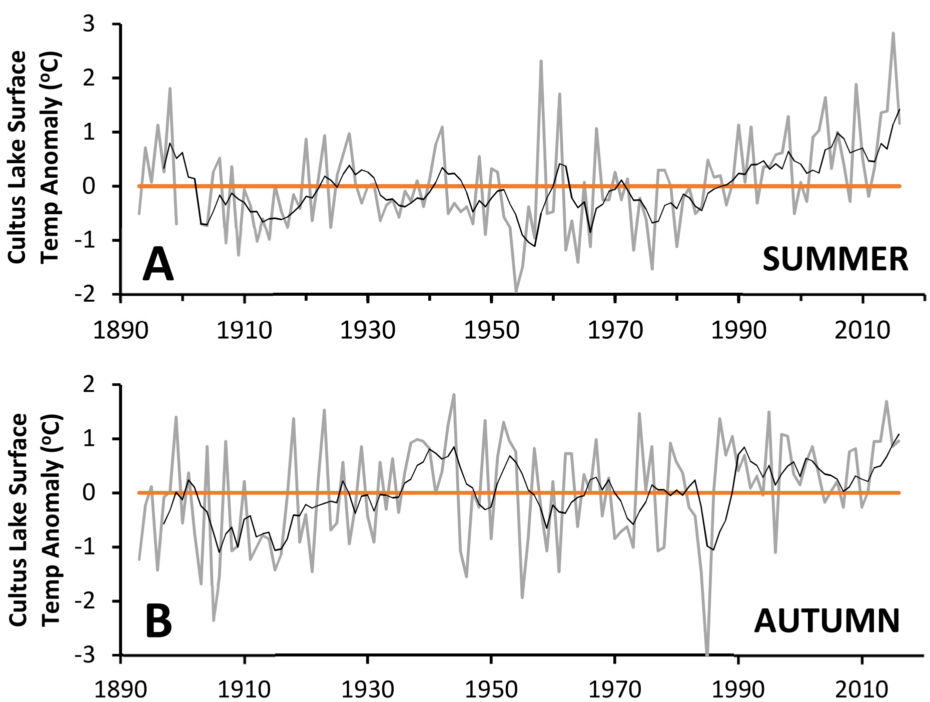

Figure 7: Reconstructed time series of Cultus Lake upper water column (0-5m) temperature anomalies during A) the summer period (peak stratification); and B) fall period (late-stratification), reconstructed from the monthly mean air temperatures at the Aggasiz Environment and Climate Change Canada Climate Station (ID:1100120). Direct (grey lines) and 5-year averaged values (black lines) are shown.

DFO 2020), and a shift to above-average fall temperatures that have likely lengthened the annual period of lake stratification (Sumka 2017; DFO 2020).

Climate change and variability can interact with other lake stressors, and serve to amplify the 'symptoms' of lake eutrophication, such as the algal blooming and deep water oxygen losses observed in Cultus Lake (Moss et al. 2011; DFO 2020). Given current lake nutrient levels and stratification dynamics, lake primary production (i.e. algae) is now driven by air temperatures throughout the growing season (DFO 2020). Elevated spring blooming is sustained by abundant lake nutrient concentrations and an earlier onset of stratification (Sumka 2017; DFO 2020), whereby elevated algal production rapidly depletes available nitrogen (i.e. NO_3^-) in the epilimnion, a temperature-mediated phenomenon (DFO 2020). Owing to relatively high light penetration and rich nutrient reserves in the hypolimnion, primary production subsequently concentrates at the metalimnion and upper hypolimnion, forming a deep algal production layer (deep chlorophyll maximum (DCM); Figure 5), where it persists through the duration of the stratified period, constantly producing organic matter at depth.

Given the deep position of primary production in the water column, DCM formation can increase the export of organic matter the lake hypolimnion, despite declines in surface productivity (Skjoldal and Wassmann 1986; DFO 2020). As such, the prolongation and enhancement of algal production within Cultus Lake, resulting from the interaction of climatic and eutrophication forcings, likely provides a more efficient pathway for organic matter loading to the hypolimnion, enhancing aerobic decomposition and seasonal hypolimnetic oxygen losses (DFO 2020). Thus, both increases in eutrophication- and climatically-forced organic matter production, and climate change impacts on lake physical dynamics (i.e. more intense and protracted thermal stratification) are likely responsible for pronounced contemporary dissolved oxygen losses in the deep habitats of Cultus Lake (Figure 6). Although climate change is unlikely to be reversed in a reasonable time frame for lake recovery, state-based limnological modeling indicates that nutrient abatement can significantly retard the eutrophication trajectory of Cultus Lake, and likely reverse it if atmospheric sources are constrained, restoring the quality of deep rearing habitats of Cultus Lake (Putt et al. 2019; DFO 2020).

