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Recovery Potential Assessment for the Endangered Cultus Lake Sockeye Salmon (*Oncorhynchus nerka*) (2019)

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Cultus Lake Sockeye Salmon (*Oncorhynchus nerka*) were first assessed as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2002 in an emergency assessment and confirmed as such in 2003. Owing largely to socioeconomic considerations Cultus Lake Sockeye Salmon were not listed under Schedule 1 of the Species at Risk Act (SARA) at this time. In 2017, as part of a COSEWIC assessment of 24 Fraser Sockeye Designatable Units (DUs), Cultus Lake Sockeye was again assessed as endangered.

This Recovery Potential Assessment (RPA) provides an overview of Cultus Lake Sockeye biology, habitat requirements, threats, and limiting factors in Elements 1-11, and identifies recovery targets, population projections, mitigation assessments and recommendations on allowable harm in Elements 12-22.

Threats to persistence with the highest population risks include degradation of critical freshwater habitats from anthropogenic forcings, and direct population losses due to harvests in the mixed-stock fishery. Lake eutrophication, in particular, and its interactions with climate change, are newly-understood since the last assessment, and are quantified, and highly-influential mechanisms of population depression. Feasible options for mitigation of the various pathways and nutrient loadings to Cultus Lake have been developed both in the literature and this RPA, and are viewed as essential to population recovery, requiring targeted, interdisciplinary and inter-jurisdictional actions.

Recognizing the distinction between recovery and survival of a population or species, an abundance target of 7,000 spawners (four-year average) is proposed for recovery of the Cultus Lake Sockeye Salmon DU, and a generational average of 2,500 spawners is proposed as a survival target. Model results suggest that without hatchery supplementation the population will be unable to sustain itself under the current threats and limiting factors, and is predicted to continue to decline over the next three generations (12 years). With ongoing supplementation, extinction is averted, but the population is unlikely to reach survival or recovery targets within this timeframe, without active threat mitigation. Addressing fisheries-related mortality and mitigating freshwater habitat threats (i.e. lake eutrophication), in particular, are anticipated to improve population trends and are highly recommended.

1. INTRODUCTION

1.1. RATIONALE FOR RECOVERY POTENTIAL ASSESSMENT

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) is responsible for the assessment and classification of aquatic species-at-risk in Canada. Following COSEWIC assessment, imperilled species are considered for listing by the Minister under Canada's Species At Risk Act (2002) as Not at Risk, Special Concern, Threatened, Endangered, or Extirpated. Fisheries and Oceans Canada (DFO), is the responsible jurisdiction for aquatic species under *the Species at Risk Act* (SARA), and undertakes a number of actions to support implementation of the Act. Many of these actions require scientific information on the current status of the species, threats to its survival and recovery, and the species' potential for recovery. Formulation of this scientific advice has typically been developed through a Recovery Potential Assessment (RPA) following the COSEWIC assessment. This timing allows for the consideration of peer-reviewed scientific analyses into SARA processes, including the decision whether or not to list a species on Schedule 1, and during recovery planning if the species is listed.

Cultus Lake Sockeye Salmon (*Oncorhynchus nerka*) is the Designatable Unit (DU) of the anadromous Sockeye Salmon population endemic to Cultus Lake, British Columbia, Canada, which is part of the Fraser River Sockeye Salmon stock aggregate. This DU is genetically-distinct, and reproductively-isolated from other populations in Canada and elsewhere in its range (Schubert et al. 2002; COSEWIC 2017). Cultus Lake Sockeye Salmon are anadromous and semelparous, using Cultus Lake, BC as sole freshwater habitat for spawning, incubation, and rearing, prior to outmigration and maturation within migration and foraging habitat of the North Pacific Ocean. Cultus Lake Sockeye Salmon return with the late Fraser River run timing group, co-migrating with abundant late-run stocks (i.e. Late-Shuswap Sockeye Salmon; Grant et al. 2011).

Cultus Lake Sockeye Salmon were first assessed by COSEWIC in 2002 in an emergency assessment and recommended as Endangered (COSEWIC 2003; CSRT 2009). The emergency listing status was re-examined and confirmed as Endangered in May 2003 (COSEWIC 2003). In 2005, the Governor General in Council, based upon the recommendation of the Minister of Environment, decided not to list Cultus Lake Sockeye Salmon under Schedule 1 of the Species at Risk Act (2002), citing socioeconomic impacts to commercial, recreational, and indigenous fisheries (Governor General 2005). Cultus Lake Sockeye Salmon were again reviewed by COSEWIC in 2017 within an aggregate assessment of 24 Fraser River Sockeye Salmon DU's, and the Endangered status once again confirmed (COSEWIC 2017), citing the following reasons:

"Cultus Lake is one of the most heavily utilized lakes in BC and it has been developed for recreational, residential and agricultural purposes. The lake's water quality has been degraded as a result of seepage from septic systems, agricultural runoff and domestic use of fertilizers as well as by an introduced Eurasian water-milfoil (Myriophyllum sp.). The spawning population has declined steadily since 1950 and the current population size remains very small. This small population continues to face high exploitation rates as bycatch in other salmon fisheries."

The Minister of Environment has responded (Minister of Environment and Climate Change Canada 2019), indicating a decision on amending the List of Wildlife Species at Risk (Schedule 1, SARA 2002) for this species will be sought of the Governor in Council.

1.2. CULTUS LAKE, BRITISH COLUMBIA

Cultus Lake is the natal freshwater rearing area for a genetically-distinct population of Sockeye Salmon (*Oncorhynchus nerka*). Cultus Lake is a relatively small (surface area 6.3 km^2), low-elevation nursery lake ecosystem (46 m above sea level (asl)), located adjacent to the Fraser Valley, in southwestern British Columbia, Canada (Figure 1). The lake is bounded by an international watershed (69 km^2; 82% Canada, 18% USA; Putt et al. 2019), consisting of the Vedder Mountain ridge to the west, International Ridge to the east, and the Columbia Valley to the south. The lake and its watershed are situated within the Coastal Western Hemlock Biogeoclimatic Zone – Dry Maritime Subzone (Meidinger and Pojar 1991), and drain to the Pacific Ocean (118 km) via Sweltzer Creek, and the Vedder, Sumas, and Fraser rivers. The local climate is characterized as Maritime Temperate (Koppen Climate Classification; Kottek et al. 2006), with warm, dry summers, and cool, wet winters (Shortreed 2007). Annual daily average temperature is 10.8 ^oC ± 2.0 ^oC (1SD), ranging from mean daily minima in December and January (3.3^oC ± 1.9 ^oC (1 SD), to a mean daily maximum in July (18.8 ^oC ± 0.9 ^oC (1 SD) (1981-2010 Canadian Climate Normals – Stn # 1101530; Environment and Climate Change Canada 2019). Precipitation predominantly falls as rain from October to April, with an annual average of 1.67 m (95% rainfall; 1981-2010 Canadian Climate Normals –Stn # 1101530; Environment and Climate Change Canada 2019).

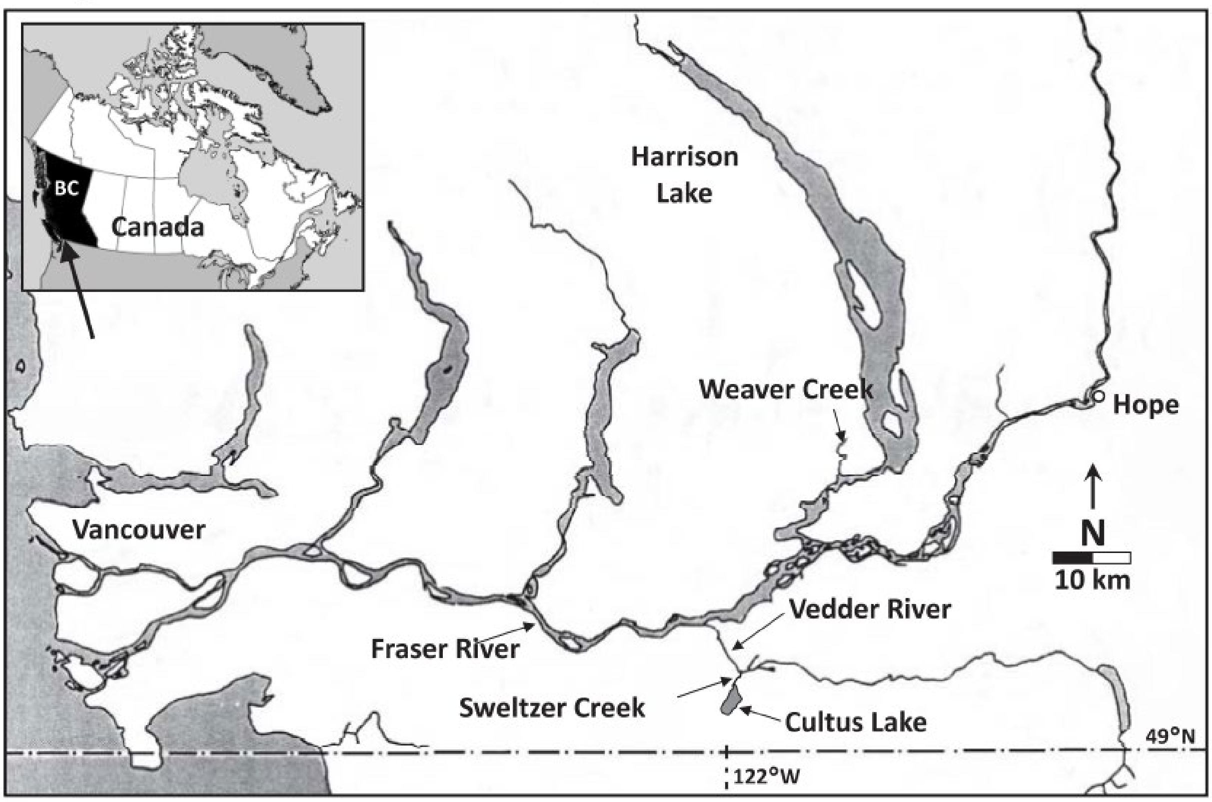


Figure 1. Location of Cultus Lake and the freshwater migration route for Cultus Lake Sockeye Salmon. Figure modified from Bradford et al. (2010).

Cultus Lake is a warm monomictic system, exhibiting water column mixing from fall to spring, and strong thermal stratification from spring to fall (Shortreed 2007; Sumka 2017). The basin is of moderate depth (z_{min} = 31 m; z_{max} = 44 m), and characterized by a simple, steep-sided morphometry, with limited littoral habitat (14% of surface area), and a relatively broad, flat profundal zone (Shortreed 2007; Figure 2). The estimated annual lake residence time is relatively short, and averages 1.8 years, owing to pronounced flushing during the wet falls and winters, when the watershed hydrograph peaks (Shortreed 2007, Putt et al. 2019). Cultus Lake is fed by a network of 11 primary creeks and streams, with the majority of the hydrological balance (80% of watershed runoff) inputted by Frosst and Spring creeks, emerging from the Columbia Valley sub-watershed (Putt et al. 2019).

Cultus Lake is a nursery lake ecosystem, used by the endemic, endangered Cultus Lake Sockeye Salmon to spawn and rear juveniles prior to outmigration to the Pacific Ocean (COSEWIC 2003). Including Sockeye Salmon, the fish community of Cultus Lake is comprised of 19 native species. Other species of salmonids include Chinook (*O. tshawytscha*), Coho (*O. kisutch*), Chum (*O. keta*), Pink (*O. gorbuscha*), Cutthroat Trout (*O. clarki clarki*), Rainbow Trout (*O. mykiss*), and Dolly Varden (*Salvelinus malma*). Cyprinids found in Cultus Lake include Northern Pikeminnow (*Ptychocheilus oregonensis*), Redside Shiner (*Richardsonius balteatus*), , Longnose Dace (*Rhinichthys cataractae*), and Peamouth (*Mylocheilus caurinus*). Largescale Sucker (*Catostomus macrocheilus*) are also present, as are Threespine Stickleback (*Gasterosteus aculeatus*). Cultus Lake hosts three sculpin taxa, including the Prickly Sculpin (*Cottus asper*), Coastrange Sculpin (*C. aleuticus*), and the endemic Cultus Pygmy Sculpin (*C. aleuticus*; Coastrange Sculpin, Cultus Population). The Cultus Pygmy Sculpin is currently listed under Schedule 1 of SARA as threatened, due to its limited range and local freshwater habitat threats, and is currently being considered by the Minister for up-listing to Endangered status given the known anthropogenic degradation of same (Minister of Environment and Climate Change Canada 2020). Two species of Lamprey, the Western Brook Lamprey (*Lampetra richardsoni*) and the River Lamprey (*L. ayresi*) can also be found in the lake. A White Sturgeon (*Acipenser transmontanus*), has also been caught in the lake, though they are not thought to naturally inhabit the system continuously.

Cultus Lake has a relatively lengthy development history, dating back to the mid-1800's, when mining trails and camps were established within the watershed, followed by logging in the early 1900's (peaking in the 1920's; Cramer 2005; Gauthier et al. 2021). Agricultural development within the Columbia Valley closely followed forestry (1930's), as did an increasing presence of permanent housing (Soutar 2005; Gauthier et al. 2021). Recreational values have long been important at Cultus Lake, exemplified by the establishment of the Cultus Park in 1924 and Park Board in 1932, and summer cottages and other facilities (i.e. golf course) as the number of permanent residents in the area continued to increase through the 1940's and 1950's (Soutar 2005; Gauthier et al. 2021). By the mid 1950's the lake received over 167,000 visitors annually (Chilliwack progress, December 11, 1957). Development and recreation in the catchment has continued since then, with contemporary estimates of 2-3 million visitors to the Cultus Lake annually (Delcan 2012). Given this modern context, Cultus Lake is considered peri-urban (Putt et al. 2019), indicating that while local development is still somewhat diffuse, the lake receives undue anthropogenic stresses from expanding nearby populations and their activities.

Owing to its high recreational value and traffic, Cultus Lake has also been colonized by several invasive species. Eurasian Watermilfoil (*Myriophyllum spicatum*) was known to have invaded Cultus Lake by the late 1970's, likely transmitted by propagules on vessels, and has become the dominant littoral zone aquatic macrophyte, displacing much of native macrophyte guild from nearshore environments, which includes *Chara* spp., pondweeds (*Potamogeton* spp.), Coontail (*Ceratophyllum demersum*), Northern Watermilfoil (*Myriophyllum sibiricum*), and Water Buttercup (*Ranunculus aquatalis* var. *capillaceus*) (Ricker 1952; Shortreed 2007). Eurasian Watermilfoil is estimated to occupy over 60% of nearshore habitats within the lake (by area), from 1-8 m depth (Stables 2004; DFO 2014). Invasive Curly Leaf Pondweed (*Potamogeton crispus*) has also been observed within the lake. As of spring 2018, invasive Smallmouth Bass

(*Micropterus dolomieu*) have been reported in Cultus Lake, though given the range of age classes observed, they were likely present for several years prior to identification, and have been confirmed to be reproducing and likely expanding in abundance within Cultus Lake.

1.3. WILD SALMON IN THE CONTEXT OF SARA WILDLIFE SPECIES

Under Canada's Policy for the Conservation of Wild Pacific Salmon (aka. Wild Salmon Policy (WSP)), Pacific salmon are considered 'wild', if they have spent their entire life cycle in the wild, and arose from fish that naturally spawned and lived in the wild (DFO 2005). Wild Pacific salmon are formally taxonomically represented by five extant species (i.e. Chinook, Coho, Sockeye, Pink, and Chum salmon; Groot and Margolis 1991). However, owing to local adaptation to the diversity of marine and freshwater habitats colonized and utilized within any given species (Groot and Margolis 1991; Quinn 2005), and the rapid evolution afforded by a semelparous life history (Hendry et al. 2000), wild Pacific salmon exhibit extreme genetic and phenotypic diversity within and across species (Quinn 2005). This diversity leads to a complex, hierarchical population structure from local spawning sites to taxonomical species, resulting in a geographic network of demes, the basic level of genetic organization within Pacific salmon (DFO 2005). Although straying and associated genetic variation occurs, distal separation between spawning sites leads to independently-functioning aggregates, managed as Conservation Units (CU) in Canada (DFO 2005). Conservation Units (CU) are aggregates of wild salmon sufficiently isolated from other groups that, if extirpated, are unlikely to recolonize naturally within an acceptable time frame (DFO 2005).

In assessing recovery potential under SARA, it is important to ensure terminological homology in defining the level of organization at which assessment is focussed. Under Canada's Species at Risk Act (S.C. 2002 c. 29; SARA), 'wildlife species', is the focal level of taxonomic identity, and is defined as follows:

"a species, subspecies or biologically distinct population of animal, plant or other organism, other than a bacterium or virus, that is wild by nature and native to Canada without human intervention for at least 50 years"

Under Canada's Policy for the Conservation of Wild Pacific Salmon, Pacific salmon CU's are homologous with the definition of 'wildlife species' in SARA (DFO 2005). However, the SARA 'wildlife species' definition recognizes that conservation of biological diversity requires protection for taxonomic entities below the species level (i.e. Designatable Units or DU's), and empowers COSEWIC with a mandate to assess those entities when warranted. DU's should be discrete and evolutionarily significant units of the taxonomic species, where "significant" means that the unit is important to the evolutionary legacy of the species as a whole, and if lost would likely not be replaced through natural dispersion (SARA 2002). While DU's and CU's may not be the same across Pacific salmon populations within a species, Cultus Lake Sockeye Salmon are genetically distinct from other Canadian Sockeye Salmon populations (Beacham and Withler 2017), and the boundaries for the CU defined under the WSP and the DU as defined by COSEWIC are the same. As such, the terms are considered homologous, and in this case, are considered synonymous.

In an attempt to conserve Cultus Lake Sockeye Salmon, concerted conservation hatchery enhancement has been undertaken on the population since 2002, including broodstock and captive broodstock enhancement, with sizeable proportions in any given contemporary brood the consequence of such interventions (CSRT 2009). The Species at Risk Act (SARA 2002), definition of 'wildlife species' includes the term 'wild by nature', which according to recent legal interpretations might include captive individuals with recent wild ancestors (COSEWIC 2010). Although hatchery-origin fish were not included by COSEWIC in their assessment of Cultus

Lake Sockeye Salmon (COSEWIC 2017), as per the COSEWIC Manipulated Populations Guidelines, ‘wildlife species’ includes all intra-limital reintroductions (i.e. within their natural range) as part of the wildlife species being assessed (COSEWIC 2010). Therefore, hatchery-supplemented individuals (i.e. enhanced and captively-bred) released into Cultus Lake are included in the definition of a ‘wildlife species’ under SARA and therefore are included herein for the purposes of this Recovery Potential Assessment.

2. BIOLOGY, ABUNDANCE, DISTRIBUTION AND LIFE HISTORY PARAMETERS

2.1. ELEMENT 1: SUMMARY OF THE BIOLOGY OF CULTUS LAKE SOCKEYE SALMON

2.1.1. Biology

Sockeye Salmon are one of the five highly-migratory, anadromous and semelparous Pacific Salmon species, whose life-histories are completed over thousands of kilometers from natal freshwater habitats to the vast expanses of the North Pacific Ocean. In contrast to the other salmon species, Sockeye Salmon primarily use freshwater lake ecosystems to rear their young prior to outmigration to the marine environment (Burgner 1991).

Cultus Lake Sockeye Salmon are an extant, genetically-distinct CU within the Fraser River Sockeye Salmon Complex (24 CU’s), belonging to the Late-Run timing group (stock management); a collection of co-migrating Fraser Sockeye Salmon stocks that typically enter the Fraser River between late-July and mid-October (Grant et al. 2011). Characteristic of most Fraser River Sockeye Salmon life histories, Cultus Lake Sockeye Salmon exhibit a four year brood line cycle, typically returning to their natal spawning grounds on the shores of Cultus Lake in the fourth year of life, although some age-class variation (i.e. 3-5 year old returning spawners) is observed within the CU.

2.1.1.1. Spawning migration

The Cultus Lake Sockeye Salmon spawning migration typically begins in early August, and continues through late-November. Upriver migration for this population is not particularly arduous, with spawning adults transiting 118 km from the mouth of the Fraser River to Cultus Lake via the Fraser, Sumas, and Vedder Rivers, and Sweltzer Creek, a total elevation gain of 46m asl. (Shortreed 2007). Sockeye Salmon demonstrate a strong homing behaviour to their natal spawning grounds (Burgner 1991; Quinn 2005), largely regulated in freshwater by juvenile olfactory imprinting on odours associated with these environments (Dittman and Quinn 1996). As part of the transition from marine to freshwaters, Sockeye Salmon largely cease feeding, and rely exclusively on stored energy for upriver migration, the completion of sexual maturation, and spawning activities (Burgner 1991).

2.1.1.2. Reproduction

Cultus Lake Sockeye Salmon are among the last Fraser stocks to spawn each year, with spawning taking place from late-November and through December (Schubert 1998). Cultus Lake Sockeye Salmon spawn exclusively within the lake. Preferential redd (nest) habitat is characterized by substrate material of sufficient size to create interstitial space for eggs to rear in. Adequate flow of oxygenated water past the eggs is required for their survival. In Cultus Lake, Sockeye Salmon have historically spawned in Spring Bay, Lindell Beach, Salmon Bay, Snag Bay (Honeymoon Bay), and along the eastern and southern margins of the lake (Figure 2). In more recent years, however, spawning has only been observed by remotely operated vehicles (ROV) in Spring Bay. Given the deep depths of contemporary spawning, and a lack of systematic investigation, it is not known whether other areas of the lake may be used consistently or inconsistently for spawning. Additional ROV surveys are required to understand extant spawning locations and locational changes through time. Cultus Lake Sockeye Salmon females typically have an average of approx. 3500 eggs.

Emergence typically occurs in April and May (CSRT 2009), but as with all salmonids is dictated by ambient temperatures during the incubation period (i.e. accumulated thermal units, ATU; Burgner 1991; McPhail 2007). Historically, Cultus Lake Sockeye Salmon emergence occurs over a broader period, reflecting the protracted spawning window (Burgner 1991), however it is unclear with warming water temperatures in Cultus Lake (Shortreed 2007; Sumka 2017) whether this remains the case. Eggs and newly hatched alevins may be susceptible to predation by suckers and sculpins (CSRT 2009).

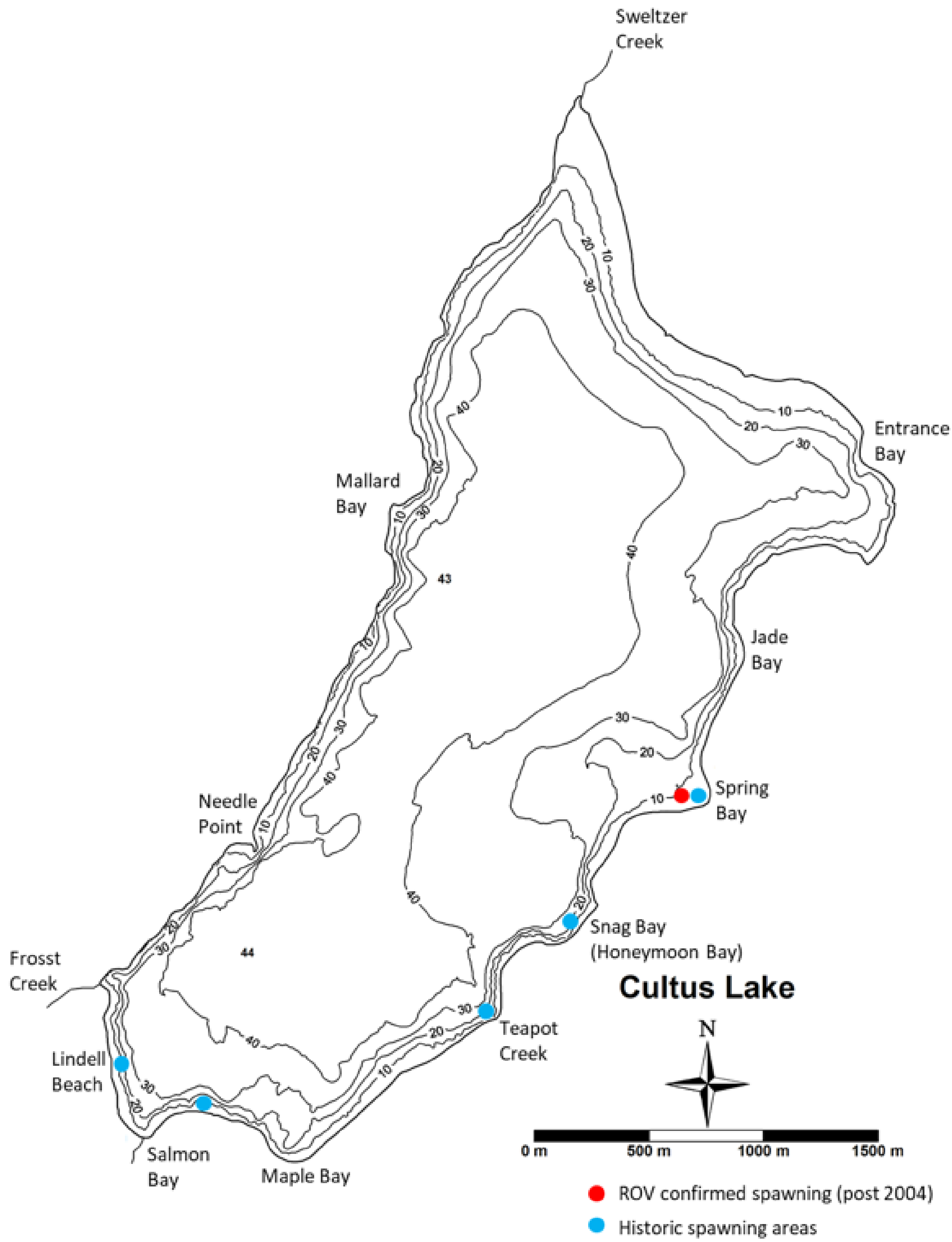


Figure 2. Bathymetric chart of Cultus Lake showing the historical and more recently confirmed spawning locations of the Cultus Lake Sockeye Salmon (Oncorhynchus nerka).