Species at Risk in Cultus Lake

Cultus Lake serves as critical habitat for two fish species at risk, the endangered coastrange sculpin (*Cottus aleuticus*, Cultus population), which completes its life history within the lake (Woodruff 2010; Chiang et al. 2015; DFO 2017; Loudon 2020), and the endangered Cultus Lake Sockeye Salmon (*Oncorhynchus nerka*), which uses the lake for adult spawning, egg incubation, and rearing of juveniles (Shortreed 2007; DFO 2020). Water quality degradation is a primary threat, risking extinction for both species, with eutrophication having the potential to disrupt physical, biological, and chemical aspects of their freshwater habitat (Schubert et al. 2002; COSEWIC 2003, 2010; Chiang et al. 2015).

Both fish species at risk in Cultus Lake are directly threatened by lake eutrophication, through degradation of their critical habitat (Putt et al. 2019; DFO 2020; Loudon 2020). Warming lake surface temperatures, which now exceed 24.5 ^{o}C in some years, appear to impose constraints on juvenile

Sockeye Salmon use of upper water column during summer and fall, when the lake is strongly thermally stratified, largely remaining at or below the thermocline for this period (Figure 8; DFO 2020). Juvenile Sockeye Salmon routinely undergo a behaviour called diel vertical migration, whereby fry in the open water area, make a vertical migration from the deep, low-light hypolimnion, where they reside during the daylight hours, up into the upper water column during the dusk to dawn period to feed (Clark and Levy 1988; Scheuerell and Schindler 2003; DFO 2020). It is believed this behaviour is an adaptation to maximize feeding, while avoiding predation from other fish (Scheuerell and Schindler 2003).

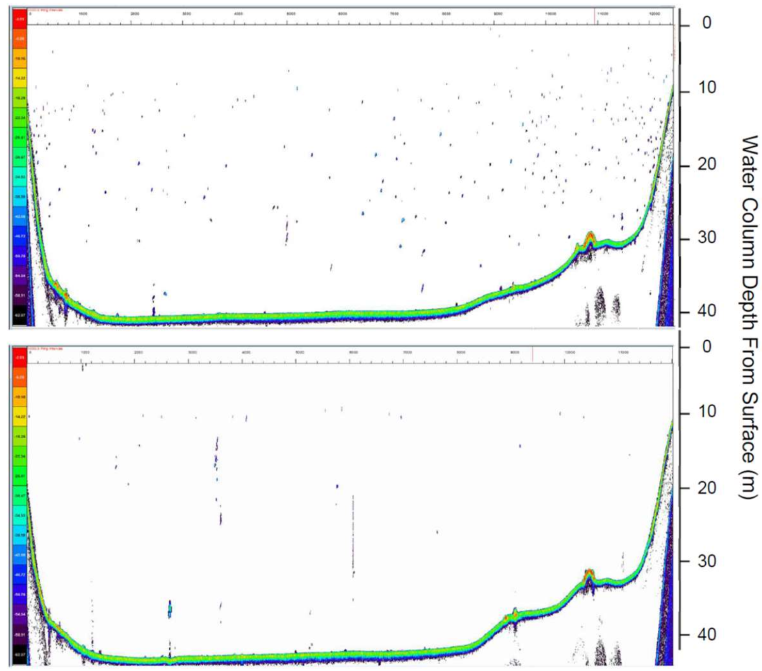

Figure 8. Example of downward facing summer hydroacoustic echograms from A) night and B) daytime periods collected by DFO's Lakes Research Program in August 2009. Individual dots indicate pelagic hydroacoustic targets (principally Sockeye Salmon; verified by mid-water trawl). Vertical lines evident in the echograms are artefacts of air bubble columns emanating from the lake sediments. As summarized in DFO (2020).

In Cultus Lake, diel vertical migration is very pronounced, and juvenile Sockeye Salmon reside in the deepest waters of Cultus Lake for the lengthy period daily in close association with the lake sediments (Figure 8). As a direct result of lake eutrophication and interactions with climate change, this area of the lake is now a seasonally-stressful environment for fish, owing to low dissolved oxygen concentrations during the summer and fall (i.e. hypoxic; Figure 6), and possibly internal loading of redox-sensitive contaminants from the sediments (i.e. metals, hydrogen sulfide; Figure 7; DFO 2020).

Survival within Cultus Lake is now the primary population limitation for the endangered Cultus Lake Sockeye Salmon, and is inversely related to both lake surface warming and the intensity of thermal stratification in the spring through fall period (DFO 2020). Warmer air temperatures not only promote increased lake stability, but due to lake eutrophication, also strongly enhance primary production, which leads to enhanced organic matter production and oxygen losses in the hypolimnion (DFO 2020). Climate warming is predicted to continue, with a mean projected warming of +3.1^{o}C in southern British Columbia by 2050 from the 1961-1990 baseline (PCIC 2020). As such, if nutrient levels in Cultus Lake remain elevated as a function of human-caused lake eutrophication, rising air and water temperatures will continue to strongly limit freshwater survival of Cultus Lake Sockeye Salmon, posing a significant risk to its extinction (Putt et al. 2019; DFO 2020). Improving freshwater salmon survival, through nutrient management and reversal of deep water habitat degradation, is the only scenario predicted to permit population recovery (DFO 2020).

Although less studied, deep water oxygen declines within Cultus Lake pose a threat to the persistence of the endemic Cultus Lake Pygmy Sculpin (Chiang et al. 2015; Putt et al. 2019; Loudon 2020), which extensively uses the deeper portions of Cultus Lake to complete critical life functions (Woodruff 2010; Loudon 2020). The species was recently up-listed to “endangered” status from “threatened”, based upon the degradation of its deep water critical habitat highlighted by DFO’s Lakes Research Program (Chiang et al. 2015; SARA 2020). Loudon (2020) demonstrated that fall hypoxia in the deepest waters of Cultus Lake, across years, was associated with few trapping captures of Cultus Lake Pygmy Sculpin, suggesting they may be avoiding, dying, or suppressing activity within these degraded environments. The population is difficult to estimate, but existing information from DFO Lakes Research Program mid-water trawls suggest it may be declining (Chiang et al. 2015).

What does the future hold for Cultus Lake?

Putt et al. (2019) used a state-based limnological model to predict future water quality changes in Cultus Lake, relative to current and past conditions. The model used data and discipline-specific expert opinions on anticipated changes in within-watershed nutrient loadings (i.e. local agriculture, bird guano, septic leachate, salmon carcasses) and direct atmospheric deposition on the lake, and realistic expectations for mitigating within-watershed nutrient loadings. Cultus Lake is predicted to continue to increase in nutrient status (i.e. TP,TN) and algal production, with a high likelihood of transitioning to a new lake state (i.e. mesotrophy) within the next 25 years (Putt et al. 2019; Figure 9). Realistic, within-watershed nutrient abatement measures are predicted to improve water and associated habitat quality in Cultus Lake. Doing so is essential to the overall problem, however, local efforts will only serve to slow the rate of lake degradation, if sources and loadings from regionally-contaminated Fraser Valley Airshed are not addressed. Since climate

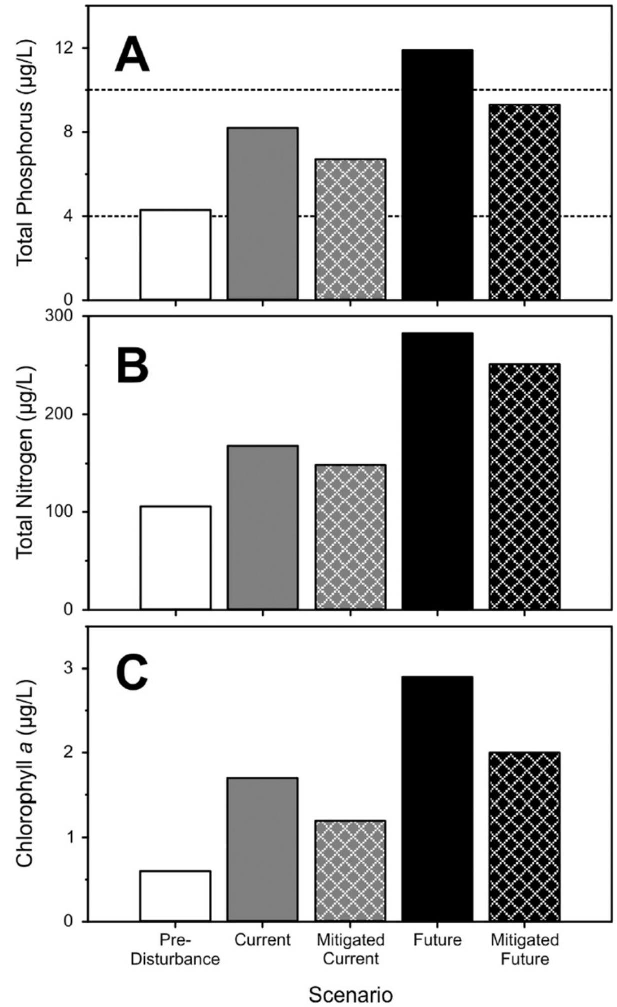

Figure 9: Cultus Lake model results for current epilimnetic water quality parameters A) total phosphorus (TP), B) total nitrogen (TN), and C) chlorophyll-*a* (grey bars), relative to those prior to significant human influence (white bars), and predicted under an expert-informed future development scenario 25 years in the future (black bars). Also shown, are estimated lake responses to realistic mitigation of current within-watershed nutrient sources (grey bars with hash marks), and the future development scenario with the same mitigations applied (black bars with hash marks). Dotted reference lines in Panel A indicate the Canadian Council of Ministers of Environment thresholds (CCME 2004) for phosphorus-inferred aquatic system trophic status (lower – ultra-oligotrophy-oligotrophy threshold (4 µg/L TP); upper - oligotrophy-mesotrophy threshold (10 µg/L TP)).

change and lake internal loading was not explicitly accounted for in this modelling, the state of predicted lake conditions, and the timeline (i.e. 25 years) over which they are expected to develop, are likely to be conservative.