2.1.1.3. Freshwater Rearing

Fry emergence from the gravel substrate and eventual movement offshore into deeper waters typically begins in April and continues for approximately the next two months (Mueller and Enzenhofer 1991). Once offshore, fry exhibit strong diel vertical migration behaviour; staying deep in the profundal zone (near the lake sediments) during daylight hours, presumably to avoid predation, and moving up into the water column at night to feed (Clark and Levy 1988; Scheuerell and Schindler 2003). Most fry rear in the lake for one year, although a smaller proportion of the population rear for two years. During this life stage, fry feed on zooplankton such as *Daphnia* spp. and copepods (Shortreed 2007). Three-spined Sticklebacks, juvenile Kokanee, and Cultus Pygmy Sculpin have all been found to have a diet that overlaps with Cultus Lake Sockeye Salmon fry, though due to the relatively high biological productivity of the lake, competition with other species does not appear to be a limiting factor at this time. Native predators of juvenile Sockeye include Northern Pikeminnow, Dolly Varden, Coho Salmon, Cutthroat Trout and Rainbow Trout (Ricker 1941). As of 2018, invasive Smallmouth Bass have been identified in Cultus Lake, a known predator of juvenile salmon in other systems (Carey et al. 2011), and have been demonstrated to predate upon juvenile Sockeye Salmon in Cultus Lake (Wendy Margetts, Thompson Rivers University, British Columbia, pers. comm.).

2.1.1.4. Outmigration

In the spring following lake rearing, juvenile Cultus Lake Sockeye Salmon typically migrate downstream as age-1 smolts. In anticipation of the move from freshwater to marine environments, Sockeye Salmon fry undergo substantial physiological and morphological changes in a process known as smoltification (Burgner 1991). This transformation includes changes to shape, colour and osmoregulation, and is understood to be triggered by photoperiod changes for fish that have grown to a given size (Burgner 1991). Smolt migration out of Cultus Lake is one of the earliest among Fraser populations (Hartman et al. 1967), typically beginning in mid- to late-March, and finishing by late-May. The downstream migration occurs via Sweltzer Creek and the Vedder River, down the Fraser River and through the estuary and into the Salish Sea (Strait of Georgia). From there, Cultus Lake Sockeye Salmon typically migrate northward along the continental shelf before entering the North Pacific Ocean in winter (Tucker et al. 2009).

2.1.1.5. Ocean rearing

Sockeye Salmon can remain in the Pacific Ocean from one to four years, but most stay for two to three years before returning to their natal freshwater environments to spawn and die (Burgner 1991). During their time at sea, Fraser River Sockeye Salmon are distributed throughout the Gulf of Alaska and south to a latitude of ~ 46 °N (Forrester 1987). Sockeye Salmon grow substantially at sea, with over 98% of their final biomass accrued from marine resources (Quinn 2005). Growth occurs primarily in the summer when prey is more readily available, and warmer temperatures increase metabolic rates (Quinn 2005). Sockeye feed on zooplankton, small fish and squid (Manzer 1968), but are highly adaptable to changes in the availability of marine prey (Kaeriyama et al. 2004; Farley et al. 2018).

2.2. ELEMENT 2: EVALUATION OF THE RECENT SPECIES TRAJECTORY FOR ABUNDANCE, DISTRIBUTION AND NUMBER OF POPULATIONS

The assessment of Cultus Lake Sockeye Salmon is based upon counts of spawners passing into the lake through a counting fence that has been continuously operated since the 1920s. Adult fence counts were used to assess total abundances and recent trends. Counts are shown in Figure 3 which includes additional years of data since the COSEWIC assessment. The COSEWIC assessment was based on natural-origin spawners (i.e., hatchery fish are removed from the counts); the contribution of hatchery-origin spawners in also shown in the figure (red bars). The most recent generational (4-year, 2015-2018) averages are 254 natural-origin spawners, and 941 hatchery-origin spawners. Persistence of small annual population abundances, particularly relative to historical production, suggest a re-assessment of the current **endangered** status is not warranted at this time.

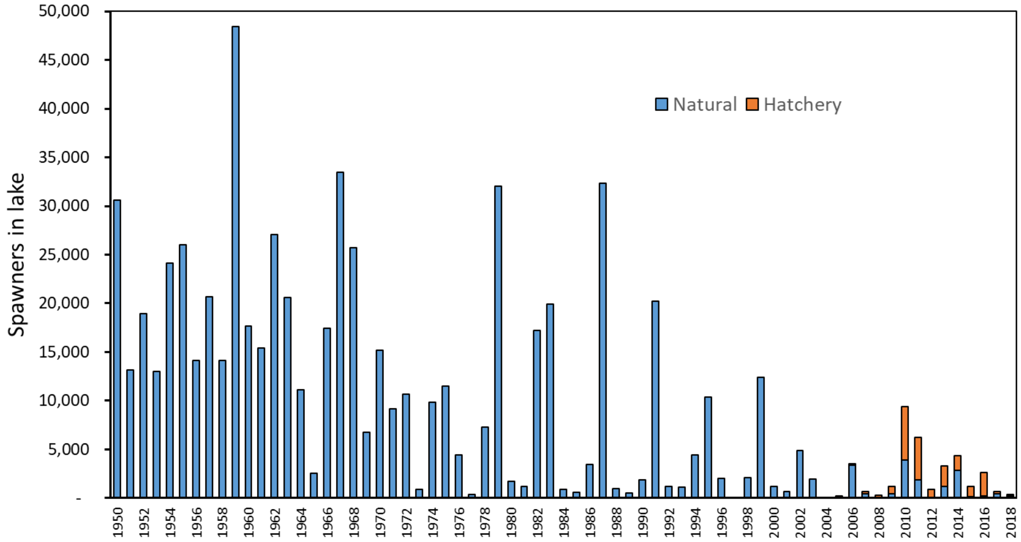


Figure 3. Number of adult spawners passed into Cultus Lake through the counting fence.

2.3. ELEMENT 3: ESTIMATES OF THE CURRENT OR RECENT LIFE-HISTORY PARAMETERS FOR CULTUS LAKE SOCKEYE SALMON

The Cultus Lake Sockeye Salmon population has a detailed set of life history parameter estimates that extend back to 1920. Table 1 contains summary statistics for estimates used in the population projections. Most are based upon data collected since 1999. Where available, comparisons were made to the earlier (1920-1990) period. Most parameters are based upon data collected from the weir located on Sweltzer Creek, downstream of the lake outlet, which provides accurate estimates of adults entering the lake, and smolts emigrating from it, as well as data on biological characteristics of the fish.

Smolt-recruit survival is survival from the smolt enumeration fence to recruitment, defined as the sum of the number of mature fish reaching the lake and those caught in fisheries. Computing smolt-recruit survival requires estimates of fishing mortality (exploitation rate) and are based on fishery reconstructions. Exploitation rates are subject to unknown levels of uncertainty. This is particularly true in the recent period when the rarity of Cultus fish in catches requires the use of estimates from nearby more abundant populations as surrogates.

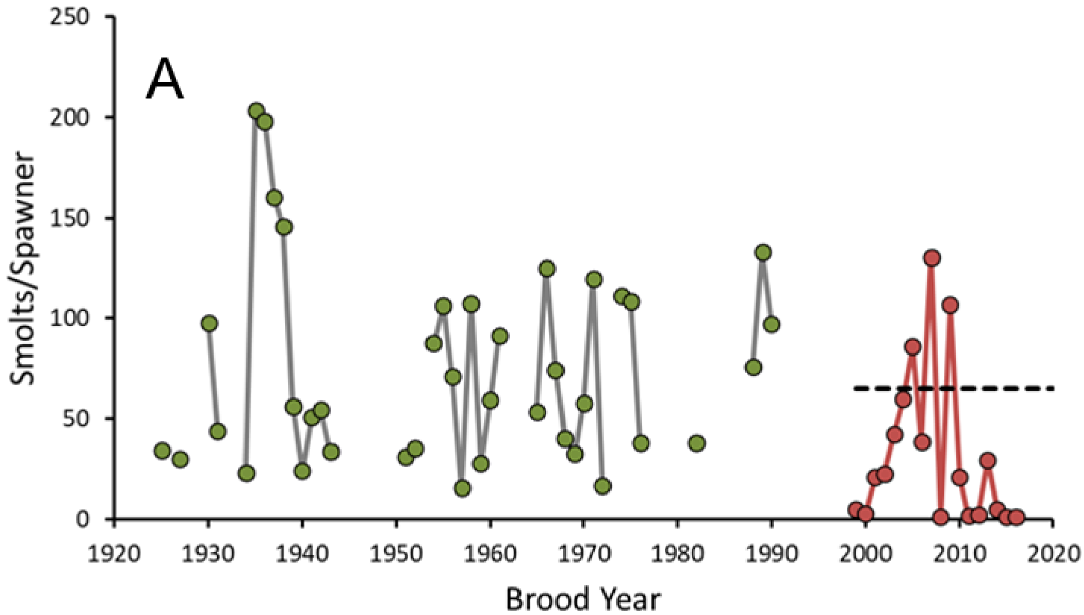
Smolt-spawner survival is the survival of fish between when they leave the lake as smolts to when they return to the lake as adults. These estimates are considered to be very accurate as they are based solely on weir counts. Smolt-spawner survival is lower than smolt-recruit survival because the latter excludes fishing mortality.

It is important to note the declines in smolt production (as smolts/spawner) and smolt-recruit survival, relative to historical averages. Reductions in fishing mortality have compensated for reduced smolt-recruit survival, resulting in little difference in the smolt-spawner survival rates between the historical and recent period.

Recently, years of very low rates of smolt production have occurred with increasing frequency (Figure 4). Smolt production rates are far below those needed for population survival or recovery (Figure 4A; dashed line).

Table 1. Life history parameters for Cultus Lake Sockeye Salmon. Mean and ranges for the recent period describe the data used in the forward projections. Historical data are provided for comparison.

Parameter	**Mean**	**Range**	**Years**	**Historical Mean**	**Source and comment**
Fecundity	3563	3088-3998	2002-2018	4094	Recent: hatchery broodstock records Historic: Foerster 1968.
Smolts/Spawner	31.6	1-107	1999-2016	76.2	Historical data 1925-1990, years intermittent.
Smolt-Recruit survival	0.026	0.009-0.055	1999-2016	0.081	Recruit is pre-fishery abundance. Historical 1950-1990
Smolt-spawner survival	0.017	0.010-0.040	1999-2016	0.020	Survival from smolt to spawner returning to fence, historical 1925-1990.
Exploitation rate	0.26	0.03-0.71	1999-2018	0.67	DFO (2018a, Table 1: “Post season direct” series), includes a provisional value of 0.50 for 2018. Historical data 1954-1998.



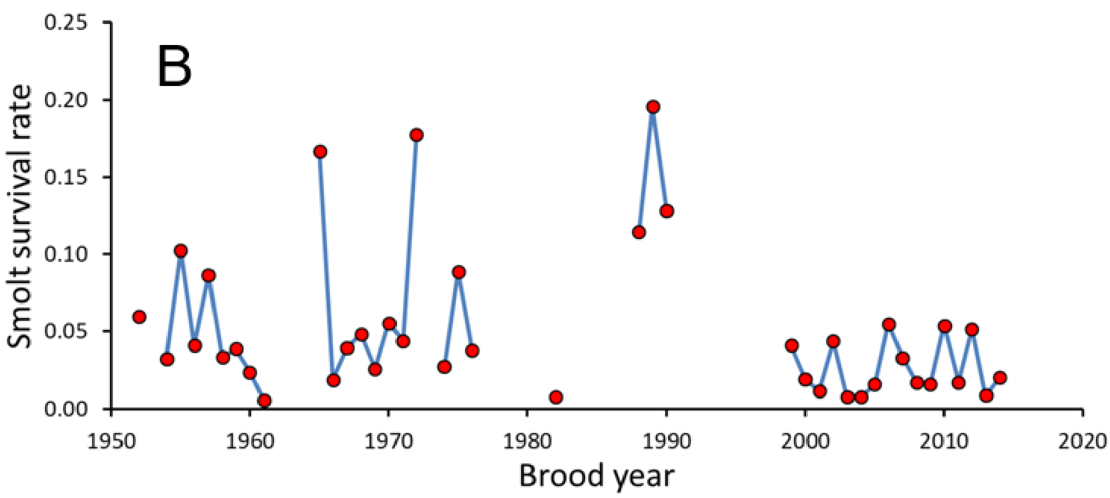


Figure 4. Time series of Sockeye Salmon smolt production rates from Cultus Lake. Historical (green) and recent (red) periods are delineated. A) Smolts/spawner is the ratio of natural-origin smolts produced per parent spawner (including hatchery origin spawners in recent years) passed into the lake 2 years earlier. The dashed line indicates the approximate level of smolt production required for population survival (i.e., the replacement level) under current levels of exploitation and recent ocean survival rates. B) Smolt to adult survival rates for lake-origin smolts. Smolt survival rates are calculated from unmarked smolt abundances and adult returns to the fence at Cultus Lake, and estimated exploitation rates. For brood years 2000-2014 the average of the "post season direct" and "post-season proxy" exploitation rate series (DFO 2018a) was used.

3. HABITAT AND RESIDENCE REQUIREMENTS

3.1. ELEMENT 4: HABITAT PROPERTIES THAT CULTUS LAKE SOCKEYE SALMON NEED FOR SUCCESSFUL COMPLETION OF ALL LIFE-HISTORY STAGES

3.1.1. Spawning and egg incubation habitat

Reproduction (i.e. spawning) is a critical life function of all fish species. Sockeye Salmon principally spawn and incubate their eggs within freshwater ecosystems hydrologically connected to the Pacific Ocean, exhibiting substantial diversity in site selection and timing. Spawning and incubation habitat is selected for substrate composition (approx. 25 mm median particle size; Quinn 2005) and permeability, the interstitial water quality and flows of the spawning substrate, and temperature (Burgner 1991). Spawning sites include a range of habitats, including rivers, lakes and their tributaries. Cultus Lake Sockeye Salmon are obligate lakeshore spawners (Ricker 1966), and appear to select spawning sites (features), within Cultus Lake, associated with oxic groundwater upwelling and/or lake water circulation attributes (CSRT 2009).

Cultus Lake Sockeye Salmon spawn relatively deeply (December mean spawning depth approx. 13.5 m; 2009-2018) and late in the year, at low-temperatures and typically isothermal conditions within Cultus Lake (7.48 $^{o}C \pm 1.07$ (1 SD), measured from central basin; 2009-2018). This behaviour is thought to require the selection of warmer groundwater upwelling (approx. 8 ^{o}C), which may confer the required faster development of embryos to permit spring emergence in April and May (Ricker 1937, Brannon 1987, CSRT 2009). The more quiescent conditions within deep lakeshore spawning environments selected by Cultus Lake Sockeye Salmon likely reduces certain early-life stage stressors experienced by stream- and riverine-spawning populations, such as substrate scouring, erosion, and frazzle ice development, which may in turn reduce physical damage to eggs. However, unlike stream environments, whereby riverine flows oxygenate incubating embryos, in lakeshore spawning environments, oxygenated water circulation is required from either groundwater sources and/or winter lake mixis under an isothermal water column (CSRT 2009).

Spawning site locations within Cultus Lake selected by Sockeye Salmon have changed significantly over the period of record. Historical site locations included Lindell Beach, Snag Point, Spring Bay, Mallard Bay, Salmon Bay, and Snag Bay (Honeymoon Bay; CSRT 2009). However, underwater remotely operated vehicle (ROV) surveys in 2002-2004 confirmed spawning at approximately half of the historically-known spawning locations, including Spring Bay, Lindell Beach, Salmon Bay, Honeymoon Bay (Figure 2; CSRT 2009). Post-2004, mature adults have only been observed spawning in Spring Bay in sporadic ROV surveys conducted by DFO (Paul Welch, DFO, Kamloops, British Columbia, pers. comm.). Given the limited ROV surveillance and deep depths of contemporary spawning within Cultus Lake, utilization of other deep spawning areas cannot be ruled out.

Cultus Lake Sockeye Salmon appear to also select a wider range of spawning location depths including deeper sites (< 2-17 m; Pon et al. 2010) than in the past (0.5-6 m; CSRT 2009). Although the mechanisms underpinning this behavioural change are largely unknown, the apparent shift in spawning depths may be compensatory, in relation to colonization and broad littoral substrate coverage (62%; depths 1-8 m) by invasive Eurasian watermilfoil (Stables 2004; DFO unpublished data 2014). Other potential contributing factors to the apparent deepening of spawning, may include rising surface water temperatures and/or spatiotemporal changes to groundwater delivery associated with climate change (Sumka 2017), degrading water quality and substrate suitability (i.e. higher interstitial biological oxygen demand (BOD) associated with organic matter deposition and decomposition from ongoing lake eutrophication; Shortreed 2007; Putt et al. 2019), nearshore habitat modifications (i.e. shoreline hardening, riparian vegetation and shade removal), and/or changes in the nearshore predator guild (i.e. increased piscivore populations, invasive Smallmouth Bass). Lake substrates from 1-20 m depth were previously identified as important spawning habitat for Cultus Lake Sockeye Salmon, particularly at Lindell Beach, Mallard Bay at the south and western margins of the lake, respectively, and Snag Point, Spring Bay, Salmon Bay, and Snag Bay (Honeymoon Bay), along the base of International Ridge (CSRT 2009). These environments are characterized by substrates of deep fractured shale benches (International Ridge sites) and cobble (Lindell Beach, Mallard Bay). Alevin life stages (yolk sac attached) use interstitial pore waters and substrates for cover while maturing, prior to emergence.

Given the disproportionate sensitivity of early life stages to mortality, and the extensive use of quality lake substrates for spawning, egg incubation, and alevin maturation, all spawning-quality gravels, cobble, and shale within the lake are identified as key features for completion of spawning and incubation critical life functions of the Cultus Lake Sockeye Salmon. Moreover, given the obligate nature of shoreline spawning within Cultus Lake, the importance of interstitial water quality, oxygen levels, and flushing to successful egg incubation, hyphoreic ground water zones and their associated aquifers are considered critical features for species persistence, as has been noted by the Cultus Lake Sockeye Salmon Recovery Team (CSRT 2009).

3.1.2. Juvenile Rearing Habitat

Early free-swimming juvenile life stages of Sockeye Salmon are initially closely associated with nearshore substrates (i.e. onshore fry; Burgner 1991). As maturation occurs, onshore fry utilize littoral resources, typically from early June to mid-July, feeding upon aquatic insect larvae and crustacean zooplankton (Quinn 2005). Contemporary information on the timing of emergence of free-swimming juvenile Sockeye Salmon and onshore residence within Cultus Lake is largely lacking. Historically, by late-July the majority of Cultus Lake Sockeye Salmon fry had moved offshore, to exploit zooplankton within pelagic food webs, which are largely constrained to the euphotic zone (Shortreed 2007). As with most Sockeye Salmon populations, once offshore, Cultus Lake fry undergo diurnal vertical migrations (DVM), feeding in the water column during crepuscular periods, and occupying deep, low-light environments of the lake during daylight hours, presumably to avoid predation (Clark and Levy 1988; Scheuerell and Schindler 2003). Comparative observations from hydroacoustic and trawl surveys indicate that during the daylight period, Cultus Lake Sockeye Salmon fry are in close association with the profundal lake sediments (Levy 1989; Garrett Lidin, DFO, Cultus Lake, British Columbia, pers. comm.). Similar observations during nighttime indicate modern utilization of the lake epilimnion during the stratified period is limited (Garrett Lidin, DFO, Cultus Lake, British Columbia, pers. comm.). The mechanisms for the latter are unknown, however, maximum summer epilimnetic temperatures in Cultus Lake (> 24.5 ^{o}C) now exceed the thresholds for severe declines in growth (i.e. 20-24 ^{o}C; Brett and Higgs 1970) and approach or exceed the thermal tolerances for prolonged exposure of juvenile Sockeye Salmon (Brett 1952), which may limit the available lake rearing volume commensurately during much of the stratified period. During the destratified period (i.e. typically December-April), however, Cultus Lake Sockeye Salmon fry have the potential to use the entire water column of the pelagic zone.

To satisfy the critical life function of lake rearing, and sufficient growth and survival to undergo outmigration, the ecological integrity of the nursery ecosystem is essential. In particular, pelagic food web structure and functioning, and water quality are key features critical to the persistence of Cultus Lake Sockeye Salmon. Important habitat attributes include the maintenance of abundant, sustained, and edible zooplankton prey items, including *Daphnia* spp., which are supported by high water clarity, moderate nutrient levels, and edible, diverse, moderately-productive algal assemblages. Given the importance of prolonged profundal habitat use during the daylight phase of the diurnal vertical migration cycle, oxic water (i.e. >5 mg/L dissolved oxygen) throughout the water column, and in particular in the deep waters, is a critical attribute to species persistence. Additionally, at depressed abundances, the influences and interactions of predators and pathogens/parasites/diseases on in-lake juvenile Sockeye Salmon persistence are potentially key factors, and thus moderate predator densities and minimal pathogen/ parasite/ disease occurrences are considered key features and attributes.

3.1.3. Juvenile freshwater outmigration habitat

Most Cultus Lake Sockeye Salmon leave the lake in the spring (late March – late May) at one year of age. Smolts exit via the outlet at the north end of Cultus Lake and move downstream through Sweltzer Creek for ~3 km, the Vedder River for ~13 km, and the Sumas River for ~3 km, before entering the Fraser River. Habitat connectivity through this migration pathway is largely uninterrupted with the exception of the smolt enumeration fence positioned just downstream of the lake outlet. Water temperatures in Sweltzer Creek are approx. 7 ^{o}C in late-March as smolts begin their migration and warm to approx. 15 ^{o}C by late May (DFO, unpublished data). The smolts continue down the Fraser River for another 93 km before entering the Salish Sea (Strait of Georgia). Sockeye Salmon generally spend little time in the estuary (Healey 1982) but may spend 43-54 days, on average, moving through the Strait (Preikshot et al. 2012). Key habitat features and attributes include unimpeded downstream passage, sufficient water flows, and the maintenance of amenable water temperatures (i.e. < 18 ^{o}C).

3.1.4. Ocean rearing habitat

Anadromous Sockeye Salmon complete approximately half of their life histories in the Pacific Ocean, further rearing and maturing to achieve sufficient biomass to return and spawn in natal freshwater environments (Burgner 1991). As definitive information on the Pacific Ocean range for Cultus Lake Sockeye Salmon is lacking, it is assumed that marine habitat requirements are similar to other lake-type Sockeye Salmon. Although ocean maturation occurs over a much broader geographical expanse (i.e. northeast Pacific), ocean rearing habitats share broadly analogous features to those during the freshwater rearing phase. In particular, productive food webs for all size-classes of ocean-resident Cultus Lake Sockeye Salmon, including key prey items such as euphasiids, amphipods, fish, juvenile shrimp, and decapod larvae are a key feature of biomass accrual, swim performance, and survival, with the dominant prey items varying by ocean domain and through time (Brodeur et al. 2003; Farley et al. 2018). Key oceanic food web attributes include abundant prey biomass, and phenological and spatial matches between prey items and maturing Sockeye Salmon along the continental margin and within the open ocean.

As in freshwater, juvenile Pacific salmon in the ocean are subjected to predation. Piscivorous fish, marine mammals, birds, and cetaceans, all actively feed on Sockeye Salmon in estuarine, continental shelf, and open ocean habitats, and thus low to moderately-abundant marine predator guilds, yielding low to moderate predation rates, are likely a key to persistence, particularly at low population densities of Cultus Lake Sockeye Salmon. Marine fisheries are also a key mortality source for Cultus Lake Sockeye Salmon (CSRT 2009), and a selective forcing on key features of ocean habitats (i.e. fish guilds, trophic relationships), and thus their minimization limits ecosystem transformations that may be impactful to persistence (Jennings and Kaiser 1998; Coleman and Williams 2002). Similarly, the broad-scale production of hatchery-origin Pink and Chum salmon has been implicated in impacting the carrying capacity of the North Pacific Ocean for Sockeye Salmon, through direct competition, as demonstrated by significant negative correlations between hatchery-origin salmon biomass and those of wild Sockeye Salmon stocks in the Ocean (Ruggerone et al. 2010; Ruggerone and Irvine 2018). As such, moderate competitor biomasses are likely key oceanic ecological features and attributes important to persistence.

3.1.5. Adult Freshwater Migratory Habitat

Cultus Lake Sockeye Salmon return to Cultus Lake as part of the Fraser River Late Run aggregate, typically from September through late-November. Early migrants mature within the lake until spawning, which now occurs from November to early-January (CSRT 2009). Adult Cultus Lake Sockeye Salmon return over the same freshwater pathway as out-migrating smolts. After entering the Fraser River, they swim upstream for 93 km before moving through the Sumas and Vedder rivers, Sweltzer Creek and into Cultus Lake. Upon entering Cultus Lake, adult Sockeye Salmon quickly move to cooler waters in the depths of the lake. From acoustic tagging work in 2006 and 2007, fish generally held at depths below the thermocline in water temperatures of 6-8 ^{o}C (Pon et al. 2010).