Sumka (2017) coupled the Cultus Lake hydrodynamic thermal model to the outputs of a down-scaled Global Climate Model (GCM; Canadian Regional Climate Model RCM4), used to predict the future climates of southern British Columbia under warming (ECC 2017). For both moderate and extreme warming scenarios, Cultus Lake is predicted to experience more intense and prolonged thermal stratification and discontinuous annual mixing, which is likely to further significantly degrade lake water quality, critical habitats for species at risk, and lake ecosystem services relied upon by society (Putt et al. 2019; DFO 2020; Loudon 2020).

Since climate change is interactive with lake eutrophication (Moss et al. 2011), and the trajectory of this global problem is unlikely to be reversed in the near-term, a focus on abatement of all excess nutrient sources to Cultus Lake is critical to reduce the 'reactivity' of Cultus Lake to climate warming and avoid crossing ecological thresholds that compromise the persistence of species at risk and lake ecosystem services relied upon by society (DFO 2020). Internal loading of nutrients from the lake sediments, in particular, is an emerging threat with the potential to drive runaway lake eutrophication and water quality declines, the timing of which is very difficult to predict.

Watershed to Airshed Recommendations for Nutrient Abatement at Cultus Lake

A mixed watershed-to-airshed strategy to nutrient abatement required

Lake eutrophication is a reversible phenomenon, provided targeted lake management measures are implemented in a timely fashion. While it is important to mitigate both nitrogen and phosphorus loading to Cultus Lake, limiting phosphorus loading is predicted to yield the greatest reductions in algal production and associated habitat degradation, yielding the greatest improvements in lake water quality (Figure 9; Shortreed 2007; Putt et al. 2019; DFO 2020).

Mitigation of the local (i.e. within-watershed) nutrient sources identified in Putt et al. (2019), is essential to reversing the eutrophication Cultus Lake (Figure 9), and must be a key focus, while broader airshed mitigation strategies can be developed and enacted. Addressing the primary, local P-loads (i.e. septic leaching, guano deposition, local agricultural runoff) is predicted to retard the rate of lake eutrophication and thus must be a near-term management focus for Cultus Lake to preserve societal valuations, species at risk, and ecosystem services (*see* Putt et al. 2019).

Given the magnitude and extent of regional nutrient deposition from the Fraser Valley Airshed, atmospheric deposition will continue to degrade Cultus Lake and other regional aquatic ecosystems, should primary nutrient emissions (e.g. agriculture, transportation) to the shared regional airshed not be addressed (Putt et al. 2019). Interestingly, the environmental chemistry of phosphorus, particularly its lack of a stable gaseous phase and affinity for binding to particles (i.e. aerosols, dust), may provide an opportunity to interrupt its atmospheric transport to Cultus Lake (i.e. reduce dust loading to the Fraser Valley Airshed; Putt et al. 2019; DFO 2020).

While all P sources to the regional airshed need to be identified and quantified in order to focus abatement priorities, agriculture is unarguably the dominant source of phosphorus within the Fraser Valley (Bittman et al. 2017). Putt et al. (2019) hypothesize that optimization (i.e. soil-specific dosing) of the significant amounts of P applied to the regional landscape via agriculture, coupled with targeted interruptions to seasonal dust entrainment to the regional atmosphere (i.e. modified low- or no-tillage practices, minimization of bare soil land exposure, reduced liquefied manure spraying, reductions in poultry barn exhaust bio-aerosols) could substantially reduce atmospheric P loading to the regional airshed and thus regional aquatic ecosystems. An integrated landscape-to-airshed nutrient management approach inclusive of stakeholders, governments, and Indigenous communities, and their individual and shared values, will be essential to reduce airshed P deposition, and halt or reverse eutrophication trends at Cultus Lake and across the region. Failure to do so could result in significant impacts on cultural and socioeconomic valuations, lake-derived ecosystem services, and species at risk.

Cultus Lake as a Bellwether for Regional Change in Aquatic Ecosystems

We know a fair amount about Cultus Lake, largely because of the long history of scientific inquiry focused on its fish and associated fisheries (Foerster 1927; Ricker 1937; Shortreed 2007; Sumka 2017; DFO 2020; Loudon 2020; Gauthier et al. *accepted*). However, given the common and contaminated Fraser Valley Airshed is the primary source of nutrients to the system, it stands to reason that airshed nutrient deposition is an influence on other aquatic ecosystems within the region.

In fact, nutrient contamination of the regional airshed appears to have been an influence on the aquatic ecosystems of southern British Columbia for nearly a century, most likely intensifying with N and P emissions from agriculture (Holtgrieve et al. 2011; Gauthier et al. *accepted*). To the west of Cultus Lake, nitrogen deposition has increased since the early-1900's, as inferred from lake sediment archives at Loon Lake, BC, an otherwise pristine ecosystem and watershed peripheral to the Fraser Valley (north side), but within the UBC Malcolm Knapp Research Forest (Holtgrieve et al. 2011). The timing of changes is consistent with the early eutrophication of Cultus Lake, although local agriculture within the Columbia Valley was also likely a significant contributor to lake change (Gauthier et al. *accepted*). To the east of Cultus Lake, Vingarzan et al. (2002) documented significant nutrient loadings to the Elk Creek watershed from the atmosphere by volatile and particulate inputs of nitrogen and phosphorus, largely sourced from agricultural emissions and dust, and transported via regional atmospheric circulation to the watershed.

Given the apparent broad reach of atmospheric nutrient deposition within southern British Columbia, and its clear responsiveness to climate warming and variability (Sumka 2017; DFO 2020), Cultus Lake is an important, data-rich bellwether of regional environmental change. Research to date provides a lens through which other aquatic ecosystems can be viewed, establishing large-scale drivers (i.e. atmospheric nutrient deposition, climate change) of regional aquatic change. This is particularly important in a peri-urban landscape where development pressures intensify multiple stresses and impacts on nearby aquatic ecosystems, and monitoring data are almost certainly lacking.

Acknowledgements

The research and interpretations presented are built upon and dedicated to the many who found answers to scientific curiosity at Cultus Lake, including our many students and collaborators. Special appreciation is extended to the members of Fisheries and Oceans Canada's Science Branch who have dedicated significant portions of their careers to Cultus Lake and its species at risk, including Dr. William E. Ricker, Ken Shortreed, Jeremy Hume, Neil Schubert, Dr. Michael Bradford, and all members, past and present, of the Cultus Lake Sockeye Conservation Team (CLSRT) and the Cultus Lake Aquatic Stewardship Strategy (CLASS).

Literature Cited

Alberti, M., Booth, D., Hill, K., Coburn, B., Avolio, C., Coe, S., and D. Spirandelli. 2007. The impact of urban patterns on aquatic ecosystems: An empirical analysis in Puget lowland sub-basins. Landscape and Urban Planning. 80: 345-361.

Bittman S., Sheppard, S.C., Poon, D., and D.E. Hunt. 2017. Phosphorus flows in a peri-urban region with intensive food production: A case study. Journal of Environmental Management. 187: 286–297.

British Columbia Ministry of Environment (BC MoE). 2016. Indicators of climate change for British Columbia. 2016 Update. 61pp.

British Columbia (BC) Parks. 2018. BC Parks 2017/18 Statistics Report.

Canadian Council of Ministers of the Environment (CCME). 2004. Canadian Water Quality Guidelines for the Protection of Aquatic Life; Phosphorus: Canadian Guidance Framework for the Management of Freshwater Systems. In: Canadian environmental quality guidelines, Canadian Council of Ministers of the Environment, Winnipeg. 2004. http://ceqg-rcqe.ccme.ca/download/en/205

Carpenter, S.R., Caraco, N.F., Corrrell, D.L., Howarth, R.W., Sharpley, A.N., and V.H. Smith 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. Ecological Applications. 8: 559–568.

Chaing, E., Pon, L.P., Selbie, D.T., Hume, J.M.B., Woodruff, P., and G. Velema. 2015. Identification of critical habitat for Coastrange Sculpin (Cultus Population) (*Cottus aleuticus*). Canadian Science Advisory Secretariat. Research Document. 2015/033. vii+ 23pp.

Christensen, M.R., Graham, M.D., Vinebrooke, R.D., Findlay, D.L., Paterson, M.J., and Turner, M.A. 2006. Multiple anthropogenic stressors cause ecological surprises in boreal lakes. Global Change Biology. 12(12): 2316–2322.

Clark, C.W., and D.A. Levy. 1988. Diel vertical migrations by juvenile Sockeye Salmon and the antipredation window. The American Naturalist 131: 271-290.

Committee on the Status of Endangered Wildlife in Canada (COSEWIC). 2003. Assessment and status report on the sockeye salmon *Oncorhynchus nerka* (Cultus Population) in Canada. Committee on the Status of Endangered Wildlife in Canada. Ottawa. ix + 57 pp.

COSEWIC. 2010. Assessment and Status Report Coastrange Sculpin Cottus aleuticus Population (English Edition). Committee on the Status of Endangered Wildlife in Canada. Ottawa. xi + 28pp.

COSEWIC. 2017. COSEWIC Assessment and Status Report on the Sockeye Salmon (*Oncorhynchus nerka*) 24 Designatable Units in the Fraser River Drainage Basin in Canada 2017. Committee on the Status of Endangered Wildlife in Canada. https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/cosewic-assessments-status-reports/sockeye-salmon-2017.html

Cramer, F.H. 2005. The valley beyond: A history of Columbia Valley & Lindell Beach. Columbia Valley Ratepayers Association. Lindell Beach, Canada.