Key features for adult migratory habitat are thus similar to those of outmigrating smolts. Key habitat features and attributes include unimpeded upstream passage, sufficient water flows for adult passage, and the maintenance of amenable water temperatures (i.e. < 19-21^{o}C), as higher temperatures have been shown to impede or interrupt spawner migrations (Hodgson and Quinn 2002; Hyatt et al. 2003). Endemic and transmitted diseases, parasites, and pathogens (i.e. bacterial kidney disease (BKD), infectious hematopoietic necrosis virus (IHNV), *Parvicapsula* spp.) are also influential to the survival of Cultus Lake Sockeye Salmon (Bradford et al. 2010; Ackerman et al. 2014), and thus low infection rates and parasite loads are key features and attributes for persistence.

3.2. ELEMENT 5: INFORMATION ON THE SPATIAL EXTENT OF THE AREAS IN CULTUS LAKE SOCKEYE SALMON’S DISTRIBUTION THAT ARE LIKELY TO HAVE THESE HABITAT PROPERTIES

3.2.1. Freshwater distribution

Cultus Lake Sockeye Salmon’s spawning and juvenile rearing habitat is confined to the wetted bounds of Cultus Lake. Due in part to the depths at which adult Cultus Lake Sockeye Salmon spawn, there is limited information on the current locations of viable spawning habitat within the lake, but the extent has contracted over time (CSRT 2009). Recently, spawning has been visually-confirmed by remotely operated vehicle (ROV) in Spring Bay (Figure 2; Brian Leaf, DFO, Kamloops, British Columbia, pers. comm.), but the total amount of suitable spawning habitat is unknown.

Recently-hatched and free-swimming juvenile Sockeye Salmon are understood to initially use nearshore habitats before moving offshore in July. However, there has not been a thorough survey of all nearshore habitats in Cultus Lake to determine the extent of juvenile salmon habitat during this life stage. Offshore habitats for juvenile Cultus Lake Sockeye Salmon from July until smolt out-migration consist of all areas within the lake. As noted, juvenile Cultus Lake Sockeye Salmon are typically not found in the first 0-4 m of depth from the surface during the stratified period.

Adult and smolt freshwater migration habitats between Cultus Lake and the Pacific Ocean include Sweltzer Creek (approx. 3 km), the Vedder River (approx. 13 km), the Sumas River (3 km), and the Fraser River (approx. 93 km), and the brackish Fraser River Estuary.

3.2.2. Marine distribution

Relatively limited information is available for quantifying the marine habitats used by Cultus Lake Sockeye Salmon. From tagging studies, juveniles spend 25.6 to 34.1 days in the Salish Sea (Strait of Georgia) where they generally move northward along the mainland coast and through Johnstone Strait (Welch et al. 2009). Although juvenile migration strategies are known to vary substantially among species of salmon and populations, the majority of Cultus Lake Sockeye Salmon historically followed this northward migration path, as opposed to migrating around the southern tip of Vancouver Island (Melnychuk et al. 2010). The migration distribution and timing is expected to overlap with that of other Fraser Sockeye populations, which includes the Gulf of Alaska and south to a latitude of approx. 46 °N (Forrester 1987).

3.3. ELEMENT 6: THE PRESENCE AND EXTENT OF SPATIAL CONFIGURATION CONSTRAINTS

At present there are no known persistent spatial constraints or barriers to habitat access for all life stages of Cultus Lake Sockeye Salmon, with the exception of a long-standing salmon enumeration fence on Sweltzer Creek. The enumeration fence is operated by DFO and is used to count out-migrating smolts in the spring and returning adults in the late-summer to late-fall. During operation, the fence is checked on a regular basis; juveniles may be held in the live trap up to 8 hrs prior to enumeration, and adults are occasionally held up by the fence for operational purposes related to the collection of brood stock for the hatchery supplementation program. During times of higher migrating salmon abundances, the fence is monitored more frequently and holding times are reduced. For smolts, in particular, delays at the fence may increase the risk of predation. Smallmouth Bass have been reported entering the smolt enumeration trap, and have been observed in Sweltzer Creek directly upstream of the fence during smolt migration timing. Other predators including Mergansers (*Mergus merganser*), Minks (*Neogale vision*), Raccoons (*Procyon lotor*), and River Otters (*Lontra canadensis*) have been observed in proximity to the counting fence (Dennis. Klassen, DFO, Kamloops, British Columbia, pers. comm.), and may contribute to overall mortality.

3.4. ELEMENT 7: EVALUATE THE CONCEPT OF RESIDENCE AND DESCRIPTION FOR CULTUS LAKE SOCKEYE SALMON

Under Canada's *Species At Risk Act* (SARA 2002), a species' residence is defined as:

"*a dwelling-place, such as a den, nest or other similar area or place, that is occupied or habitually occupied by one or more individuals during all or part of their life cycles, including breeding, rearing, staging, wintering, feeding or hibernating*" (s.2(1)).

Application of SARA Section 33 (Residence) to aquatic species at risk requires the following four conditions be met for the concept of a residence to be applied:

1. There is a discrete dwelling-place that has a structural form and function similar to a den or nest;
2. An individual of the species has made an investment in the creation and/or modification of the dwelling-place;
3. The dwelling-place makes possible the successful performance of essential life-cycle functions such as spawning and rearing; and

4. The dwelling-place is occupied by one or more individuals during all or parts of their life cycle.

Redds (spawning nests) produced during salmonid reproduction most closely match the criteria for a "residence", as defined by SARA Section 33. As spawning sites, nests for deposition and incubation of salmonid eggs, and interstitial rearing habitat for alevins prior to emergence, redds meet the structural form and function criteria of a residence. Moreover, females have invested energy in redd creation, and they are essential for successful incubation and hatching of thousands of eggs from an individual female (est. 2000-5000 for Sockeye Salmon; Burgner 1991). Cultus Lake Sockeye Salmon are obligate lakeshore spawners, using areas of the littoral zone and submerged benches within Cultus Lake (COSEWIC 2003; CSRT 2009). As such, these areas of Cultus Lake are considered residences under Canada's Species at Risk Act.

4. THREATS AND LIMITING FACTORS TO THE SURVIVAL AND RECOVERY OF CULTUS LAKE SOCKEYE SALMON

4.1. ELEMENT 8: THREATS TO THE SURVIVAL AND RECOVERY OF CULTUS LAKE SOCKEYE SALMON

DFO (2014) outlines a two-step standardized approach to threat assessment, which includes an evaluation of threats at the population level, followed by an evaluation of threats at the species level. As Pacific salmon exhibit highly-localized adaptation to natal habitats, and compressed life cycles (3-5 years; Groot and Margolis 1991), resulting in rapid evolutionary divergence (Hendry et al. 2000), individual populations are often defined and managed as Conservation Units (CU; DFO 2005; Holtby and Ciruna 2007) or Designated Units (DU; SARA 2002) in Canada, and similarly as Evolutionary Significant Units (ESU) in the United States of America (Waples 1991). Owing to the significant divergence amongst populations, individual populations are effectively treated as species for the purposes of conservation. As such, we have integrated the two step process, considering only the Cultus Lake Sockeye Salmon DU.

Threats herein are defined as any human activity or process that has caused, is causing, or may cause harm, death, or behavioural changes to a wildlife species at risk, or the destruction, degradation, and/or impairment of its habitat, to the extent that population-level effects occur (DFO 2014). A human activity may exacerbate a natural process (DFO 2014). Limiting factors are defined as non-anthropogenic factors that, within a range of natural variation, limits the abundance and distribution of one or more individuals of a wildlife species or a population (e.g., age at first reproduction, fecundity, age at senescence, prey abundance, mortality rate; DFO 2014). Primary threats and limiting factors for Cultus Lake Sockeye Salmon were evaluated and prioritized in a table following the requirements laid out by DFO (DFO 2014) (Tables 2 and 3). The DU-level threat and limiting factor risk is calculated using rankings for level of impact and likelihood of occurrence and plotting them in the Threat Risk Matrix, to derive an overall threat or limiting factor risk as per DFO (2014).

4.1.1. Incidental Fisheries Interceptions (Adults)

Cultus Lake Sockeye Salmon spawners return with the late Fraser River run timing group, co-migrating with abundant late-run stocks (i.e. Late-Shuswap Sockeye Salmon; Grant et al. 2011). As such, they are intercepted as *incidental harvest* in the mixed-stock Fraser River Sockeye Salmon fishery, at varying estimated incidental exploitation rates, tied to the co-occurrence of fisheries on more abundant stocks (2004-2018, 3-71%; DFO 2018a, 2019a; Figure 5). Previous assessments have highlighted the mixed stock fishery as a key driver of depressed population abundances (CSRT 2009; Cohen 2012). Additionally, Canadian Sockeye Salmon are harvested in international fisheries located along their migration routes (i.e. Alaska; Rosenberger et al. 2022), which represents uncertain, but potentially influential losses to the population, particularly at recent depressed abundances. Losses of returning adults in fisheries impinges upon genetic diversity in the population, which is already low on some brood lines (CSRT 2009), and may in turn affect fitness responses to current and future stressors (Allendorf et al. 2008; Allendorf and Hard 2009).

The BC South Coast Salmon Integrated Fisheries Management Plan (IFMP) defines allowable exploitation for Cultus Lake Sockeye Salmon as the greater of 1) the low abundance exploitation rate (LAER) identified for Late Run Sockeye Salmon, or 2) the exploitation rate that is consistent with continued rebuilding of the population, based upon in-season information on returns and potential numbers of effective spawners (DFO 2019a). Marine fishery incidental harvest of Cultus Lake Sockeye Salmon has been highlighted as a primary causal mechanism responsible for endangerment, owing to high exploitation rates through the 1990's, and an ongoing factor suppressing population recovery (CSRT 2009; DFO 2019a), with harvest management a key strategy to assist in stabilizing and recovering the population (CSCT 2009).

Despite the intent of the pre-season IFMP to balance stock conservation with fisheries exploitation, and noting substantial uncertainties in estimating exploitation rates for Cultus Lake Sockeye Salmon at low stock abundances, published, quality-assured, post-season exploitation rate estimates (Post Season ER (proxy), $PS\text{-}ER_{proxy}$; Post-Season ER (direct), $PS\text{-}ER_{direct}$) indicate incidental marine harvests have removed significant numbers of the Cultus Lake Sockeye Salmon from the population in some years (DFO 2018a; 2019a). Stock exploitation rates have exceeded IFMP maximum allowable limits approx. 47-50% annually (ER performance/population abundance ranges reflect statistics for the two ER series) over the 15 years of record (period since last SARA listing consideration), and 75-100% annually in years coinciding to the dominant Adams River Sockeye Salmon run over the period of record (Figure 5; DFO 2018a, 2019a). Harvests in years exceeding IFMP limits are estimated to account for annual losses of 22-71% (mean = 41-44%) of the returning Cultus Lake Salmon population, on any given brood line. Given the known population effects of marine harvest on Cultus Lake Sockeye Salmon (CSRT 2009), ongoing fisheries harvests are deemed to be a high population level risk, with very high certainty, making incidental harvest a primary factor constraining the recovery potential of Cultus Lake Sockeye Salmon (Table 2).

Although likely of a lesser effect, mistaken identifications in the Fraser River and Vedder River recreational fishery, and possibly unreported harvest may induce further losses on an annual basis that cannot reliably be constrained with existing data.

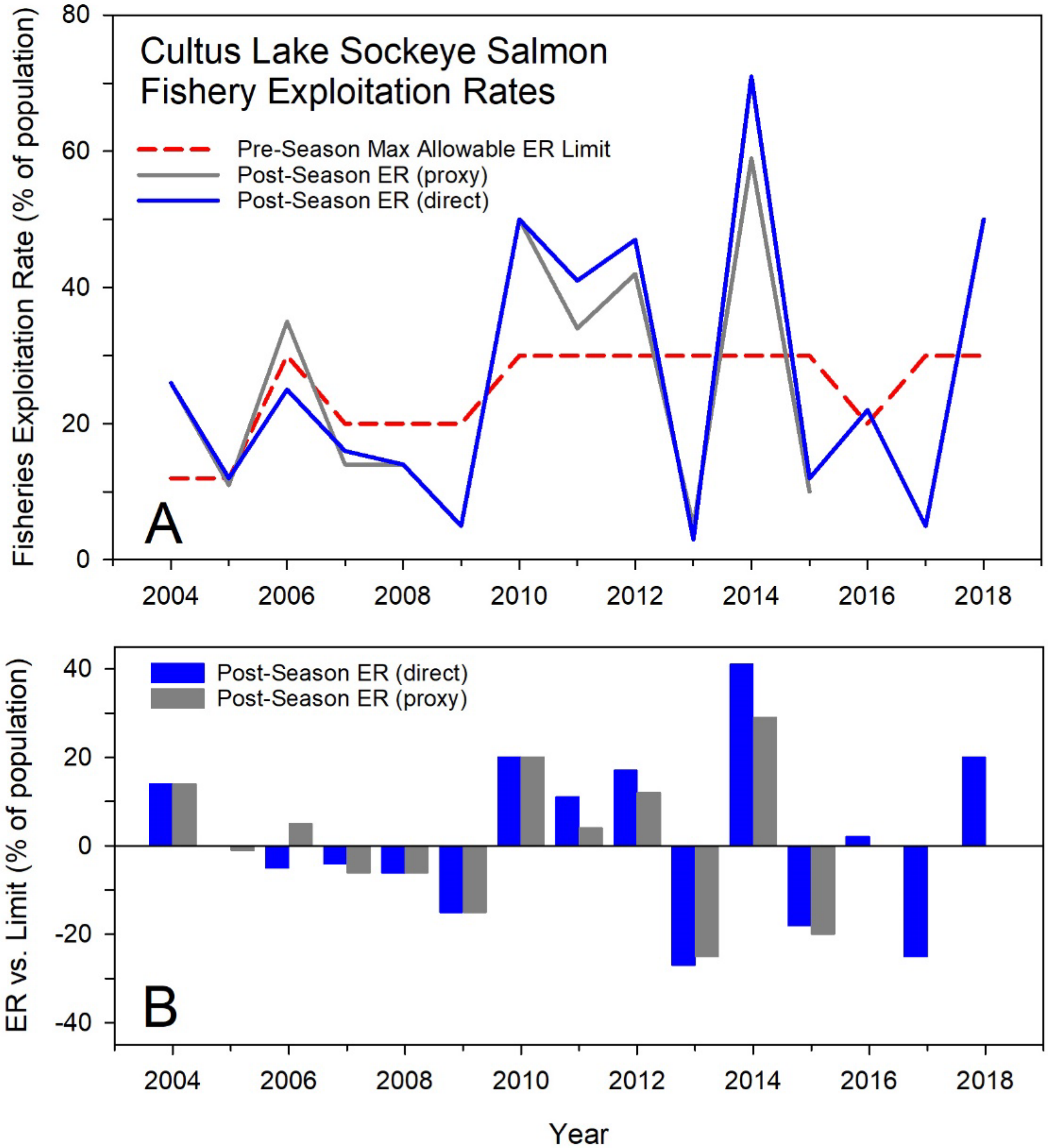


Figure 5. Time series estimates of Fraser River Sockeye exploitation rates and fisheries performance relative to established fishery limits. Panel A) indicates estimates of post-season incidental fisheries mortality on Cultus Lake Sockeye Salmon in the mixed stock Fraser River fishery from post-season proxy-derived (PS-ER$_{proxy}$; grey line) and direct (PS-ER$_{direct}$; blue line) fisheries exploitation (DFO 2018a), relative to the Integrated Fisheries Management Plan (IFMP) pre-season ER limits (dashed red line; DFO 2019a). Panel B) highlights fisheries performance for proxy-derived (grey bars) and direct (blue bars) estimated exploitation rates, relative to the IFMP pre-season ER limits (DFO 2019a). Note Direct ER estimates for 2018 are preliminary and acquired from the IFMP (DFO 2019a), and proxy ER estimates were not available for the 2016-2018 period; DFO 2018a).

4.1.2. Pacific salmon hatchery production and interactions (All life stages)

In some circumstances, hatchery production can have negative impacts on the fitness and productivity of wild populations (Gardner et al. 2004; Naish et al. 2007). Genetic risks include the propagation of selected traits that may be advantageous within captivity but not in the wild (Ford 2002). Rearing in the hatchery environment for example, has been shown to have deleterious effects on fitness traits such as survival, swimming endurance, and predator avoidance (Chittenden et al. 2010), and genetic comparisons of hatchery and wild reared Coho Salmon (*O. kisutch*) demonstrated that rearing in the captive environment can lead to epigenetic reprogramming related to decreased fitness (Le Luyer et al. 2017). Releases of supplemental hatchery-produced salmonids can also lead to negative ecological interactions between wild and hatchery-origin fish in natural environments, through competition and direct and indirect predation threats (Gardner et al. 2004, DFO 2013). As well, concerns regarding the potential transmission of disease from hatchery reared fish to wild fish are relevant, however, there are relatively few well documented cases of this occurring (Naish et al. 2007; Nekouei et al. 2019). Hatchery-related disease transmission risks can be mitigated in part through responsible husbandry practices and observing biosecurity protocols (DFO 2013).

For Cultus Lake Sockeye Salmon, poor natural smolt production has resulted in the population being heavily-supplemented by hatchery production, a scenario that is likely to continue for at least the next generation. High rates of hatchery production are necessary to allow the population to persist in the face of other threats, but may be increasing the risk that the fitness of natural-origin spawners is being impacted. There is currently no direct evidence that the fitness of natural-origin spawners is being affected by the hatchery program, but recent declines in the survival of hatchery fry releases to the lake, and smolt releases into Sweltzer Creek are noteworthy. While Cultus Lake Sockeye Salmon enhancement has been ongoing since 2000, studies have shown that hatchery supplementation can be successful over the long-term when programs are designed to minimise potential negative impacts on fitness (Janowitz-Koch et al. 2019). Improving the understanding of epigenetics as it relates to hatchery-based rearing of Cultus juvenile Sockeye Salmon may be beneficial, as this has important applications to supplementation programs (Gavery and Roberts 2017). Hatchery production effects on genetics and fitness is considered a medium level population threat, with a medium level of certainty (Table 2).

Hatchery-produced salmon can induce density-dependence in the growth and survival of co-occurring wild populations throughout their life history. Density-dependence in Sockeye Salmon populations during lake-rearing occurs at elevated densities (Foerster 1944; Burgner 1991; Schindler et al. 2005; Freshwater et al. 2017). Given the enriched trophic status of Cultus Lake (e.g. strong bottom-up food web forcing), the relatively low densities of in-lake fry, and the large sizes of smolts leaving the system, freshwater competition for food web resources arising from hatchery enhancement, at current in-lake densities, is likely negligible.

The hatchery production of Pacific salmon (i.e. Chum, Pink, Sockeye) from several countries around the North Pacific has increased considerably over the last century, constituting substantial components of modern marine salmon biomasses (Ruggerone and Irvine 2018). Hatchery-origin salmonids can induce density-dependent competition with wild Pacific salmon in the marine rearing environment, yielding impacts on stock productivity (Tatara and Berejikian 2012; Ruggerone and Irvine 2018; Connors et al. 2020). The nature and magnitude of these influences are complex, and in the Pacific Ocean, can be mediated spatially and through interactive effects with environmental conditions (i.e. sea-surface temperatures; Connors et al. 2020).

Observed declines in the Cultus Lake Sockeye Salmon spawner time series do not temporally track established increases in multi-specific Pacific salmon outplants from hatcheries over the past century (Ruggerone and Irvine 2018), suggesting that they are likely not a primary forcing on stock declines. However, elevated inter- and intra-specific marine competition from hatchery-origin Pacific salmon, may elicit additive influences on marine growth and survival that may contribute to cumulative marine stresses on Cultus Lake Sockeye Salmon maturing in the Pacific Ocean. Given the general lack of inquiry and evidence for a marine density-dependent influence on Cultus Lake Sockeye Salmon specifically, hatchery competition in the marine environment is considered a largely unknown population level risk, with low certainty (Table 2).

4.1.3. Pollution (All life stages)

Elevated mortality or sub-lethal effects resulting from aquatic pollutants in marine and freshwater habitats occupied by Cultus Lake Sockeye Salmon was deemed to be a medium-level population risk with low certainty, with the lack of certainty primarily a result of no qualified stock-specific information on any risks of exposure and effects at various life stages (Table 2). As noted in the Sakinaw Sockeye Salmon Recovery Potential Assessment (DFO 2018b), industrial activities within the Georgia Basin, such as shipping, agriculture and industrial development contribute pollutants to the marine environment as a result of collisions, spills, loss of ships at sea, coastal runoff and direct water discharge, may impose a cumulative contaminant burden on migrating salmon (juveniles and adults). In particular, there is potential for oil and gas transmission through coastal waters to increase from the Vancouver area in the future, which will increase the probability that a spill will occur. Although not constrained to the estuary and early-marine areas, pollution threats would have the greatest impacts if spills and/or discharges overlap spatially and temporally with salmon migration and rearing.

In Cultus Lake, contaminant sources arising from recreational vessel traffic (e.g. polycyclic aromatic hydrocarbons (PAH’s)), septic leachate (e.g. environmental estrogens, contaminants), bird guano, and the airshed and/or watershed (e.g. mercury, polychlorinated biphenyls (PCB), polybrominated diphenyl ethers, (PBDE), PAH, organochlorine pesticides, metals) may pose stresses on juvenile Cultus Lake Sockeye Salmon life stages. Tovey et al. (2008) documented elevated levels of Cr, Ni, Fe, Ba, Cd, Mn, Se, Cu and Zn, and several PAH’s in Cultus Lake that exceeded sediment quality guidelines for the protection of aquatic life. Under certain limnological circumstances, such as reducing conditions at the sediment-water interface, redox-sensitive nutrients and contaminants may be liberated to the overlying water column (Pettersson 1998; Wetzel 2001), potentially stimulating (nutrients) or contaminating (toxicants) food webs impacting rearing juvenile salmon, or be transmitted into salmonid food webs through connective processes, such as benthic-pelagic coupling (Vander Zanden and Vadeboncoeur 2002). Limnological monitoring of near-sediment nutrient concentrations indicates demonstrative internal loading is occurring within Cultus Lake (see next section). However, the state of knowledge of contaminant sources and mobility in Cultus Lake is largely unknown, and thus the certainty on lethal to sub-lethal effects on Cultus Lake Sockeye Salmon is limited. An exception in our knowledge is the effect of excess loading of nutrients to Cultus Lake, which has been defined (Putt et al. 2019), and is covered in the next section.

4.1.4. Nursery Lake Eutrophication (Spawners, Eggs, Alevin, Fry, Parr, Smolts)

Cultural eutrophication, the excess loading of nutrients (i.e. phosphorus and nitrogen) to aquatic environments from anthropogenic sources, is one of the most pervasive, population-associated impacts on freshwater quality in Canada and across the globe, but a problem that is readily reversible if addressed through timely identification and abatement of nutrient loadings (Chambers et al. 2001; Schindler 2012; Putt et al. 2019). Cultus Lake is undergoing eutrophication from primarily anthropogenically-sourced nutrients, which is degrading nursery ecosystem habitats for Sockeye Salmon and other species at risk (Shortreed 2007; Putt et al. 2019; Gauthier et al. 2021).

Watershed hydrological and nutrient mass balance modeling highlights nutrient loading to Cultus Lake arises from multiple sources (Putt et al. 2019). Watershed runoff contributes the majority of total P (53%) and N (73%) loads to Cultus Lake, with substantial local N contributions arising from the agricultural Columbia Valley (41% of total N load). Other significant local P loadings to Cultus Lake arise from septic leaching (19%) and guano deposited by migratory gulls, diurnally migrating between the Fraser Valley and Cultus Lake from fall through spring (22%). Up to 66% of the N and 70% of the P delivered to Cultus Lake in watershed runoff, however, is ultimately sourced via atmospheric deposition from the nutrient-contaminated regional airshed, with direct atmospheric deposition on the lake surface contributing an additional 17% of N and 5% of P. As such, atmospheric deposition is the largest single source of nutrient loading to Cultus Lake annually, cumulatively 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 intensifying agricultural and to some extent urban and transportation activities in the adjacent Fraser Valley (Environment Canada and US Environmental Protection Agency 2014; Metro Vancouver 2018).

Lakes typically respond to cultural eutrophication through the stimulation of excess algal and/or macrophyte biomasses, resulting in elevated in-lake organic matter (OM) loads (Wetzel 2001). Associated aerobic microbial decomposition of OM in various lake receiving environments (i.e. deep waters, sediments, interstitial pore waters) scales proportionately, increasing biological and chemical oxygen demands, resulting in dissolved oxygen depletion at depth (Wetzel 2001; Smith and Schindler 2009; Moss et al. 2011; Müller et al. 2012).