Delcan. 2012. Cultus Lake Traffic and Transportation Study. Delcan Corporation. SW1193SWA. Vancouver, BC.

Duguay, C.R., Prowse, T.D., Bonsal, B.R., Brown, R.D., Lacroix, M.P., and P. Ménard. Recent trends in Canadian ice cover. Hydrological Processes. 20: 781-801.

Fisheries and Oceans Canada (DFO). 2017. Action Plan for the Cultus Pygmy Sculpin (*Cottus aleuticus,* Cultus Population) in Canada. Species at Risk Act Action Plan Series. Fisheries and Oceans Canada, Ottawa. v + 34pp.

Edmondson, W.T., and J.T. Lehman. 1981. The effect of changes in the nutrient income on the condition of Lake Washington. Limnology and Oceanography. 26: 1-29

Environment Canada (EC). 2019. Canadian Climate Normals. Environment Canada Climate; http://climate.weather.gc.ca/historical_data/search_historic_data_e.html

Environment Canada (EC) and U.S. Environmental Protection Agency (US EPA). 2014. Georgia Basin - Puget Sound Airshed Characterization Report, 2014. Vingarzan R., So R., Kotchenruther R., eds. Environment Canada, Pacific and Yukon Region, Vancouver (BC). U.S. Environmental Protection Agency, Region 10, Seattle (WA). ISBN 978-1-100 22695-8. Cat. No.: En84-3/2013E-PDF. EPA 910-R-14-002.

Environment and Climate Change Canada (ECC). 2017. Canadian regional climate model. RCP4. Government of Canada.

ECCC. 2020. Water basics: The hydrological cycle. https://www.canada.ca/en/environment-climate-change/services/water-overview/basics/hydrologic-cycle.html

Fraser Valley Regional District (FVRD). 2011. District Statistics. Fraser Valley Regional District 2011.

Foerster, R.E. 1925. Studies in the ecology of the sockeye salmon (*Oncorhynchus nerka*). Contributions to Canadian Biology, New Series 2: 335-422.

Gauthier et al. *in review.* Evaluating the congruence between DNA-based and morphological taxonomic approaches in water and sediment traps : Analyses of a 36-month time series from a temperate monomictic lake. Limnology and Oceanography.

Gauthier, J., Gregory-Eaves, I., Bunting, L., Leavitt, P.R., Tran, T., Godbout, L., Finney, B.P., Schindler, D.E., Chen, G., Holtgrieve, G., Shapley, M., and D.T. Selbie. *accepted.* Ecological dynamics of a peri-urban lake: A multi-proxy paleolimnological study of Cultus Lake (British Columbia) over the past ~200 years. Journal of Paleolimnology.

Government of British Columbia. 2020. B.C. Airsheds. https://www2.gov.bc.ca/gov/content/environment/air-land-water/air/air-quality-management/airsheds Accessed. 05/2020.

Holtgrieve, G.W., Schindler, D.E., Hobbs, W.O., Leavitt, P.R., Ward, E.J., Bunting, L., Chen, G.J., Finney, B.P., Gregory-Eaves, I., Holmgren, S., Lisac, M.J., Lisi, P.J., Nydick, K., Rogers, L.A., Saros, J.E., Selbie, D.T., Shapley, M.D., Walsh, P., and A.P. Wolfe. 2011. A coherent signature of anthropogenic nitrogen deposition to remote watersheds of the Northern Hemisphere. Science. 334:1545-1548.

ISL. 2014. Cultus Lake Sanitary Sewer Infrastructure Assessment. Final Report to the Fraser Valley Regional District. 70pp.

Janmaat, J., and A. Cebry. 2019. Cultus Lake Environmental Services Evaluation. Phase 1. April 2019 Revision. A report to the Cultus Lake Aquatic Stewardship Strategy (CLASS). 72pp.

Kottek, M., Grieser, J., Beck, C., Rudolph, B., and F. Rubel. 2006. World map of the Koppen-Geiger climate classification updated. Meteorologische Zeitschrift. 15: 259-263.

Loudon, K. 2020. Spatiotemporal trends in habitat use and limnological evidence of seasonal degradation of freshwater critical habitat for threatened coastrange sculpin in Cultus Lake, BC. Master of Natural Resources Capstone Report. Oregon State University. 57pp.

Mantua, N.J., Hare, S.R., Zhang, Y., Wallace, J.M., and R.C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society. 78: 1069-1079.

McKendry, I.G. 2010. Air quality in the Lower Fraser Valley and Waste to Energy Incineration – An Overview. Report to the Fraser Valley Regional District. 12pp.

Meidinger D, and J. Pojar. 1991. Ecosystems of British Columbia. BC Ministry of Forests Special Report Series #6. 342 pp.

Metro Vancouver. 2018. 2015 Lower Fraser Valley Air Emissions Inventory and Forecast: Final Report and Summarized Results. 20pp.