While strongly exacerbated by enhanced lake organic matter loads, eutrophication-forced oxygen depletion in lakes is modulated by seasonal changes in lake physics. Springtime warming and surface heat absorption in temperate lakes induce a physical density separation of warmer surface (epilimnion) and cooler deeper waters (hypolimnion), known as thermal stratification, which effectively isolates lake epilimnia from hypolimnia until fall air and associated water cooling is sufficient to permit winds to overturn and reoxygenate the water column (Wetzel 2001; Sumka 2017). This annual process strongly influences the recharge of dissolved oxygen (DO) to the deeper environments in lakes (e.g. hypolimnion, profundal zone, benthic zone), and in those experiencing eutrophication, can promote increased hypolimnetic oxygen depletion (Müller et al. 2012). Low DO at the sediment-water interface can facilitate redox reactions that release nutrients and other toxicants into the overlying water column (e.g. eutrophication positive feedback), in a process known as internal loading, effectively reversing the function of sediments in sequestration of nutrients, to sources (Pettersson 1998; Wetzel 2001).

The eutrophication of Cultus Lake is a primary driver of critical freshwater habitat degradation and population change not captured in previous species at risk assessments. Subsequent sections highlight the specific key pathways of effect for Cultus Lake Sockeye Salmon.

4.1.4.1. Lake Eutrophication: Hypolimnetic Oxygen Depletion in Cultus Lake and Sockeye Salmon In-Lake Survival

Hypolimnetic oxygen depletion is occurring in Cultus Lake in response to lake eutrophication, with mid-hypolimnetic (30m) dissolved oxygen (DO) levels late in the stratified period reduced by approximately half between the 1920’s and early-2000’s (Shortreed 2007). Near-sediment (profundal) DO concentrations currently reach hypoxic to anoxic levels during the fall period prior to lake turnover (Figure 6), and are most pronounced in the deepest parts of Cultus Lake.

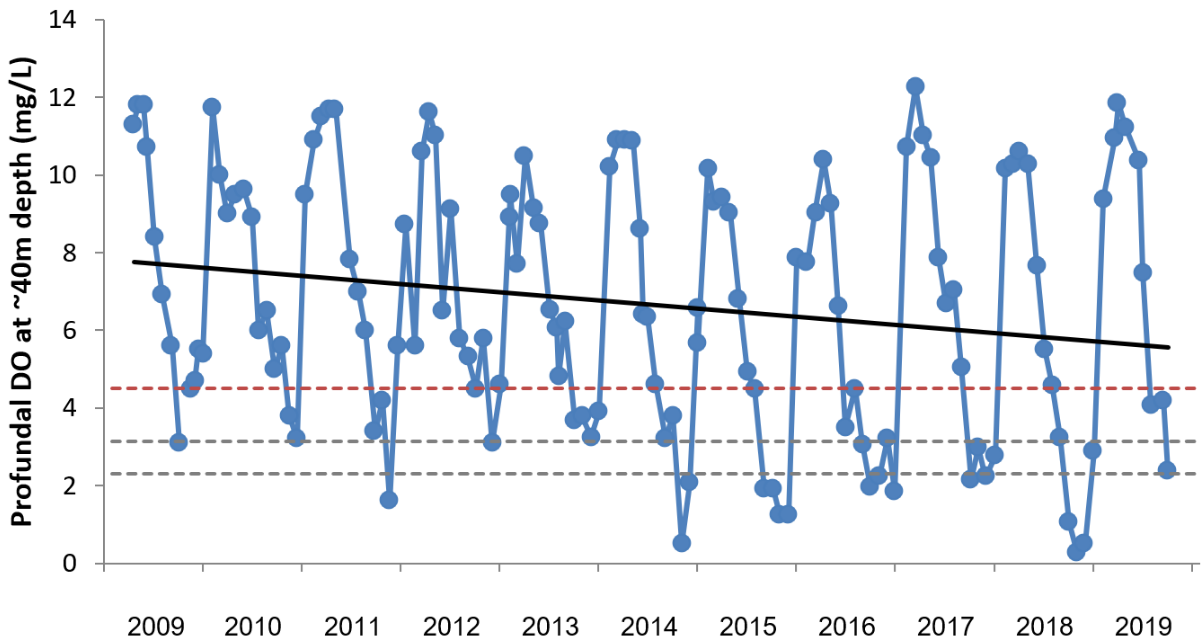


Figure 6. Monthly time series 2009-2019 of profundal zone (near sediment) dissolved oxygen (DO) concentrations at the long-term DFO limnological sampling location within Cultus Lake, BC. The solid black line indicates the long-term trend in DO values. The red dashed line indicates the hypoxic threshold for effects on juvenile Sockeye Salmon survival (4.5 mg/L; Ruggerone 2000). The grey dashed lines indicate 24 hr sockeye salmon survival thresholds for 45% survival (upper; 3.15 mg/L) and 0% survival (lower; 2.3 mg/L) from Ruggerone (2000).

Like many populations, Cultus Lake Sockeye Salmon fry undergo diurnal vertical migrations within Cultus Lake (Levy 1989; DFO unpublished data), feeding higher in the water column (i.e. upper hypolimnion, metalimnion) during the crepuscular periods, and residing in the deep waters (i.e. profundal zone) during the daylight hours, presumably to avoid predation (Clark and Levy 1988; Scheuerell and Schindler 2003). Comparison of paired day-night hydroacoustic profiles collected by DFO's Lakes Research Program suggests Cultus Lake Sockeye Salmon fry are repeatedly in close association with the lake sediments during the deep phase of their diurnal vertical migration (i.e. juveniles indistinguishable from substrate using research-grade hydroacoustics), inducing exposure to low-oxygen conditions, and potentially toxicants released from lake sediments into the overlying water column through internal loading (Figure 7). Dissolved oxygen depletion is considered a primary negative forcing and threat on the freshwater survival and persistence of Cultus Lake Sockeye Salmon. As discussed in subsequent sections, hypolimnetic oxygen depletion is also responsible for (i.e. internal loading) and/or highly interactive with other threats (i.e. climate change).

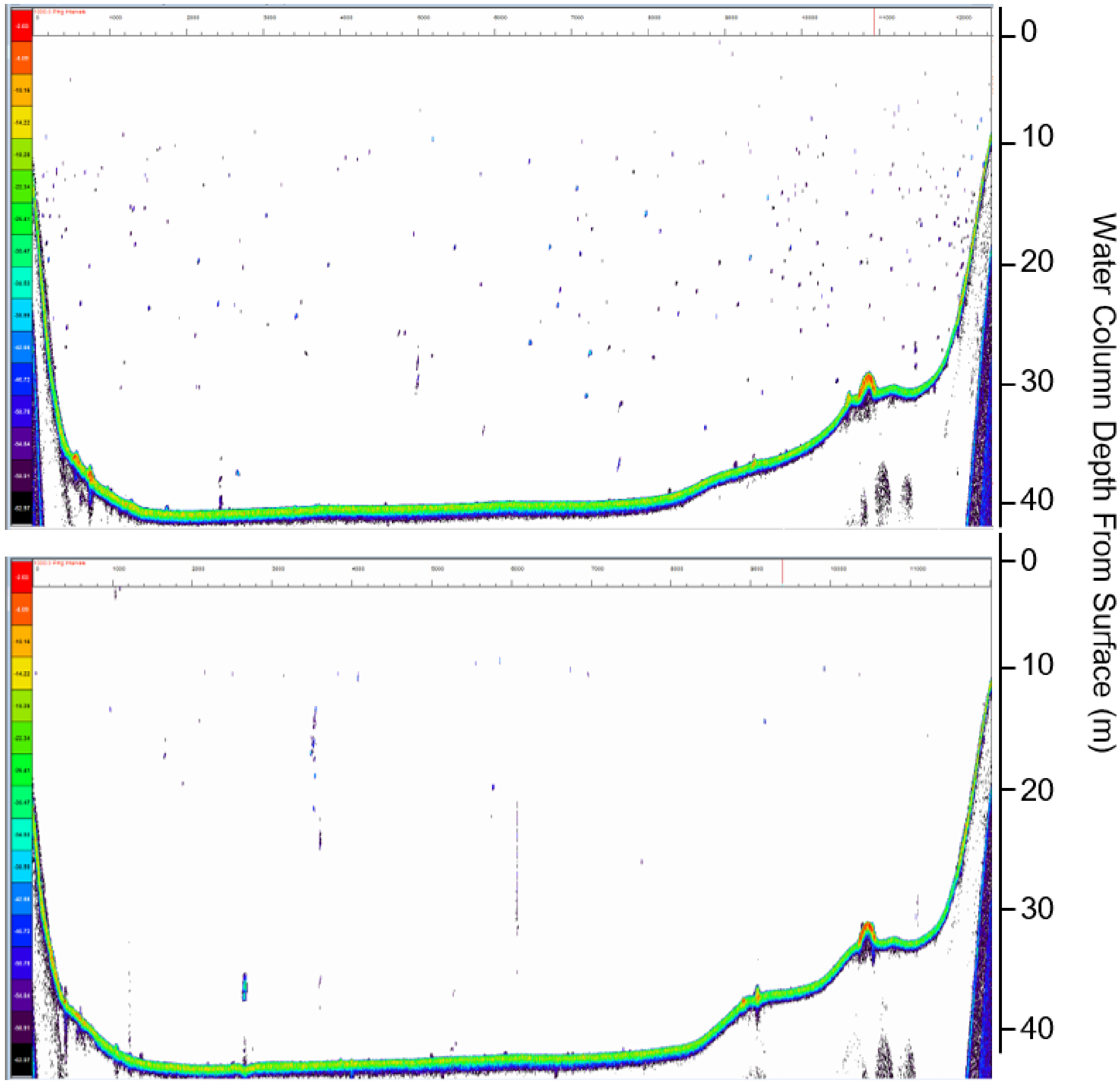


Figure 7. Example hydroacoustic echograms from A) night and B) daytime periods collected by DFO's Lakes Research Program in August 2009. Individual dots indicate pelagic hydroacoustic targets (principally Sockeye Salmon; verified by mid-water trawl). Vertical lines evident in the echograms are artefacts of air bubble columns emanating from the lake sediments.

Owing to higher eutrophication-induced primary productivity, the stratified period deep water DO depletion trajectory within Cultus Lake is now strongly mediated by primary production in the overlying water column, commencing with the spring bloom (March-April-May (MAM)). The spring bloom (as captured by monthly photosynthetic rates (PR)), which occurs through the onset of thermal stratification, sets the initial stratified period profundal DO availability in Cultus Lake, with lower MAM PR associated with higher MAM profundal DO (2009-2017 MAM Euphotic PR vs. Profundal MAM DO; $r^2 = 0.60$, $p = 0.037$, $n = 8$). Profundal DO depletion continues through the summer (June-July-August (JJA)) forced by euphotic primary production (via associated aerobic decomposition of organic matter delivered to the hypolimnion) during the growing window (2009-2017 Mean MAM-JJA Euphotic PR vs. Profundal JJA DO; $r^2 = 0.61$, $p = 0.01$, $n = 8$). Fall (September-October-November (SON)) profundal DO minima are similarly set by prior growing season primary production (2009-2017 Mean MAM-JJA PR vs. Profundal SON DO; r^2 = 0.69, p =0.01, n = 8) and associated profundal DO concentrations (2009-2017 Mean MAM-JJA Profundal DO vs. Profundal SON DO; r^2 = 0.74, p = 0.01, n = 7), but may be modified by recharge from plunging inflows occurring from the steep sided topography during periods of elevated fall precipitation, and earlier breakdown of thermal stratification in colder years.

Cultus Lake Sockeye Salmon fall fry-to-smolt survival (marked and unmarked fish) is negatively related to the intensity of the spring bloom (2009-2017 FF-SMOLT SURVIVAL vs. Profundal MAM PR; r^2 = 0.57, p = 0.05, n = 7), and consistent with a more direct relationship, and beneficial effect of profundal DO on survival, fall fry-to-smolt survival is most strongly and positively related to maximal stratified period profundal DO (2009-2017 FF-SMOLT SURVIVAL vs. Profundal MAM DO; r^2 = 0.79, p = 0.008, n = 7). The temporal offset between lake drivers and Cultus Lake Sockeye Salmon fall fry-to-smolt survival most likely reflects the importance of the spring period in establishing maximal stratified period profundal dissolved oxygen conditions near the onset of stratification, and the influence of growing season limnological dynamics, which culminate to produce elevated euphotic OM exports and deep water decomposition at lake senescence (i.e. autumn). These OM exports impose hypoxic to anoxic conditions in the profundal zone. Given the strength of the relationships between primary productivity, profundal oxygen, and fall fry-to-smolt survival, hypolimnetic oxygen depletion in Cultus Lake is considered a primary driver of Cultus Lake Sockeye Salmon freshwater survival, through direct oxygen stresses and/or indirectly via an oxygen-mediated stressor mechanism, such as internal loading of redox-sensitive toxicants from lake sediments. Thus eutrophication-forced hypolimnetic oxygen depletion is considered a high level population threat with very high certainty (Table 2).

4.1.4.2. Lake Eutrophication: Sediment Internal Loading of Limiting Nutrients

Internal loading is a feature of annual nutrient cycling in most lake ecosystems to some extent, but is most pronounced in stratified systems of elevated trophic status, such as those experiencing cultural eutrophication (Pettersson 1998; Wetzel 2001). Although many factors are important (i.e. iron, anaerobic microbial activity, pH, oxygen), internal loading is largely oxygen-mediated in lakes, whereby profundal oxygen losses force oxidation-reduction (redox) shifts at the sediment-water interface that, through multiple chemical, physical, and biological pathways, facilitate the release of redox-sensitive nutrients (i.e. P, N) and toxicants (i.e. metals, hydrogen sulfide, methane) into the overlying water column (Pettersson 1998; Shaw et al. 2004).

If left unabated, internal loading can induce non-linear increases in lake trophic status, and dominate nutrient cycles in eutrophied ecosystems, reinforcing and enhancing the nutrient enrichment trajectory, and posing risks to ecological integrity (Wetzel 2001; Nürnberg 2009). Monitoring conducted in 2014 by DFO's Lakes Research Program has demonstrated that several key eutrophication-associated nutrients (i.e. P, NO_3^-, NH_4^+) are released from the sediments into the overlying water column of Cultus Lake during the spring bloom and the fall period of lake senescence (Figure 8). Of particular concern to ongoing eutrophication is the release of phosphorus, the primary nutrient limiting algal productivity in Cultus Lake (Shortreed 2007; Gauthier et al. 2021), given its potential to induce runaway eutrophication, and intensified hypolimnetic oxygen depletion.

Tovey et al. (2008) identified a number of contaminants at elevated concentrations in Cultus Lake sediments (e.g. Fe, Ba, Ni, Mn, Cr, Cd, Se, Hg) that are redox-sensitive, or that have aquatic mobility tied to chemical reactions and/or microbial activity that occur under low oxygen conditions, and can be toxic to freshwater fish if released into the overlying water column. Moreover, during profundal water sampling from August to December of 2017, a 'rotten egg' smell was detectable from the deepest profundal waters in Cultus Lake. This is a classical indication of elevated sulfates in water, and as redox potential declines to less than approx. 100mV via bacterial decomposition, as was recorded during the 2017 late-season sampling, sulfate is reduced to hydrogen sulfide (H_2S; Wetzel 2001), a very strong fish toxicant, even at low levels, particularly under low oxygen conditions (Smith and Oseid 1972; Wetzel 2001; Luther et al. 2004). As such, the release of toxicants to the profundal zone of Cultus Lake may be a key deleterious outcome of eutrophication-driven OM decomposition and hypolimnetic oxygen depletion.

Owing the known occurrence and intensity of internal loading in Cultus Lake (i.e. nutrients), the reinforcing effects of internal loading on lake eutrophication and hypolimnetic oxygen depletion, and the strong potential for the release of redox-sensitive toxicants, particularly during seasonal lake senescence, internal loading of limiting nutrients and possibly contaminants to the Cultus Lake water column from its sediments is deemed a high level population threat with very high certainty (Table 2).

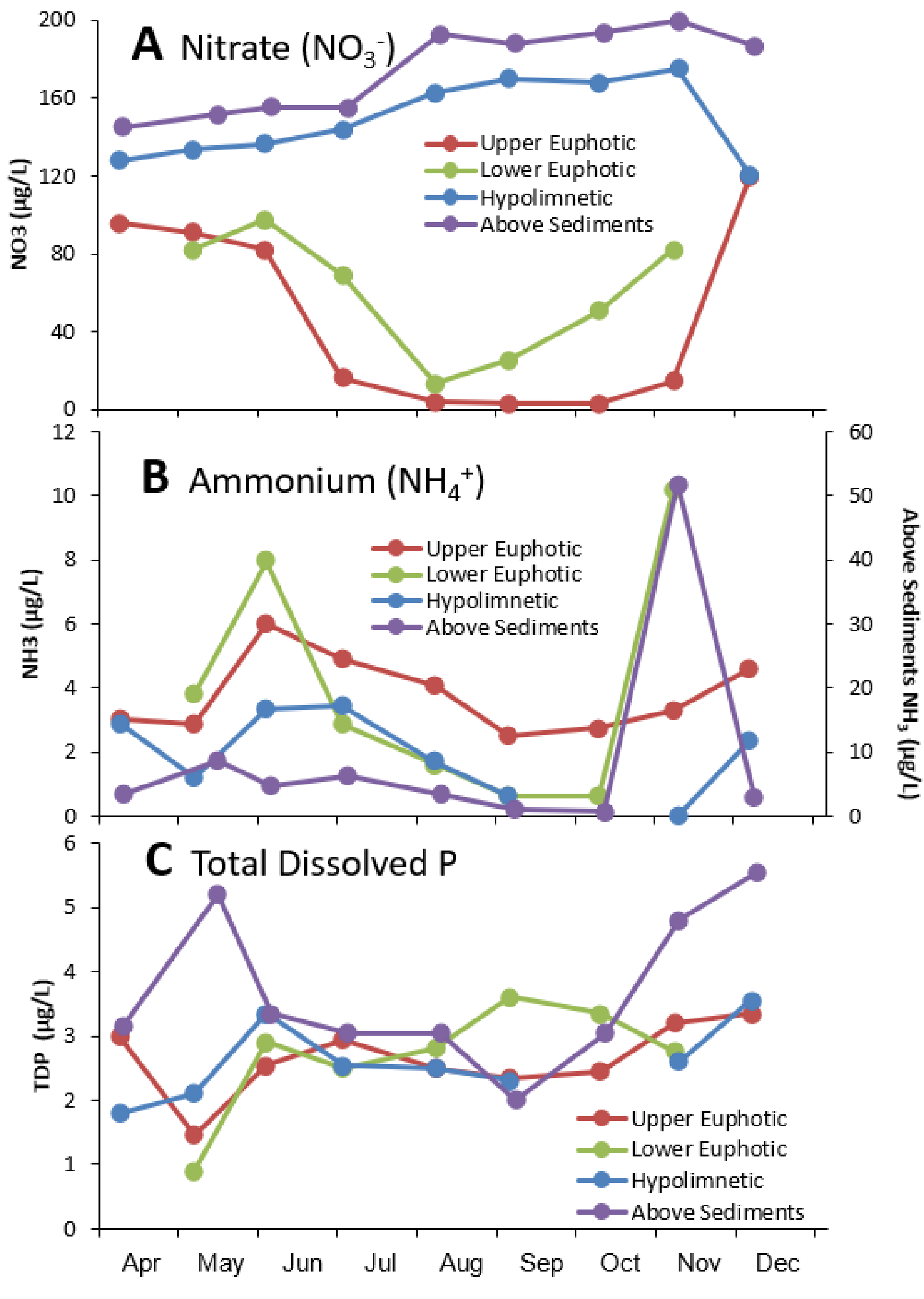


Figure 8. 2014 time series of redox-sensitive nutrients A) nitrate (NO_3^--N); B) ammonium (NH_4^+-N); and C) total dissolved phosphorus (TDP) in the Cultus Lake water column. Note the buildup of hypolimnetic nitrate through the stratified period (April-Nov) in panel A) and pulses of ammonium and phosphorus 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.

4.1.4.3. Lake Eutrophication: Organic Matter Sedimentation and Impacts on Spawning and Incubation Habitats

Although difficult to quantify, due to the range of depths of contemporary spawning by Cultus Lake Sockeye Salmon (< 2-17 m; Pon et al. 2010), eutrophication-forced increases in lake productivity may negatively influence the abundance of suitable spawning sites, and the incubation success of deep lake spawning within Cultus Lake. Nearshore visual observations indicate increased littoral organic floc and periphytic algal coverage, and enhanced organic matter loads to spawning substrates have undoubtedly increased with eutrophication, as likely have interstitial biological oxygen demands during incubation in areas not recharged by oxic groundwater exchange (Colby et al. 1972).

Dissolved oxygen requirements for egg development and survival vary depending upon the organismal developmental stage and water temperature (Sigma 1983). At substrate interstitial temperatures of 4-7°C, indicative of the spawning period and locations in Cultus Lake, oxygen concentrations of ≤ 4 mg/L will result in severe detrimental effects, while concentrations ≥ 8 mg/L are considered suitable for development to the eyed egg stage (Sigma 1983, Kondolf 2000). Dissolved oxygen requirements increase to ≥ 10 mg/L post-eyed egg (Sigma 1983).

Limited quantitative data exist on interstitial pore-water oxygen concentrations from spawning locations in Cultus Lake, however, measurements taken at Lindell Beach and Snag (Honeymoon) and Spring bays in the winter of 2003-2004, indicated only the Lindell Beach area, which receives oxygen-depleted water from the nitrate-contaminated Columbia Valley Aquifer (Zubel 2000), had limiting interstitial oxygen concentrations of 5.2-7.3 mg/L, at a time when Cultus Lake Sockeye Salmon still used the area for spawning (Jeremy Hume, North Vancouver, British Columbia, pers. comm.). Modern estimates, following more than a decade of pronounced eutrophication are lacking, and should be a focus of ongoing assessments. Contemporary spawning locations, as verified by ROV, appear to have contracted to deep sites along the eastern margin of the lake (Figure 2), which are characterized by rapid groundwater transit through fractured shale deposits at the base of the high-gradient streams draining International Ridge (Putt et al. 2019), and likely represent the few sites within Cultus Lake still receiving appreciable oxic groundwater upwelling. In addition to the expansion of invasive Eurasian Watermilfoil invasion to approx. 62% of the littoral zone (DFO Lakes Research Program, unpublished data), degradation of historical spawning locations may impose a spatial constraint on the extent of suitable spawning areas, the success of egg and alevin survival, and possibly enhanced egg mortality, without reductions in lake nutrient levels. Although limited contemporary information on interstitial oxygen conditions exists for Cultus Lake, given the contracted spatial nature of extant spawning both to and within Cultus Lake, and the known effects of eutrophication on pore-water biological oxygen demands in other systems, eutrophication-forced sedimentation of spawning substrates is deemed a high level population threat, with medium certainty (Table 2).

4.1.5. Invasive Eurasian Watermilfoil

Eurasian Watermilfoil (*Myriophyllum spicatum,* EWM) is an invasive aquatic macrophyte to North America, that has been present in the littoral zone of Cultus Lake since at least the 1970's. EWM is found from approx. 1 m depth to a maximum of 8 m depth. From the most recent acoustic survey of EWM coverage in 2014, a nearshore (to 8 m depth) average coverage of 62.4% was observed across the entirety of the lake perimeter, though some areas were as high as 89.5% and others as low as 39.3% (Garrett Lidin, DFO, Cultus Lake, British Columbia, pers. comm.). Previous estimates of nearshore coverage range from 17% in 1977 to 29% in 1991 (Mossop and Bradford 2004), and between 64% and 68% in 2004 (Stables 2004).

The direct impacts of EWM on Sockeye Salmon in Cultus Lake are unknown, but it has been previously identified as a potential threat to Cultus Lake Sockeye Salmon through provision of refuge and rearing habitat for juveniles of predator species (CSRT 2009). EWM also has the potential to impact Cultus Lake Sockeye Salmon by encroaching upon historic spawning habitats. Although there is no direct mechanistic evidence of this, the number of actively-used spawning locations has declined in the past few decades, while at the same time, EWM has spread through much of the lake's nearshore habitat. While historic accounts reported spawning in depths ranging from 0.5 m to 6 m in numerous bays and beaches throughout Cultus Lake, more recent observations have suggested that spawning now occurs in fewer locations and at depths that include deeper habitat (range: <2 to 17 m) (CSRT 2009; Pon et al. 2010); a shift that places spawning sites deeper than the known light-limited maximum depth of milfoil growth in Cultus Lake. Dense EWM beds can impact the nearshore water temperatures and dissolved oxygen content (Unmuth et al. 2000), and the annual senescence and decomposition of large biomasses of canopy organic matter produced by EWM, can significantly decrease hypolimnetic oxygen concentrations in stratified lakes (Wetzel 2001); the latter process can be particularly severe in fall, and can coincide with the incubation timing of Sockeye eggs and post-growing season rearing of the previous cohort. Moreover, as EWM obtains the majority of its nutrients (e.g. N and P) from its substrate, annual senescence of EWM stands may be a key vector in mobilization of phosphorus from Cultus Lake sediments to the water column, releasing them upon decomposition (Smith and Adams 1986), contributing to lake eutrophication. Owing to the general lack of evidence for a causal impact on survival of Cultus Lake Sockeye Salmon, invasive EWM it is considered a low level population threat with low causal certainty (Table 2).

4.1.6. Climate Change and Regional Climate Variability

4.1.6.1. Climate Impacts on Freshwater Habitat and Juvenile Sockeye Salmon

Climate change is a primary global forcing on lake ecosystems (O'Reilly et al. 2015) that is highly interactive with other lake stressors, including eutrophication (Moss et al. 2011), and can induce cascading and often complex interactive effects on the physical and chemical attributes of lakes, and the structure and functioning of aquatic biota (Adrian et al. 2009). Numerous studies highlight increases in lake surface temperatures over recent decades (e.g. O'Reilly et al. 2015) in response to warming air and ocean surface temperatures (IPCC 2013). Most notably, the annual strength and duration of thermal stratification has been increasing with warming, with the most pronounced temperature increases observed in warm, deep lakes (Kraemer et al. 2015).

Shortreed (2007) first postulated that climate warming may be impacting Cultus Lake, comparing lake surface temperatures in 2001-2003 with data collected in the 1920's and 1930's. Synoptic meteorological conditions in western North America are strongly influenced by quasi-periodic, coupled ocean-atmospheric processes, such as the Pacific Decadal Oscillation and the El Niño-Southern Oscillation, which induce large changes in continental air temperatures and precipitation (Stahl et al. 2006), making climate change forcing conclusions based upon single, disjunct time period comparisons problematic (BC Ministry of Environment 2016). Sumka (2017), however, developed a one-dimensional hydrodynamic model to characterize the seasonal thermal dynamics in Cultus Lake, past and present, confirming Cultus Lake has experienced pronounced warming over the past century (1923-2016 total heat content increases of 0.80 $MJ/m^2/yr$), lengthening the stratified period by approx. 0.18 days/yr, and advancing the onset of annual stratification by ~ 2 weeks over the same period.

Cultus Lake monthly upper water column (0-5 m) temperatures are strongly coupled to mean monthly air temperatures recorded at the nearby Environment and Climate Change Canada Agassiz Climate Station (ID 1100120) with approximately a one month thermal lag in water heating (2001-2017 0-5 m WATER TEMP vs. MM AIR TEMP (1 month lead); $r^2 = 0.89$, $p < 0.0001$, $n = 126$; Figure 9 A; Gauthier et al. 2021). Applying this relationship to the Adjusted and Homogenized Daily Climate Data archived for the Agassiz instrumental record (Environment and Climate Change Canada 2017), demonstrates that upper water column temperatures within Cultus Lake have likely fluctuated for some time, associated with regional climate variability (Figure 9 B,C). However, our reconstruction indicates pronounced increases in summer upper water column temperatures following the ca. 1970's (Figure 9 B), a period of known regional warming that is coincident with a shift to a warm phase of the Pacific Decadal Oscillation (Mantua et al. 1997), and a shift to above-average fall temperatures that may promote seasonal protraction of lake stratification (Figure 9C).

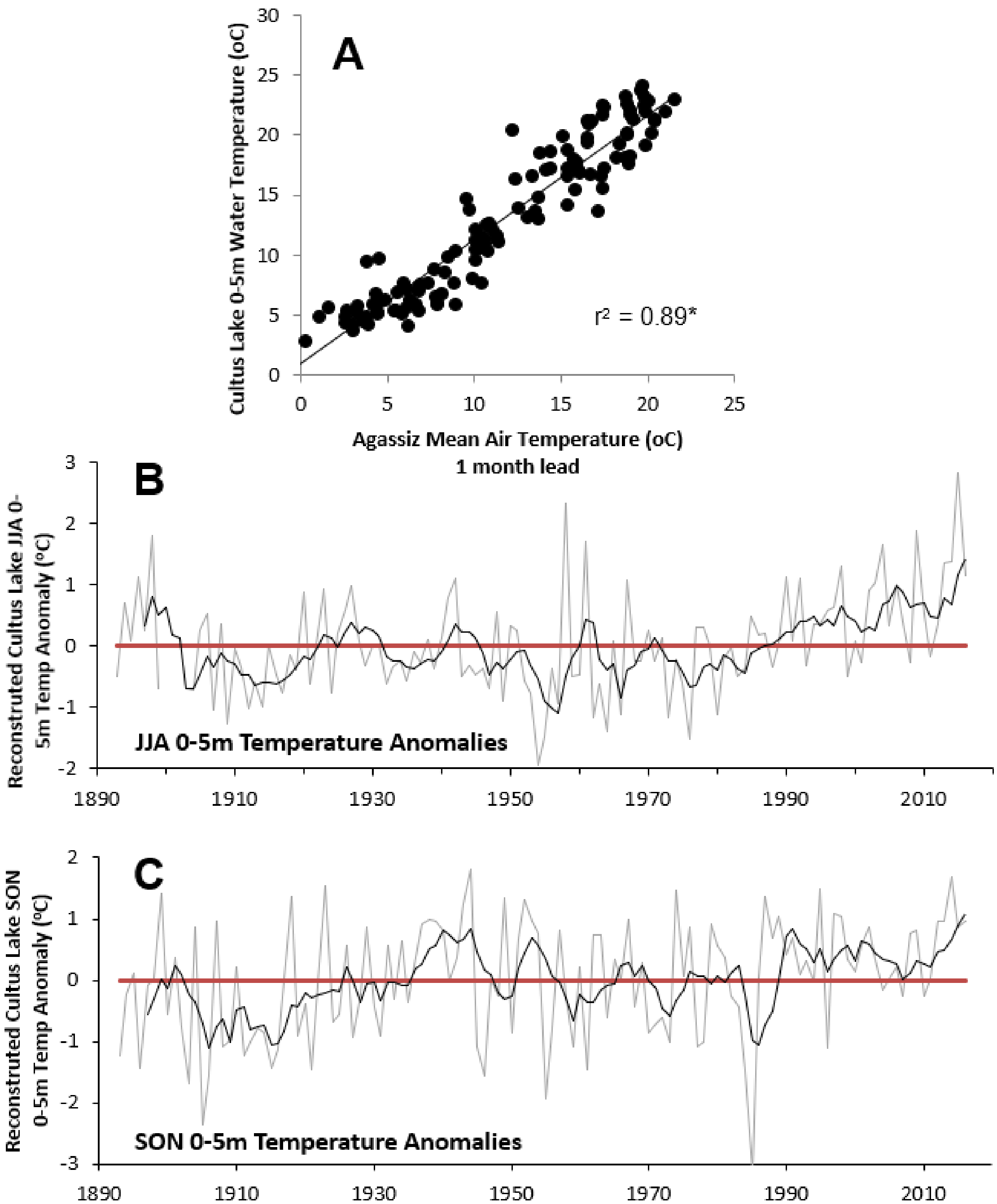


Figure 9. Atmospheric-upper water column (0-5m) physical coupling within Cultus Lake. A) Relationship between mean monthly air temperatures (ECC Agassiz Climate ID:1100120) and Cultus Lake 0-5 m mean monthly temperatures (2001-2017); and Centennial-scale reconstructions of 0-5m temperature anomalies in Cultus Lake B) summer (JJA) (i.e. peak stratification) and C) autumn (SON) upper water column temperatures (i.e. late-stratification period) from the long-term average (horizontal red lines). Direct (grey lines) and 5-year averaged values (black lines) in B) and C) are shown.

Commensurate with climatically-mediated surface warming on the intensification and protraction of lake thermal stratification, and consistent with the modelling results of Sumka (2017), stratified period (April-November) lake stability, the relative resistance to lake turnover indicated by the Schmidt Stability Index (SSI; Schmidt 1928; Costella et al. 1983) is strongly related to monthly mean air temperatures recorded at the ECC Agassiz Climate Station (ID: 1100120) with a one month thermal lag in the lake data (2001-2017 SSI vs. MM AIR TEMP (1 month lead); $r^2 = 0.85$, $p < 0.001$, $n = 89$).

Increasing upper water column temperatures in Cultus Lake, which now exceed 24.5 °C in the epilimnion in some years, may impose thermal stresses on growth and survival of Cultus Lake Sockeye Salmon fry during foraging near and/or within the upper water column, particularly during the summer months (Brett 1952, Brett and Higgs 1970, Akbarzadeh et al. 2021). Contemporary hydroacoustic and trawl surveys indicate limited use of the lake epilimnion during summer and fall, when the water column is stratified (DFO Lakes Research Program, unpublished data). Genomic evidence indicates thermal stresses in Cultus Lake Sockeye Salmon, which is additive and potentially interactive with hypoxic stresses (Akbarzadeh et al. 2021). While juvenile Sockeye Salmon appear to be largely constrained to the metalimnion (thermocline) and hypoxic hypolimnetic zones of Cultus Lake during the latter growing window (Figure 7), (Shortreed 2007), both thermal and low oxygen stressors are impacting juvenile Sockeye Salmon during freshwater residence (Akbarzadeh et al. 2021).

The in-lake survival of juvenile Cultus Lake Sockeye Salmon is strongly related to climatically-forced upper water column temperatures and associated forcings on lake physics. In particular, Autumn upper water column temperatures are strongly, negatively related to Cultus Lake Sockeye Salmon fall fry-to-smolt survival (2009-2017 SON TEMP vs. FF-SMOLT SURVIVAL $r^2 = 0.70$ $p = 0.005$, $n = 9$), as is overall lake stability during the growing window (2009-2017 APR-NOV SSI vs. FF-SMOLT SURVIVAL $r^2 = 0.69$, $p = 0.005$, $n = 9$). The lake physical linkages to juvenile survival, and the seasonal temporal offset (Autumn to overwinter), with limnological correlates preceding in-lake survival bottlenecks, suggests that the relationship is unlikely entirely a direct temperature effect (although direct and delayed sub-lethal to lethal thermally-forced effects cannot be ruled out), but rather the effect of climatic and temperature forcings on lake physics, with cascading effects on survival-linked mechanisms (i.e. hypolimnetic oxygen depletion, internal loading). The direct impacts of sub-lethal and lethal epilimnetic temperatures are considered a medium population level risk, with medium causal certainty (Table 2).

In fact, climate change (and variability) is highly interactive with other lake stressors, and serves to exacerbate the 'symptoms' of lake eutrophication (Moss et al. 2011). At contemporary eutrophied nutrient concentrations, monthly primary production in Cultus Lake is coupled with mean monthly air temperatures (1-month climate lead) throughout the growing season (2009-2017 MM AIR TEMP (1 month lead) vs. MM log(PR) ; $r^2 = 0.57$ $p < 0.001$, $n = 106$), and primary production continues throughout the year, although as is typical of most temperate lakes, relatively reduced fall through spring. Elevated primary production during the spring bloom is forced by abundant initial nutrient concentrations (largely anthropogenically-derived; Putt et al. 2019) and an earlier onset of stratification (Sumka 2017). Through the spring bloom, autotrophic uptake rapidly depletes readily-bioavailable nitrogen (i.e. NO_3^-) in the epilimnion, a temperature-mediated phenomenon (2009-2017 MM AIR TEMP (1 month lead) vs. NO_3^-; $r^2 = 0.71$. $p < 0.001$, $n = 106$), and owing to relatively high light penetration and abundant hypolimnetic nutrient reserves, primary production concentrates at the metalimnion and upper hypolimnion, forming a deep chlorophyll maximum (DCM; Figure 10 A), which persists through the stratified period.

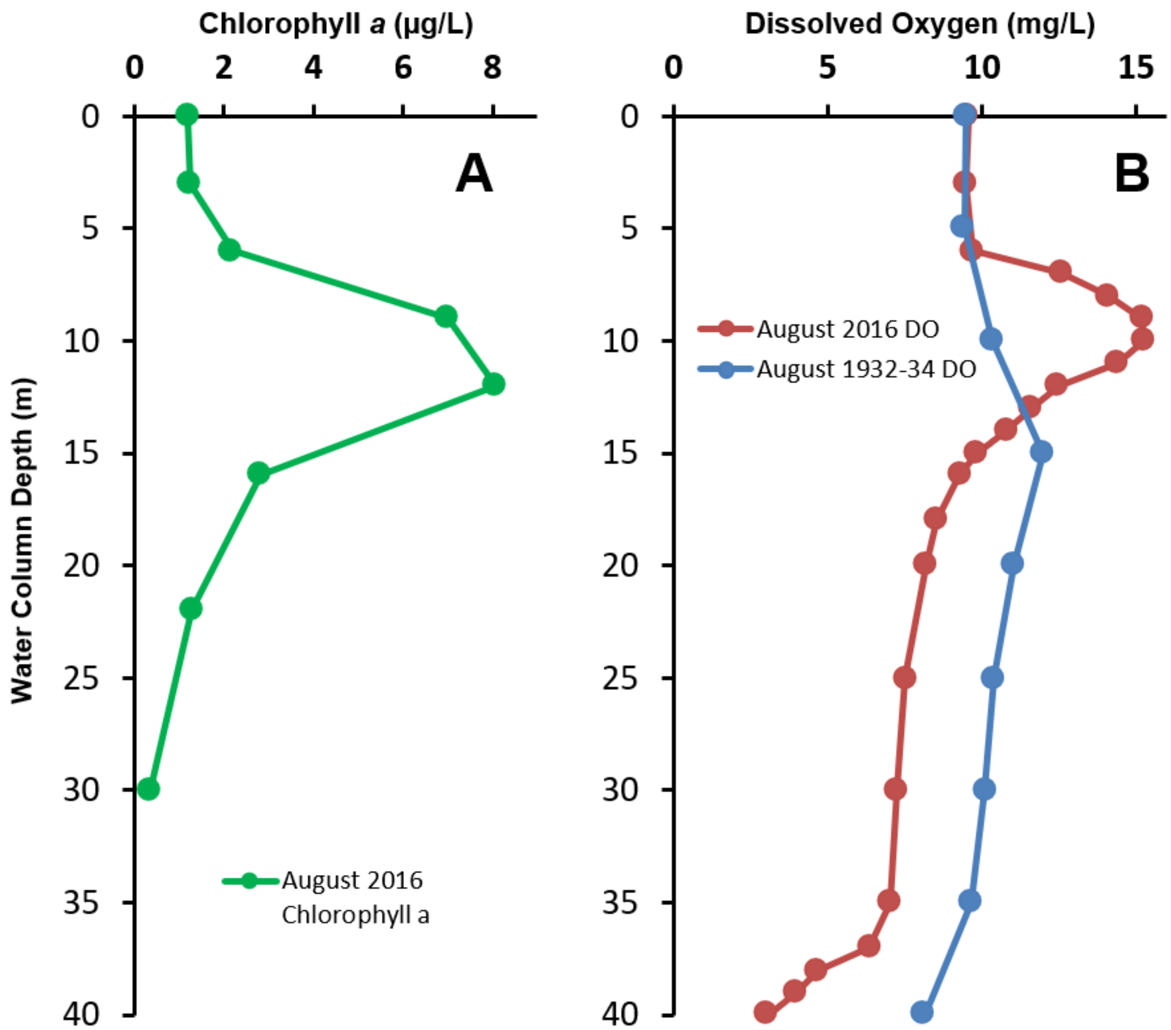


Figure 10. Example profiles of late-summer A) Deep chlorophyll maximum (DCM) formation in Cultus Lake (2016) and B) DCM-resultant oxygen maxima in 2016 versus historical measurements in the 1930's made by Ricker (1937). Notable are the recent dissolved oxygen deficits in the bottom ~ 5m of the water column.

Contrasting data from 1930's indicates the DCM (as inferred from dissolved oxygen concentrations, the by-product of photosynthesis; Shortreed 2007; Figure 10B) is a seasonal production feature that existed in a diminished capacity historically, but that is much more pronounced under lake eutrophication and climate change (Ricker 1937, Shortreed 2007). Moreover, hypolimnetic oxygen depletion was negligible relative to the post-eutrophication state (Shortreed 2007; Figure 10B).

Given the deep position of primary production maxima within the water column, at or below the depth of the mixed layer for much of the stratified period, DCM can increase the export of OM to lake hypolimnia, relative to epilimnetic primary production, where OM can be recycled and remain within the euphotic zone (Skjoldal and Wassmann 1986). As such, the prolongation and enhanced DCM production within Cultus Lake, likely provides a more efficient export pathway for OM to the hypolimnion, enhancing aerobic decomposition and seasonal hypolimnetic oxygen losses. Thus, both the absolute increases in eutrophication- and climatically-forced OM, and the seasonal climatically-driven changes to the 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, which are impacting Cultus Lake Sockeye Salmon freshwater survival. A relatively new line of evidence on juvenile survival constraints, not included in previous assessments, cultural eutrophication, climate change, and their interactions are deemed primary threats to the persistence of Cultus Lake Sockeye Salmon. Although climate change is unlikely to be reversed in a reasonable time frame for recovery, state-based limnological modeling indicates that nutrient abatement can significantly retard the eutrophication trajectory, and likely reverse it if atmospheric sources are constrained, restoring the quality of deep rearing habitats of Cultus Lake (Putt et al. 2019). Owing to the state of evidence, and the degradation and potential catastrophic loss of freshwater habitat for Cultus Lake Sockeye Salmon without targeted lake management, climate change interactions with lake eutrophication are considered a high level population threat, with high causal certainty (Table 2).

4.1.6.2. Climate Impacts on Marine Habitat and Sockeye Salmon

The Pacific coupled ocean-atmospheric system is dynamic, with natural variability strongly linked to ecosystem changes in various North Pacific ocean domains inhabited by anadromous Pacific salmon during marine maturation (Burgner 1991), from the continental shelf to the open ocean (Mantua et al. 1997; Miller et al. 2004; Di Lorenzo et al. 2008). High-frequency modes (i.e. years to decades) of quasi-periodic variations in coupled ocean-atmospheric circulation patterns and resultant sea surface temperatures, such as those expressed by the El Niño-Southern Oscillation (ENSO), the North Pacific Gyre Oscillation (NPGO) and the Pacific Ocean Decadal Oscillation (PDO), yield large and dynamic physical changes in Pacific Ocean extratropical waters (Mantua et al. 1997; Di Lorenzo et al. 2008; Soulard et al. 2019). Cascading influences on ocean physics, chemistry and the structure and functioning of marine ecosystems have complex direct and indirect implications for the marine spatial residence, feeding ecology, growth, abundance, condition, demographics, fecundity, and ecological interactions of Pacific salmon (Mantua et al. 1997; Kaeriyama et al. 2004; Di Lorenzo et al. 2008; Reed et al. 2011; Martins et al. 2012; Connors et al. 2020).

Similarly, directional climate change is modifying ocean conditions, circulation, and ecosystems, with potential implications for Pacific salmon (Okey et al. 2014; Soulard et al. 2019). Warmer sea surface temperatures affect the metabolism of Sockeye Salmon at all life stages in the marine environment (i.e. post-smolt to returning adult; Martins et al. 2012). Warming marine waters generally decrease growth and survival in juvenile Fraser River Sockeye Salmon during early-marine residence (Hinch et al. 1995; Martins et al. 2012). Survival and size-at-maturity is negatively related to SST during the last few months of marine residence (Pyper and Peterman 1999; McKinnell 2008; Martins et al. 2012)), and body size and energy density during the last year of marine residence (Hinch et al. 1995; Crossin et al. 2008; Martins et al. 2012). These environmental influences on Sockeye Salmon may affect marine growth and survival through enhanced metabolic rates (Hinch et al. 1995; Martins et al. 2012), modifications and limitations in food web availability (Aydin et al. 2000; Mackas et al. 2007; Richardson et al. 2008), and/or constraints on thermally suitable habitat (Abdul-Aziz et al. 2011; Martins et al. 2012), with the latter possibly leading to increased competition as a result of density (Martinson et al. 2008; Martins et al. 2012). Climate change may also be influencing the marine distribution of Sockeye Salmon in both space and time, influencing arrival timing, and the proportional amounts of time spent in freshwater vs. marine habitats, prolonging marine residence, and inducing phenological mismatches between salmon residence in the Pacific Ocean and available food web resources (Cline et al. 2019). Moreover, on longer time scales, changes to marine distributions, including a potential poleward migration of Pacific salmon natal ecosystem use and marine migrations may be expected (Welch et al. 1998; Healey 2011). Despite the various marine influences on survival of Pacific salmon during their ocean phase, there is no apparent evidence of directional change in survival or variation in the smolt-adult and marine survival time series for Cultus Lake Sockeye Salmon, however, observed variations in survival for both series may reflect the influences of climatic and other drivers on marine survival. Owing to the potential for ‘stochastic’ climate variability and change influences on marine survival, over half of the life history, and acknowledging a lack of quantitative evidence for a directional survival impact on Cultus Lake Sockeye Salmon, marine climate change and variability are considered medium level population threats with a medium level of causal certainty (Table 2).

4.1.7. Marine Net-Pen Aquaculture

Marine fin fish aquaculture along the coast of British Columbia has been recognized as a potential threat to Fraser Sockeye Salmon and was a prominent component of a judicial inquiry into their decline (Cohen 2012). Impacts of salmon farm waste on the quality of nearby marine habitat, and the potential for escape of farmed Atlantic Salmon (*Salmo salar*), were unlikely to have had population level effects on wild Fraser River Sockeye Salmon, but the risk of disease and pathogen transmission from salmon farms to wild Sockeye Salmon could not be eliminated, due to an insufficient scientific understanding of the interactions between the two (Cohen 2012). Also noted was that the available data limited the statistical power available to infer relationships between Sockeye abundance or survival with trends in pathogens related to fish farms (Korman 2011).

In response to the recommendations of the Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River, DFO conducted a series of risk assessments to examine the threats of transfer of nine different pathogens between farmed Atlantic Salmon and wild Fraser Sockeye Salmon. The risk assessments determined that minimal risk was posed to Fraser River Sockeye Salmon abundance and diversity by the following pathogens: Infectious Hematopoietic Necrosis Virus, *Aeromonas salmonicida*, *Yersinia ruckeri*, *Renibacterium salmoninarum*, *Piscirickettsia salmonis*, Piscine Orthoreovirus (PRV-1), *Moritella viscosa*, *Tenacibaculum maritimum*, and Viral haemorrhagic septicaemia virus IVa (VHSV-Iva) (DFO 2017, 2019b, 2020a-g). Although there is no direct evidence of the impact of Atlantic Salmon farms on Cultus Lake Sockeye Salmon specifically, juveniles are known to migrate northward along the mainland coast of British Columbia (Welch et al. 2009). The conclusions drawn and uncertainties regarding the impacts of Atlantic Salmon net-pen aquaculture upon Fraser River Sockeye Salmon at large can likely be generalized to the Cultus Lake population. However, given a lack of direct evidence of impacts on survival, the population threat risk level of net-pen aquaculture is unknown, with a low level of causal certainty (Table 2).

4.1.8. Invasive Smallmouth Bass

In May of 2018, invasive Smallmouth Bass (*Micropterus dolomieu*; shortened to SMB) were reported by anglers in Cultus Lake for the first time. Preliminary work to date has established that there are multiple SMB age classes present in the lake, with active breeding taking place at the north end in the late-spring months. Observations include the presence of large (e.g. >35 cm) SMB in close proximity to the outlet of the lake, during a timing window that corresponds to the outmigration of Sockeye Salmon smolts. SMB were also observed immediately upstream of the Sweltzer enumeration fence at the same time that Cultus Lake Sockeye Salmon smolts were passing through on their way downstream. Examination of SMB stomachs from Cultus Lake have confirmed evidence of juvenile Sockeye Salmon predation by SMB (Wendy Margetts, Thompson Rivers University, British Columbia, pers. comm.), which are a known predator of Sockeye and other Pacific salmon juveniles in other systems in which they have been introduced (Fayram and Sibley 2000; Fritts and Pearsons 2004; Tabor et al. 2007). In some cases SMB predation on juvenile salmon can exceed that of Northern Pikeminnow (Tabor et al. 1993); a common natural predator historically identified as a threat to Sockeye production in Cultus Lake (Ricker 1941; CSRT 2009). In particular, juvenile Sockeye Salmon that have not yet moved offshore, and smolts may be the life stages that are most susceptible to SMB predation (Fayram and Sibley 2000). In Cultus Lake, further study is warranted to determine the extent and spatial arrangement (i.e. outlet, counting fence) of SMB predation upon juvenile Sockeye Salmon, characterizing the threat that this invasive species presents. Given the recent invasion of Cultus Lake by SMB, and evidence of the occurrence of predation upon *O. nerka*, a risk to juvenile Cultus Lake Sockeye Salmon is likely. While novel predation from SMB has the potential to be highly influential on Cultus Lake Sockeye Salmon in their natal and migratory habitats, in light of the lack of evidence indicating direct impacts on the population status and trends, this emergent threat is considered a low population-level risk with low causal certainty at this time (Table 2).

Table 2. Threats to the survival and recovery of Cultus Lake Sockeye Salmon. Threats are ranked based upon their current biological risk score.