Moss, B., Kosten, S., Meerhoff, M., Battarbee, R.W., Jeppesen, E., Mazzeom, N, Havens, K., Lacerot, G., Liu, Z., De Meester, L., Paerl, H., and M. Scheffer. 2011, Allied attack: climate change and eutrophication. Inland Waters. 1: 101–105.

Mossop, B. and. M.J. Bradford. 2004. Review of Eurasian watermilfoil control at Cultus Lake and recommendations for future removals. Fisheries and Oceans Canada; Fraser River Stock Assessment. 26 pp.

Mueller, H., Hamilton, D.P., and G.J. Doole. 2016. Evaluating services and damage costs of degradation of a major lake ecosystem. Ecosystem Services. 22: 370-380.

Müller, B., L.D. Bryant, A. Matzinger, and A. Wüest. 2012. Hypolimnetic oxygen depletion in eutrophic lakes. Environmental Science and Technology 46: 9964-9971.

O'Reilly, C.M., Sharma, S., Gray, D.K., Hampton, S.E., Read, J.S., Rowley, R.J., Schneider, P., Lenters, J.D., McIntyre, P.B., Kraemer, B.M., Weyhenmeyer, G.A., Straile, D., Dong, B., Adrian, R., Allan, M.G., Anneville, O., Arvola, L., Austin, J., Bailey, J.L., Baron, J.S., Brookes, J.D., de Eyto, E., Dokulil, M.T., Hamilton, D.P., Havens, K., Hetherington, A.L., Higgins, S.N., Hook, S., Izmest'eva, L.R., Joehnk, K.D., Kangur, K., Kasprzak, P., Kumagai, M., Kuusisto, E., Leshkevich, G., Livingstone, D.M., MacIntyre, S., May, L., Melack, J.M., Mueller-Navarra, D.C., Naumenko, M., Noges, P., Noges, T., North, R.P., Plisnier, P-D., Rigosi, A., Rimmer, A., Rogora, M., Rudstam, L.G., Rusak, J.A., Salmaso, N., Samal, N.R., Schindler, D.E., Schladow, S.G., Schmid, M., Schmidt, S.R., Silow, E., Soylu, M.E., Teubner, T., Verburg, P., Voutilainen, A., Watkinson, A., Williamson, C.E., and G. Zhang. 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophysical Research Letters. 42: 10773-10781.

Pacific Climate Impacts Consortium (PCIC). 2020. Plan2Adapt. Downscaled 2050's (2040-2069) climate projections for the Vancouver-Fraser Region. https://services.pacificclimate.org/plan2adapt/app/

Paul, M.J., and J.L. Meyer. 2001. Streams in the urban landscape. Annual Review of Ecology and Systematics. 32: 333-365.

Pojar, J., Klinka, K., and D.V. Meidinger. 1987. Biogeoclimatic ecosystem classification in British Columbia. Forest Ecology and Management. 22: 119-154.

Putt, A.E. 2014. Spatiotemporal nutrient loading to Cultus Lake: Context for eutrophication and implications for integrated watershed-lake management. Master of Resource Management Thesis. School of Resource and Environmental Management. Simon Fraser University. 111pp.

Putt, A.E., MacIsaac, E.A., Herunter, H.H., Cooper, A.B., and D.T. Selbie. 2019. Eutrophication forcings on a peri-urban lake ecosystem: Context for integrated watershed to airshed management. PLoS ONE. 14(7): e0219241

Rhodes, C., Bingham, A., Heard, A.M., Hewitt, J., Lynch, J., Waite, R., and M.D. Bell. 2017. Diatoms to human uses: linking nitrogen deposition, aquatic eutrophication, and ecosystem services. Ecosphere. Special Feature: Air Quality and Ecosystem Services. e01858.

Ricker, W.E. 1937. Physical and chemical characteristics of Cultus Lake, British Columbia. Journal of the Fisheries Research Board of Canada. 3: 363-402.

Robinson, M. 2011. Cultus Lake User Survey Report. Fraser Basin Council Report on behalf of the Cultus Lake Aquatic Stewardship Strategy (CLASS). 36pp.

Ruggerone, G.T. 2000. Differential survival of juvenile sockeye and coho salmon exposed to low dissolved oxygen during winter. Journal of Fish Biology. 56:1013-1016.

Scheuerell, M.D., and D.E. Schindler. 2003. Diel vertical migration by juvenile sockeye salmon: Empirical evidence for the antipredation window. Ecology. 84: 1713-1720.

Schindler, D.W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Canadian Journal of Fisheries and Aquatic Sciences. 58: 18–29.

Schindler, D.W. 2006. Recent advances in the understanding and management of eutrophication. Limnology and Oceanography. 51: 356-363.