Threat	Life History Stage	Likelihood of Occurrence	Level of Impact	Causal Certainty	Population Level Threat Risk	Threat Occurrence	Threat Frequency	Threat Extent
Fisheries Interceptions: Direct population losses	**IMMATURE, ADULT**	Known	High	Very High (1)	High (1)	Historical, Current, Anticipatory (assuming no change in fisheries management)	Recurrent	Broad
Hatchery Production of Pacific Salmon: Genetic impacts on fitness reductions in wild population	**ALL LIFE STAGES**	Likely	Medium	Medium (3)	Medium (3)	Current, Anticipatory	Recurrent	Extensive
Marine Competition with hatchery-origin Pink and Chum salmon	**ADULTS, IMMATURES, SMOLTS**	Likely	Unknown	Low (4)	Unknown (4)	Current	Recurrent	Broad
Pollution: Elevated mortality or sub-lethal effects due to aquatic pollutants	**ALL LIFE STAGES**	Likely	Medium	Low (4)	Medium (4)	Historical, Current, Anticipatory	Recurrent	Extensive
Lake Eutrophication: Low oxygen in spawning beds	**EGGS, ALEVIN**	Likely	High	Medium (3)	High (3)	Historical, Current, Anticipatory (assuming no lake management)	Recurrent	Extensive
Hypoxic-anoxic hypolimnetic and profundal oxygen levels	**EGGS, ALEVIN, FRY, PARR**	Known	Extreme	Very High (1)	High (1)	Historical, Current, Anticipatory (assuming no lake management)	Recurrent	Extensive
Sediment internal loading	**EGGS, ALEVIN, FRY, PARR**	Known	High	Very High (1)	High (1)	Historical, Current, Anticipatory (assuming no lake management)	Recurrent	Extensive

Table 2 (cont'd). Threats to the survival and recovery of Cultus Lake Sockeye Salmon. Threats are ranked based upon their current biological risk score

Threat	Life History Stage	Likelihood of Occurrence	Level of Impact	Causal Certainty	Population Level Threat Risk	Threat Occurrence	Threat Frequency	Threat Extent
Invasive Species:								
Eurasian Watermilfoil effects on spawning sites and aerobic organic matter decomposition	**ADULTS, EGGS, ALEVIN, FRY, PARR**	Known	Low	Low (4)	Low (4)	Historical, Current, Anticipatory	Recurrent	Broad
Predation by Smallmouth Bass	**ALEVIN, FRY, PARR, SMOLTS**	Known	Unknown	Low (4)	Low (4)	Current, Anticipatory	Continuous	Extensive
Migration corridor habitat modifications:								
Dyking, channelization, enumeration fence	**ADULTS, SMOLTS**	Known	Unknown	Low (4)	Unknown (4)	Historical, Current, Anticipatory	Continuous	Extensive
Climate Change and Variability:								
Freshwater:								
Sub-lethal to lethal lake epilimnion temperatures	**FRY, PARR**	Known	Medium	Medium (3)	Medium (3)	Historical, Current, Anticipatory	Recurrent	Extensive
Interaction with lake eutrophication (enhanced deep anoxia/hypoxia)	**ADULTS, EGGS, ALEVIN, FRY, PARR, SMOLTS**	Known	High	High (2)	High (2)	Historical, Current, Anticipatory (assuming no lake management)	Continuous	Extensive
Marine:								
Impacts on fecundity, growth, survival	**ADULTS, IMMATURES, SMOLTS**	Known	Medium	Medium (3)	Medium (3)	Historical, Current, Anticipatory	Continuous	Extensive
Net-Pen Aquaculture:								
Disease, parasites	**ADULTS, SMOLTS**	Likely	Unknown	Low (4)	Unknown (4)	Historical, Current	Recurrent	Broad

4.2. ELEMENT 9: ACTIVITIES MOST LIKELY TO THREATEN (I.E., DAMAGE OR DESTROY) THE HABITAT PROPERTIES IDENTIFIED IN ELEMENTS 4-5

Lake eutrophication forcings, climate change and climate variability are the activities most likely to threaten habitat properties of Cultus Lake Sockeye Salmon identified in Elements 4-5. The pathways and consequences of these activities are described in Element 8.

4.3. ELEMENT 10: NATURAL FACTORS THAT WILL LIMIT SURVIVAL AND RECOVERY OF CULTUS LAKE SOCKEYE SALMON

Several natural factors may limit the natural survival and recovery of Cultus Lake Sockeye Salmon. Inherent vulnerabilities are associated with stochastic events and the limited distribution of the population in the wild (i.e. one nursery lake), and in captivity (i.e. one hatchery), deemed a medium level threat with low causal certainty. In addition, the following natural factors have been identified as primary limiting factors for the population:

4.3.1. Variability in marine conditions

Marine climate variability and its impacts on the productivity of Pacific salmon populations is well documented (Beamish and Bouillon 1993; Mantua et al. 1997; Martins et al. 2012). Paleolimnological records over the past two millennia have shown fluctuations in Sockeye Salmon abundances corresponding to major changes in the climate of the Pacific Ocean (Finney et al. 2002), and in the past 300 years, similar records have shown that Sockeye Salmon abundances followed fluctuations in sea surface temperatures (Finney et al. 2000). While there is limited information specific to the Cultus Lake Sockeye Salmon marine life history, the impacts of variability in marine conditions have been documented on Fraser Sockeye Salmon more broadly (Healey 2011, Martins et al. 2012). Warmer marine temperatures, which have yielded increases in survival and growth in Alaskan Sockeye Salmon stocks during early marine life stages (post-smolt), have shown the opposite for Fraser River populations (Mueter et al. 2002). Warmer temperatures have also been linked to decreased body size in mature adults (Cox and Hinch 1997; Pyper and Peterman 1999), which can have implications for upriver migration and spawning success (Crossin et al. 2004; Healy 2011). Moreover, susceptibility to disease and pathogens in the marine environment is influenced by increasing temperatures (Kent 2011).

While the effects and mechanisms are complex, an extensive review of the literature covering the effects of climate variability on Sockeye Salmon across all life stages by Martins et al. (2012), supported the observations that common impacts were more strongly felt at regional and local scales as opposed to larger (i.e. ocean-wide) scales (e.g. Mueter et al. 2002). Owing to the known coupling of Sockeye Salmon abundances to variable marine ocean-climate forcings, and predictions of increased climate extremes, increasing variability in marine conditions is considered a medium level population risk, with medium causal certainty (Table 3).

4.3.2. Variability in freshwater conditions

Lake ecosystems are tightly linked to atmospheric forcings (Wetzel 2001; Adrian et al. 2009). Synoptic climate patterns in western North America are broadly forced by coupled ocean-atmospheric variability in the Pacific Ocean (Stahl et al. 2006; British Columbia Ministry of Environment 2016). Quasi-periodic oscillatory patterns spanning the tropical-extratropical Pacific Ocean (e.g. El Niño-Southern Oscillation, Pacific Decadal Oscillation) induce large-scale fluctuations in continental temperature and precipitation regimes (Stahl et al. 2006).

In Section 4.1.6, we demonstrate tight thermal coupling of Cultus Lake physical dynamics (i.e. upper water column temperatures, seasonal patterns of thermal stratification) to regional climatic forcings (e.g. climate change and climate variability). Our reconstruction of upper water column temperatures over the past century (Figure 9), suggests pronounced climate-mediated temperature variability in Cultus Lake is an intrinsic feature of the system. As such, it is reasonable to assume that future air temperature variations will continue to force physical variability in Cultus Lake, with cascading effects on water chemistry and ecological structure and function. Moreover, increasing water temperatures can increase the susceptibility of Pacific salmon to disease and pathogens in the freshwater environment (Wagner et al. 2005; Bradford et al. 2010; Kent 2011).

In concert with anthropogenic forcings, periodic climate variations may serve to exacerbate (i.e. warm phases) or dampen (i.e. cold phases) the deleterious effects of lake eutrophication (e.g. hypolimnetic oxygen depletion, internal loading from lake sediments), although with the shifting baseline of warming lake temperatures, and the propensity of increased atmospheric variability under climate change (Coumou and Rahmstorf 2012) this relationship may become more dynamic, leading to more extreme variability in the ability of Cultus Lake to support Sockeye Salmon. In the absence of prescribed abatement of nutrient loadings to Cultus Lake (see Putt et al. 2019), which enhance the biological reactivity of lakes to climate drivers (Moss et al. 2011), such extremes could push the ecosystem past key thresholds (i.e. runaway eutrophication from internal loading, reinforced changes to food web structure and functioning, phenological mismatches in emergence timing versus food web resources/predation), further imperilling Cultus Lake Sockeye Salmon during sensitive early life history phases in freshwater. As such, particularly should lake management abating nutrient loading not proceed, increased variability in freshwater conditions is considered a high level population risk, with a very high level of causal certainty (Table 3).

4.3.3. Change in adult migration timing

In the early 1990s adult Cultus Lake Sockeye Salmon, along with other late-run populations, began to enter freshwater earlier than they had in the past (Cooke et al. 2004). This change in behaviour resulted in the median arrival date at the Sweltzer Creek fence advancing from about November 1 to September 15, exposing migrants to higher river temperatures and flows, and amplifying stresses to individuals (Bradford et al. 2010). As the timing of spawning has not changed, the period of holding in freshwater prior to spawning has increased by at least 45 days. This prolonged period of freshwater residence is thought to contribute to higher rates of pre-spawning mortality among adults (Bradford et al. 2010), though it is noted that estimates of pre-spawn mortality for this population are highly uncertain, due to deep in-lake spawning and the associated challenges with carcass recovery to determine spawning success. As such, timing in adult migration timing as a risk for pre-spawning mortality is considered a high level population risk, with medium causal certainty (Table 3).

4.3.4. Pathogens, parasites and diseases

There are multiple pathogens and parasites that affect Cultus Lake Sockeye Salmon. *Parvicapsula minibicornis* is a myxosporean parasite that is common to adult Cultus Lake Sockeye Salmon (Bradford et al. 2010). *P. minibicornis* initially infects the kidney but also the gills, and is thought to cause renal failure (Raverty et al. 2000) and respiratory impairment (Bradford et al. 2010). More severe *P. minibicornis* infection was found in later migrating Cultus Lake Sockeye Salmon in 2007, which was suspected to be due in part to increased exposure to warmer river temperatures (Bradford et al. 2010), known to affect Sockeye Salmon physiological performance (Wagner et al. 2005).

Juvenile Cultus Lake Sockeye Salmon are commonly found with the copepod *Salmincola californiensis* attached within branchial cavities and at the base of their fins. In high numbers, this copepod can cause tissue damage and even death to the host (Kabata and Cousens 1977). Other parasite species from the following taxa have also been observed on Cultus juveniles: Myxosporea, Monogenea, Trematoda, Cestoda, Nematoda, and Acanthocephala (Bailey and Margolis 1987).

Bacterial kidney disease (BKD) is caused by *Renibacterium salmoninarum*, and affects all species of Pacific salmon. BKD causes an infection particularly in the kidneys, but also other organs (Fryer and Lannan 1993). Sockeye are highly susceptible to BKD across a range of temperatures, though warmer temperatures result in a shorter time to death (Sanders et al. 1978). BKD has been found in relatively few Cultus Lake Sockeye Salmon adults taken as part of the broodstock program, which are screened for disease (Ackerman et al. 2014).

Pathogens, parasites, and diseases can be exacerbated by interactions with environmental changes (Teffer et al. 2022), and many are endemic within the Cultus Lake Sockeye Salmon (Bradford et al. 2010). Genomic evidence indicates *Ichthyoptherius multifiliiis* epizootics occur in Cultus Lake Sockeye Salmon, subsequent to thermal and hypoxic stresses in Cultus Lake, and may reveal delayed environment x pathogenic interactions (Akbarzadeh et al. 2021). As uncertainty is pronounced in the episodic nature of pathogen, parasite, and disease outbreaks, and their effects on the Cultus Lake Sockeye Salmon population, they are considered to be a low level population risk with low causal certainty (Table 3).

4.3.5. Predation

Predation of juvenile Sockeye Salmon in Cultus Lake has long been identified as a natural factor that impacts the productivity of this population (Ricker 1941). Predation at the egg stage in Cultus Lake, has been attributed to suckers and sculpins (CSRT 2009). Native fish species occurring in Cultus Lake, that are known to prey upon free swimming juvenile Sockeye Salmon, include Northern Pikeminnow, Dolly Varden, Cutthroat Trout, Coho Salmon, Prickly Sculpin, Rocky Mountain Whitefish, and Residual Sockeye and Kokanee (Ricker 1941). Among these, Northern Pikeminnow, in particular, have been identified as a significant predator, and there have been multiple predator control efforts targeting Northern Pikeminnow in Cultus Lake (Mossop et al. 2004). Despite the focus on Northern Pikeminnow, Ricker (1941) noted that trout and char species were more voracious predators, responsible for more juvenile Cultus Lake Sockeye Salmon taken per piscivore. However, the abundance of trout and char in Cultus Lake is unknown, and reports of recent increases in their populations are limited to anecdotal accounts from local fishermen. Out-migrating smolts are also susceptible to Minks, Mergansers, Raccoons, and River Otters; all of which have been observed predating on smolts migrating down Sweltzer Creek (Dennis. Klassen, DFO, Kamloops, British Columbia, pers. comm.). The impact of predators on juvenile Cultus Lake Sockeye Salmon was identified as a threat to recovery, though the impact was unknown given the depressed status of the Cultus population (CSRT 2009). Freshwater predation from native aquatic and terrestrial predators is considered a medium population level risk with medium causal certainty (Table 3).

Returning adults may also face predation threats from marine mammals (e.g. seals and sea lions) in coastal marine and estuarine environments, and the lower Fraser River (Christensen and Trites 2011; Walters et al. 2020). Marine predators in the Salish Sea include marine birds, Coho Salmon, Chinook Salmon, Spiny Dogfish (*Squalus acanthias*) and River Lamprey (*Lampetra ayresi*) (Beamish and Neville 2001). Other marine predators include Harbor Seals (*Phoca vitulina*) and Killer Whales (*Orcinus orca*). The impacts of marine predators on Fraser Sockeye Salmon is limited due to a paucity of data and logistic challenges of assessing predation at sea, and thus presents a low population-level risk with low causal certainty in occurrence.

Table 3. Limiting factors to the survival and recovery of Cultus Lake Sockeye Salmon. Threats are ranked based upon their current biological risk score.

Limiting Factor	Life History Stage	Likelihood of Occurrence	Level of Impact	Causal Certainty	Population Level Threat Risk	Threat Occurrence	Threat Frequency	Threat Extent
Pathogens, Parasites and Diseases: e.g. *Salmonicola*, *Parvicapsula*, BKD, IHN	**ADULTS, FRY, PARR, SMOLTS, IMMATURES**	Known	Medium	Low (4)	Low (4)	Historical, Current, Anticipatory	Recurrent	Broad
Change in Adult Migration Timing: Increased diseases and pathogens, pre-spawning mortality	**ADULTS**	Known	High	Medium (3)	High (3)	Historical, Current, Anticipatory	Recurrent	Extensive
Freshwater Predation: Native predators	**EGGS, FRY, PARR SMOLTS**	Known	Medium	Medium (3)	Medium (3)	Historical, Current, Anticipatory	Continuous	Extensive
Marine Predation: Native marine mammals, piscivores, birds	**SMOLTS, IMMATURES, ADULTS**	Known	Low	Low (4)	Low (4)	Historical, Current, Anticipatory	Continuous	Extensive
Increased Variability in Freshwater Conditions	**ADULTS, EGGS, ALEVIN, FRY, PARR, SMOLTS**	Known	High	Very High (1)	High (1)	Historical, Current, Anticipatory (assuming no lake management)	Recurrent	Extensive
Increased Variability in Marine Conditions	**ADULTS, IMMATURES**	Known	Medium	Medium (3)	Medium (3)	Historical, Current, Anticipatory	Recurrent	Extensive
Limited Freshwater Distribution Susceptibility to catastrophic events; habitat degradation	**ADULTS, EGGS, ALEVIN, FRY, PARR, SMOLTS**	Known	Medium	Low (4)	Medium (4)	Historical, Current, Anticipatory	Recurrent	Extensive

4.4. ELEMENT 11: DISCUSSION OF THE POTENTIAL ECOLOGICAL IMPACTS OF THE THREATS IDENTIFIED IN ELEMENT 8 TO THE TARGET SPECIES AND OTHER CO-OCCURRING SPECIES. EXISTING MONITORING EFFORTS AND ANY KNOWLEDGE GAPS

The ecological impacts of the threats identified in Element 8 are covered therein. For most threats, it is presumed that Cultus Lake Sockeye Salmon would benefit from higher population productivity, if the identified threat is abated. One exception is the threat of potentially reduced genetic fitness as a result of the supplementary hatchery production of Cultus Lake Sockeye Salmon. Given the limited extent of natural spawning, removal of hatchery supplementation would be expected to have a negative impact on productivity of this population.

Co-occurring species including competitors and predators will have varying responses to the identified threats in Element 8. For many, impacts on the lake habitat such as pollution and eutrophication will have negative impacts, but the extent to which these threats impact other species is largely dependent upon their specific biology. Additional negative impacts include habitat degradation that facilitates the proliferation of invasive species, such as Eurasian Watermilfoil and Smallmouth Bass (i.e. increased nutrient status and water temperatures).

One particular co-occurring species of concern is the endemic Coastrange Sculpin, Cultus Population (*Cottus aleuticus*; syn. Cultus Pygmy Sculpin), which is listed as *threatened* under Schedule 1 of SARA, and currently under consideration for up-listing to endangered status, based upon degradation of its critical habitat, Cultus Lake (Minister of Environment and Climate Change 2020). Cultus Pygmy Sculpin share trophic and profundal habitat residence overlaps with juvenile Cultus Lake Sockeye Salmon, and it is anticipated that all proposed mitigation measures will have a positive effect on this species, which has evolved a unique life history within Cultus Lake since the Pleistocene deglaciation.

4.5. MONITORING

The following threats are identified as having received some level of monitoring:

1. Pollution in the form of nutrient inputs to the lake are monitored through monthly limnological surveys of Cultus Lake by DFO's Lakes Research Program. The surveys however, do not cover other pollutants such as heavy metals, contaminants, and the potential seasonal evolution of hydrogen sulfide (H_2S) in the deep waters.
2. The nutrient status of Cultus Lake, as a function of lake eutrophication, has been monitored as part of the regular monthly limnological surveys by DFO's Lakes Research Program since 2009.
3. Eurasian Watermilfoil has been assessed on a relatively infrequent basis in the past, with the last two surveys in 2004 and 2014 using hydroacoustic methods to quantify the extent of milfoil coverage around the perimeter of the lake.
4. Genetic diversity impacts of hatchery production are carefully considered as a core tenet of the conservation enhancement program.
5. Though a recently identified threat, the presence of invasive Smallmouth Bass, has been identified and opportunistically monitored through reported angler catch. The extent of spawning and population demographics are being monitored *ad hoc* by the BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development with support from academia and DFO.

4.6. KNOWLEDGE GAPS

Several key knowledge gaps exist regarding the ecological impacts of the identified threats to Cultus Lake Sockeye Salmon. Uncertainties exist in the estimation of both domestic and international marine fisheries exploitation rates, the resolution of which would improve certainty and action on fisheries management mitigation measures. The role of internal loading of toxicants (i.e. *in situ* metals in lake sediments; evolution of H_2S) in regulating the survival of juvenile Sockeye Salmon rearing in Cultus Lake should be assessed, given the oxygen-mediated mechanisms identified herein. The extent of predation on juvenile Cultus Lake Sockeye Salmon by invasive species (i.e. Smallmouth Bass) is not fully known. Moreover, the extent to which bass population expansion, as a consequence of apparent failures to stem the ongoing invasion, will impact Cultus Lake Sockeye Salmon is unknown. Marine predation is largely unquantified, and thus changing rates (i.e. marine mammal expansion, novel southern predator range expansion under climate change), and their influence on stock productivity remain knowledge gaps. Further uncertainties exist around the ecological influences of Eurasian watermilfoil on spawning habitat and predator recruitment. Additionally, comprehensive updates are required on spawning locations, depths, and behaviours within Cultus Lake, as visual ROV surveys have not been completed in over a decade and a half.

5. RECOVERY TARGETS

5.1. ELEMENT 12: PROPOSED CANDIDATE ABUNDANCE AND DISTRIBUTION TARGETS FOR RECOVERY

Recovery is defined as “a return to a state in which the population and distribution characteristics, and the risk of extinction are all within the normal range of variability for the wildlife species”;

Survival is “the achievement of a stable or increasing state where a wildlife species exists in the wild in Canada and is not facing imminent extirpation or extinction as a result of human activity”, (DFO 2014).

We propose a candidate abundance target of 7,000 spawners (four-year average) returning to Cultus Lake, at the counting fence for **recovery**. This abundance target reflects an interim goal predicated upon current population status, threats, and limiting factors, as guided by the Cultus Lake Sockeye Recovery Team (CSRT 2009). The Wild Salmon Policy benchmark for Cultus Lake Sockeye Salmon at the 50% probability level (p50) ranges from approx. 15,000 spawners (S-gen) to approx. 31,000 spawners (S-msy), and as such, the interim goal, while within the ‘red zone’ of the WSP is considered progressive toward that endpoint. The 7,000 spawner target will necessarily be a mixture of hatchery and natural-origin fish and includes fish passed to the lake and those used for hatchery broodstock, though it is recognized that the WSP does not include hatchery-origin fish (DFO 2005). Ultimately a key goal is to reduce hatchery influences on the genetic diversity and fitness of Cultus Lake Sockeye Salmon. The Proportionate Natural Influence (PNI) is a measure of genetic risk useful in guiding conservation hatchery supplementation (Withler et al. 2018; described in section 5.1.3). Ongoing PNI values should be >0.72, although they may necessarily be below this reference point at the onset of the recovery program. No specific distribution target is provided but we note that this level of abundance should lead to multiple spawning areas being used in the lake, a desirable property.

To evaluate the effects of potential mitigation and recovery measures on near-term trajectories we also propose a **survival** target of a generational average of 2,500 spawners returning to the lake (as counted at the enumeration fence) with no single year less that 500, as a short-term objective, as it provides a benchmark for some level of recovery from the current state (<1,000).

The recovery targets are based upon counts of adults returning to the fence, and acknowledge that the number of fish that actually spawn will be lower, due to known mortality before and during spawning.

To be consistent with COSEWIC (2017) assessment of the population against the abundance target should be based upon the most recent 4-year arithmetic mean abundance.

Although climate change may be an influence on recovery of Cultus Lake Sockeye Salmon in the near-term (3 generations), large uncertainties exist in the ability to model survival outcomes for the species, given it's complex life history, and thus were not explicitly considered in recovery modeling.

The rationale for the above targets is provided in the following sections.

5.1.1. Abundance

A recovery goal and various targets for the Cultus Lake Sockeye Salmon DU have been set forth in the Cultus Conservation Plan (CSRT 2009); additional targets are described under Wild Salmon Policy (WSP) assessments (Grant and Pestal 2013). Here we briefly review the history of those.

CSRT (2009) states *"Our goal is to halt the decline of the Cultus sockeye population and to return it to the status of a viable, self-sustaining and genetically robust wild population that will contribute to its ecosystems and have the potential to support sustainable use."*

CSRT provide a series of hierarchical objectives that demark stages in the recovery process towards the goal.

Objective 1 is a 4-year average of 1,000 successful spawners in the lake, with no year less than 500; this objective is to protect the genetic integrity of the population. The proportion of spawners that are successful can be indexed by effective female spawner (EFS) estimates. However, for Cultus Lake, EFS estimates are challenging to obtain because they are based upon the examination of spawned-out fish collected from the lake. Due to the wide range of depths spawning takes place, and the time of year when spawning occurs (December) spawned-out carcasses are difficult to collect, and estimates of EFS are likely biased low. Hence, Objective 1 has been assessed using counts of spawners at the fence, acknowledging that the true number of successful spawners may be lower, and in some cases much lower. In these cases, genetic risks to the population may be higher than those envisioned by CSRT.

Objective 2 is based upon the presence of generational growth, for 3 of 4 successive years, to ensure a growing population. Generational growth is the ratio of 4-year average abundance to the previous 4 years, and compares parents to offspring. This objective is designed to ensure factors that affect population productivity can be managed, or mitigated, such that the population will increase over time, towards the longer-term objectives.

Objective 3 is an objective that could support a do-not-list decision. This objective is considered met, if Objectives 1 and 2 are satisfied, the causes of decline have been addressed, and emergency mitigation measures are no longer needed. No specific abundance values were provided by CSRT (2009), but a spawner abundance of approx. 7,000 fish was proposed, as there was evidence at the time that depensatory mortality ("predator pit") may limit freshwater production at lower spawner abundances. An abundance of this magnitude was also considered sufficient as a buffer against years of high pre-spawning mortality that would cause the number of effective spawners to be much lower than the fence count.

Objective 4 was associated with levels of abundance that would support sustainable use by both the ecosystem, and human harvest. No specific values were provided under the expectation that the Wild Salmon Policy ultimately provides such advice.

Two other benchmarks are provided in the 2011 WSP assessment (Grant et al. 2011). The lower benchmark is 12,000 spawners, based upon the analysis of S_{gen} (i.e. the spawner abundance that would result in recovery to maximum sustained yield (S_{msy}) in one generation), and the upper benchmark is 32,000, based upon 80% of S_{msy} (i.e. maximum sustainable yield). These are abundance levels that could be used to delineate the red/amber and amber/green WSP status boundaries of the population. In particular, the WSP lower benchmark is defined as "high enough to ensure there is a *substantial* buffer between it and any level of abundance that could lead to a CU being considered at risk of extinction by COSEWIC" (DFO 2005).

Of the proposed abundance-based targets we believe CSRT Objective 1 of 1,000 adults is too low as it would possibly expose the population to potential listing under COSEWIC criteria C (<2,500 adults), the basis for the current listing. Further, at this level of abundance, there is little buffer for events, such as pre-spawning mortality or fishery-induced mortality, that could place the population in jeopardy. We note that CSRT Objective 1 was originally devised as an interim rebuilding target rather than a recovery objective.

We propose that the SARA recovery target for Cultus Lake Sockeye Salmon should likely be in the range of CSRT Objective 3 (7,000 spawners). CSRT Objective 3 is lower than the WSP lower benchmark, which is appropriate given the definition of the WSP benchmark. This target of a generational average of 7,000 spawners is also similar to those observed between the 1970s and 1990s (Figure 1), and is therefore consistent with the definition of recovery, as abundance would be within an ecologically-relevant, recently-observed range of variability.

We propose a second, lower target that is more consistent with a survival objective, but is similar in intent to CSRT Objective 1. This target is a generational average of 2,500 spawners to the lake (as estimated at the enumeration fence), with no year less than 500 fish. This target recognizes the COSEWIC criterion C2 of 2,500 mature individuals, that was partly the basis for the status assessment (COSEWIC 2017). Moreover, achievement of this target implies significant population growth from the current population size. Thus this lower target is consistent with the definition of survival that includes an increasing trend, and small risk of imminent extinction.

5.1.2. Distribution

No specific distributional targets have been developed for Cultus Lake Sockeye Salmon. The only change in distribution likely to occur with population recovery is altered distribution of spawning along beaches of the lake itself. COSEWIC (2017) notes one known spawning area on the east side of the lake, consistent with the most recent ROV surveys (Figure 2), but the true extent of spawning is not fully known, due to lack of assessment and the depths of spawning. From the perspective of spreading risk, it is sensible to have a number of spawning areas available for use. Unfortunately monitoring spawning distribution is difficult, has not been consistent, and thus it is unclear whether multiple spawning areas are routinely used. It is likely that the distribution of spawning will expand to other spawning areas within the lake, if population abundance increases and lake habitat conditions improve.

5.1.3. Supportive breeding

Since the 2000 brood year, hatchery releases have occurred to increase the abundance of Cultus Lake Sockeye Salmon. The program consisted of a traditional hatchery program augmented by a captive breeding program that ran from 2002-2013.

There is currently no consensus on how the contributions of supplemented individuals should be factored into status assessments conducted by COSEWIC. Under the "Guidelines for Manipulated Populations", supplemented individuals can be included in the assessment if "these individuals are predicted to have a net positive effect on the wildlife species being assessed", and should be excluded if "there is evidence of reduced fitness or genetic characteristics that may corrupt local adaptations" [1].

We considered two approaches for the way in which hatchery-produced fish contribute to the recovery objectives:

Method 1: Under the assumption that genetic and other risks can be successfully managed, we include all fish (hatchery and natural origin, and broodstock) to be part of the wild population to be assessed.

This approach relies upon establishing that risks to wild populations are minimized when supplementation occurs. DFO (2018) has recently established guidelines for hatchery supplementation in the context of the Wild Salmon Policy that have the goals of ensuring that the effects of natural selection in the hatchery versus natural environment are such that the wild nature of the population is maintained. An index, known as the Proportionate Natural Influence (PNI), has been developed in the United States to monitor relative contributions of natural and artificial (hatchery) selective environments. PNI is calculated as:

PNI = pNOB/(pHOS+pNOB)

Where *pNOB* is the proportion of natural-origin fish in hatchery broodstock, and *pHOS* is the proportion of hatchery-origin fish spawning in the natural environment.

Withler et al. (2018) suggest that ongoing hatchery programs should maintain PNI values in excess of 0.72, in order to maintain "wild" status under the WSP. While ongoing hatchery supplementation has the potential to adversely affect the wild population, this value ensures that selection in the natural environment will dominate the adaptive process, minimizing genetic risks to the wild population. We propose that this genetic target be used to evaluate the recovery of wild Cultus Lake Sockeye Salmon. Under the assumption that broodstock for the hatchery program is taken at random from returning fish, the PNI standard (0.72) means that hatchery fish will comprise no more than 28% of the total population. To maintain this PNI level while recovering the wild population, the natural component of the population must have sufficient productivity to maintain its abundance. This condition implies the threats to the natural population will largely have been mitigated.

It could be argued that an ongoing supplementation program that meets this PNI target should satisfy COSEWIC's requirement that supplemented individuals should not "corrupt local adaptations". If this is the case, then both hatchery and wild fish can be included in a COSEWIC assessment as outlined in their guidelines. Further, those fish used for hatchery broodstock can be considered part of the population.

It is anticipated that the population will not meet the PNI standard during the recovery process, as hatchery interventions may be needed to increase abundance, and offset the effect of threats prior to their mitigation. Threat mitigation should result in increases in the productivity of the natural-origin component of the stock, and will cause PNI to increase, as the supplemented component of the population decreases over time. Progress towards recovery goals can be assessed in terms of both increasing abundance, and increasing PNI.

[1] COSEWIC guidelines on manipulated populations, April 2010.

Method 2: Assuming that hatchery fish present a risk, as per the COSEWIC guidelines, only natural-origin fish returning to the lake to spawn in the wild are included in the assessment. A more restrictive version of this approach would include only those fish that meet the WSP definition of "wild" (a natural origin fish with both parents being of natural origin).

This is the approach used in the most recent COSEWIC assessment, under the assumption that "hatchery fish can adversely affect the local population" (COSEWIC 2017, p. 33). While simple, this method does not account for the potentially negative effects of genetic interactions with hatchery fish. For example, greatly increasing the size of the hatchery program will result in more natural-origin spawners, however, the domestication risks may increase. Such risks can be dealt with in COSEWIC's threats assessment protocol.

5.2. ELEMENT 13: PROJECTED POPULATION TRAJECTORIES GIVEN CURRENT CULTUS LAKE SOCKEYE SALMON POPULATION DYNAMICS PARAMETERS

The Cultus Lake Sockeye Salmon simulation model (Appendix 1) was used to model population trajectories for three generations (12 years, beginning in 2019). Some simulations were run though six generations, to evaluate longer-term outcomes. The model projects the population forward in time using spawner and smolt abundances for 2015-2019 as a starting point, as well as existing hatchery releases. The probability that survival and recovery objectives will be met by the last generation is calculated, based upon 10000 Monte Carlo Trials. Extinction events (defined as four consecutive years of <50 spawners at any time during each simulation) are tallied, as is the average PNI value in the last generation. The median size (across simulations) of the number of adults returning to the lake in the last generation (arithmetic average of the last 4 years) is computed for comparison with the 2015-2018 average of 1,167 spawners (wild + hatchery). As outlined above, the population statistics depend upon which method is used to deal with hatchery fish; results from both are presented.

For the baseline simulation, the hatchery program was assumed to have been terminated in 2019 to evaluate population trends without supplementation. However, fry and smolts that have already been released from earlier brood years are included in the simulations. Status quo scenarios of natural productivity and ongoing fishing mortality are assumed. In the second simulation we simulate hatchery production similar to the present "mixed" strategy (see section 3.3.2 for a description of hatchery strategies). Effects of future hatchery supplementation on population fitness are not simulated in the model, however, any impact that the existing program has had will be effectively included, if those effects have contributed to a reduction in survival.

Results show that without hatchery supplementation the population is unable to sustain itself and is predicted to decline over the simulation (Table 4, Figure 11). None of the recovery objectives are likely to be met, and extinction is a possible outcome. Median population size in the final 4 years is very small, and is approximately 10% of the current population. Extending the projections to six generations increases the probability of extinction to 0.76, as the population continues to decline.

Table 4. Simulation model predictions for stock performance measures under the baseline parameter set. For the population targets, the proportion of simulations that meet the objective by the last generation are shown. For extinction, the proportion of simulations during which the population goes extinct is indicated. For final two performance measures, the median (95% interval) in the last generation is shown. Simulations assume status quo exploitation rates and the "mixed" hatchery strategy (See section 3.3.2).

Performance measure	No Hatchery	Method 1	Method 2
1.Survival target (2.5K)	*0*	*0.11*	*0*
2. Recovery target (7K)	*0*	*0*	*0*
3.Extinction probability (<50 spawners)	*0.1*	*0*	*0*
4.PNI	*1.0*	*0.23 (0.10, 0.39)*	*0.23 (0.10, 0.39)*
5.Last generation abundance (fish)	*147 (24, 693)*	*1,469 (864, 2,919)*	*404(87,1,424)*

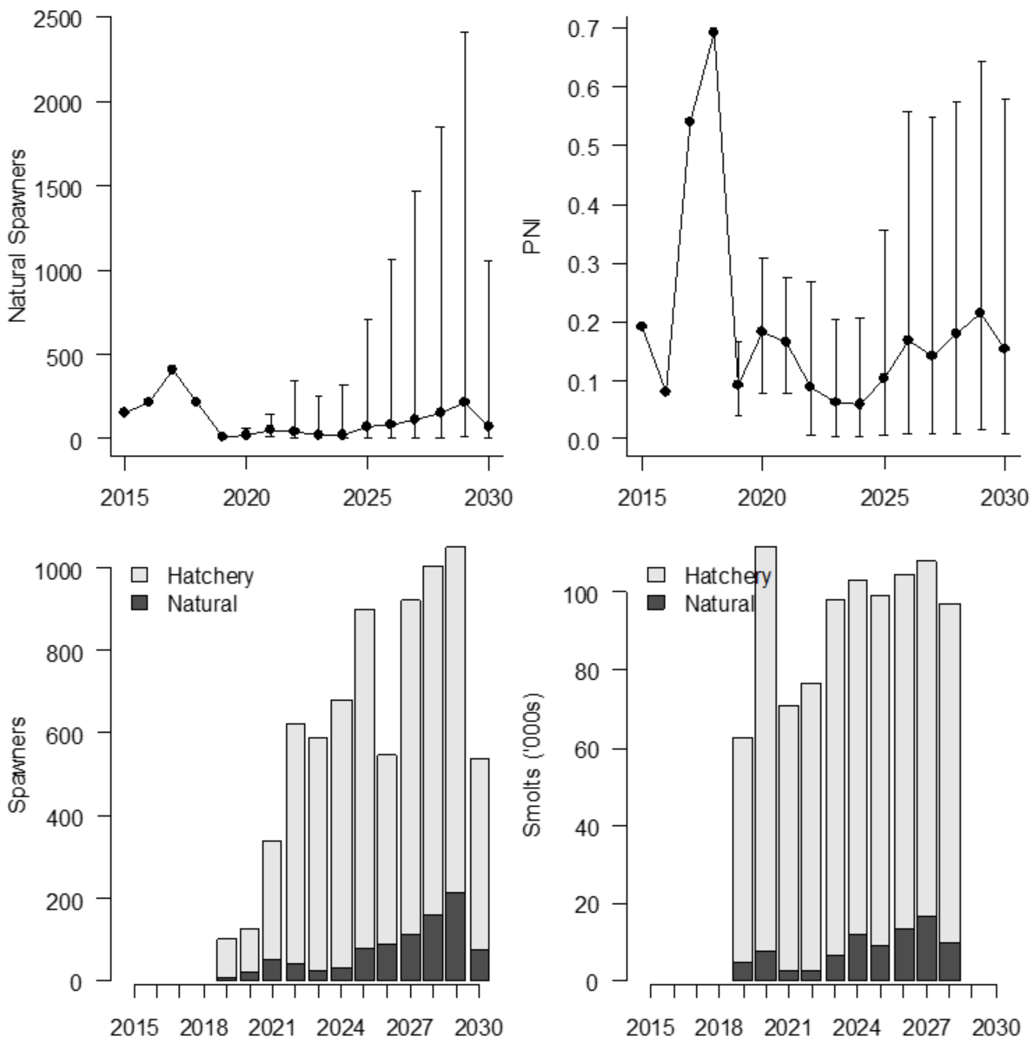


Figure 11. Results of baseline model simulations, with the mixed hatchery strategy, and status quo fishing mortality rates. Error bars are 80% intervals around medians for individual years from 10,000 Monte Carlo simulations. Stacked bars are median abundances.

With supplementation, extinction is averted, but the population is unlikely to reach survival or recovery targets within three generations. The population is also unlikely to reach either targets after six generations, as the mean population size after 24 years is only 1,680 spawners. PNI values remain far below the threshold of 0.72.

Recovery within the short timeline of three generations is hindered by the sequence of very small smolt migrations of 2017 to 2019 (see Figure 2) that are predicted to result in adult returns of only a few hundred fish in 2019-2021. This means that generational mean abundance of the first generation of the projection is smaller than the 2015-2018 base period, which restricts the potential for recovery in the next two generations.

In summary, these simulations show the population is unlikely to increase to the survival or recovery goal in 12 or 24 years under the current levels of supplementation and fishing mortality if recently-observed, anthropogenically-influenced environmental conditions continue unmitigated into the future. High levels of supplementation under this scenario may compromise the fitness of the population in the wild; changes in fitness have not been factored into these simulations. If environmental conditions deteriorate in the future, as a result of climate change, increased human impacts and/or their interactions, the probability of survival or recovery will be accordingly lower than predicted by the model.

5.3. ELEMENT 14: ADVICE ON THE DEGREE TO WHICH SUPPLY OF SUITABLE HABITAT MEETS THE DEMANDS OF THE SPECIES BOTH AT PRESENT AND WHEN THE SPECIES REACHES THE POTENTIAL RECOVERY TARGET(S)

Owing to variations in inter-annual brood strength and wide range of spawning depths used within Cultus Lake, it is difficult to assess the adequacy of freshwater habitat supply for spawning and incubation. Contraction of known spawning to deep benches on the eastern margin of Cultus Lake, from a much more broadly-distributed spawning arrangement (Figure 2), implies similar contraction in the quality of those habitats to support critical life functions of spawning and incubation. However, it is unclear at what population abundance(s) these habitats will become limiting, as little information exists on their current quality and extent. Theoretically, should the mitigatable drivers of lake habitat degradation be addressed (i.e. eutrophication), spawning and incubation habitats may be more suitable for completion of these critical life functions. Cultus Lake has historically had the productive capacity to support Sockeye Salmon escapements well in excess of 10,000 adult spawners (i.e. above the recovery target) in the period prior to the emergence of more recent drivers of freshwater habitat degradation.

The rearing volume of Cultus Lake is sizeable and productive, and likely could reasonably support much higher densities of juvenile Sockeye Salmon. Currently, habitat quality over the large volumes of the rearing area and the food web meet survival and growth requirements, however, the deep daytime residence behaviour of juvenile Cultus Lake Sockeye Salmon during their diurnal vertical migrations, in close association with the sediments, appears to be a significant constraint on freshwater survival (see Element 8). As population recovery is directly predicated upon the improvement of lake rearing habitat (i.e. profundal dissolved oxygen, oxygen-mediated habitat degradation mechanisms), management of nutrient loads are likely to simultaneously improve habitat extent and population numbers. As Cultus Lake has supported much higher densities of rearing fry, prior to lake eutrophication, it is likely that, should nutrient management be effected, and seasonal deep water oxygen restored, the habitat supply will be sufficient for the future recovery target abundances and beyond. At present, there is no known viable limitation on marine or migration habitats. However, future environmental changes associated with climate change, and their interactions with other population forcings cannot be ruled out as potential future constraints on habitat availability across the life history of Cultus Lake Sockeye Salmon.

5.4. ELEMENT 15: THE PROBABILITY THAT THE POTENTIAL RECOVERY TARGET CAN BE ACHIEVED UNDER CURRENT RATES OF POPULATION DYNAMICS, AND HOW THAT PROBABILITY WOULD VARY WITH DIFFERENT MORTALITY AND PRODUCTIVITY PARAMETERS

In this section we consider alternative fishing mortality scenarios. In the baseline runs, the exploitation rate (the proportion of recruitment removed by fishing) was set at 0.20, but was increased to 0.50 for years corresponding to the dominant cycle of the Shuswap Late Run Sockeye Salmon (every 4 years beginning in 2022). These exploitation rates are based upon recent averages from DFO (2018). In two alternative scenarios, exploitation was set to 0 and 50% of the baseline, as suggested in the RPA guidelines.

The model results indicate that fishing mortality rates affect the rates of recovery, however, recovery to the proposed targets are unlikely to be reached in the 3-generation simulations under any scenario of fishing mortality or hatchery supplementation (Table 5).

Table 5. Simulation model comparison of three fishing mortality scenarios with two levels of hatchery supplementation on the performance indicators described in Element 12. Yellow shading (#2) highlights the performance measure proposed to serve as the recovery goal. Method 1 was used to calculate performance.

Exploitation	No hatchery			Hatchery		
	0/0	***0.1/0.25***	***0.2/0.5***	***0/0***	***0.1/0.25***	***0.2/0.5***
1.Survival target	*0.0*	*0.0*	*0.0*	*0.44*	*0.27*	*0.11*
2.Recovery target	*0.0*	*0.0*	*0.0*	*0.04*	*0.01*	*0*
3.Extinction probability	*0.03*	*0.06*	*0.1*	*0*	*0*	*0*
4.Last generation PNI	*1*	*1*	*1*	*0.30*	*0.27*	*0.23*
5.Last generation abundance	*425*	*278*	*147*	*2,423*	*1,922*	*1,468*

6. SCENARIOS FOR MITIGATION OF THREATS AND ALTERNATIVES TO ACTIVITIES

6.1. ELEMENT 16: INVENTORY OF FEASIBLE MITIGATION MEASURES AND REASONABLE ALTERNATIVES TO THE ACTIVITIES THAT ARE THREATS TO THE SPECIES AND ITS HABITAT

The primary, manageable threats identified in Element 8 are addressed below. The mitigation measures highlighted, target interruption of the effects of specific, known threats, although it is acknowledged that there may be additional mitigation measures that could be implemented to improve stock recovery. Unfortunately, due to an inability to mitigate some potential threats (e.g. Eurasian Watermilfoil; Fraser Basin Council 2013) a paucity of knowledge on the effects and manageability of some emerging potential threats (e.g. invasive Smallmouth Bass), further research is required to determine the nature and magnitude of these threats, and whether mitigation is feasible.

6.1.1. Addressing Fisheries Harvests

Harvest of Cultus Lake Sockeye Salmon adults in the Fraser mixed-stock fishery, and elsewhere during their marine migration, is considered a primary threat to persistence, estimated to account for brood line losses of 22-71% in any given year. Sustained reductions in harvest rates of co-occurring fisheries will yield increased abundances of returning spawners, thereby increasing reproductive potential of the population, and likely a reduced reliance upon hatchery propagation. In conjunction with nutrient management to improve incubation and rearing conditions for juveniles, fisheries management adhering to the *precautionary approach*, such as outlined in DFO (2006), is likely a key strategy to improving adult abundances, while other mitigation measures are enacted to improve freshwater survival.

6.1.2. Lake Predator Control

As a means of mitigating in-lake mortality of juvenile Cultus Lake Sockeye Salmon, a predator control program was implemented in 2004, with the goal of reducing the existing Northern Pikeminnow population. In the early years of the program, significant numbers of Northern Pikeminnow were removed using a commercial seine vessel, and as CPUE decreased over time, capture methods were shifted to baited long lines, and eventually to a limited program of angling by local recreational fishermen. While there appeared to be a positive response of hatchery-released fry to smolt survival, following early predator removal efforts, this was short-lived, and the link between the two is uncertain as other variables factor into hatchery-origin fry in-lake survival.

While Northern Pikeminnow have long been identified as a predator of juvenile salmon (e.g. Brown and Moyle 1981), it was noted that in comparison, species of char and trout were more voracious in terms of the number of juvenile fry taken per fish in Cultus Lake (Ricker 1941). Anecdotally, recreational fishers have reported an increase in the catch of trout and char in Cultus Lake, and the potential exists for these fish to have expanded into the niche that the once numerically abundant Northern Pikeminnow held. Additional predation pressures from invasive Smallmouth Bass may be another consideration for predation control in this system, and efforts to stem the invasion should be a key strategy in reducing novel predation. Notably, many efforts to control Smallmouth Bass invasions have not met with success (Loppnow et al. 2013). In some cases, control efforts have led to overcompensation by targeting mature adults; reinforcing the invasive population (Loppnow and Venturelli 2014). Targeting young of the year may be one effective means of limiting the spread and influences of Smallmouth Bass (Loppnow and Venturelli 2014).

Mitigation of juvenile mortality may benefit from a contemporary predator control program, but considerations of past control efforts (e.g. sustained effort) and the context of other freshwater limiting factors (e.g. multi-species predation, habitat degradation) must be taken into account.

6.1.3. Addressing Lake Eutrophication

Lake eutrophication is a reversible phenomenon (Schindler 1974, 2012), with abatement of nutrient loadings to lakes eliciting water quality recovery across a broad gamut of contexts, from regional systems where local sources comprise the bulk of loadings (e.g. Lake Washington; Edmondson and Lehman 1981), to much more complex situations involving diverse landscape-atmosphere-water interactions and cross-jurisdictional authorities, such as the recovery of the Laurentian Great Lakes open waters from eutrophication in the 1970's-1990's (Smol 2006).

Eutrophication resulting from known anthropogenic nutrient sources (N and P) is directly impacting Cultus Lake (Putt et al. 2019; Gauthier et al. 2020), critical habitat for Cultus Lake Sockeye Salmon, and is a primary forcing on their persistence in the wild. Freshwater survival is now the dominant mediator of overall population abundance. Ultimately, lake recovery from eutrophication can only occur via reductions in external nutrient loadings (McCrackin et al.

2017), and in particular phosphorus (Schindler 2012), the primary limiting nutrient in Cultus Lake (Shortreed 2007; Gauthier et al. 2020).

Putt et al. (2019) constructed hydrological and nutrient mass balance models for the Cultus Lake watershed, to identify the sources and loadings responsible for lake eutrophication imperilling species at risk. Primary local (i.e. within watershed) nitrogen loadings arise from surface and groundwater contributions from the agricultural Columbia Valley in the southern extent of the watershed (40.7% total N), the other tributary sub-watersheds (32% total N), and sub-surface loadings from septic leachate (9% total N). Primary local phosphorus loadings arise from the surface and groundwater contributions from the Columbia Valley (26.4% total P), the other tributary sub-watersheds (26.8% total P), guano loading from a seasonally-resident migratory gull population (22.4% total P), and septic leachate (19.1% total P).

Putt et al. (2019) employed the BATHTUB water quality model (Walker 1985, 1996), calibrated and validated to contemporary conditions, to hind-cast the trophic status of Cultus Lake prior to eutrophication (confirmed oligotrophic; Figure 12). The model was also used to produce steady state predictions of lake conditions (i.e. epilimnetic total phosphorus, total nitrogen, chlorophyll *a* (surrogate for algal biomass)), under a variety of development and nutrient mitigation scenarios, guided by multi-sectoral, expert-informed predictions of changes in the dominant sources of nutrients to the lake (i.e. future development scenarios; 25 year time horizon). Moreover, current and future lake states were modeled with implementation of realistic within-watershed mitigation measures (i.e. mitigation scenarios; current and over a 25 year time horizon), such as achievable reductions in watershed septic leachate loadings, agricultural inputs, and avian population controls (Putt et al. 2019).

6.1.3.1. The value of local-source nutrient mitigation

Application of the local (i.e. within-watershed) mitigation options under current conditions, and over a 25-year development horizon, significantly reduced nutrient levels and algal biomass within Cultus Lake in both scenarios, maintaining the current oligo-mesotrophic lake trophic status (Figure 12), and highlighting that targeted within-watershed nutrient abatement is effective. Without mitigation, however, Cultus Lake is projected to shift into a mesotrophic state, representing a significant increase the symptoms of lake eutrophication (i.e. oxygen depletion, internal loading) that pose primary threats to Cultus Lake Sockeye Salmon. Liquid waste management planning for the watershed has been undertaken, opting for levels of P and N removal above and beyond that of traditional municipal standards (Urban Systems 2015), which should at least reduce future nutrient loadings to Cultus Lake from many current septic sources, if adhered to.

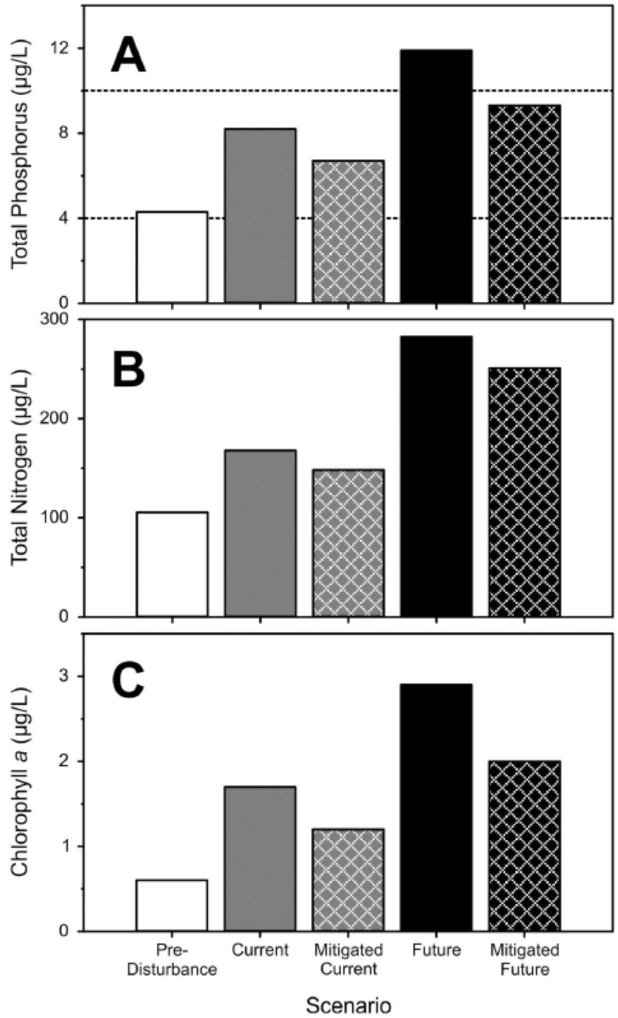


Figure 12. BATHTUB model results for current and future steady state water quality conditions in Cultus Lake with and without local (within-watershed) nutrient mitigation. Modified from Putt et al. (2019). The model was calibrated to current conditions (grey bars), hind-cast to estimate water quality conditions prior to anthropogenic disturbance of the watershed and airshed (white bars), re-run with current local nutrient sources mitigated, based upon multi-sectoral expert opinion (grey bars with hash marks), and predicted forward 25 years for two future development scenarios, without nutrient mitigation (black bars), and with the local mitigation measures in the current scenario enacted (black bars with hash marks). Total phosphorous (TP) (Panel A), total nitrogen (TN) (Panel B), and chlorophyll a (chl-a) (Panel C) are steady-state model estimates of epilimnetic growing season averages. Dotted reference lines in Panel A indicate the Canadian Council of Ministers of Environment thresholds (CCME 2004) for TP-inferred aquatic system trophic status (lower line—ultraoligotrophy-oligotrophy threshold (4 µg/L TP); upper line—oligotrophy-mesotrophy threshold (10 µg/L TP)).