Schubert N.D., Beacham, T.D., Cass, A.J., Cone, T.E., Fanos, B.P., Foy M., Gable, J.H., Grout, J.A., Hume, J.M.B., Johnson, M., Morton, K.F., Shortreed, K.S., Staley, M.J., and R.E. Withler. 2002. Status of Cultus Lake sockeye salmon (*Oncorhynchus nerka*). Canadian Science Advisory Secretariat Research Document. 2002/064. 109pp.

Selbie, D.T., Finney, B.P. Barto, D., Bunting, L., Chen, G., Leavitt, P.R., MacIsaac, E.A., Schindler, D.E., Shapley, M.D., and I. Gregory-Eaves. 2009. Ecological, landscape, and climatic regulation of sedimentary geochemistry in North American sockeye salmon nursery lakes: Insights for paleoecological salmon investigations. Limnology and Oceanography. 54:1733-1745.

Selbie, D.T., Sweetman, J.N., Etherton, P., Hyatt, K.D., Rankin, P., Finney, B.P., and J.P. Smol. 2011. Climate change modulates structural and functional lake ecosystem responses to introduced anadromous salmon. Canadian Journal of Fisheries and Aquatic Sciences. 68: 675-692.

Shortreed, K.S., Morton, K.F., Malange, K., and J.M.B. Hume. 2001. Factors limiting juvenile sockeye production and enhancement potential for selected B.C. nursery lakes. Canadian Science Advisory Report. 2001/098. 69pp.

Simmatis, B., Jeziorzki, A., Zemanek, A., Selbie, D.T., Hyatt, K., Fryer, J.K., Cumming, B.F., and J.P. Smol. 2018. Long-term reconstruction of deep-water oxygen conditions in Osoyoos Lake (British Columbia, Canada): Implications for Okanagan River sockeye salmon. Lake and Reservoir Management. 34: 392-400.

Shuswap Lake Integrated Planning Process (SLIPP). 2014. Summary: 2011-2013 Water Quality Monitoring Results for Shuswap and Mara Lakes. Consolidated Update Report. 12pp.

Smith, V.H., and D.W. Schindler. 2009. Eutrophication science: where do we go from here? Trends in Ecology and Evolution 24: 201-207.

Smith, V.H., Tilman, G.D., and J.C. Nekola. 1999. Eutrophication: impacts of excess nutrient inputs on freshwater, marine, and terrestrial ecosystems. Environmental Pollution. 100: 179–96.

Smol, J.P. 2008. Pollution of Lakes and Rivers. A Paleoenvironmental Perspective. Blackwell Publishing. Malden MA USA 383pp.

Soutar, M. 2005. Cultus Lake: a natural paradise. Chilliwack Museum and Archives, Chilliwack, BC, Canada. 36pp.

Species at Risk Act (SARA). 2002. c. 29. An Act respecting the protection of wildlife species at risk in Canada. Assent 2002-12-12.

Species at Risk Act (SARA) Secretariat. 2020. Coastrange Sculpin (*Cottus aleuticus*), Cultus population. Species at Risk Public Registry. https://species-registry.canada.ca/index-en.html#/species/300-213

Stahl, K., Moore, R.D., and I.G. Mckendry. 2006. The role of synoptic-scale circulation in the linkage between large-scale ocean-atmosphere indices and winter climate in British Columbia, Canada. International Journal of Climatology. 30: 541-560.

Sumka, M.G. 2017. Climate change impacts on a eutrophying lake: Cultus Lake, British Columbia, Canada. Master of Applied Science Thesis. Department of Civil Engineering. 85pp.

Urban Systems Ltd. 2012. Cultus Lake South Sewerage Planning Study. Prepared for the Fraser Valley Regional District; USL File No. 0999.0042.01. Chilliwack (BC). 2012.

Vincent, W.F. 2009. Effects of Climate Change on Lakes. *In* Encyclopedia of Inland Waters. G.E. Likens (ed.), Elsevier, Oxford. 3: 55–60.

Vingarzan R., Belzer W., and B. Thompson. 2002. Nutrient levels in the atmosphere of the Elk Creek Watershed, Chilliwack, BC (1999–2s000). Environment Canada Technical Report. Aquatic and Atmospheric Sciences Division, Vancouver, Canada. 74 pp.

Wetzel, R.G. 2001. Limnology: Lake and River Ecosystems. 3rd Edition. Academic Press. San Diego, CA, USA. 1006 pp.

Wilson, M.A., and S.R. Carpenter. 1999. Economic valuation of freshwater ecosystem services in the United States: 1971-1997. Ecological Applications. 9: 772-783.

Woodruff, P. 2010. A genetic and behavioural analysis of the distinctiveness of the Cultus Pygmy Sculpin (*Cottus aleuticus*) and implications for its conservation. M.Sc. Thesis. University of British Columbia. 111pp.

Zubel, M. 2000. Groundwater Conditions of the Columbia Valley Aquifer Cultus Lake, British Columbia. Report prepared for the Ministry of Environments, Lands, and Parks Water Management. 2000 Jan.; 98p.