6.1.3.2. The ultimate problem: A need to target atmospheric loadings from the regionally-contaminated airshed

Watershed-scale mitigation measures are essential to resolving the cumulative nutrient loadings problem in Cultus Lake, however, solely focussing on local nutrient inputs will only retard the ongoing eutrophication trajectory, owing to the dominant control of atmospheric nutrient deposition from the regional airshed on the lake and its watershed (63% total N load; 42% total P load; Putt et al. 2019). The regional airshed is contaminated from persistent agricultural sources, and to a lesser extent transportation and urban loadings (Environment Canada and US Environmental Protection Agency 2014; Metro Vancouver 2018; Putt et al. 2019). Thus, reducing land-based nutrient fluxes to the regional airshed is essential, benefitting a broad variety of ecological and social values (*see* Putt et al. 2019), and is likely attainable through targeted inter-sectoral cooperation involving local, provincial and federal governments, stakeholders and Indigenous communities (Putt et al. 2019). An incipient process to set targets for and effect reductions in these atmospheric loadings has been conceived and explored, but would undoubtedly have a greater degree of success with targeted inter-governmental recognition, support, and resourcing.

While nitrogen loads to the regional airshed must be reduced, interrupting the atmospheric delivery of phosphorus to the Cultus Lake watershed, via reductions in P emissions to the regional airshed, is the key abatement target to reduce lake eutrophication (Putt et al. 2019). Given its lack of a stable gaseous phase, atmospheric transport and deposition of P largely occurs via entrainment of aerosols (Mahowald et al. 2008), which may be a helpful constraint both in identifying and minimizing emissions, and reducing regional P deposition. 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 forcing of Fraser Valley P flows (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 (Bittman et al. 2017), coupled with targeted interruptions to seasonal aerosol entrainment (i.e. modified low- or no-tillage practices, minimization of bare soil land exposure, reductions in liquefied manure spraying, reductions in poultry barn exhaust bio-aerosols) could substantially reduce atmospheric P loading to the regional airshed and recipient 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 is likely to result in significant impacts on cultural and socioeconomic valuations, lake-derived ecosystem services, and species at risk.

6.1.3.3. Interim Measures

While large-scale nutrient abatements are being planned and implemented, other interim mitigative measures may be of value in ameliorating lake nutrient levels, hypolimnetic oxygen depletion, and internal loading, to sustain Cultus Lake Sockeye Salmon and other species at risk in the lake (i.e. Coastrange Sculpin, Cultus Population, *Threatened*, Schedule 1 SARA). Hypolimnetic oxygenation during the stratified period, achieved through aeration and/or liquid oxygen injections, are a reliable means of improving water quality in British Columbia lakes experiencing nutrient-related oxygen depletion (Nordin and McKean 1982; Ashley and Nordin 1999; Ashley 2000; Ashley 2008). The efficacy of such approaches on improving Cultus Lake hypolimnetic conditions is likely, but requires site-specific modeling, planning and implementation. A number of off-the-shelf designs exist and are fabricated locally to regionally (Ashley 2000). Other more invasive options, such as manual destratification, P inactivation through addition of chemicals, bacterial additions, algaecides, and hypolimnetic withdrawal are also possible, and certain combinations could be effective in interrupting internal loading and improving seasonal deep water oxygen conditions (Ashley 2008). However, any interventions applied to improve Cultus Lake water quality in support of species at risk come with some uncertainty and risk, and should be carefully designed, modeled, and evaluated prior to implementation.

6.2. ELEMENT 17: INVENTORY OF ACTIVITIES THAT COULD INCREASE THE PRODUCTIVITY OR SURVIVORSHIP PARAMETERS

6.2.1. Hatchery Supplementation

As an interim measure in the recovery process, hatchery releases can increase the abundance of returning adult spawners by increasing survival in the freshwater phase of the life cycle. In consultation with Salmon Enhancement Program staff, three alternative scenarios of hatchery releases were developed, based upon the capacity of existing infrastructure. The scenarios included exclusive smolt releases, exclusive parr releases, and a mixed release of the two life stages, with the latter being the typical strategy in recent years (Table 6). The proportion of life stages contributing to these releases has varied through time, based upon brood availability and the relative success of one strategy over others. Year-by-year release information is available from DFO's Salmon Enhancement Program (DFO SEP, unpublished data). Using the model, the performance of the hatchery strategies in Table 6 were compared. These scenarios were envisioned as traditional hatchery programs (i.e., not captive breeding) based in the principles of integrated hatchery production. While noting that in the recent history of enhancement of this population dating back to 2000, captive breeding was used up until 2013, it is viewed as a short-term measure to minimize extinction risk due to uncertainty associated with implications for long-term genetic fitness (Fleming 1994; Araki et al. 2007). Local trait adaptation through natural environmental exposure is ultimately necessary to enhance local adaptation and fitness permitting success in subsequent life history stages (Kline and Flagg 2014).

We assumed that hatchery broodstock would be taken non-selectively (with respect to natural or hatchery-origin spawners), and that no more than 50% of returning adults in any year would be used for broodstock up to the maximum listed in Table 6. The selection of 50% of broodstock is based both upon logistical constraints, as it is difficult to retain all fish that return to the lake, and biological considerations based upon the need to expose some fish to natural selection to minimize domestication effects. As noted earlier, the model assumes no further loss of population fitness beyond what may have already occurred as a result of ongoing hatchery supplementation.

Simulated survival of adults, eggs, and juveniles in the hatchery was based upon recent values, and recent data on the survival of parr and smolt survival was used to project the expected adult returns from these releases.

Table 6. The four hatchery release strategies evaluated in the simulation model. Target broodstock estimates are the number of adult spawners required to reach release targets. In years of lower returns, the rule to retain no more than 50% of the run is imposed, and the juvenile releases are correspondingly smaller. For the mixed strategy, the smolts releases are prioritized over parr releases, when realized broodstock is less than the target.

Strategy	Release	Target broodstock required (both sexes)
None	0	0
Smolts	87,500 yearling smolts	68
Parr	250,000 winter parr	202
Mixed	50,000 smolts + 150,000 winter parr	180

6.2.2. Exploitation rate management

Following results of Element 15, three scenarios of exploitation rate management were considered, the status quo, based upon recent averages, a 50% reduction, and a complete cessation of fishing mortality.

6.2.3. Freshwater survival mitigation

Poor smolt production from spawners in the lake is a primary factor contributing to the low probability of population recovery. In particular, frequent occurrence of smolt/spawner values <10 in recent years (Figure 4) contrasts with historical conditions, where the most extreme low value was 16 smolts/spawner. With mitigation of the factors causing low smolt production (e.g. lake eutrophication, profundal hypoxia/anoxia), it is expected that average natural production from the lake can be increased and the potential for recovery could be considerably higher.

There are many ways that the mitigation of low productivity could be modelled. We chose to implement a lower limit on the smolt/spawner ratio that linearly increased from the current value of 1, to a value of 20 (which is near the 5th percentile value of the historical data series) over a fixed time period. This is a generic approach that could represent the results of a variety of mitigation efforts.

For each year in the simulation, the random selection of the smolt/spawner value was restricted to those years in the recent 1999-2017 time series of natural production, where the observed smolt/spawner value was above the lower limit (line in Figure 13) for that year. This approach maintained natural variability in smolt production while reducing, over time, the incidence of the very low values that are limiting population recovery.

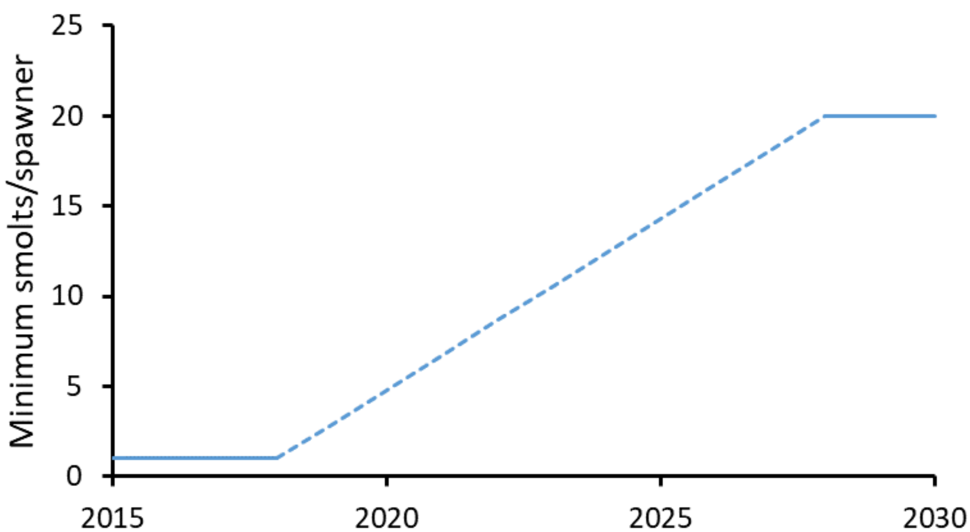


Figure 13. Minimum in-lake smolt/spawner model inputs to simulate future freshwater production mitigation. The minimum smolt/spawner was simulated to increase over 10 years from current observed minimum values to a value that was similar to that observed in the historical dataset, as indicated by the dashed line. This gradually reduced the occurrence of very low smolts/spawner values.

6.3. ELEMENT 18: IF CURRENT HABITAT SUPPLY MAY BE INSUFFICIENT TO ACHIEVE RECOVERY TARGETS (SEE ELEMENT 14), PROVIDE ADVICE ON THE FEASIBILITY OF RESTORING THE HABITAT TO HIGHER VALUES.

ADVICE MUST BE PROVIDED IN THE CONTEXT OF ALL AVAILABLE OPTIONS FOR ACHIEVING ABUNDANCE AND DISTRIBUTION TARGETS

Eutrophication, and the additive effects of climate change, are responsible for the degradation of deep water habitats in Cultus Lake, likely influencing spawning, incubation, and freshwater rearing. Hypolimnetic and severe profundal oxygen depletion, which now occurs seasonally in Cultus Lake (see Element 8), is a key threat to persistence. As noted in Elements 8 and 14, reversing lake eutrophication through nutrient abatement and other means, is likely to ameliorate rearing, incubating, and spawning habitats, and promote higher abundances of Sockeye Salmon in the population. Eutrophication is one of the most readily-solved environmental problems, which can even be achieved when loadings are complex and multi-jurisdictional (i.e. Laurentian Great Lakes). Thus the feasibility of restoring habitat quality is high, provided it is targeted, and could meet likely meet the requirements of future abundance targets.

6.4. ELEMENT 19: ESTIMATE THE REDUCTION IN MORTALITY RATE EXPECTED BY EACH OF THE MITIGATION MEASURES OR ALTERNATIVES IN ELEMENT 16 AND THE INCREASE IN PRODUCTIVITY OR SURVIVORSHIP ASSOCIATED WITH EACH MEASURE IN ELEMENT 17

The changes in mortality and consequent effects on population productivity, associated with hatchery production and fishing mortality management described in Element 18, are estimated in the simulation model and described in Element 20.

For mitigation measures designed to increase smolt production, a single generic strategy was developed (Figure 4) that is used in the simulation model (Element 20) to evaluate the potential for increases in smolt production to affect recovery. It is currently not possible to develop more explicit quantitative estimates of the effects of mitigation measures on salmon mortality or productivity.

6.5. ELEMENT 20: PROJECT EXPECTED POPULATION TRAJECTORY (AND UNCERTAINTIES) OVER A SCIENTIFICALLY REASONABLE TIME FRAME AND TO THE TIME OF REACHING RECOVERY TARGETS, GIVEN MORTALITY RATES AND PRODUCTIVITIES ASSOCIATED WITH THE SPECIFIC MEASURES IDENTIFIED FOR EXPLORATION IN ELEMENT 19

First, we compared the four hatchery supplementation strategies, and then chose one strategy and modelled the interactive effects of hatchery supplementation, habitat mitigation and exploitation rate management on the probability of achieving the recovery goals.

6.5.1. Hatchery supplementation

The relative effects of four proposed hatchery strategies were evaluated using the model with all other parameters set to the baseline conditions. Results show all hatchery strategies can significantly increase the number of spawners returning to the lake (Table 7). The smolt-only strategy performed the poorest, due to the poor survival of smolt releases. The mixed strategy and the parr-only strategy produced similar results.

While hatchery releases can increase abundance, the population will not reach any of the recovery targets under baseline conditions. The low PNI value is indicative of the population being dominated by hatchery-produced fish.

We chose the *mixed strategy* to represent the preferred hatchery supplementation scenario for subsequent simulations as it combined the benefits in increased returns, and a risk-spreading approach to the releases (resilience to catastrophic brood loss in any given early life history stanza).

Table 7. Comparison of simulation model results for implementation of the 4 hatchery scenarios as outlined in Table 6. Other parameters set to baseline values; exploitation follows the recent pattern (0.2/0.5).

	Hatchery Strategy			
Model Output	None	Parr	Smolt	Mixed
Survival Objective	0	0.11	0.01	0.11
Recovery Objective	0	0.01	0	0
P(Extinction)	0.10	0	0	0
PNI	1.0	0.20	0.33	0.23
Last generation spawners	147	1534	935	1469

In a second set of simulations we included the effects of mitigating poor freshwater production. We considered freshwater mitigation in conjunction with the mixed hatchery strategy and alternative exploitation rate scenarios and contrasted Method 1 and Method 2 for managing hatchery fish in the assessment (Tables 8 and 9).

Results showed that the probability of meeting the *recovery* goal in three generations was very small under all combinations of mitigation or management measures. However a relatively high probability of achieving the *survival* goal was possible if all mitigation and management measures were implemented successfully using Method 1 for the assessment.

Simulating for six generations shows that the mitigation and management measures can create conditions for population growth and the model predicts the recovery goal can be achieved, both in terms of abundance and PNI metrics (Figure 14). The probability of meeting the survival and recovery goals after six generations (Method 1) is 0.97 and 0.66 respectively, with a median PNI value of 0.74. These results are based upon the 0.1/0.25 exploitation rate, which represents a 50% reduction in fishing mortality over recent averages.

The model results also indicate that the current hatchery program is sized appropriately so that PNI values increase to the target range as the population increases to the recovery goal. However, if habitat mitigation can be successfully achieved it is likely that the hatchery program could be reduced or eliminated as the population increases via natural production.

Table 8. Simulation model probability outputs for achieving the survival and recovery targets in three generations, as a function of three potential mitigative measures: hatchery supplementation, habitat restoration, and exploitation rate management. Shown is the probability of reaching the target by the third generation, with corresponding PNI value. Performance measures are based on Method 1, using all fish that return to the lake.

			Performance Measure (last generation)		
Hatchery	***Habitat***	***Exploitation***	***Survival (2.5K)***	***Recovery (7K)***	***PNI***
None	*No*	0/0	0	0	1.0
		0.1/0.25	0	0	1.0
		0.2/0.5	0	0	1.0
	Yes	0/0	0.02	0.01	1.0
		0.1/0.25	0	0	1.0
		0.2/0.5	0	0	1.0
Mixed	*No*	0/0	0.44	0.04	0.30
		0.1/0.25	0.27	0.01	0.27
		0.2/0.5	0.11	0	0.23
	Yes	0/0	0.83	0.12	0.52
		0.1/0.25	0.67	0.03	0.47
		0.2/0.5	0.36	0.01	0.41

Table 9. Simulation model probability outputs for achieving the survival and recovery targets in three generations, as a function of three potential mitigative measures: hatchery supplementation, habitat restoration, and exploitation rate management. Shown is the probability of reaching the target by the third generation, with corresponding PNI value. Performance measures are based on Method 2, using only natural origin fish.

			Performance Measure (last generation)		
Hatchery	***Habitat***	***Exploitation***	***Survival (2.5K)***	***Recovery (7K)***	***PNI***
None	*No*	0/0	0	0	1.0
		0.1/0.25	0	0	1.0
		0.2/0.5	0	0	1.0
	Yes	0/0	0.02	0.01	1.0
		0.1/0.25	0	0	1.0
		0.2/0.5	0	0	1.0
Mixed	*No*	0/0	0.02	0.03	0.30
		0.1/0.25	0.01	0	0.27
		0.2/0.5	0	0	0.23
	Yes	0/0	0.18	0.03	0.52
		0.1/0.25	0.08	0.01	0.47
		0.2/0.5	0.01	0	0.41

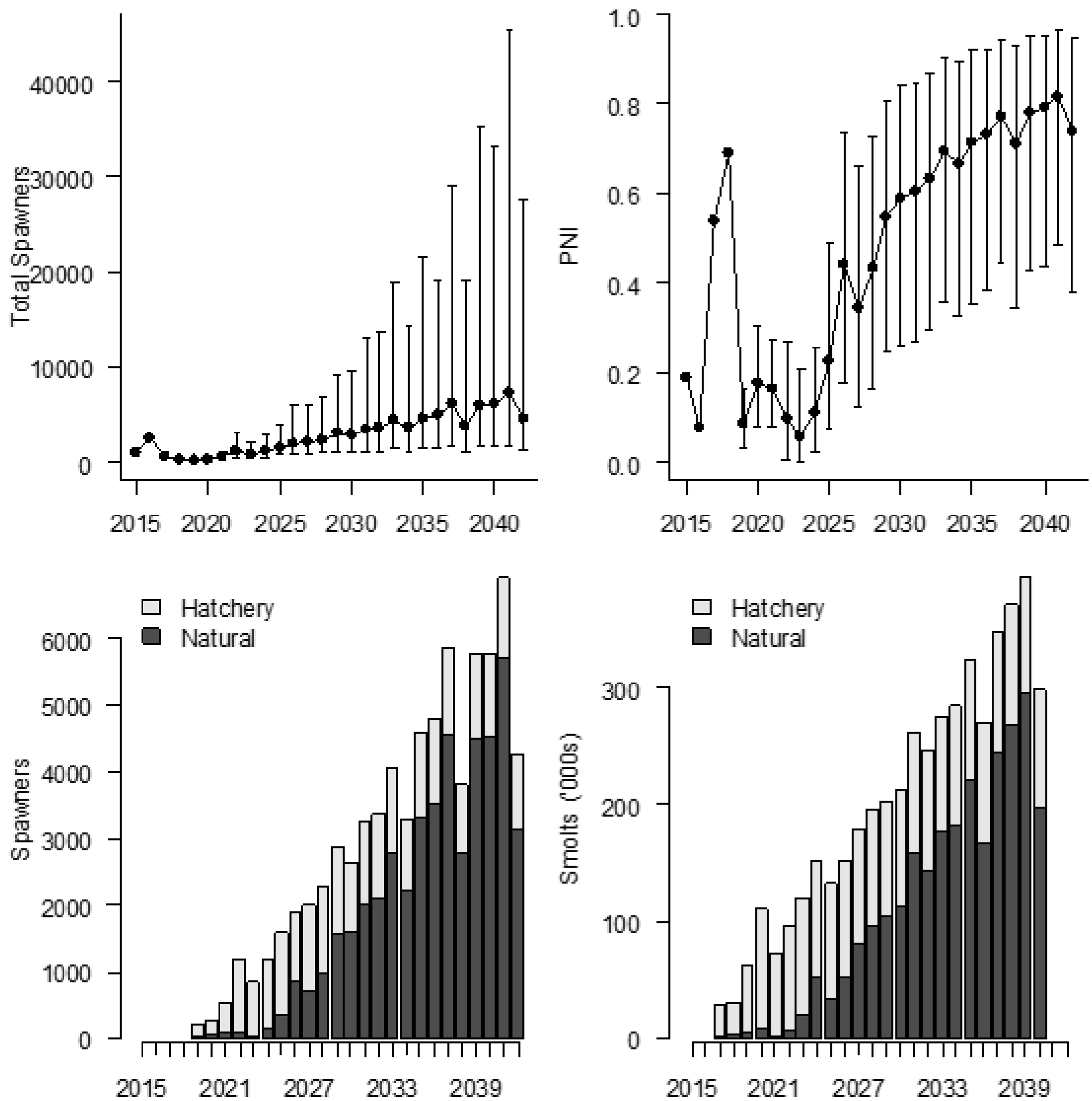


Figure 14. Simulation model projections for 6-generation simulations with hatchery supplementation, successful habitat mitigation and 0.1/0.25 harvest rate scenarios.

6.6. ELEMENT 21: RECOMMENDED PARAMETER VALUES FOR POPULATION PRODUCTIVITY AND STARTING MORTALITY RATES AND SPECIALIZED FEATURES OF THE POPULATION MODELS

No additional parameters are provided at this time. Changes in vital rates resulting from mitigation measures will be needed to explore alternative scenarios. Examples include additional data from alternative release strategies for the supplementation program, and the effects of habitat mitigations on survival rates in the lake. Additional modelling could be done if exploitation rates were estimated by more refined means, or if changes to fishing patterns or methods result in changes of fishing mortality.

7. ALLOWABLE HARM ASSESSMENT

7.1. ELEMENT 22: EVALUATION OF MAXIMUM HUMAN-INDUCED MORTALITY AND HABITAT DESTRUCTION THAT THE SPECIES CAN SUSTAIN WITHOUT JEOPARDIZING ITS SURVIVAL OR RECOVERY

All sources of harm should be reduced to the maximum extent possible. As per previous RPA assessments, there is no provision for allowable harm when the population is declining or is projected to have a negative intrinsic growth rate (e.g., Young and Koops 2011). Modelling shows the Cultus Lake Sockeye Salmon population will decline in the absence of hatchery supplementation, even when fishing mortality is eliminated, given the current survival conditions in the lake. Thus from this perspective there is no allowable harm for the wild population, and should only considered for decision in limited instances, where the intrinsic growth rate of the population is positive, and such influences can be sustained and not imperil persistence.

Hatchery supplementation can maintain a small, mostly hatchery, population of Cultus Lake Sockeye Salmon under the various scenarios of fishing mortality, but it is unlikely that survival or recovery of a wild population will occur without additional measures. The large proportion of hatchery fish (and correspondingly low PNI values) is inconsistent with COSEWIC guidelines for supplementation and may lead to the exclusion of hatchery fish from future status assessments. Under those circumstances the population will continue to be assessed as endangered, or may become extinct in the wild, having been effectively replaced with a hatchery population. Thus offsetting the effects of human-induced mortality with hatchery supplementation could be considered to be jeopardizing survival or recovery of the population in the wild.

Some level of limited human-induced mortality may be allowable if measures to increase natural-origin smolt production to levels observed historically are successful. Such mortality (either resulting from fishing or habitat impacts) would slow the rate of recovery, but it is possible that a positive population growth rate could be maintained. It is not feasible to quantify the level of mortality because the efficacy of mitigation measures is unknown.

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APPENDIX A. DESCRIPTION OF CULTUS LAKE SOCKEYE POPULATION DYNAMICS MODEL

We predict the abundance of natural- and hatchery-origin Sockeye Salmon from Cultus Lake using a simple population dynamics model (Appendix Figure 1.). The model is initialized using data from 2015-2018 and predicts the abundance of smolts and returning spawners for the next three generations (2019-2030) or longer. The model includes stochastic variation in survival rates in the lake and in the Pacific Ocean. The model can simulate a range of hatchery production and harvest rate alternatives, and potential increases to natural smolt production rates resulting from habitat or other mitigation strategies. The model calculates a series of performance measures as outlined in the RPA. As each 12-year simulation is based upon a different series of randomly selected survival rates, a large number of simulation trials are needed to calculate the expected response to a particular policy alternative. The source code for the model is presented below.

The critical assumptions in the model are:

- No density-dependence in survival rates in the lake or ocean for the 12-year simulation period. Lake density-dependence is unlikely given its sparse spawning densities, elevated trophic status, both current and forecasted juvenile Sockeye Salmon densities, and a lack of appreciable planktivorous competitor biomass. The potential for marine density dependence cannot be reliably estimated on average or by year, and estimates of marine survival do not reflect known long-term trends in hatchery salmon loadings to the North Pacific.
- Random draws of empirical estimates (approx. for brood years 2002-2017) of natural smolts produced per spawner, survival rates in the hatchery, survival of hatchery releases in the lake, and survival rates of naturally and hatchery-produced smolts in the ocean will reasonably represent conditions over the next 12 years.
- Variation in the proportion of hatchery-origin fish spawning in the lake will not influence later survival rates in the lake or ocean over the 12-year simulation period. That is, there are no additional effects of hatchery selection on survival in the wild beyond what is implicitly captured in the 2002-2017 data.

The annual number of naturally-produced smolts from Cultus Lake is predicted, based upon the brood escapement passed into the lake (hatchery+natural origin) two years earlier and a natural smolt-spawner ratio. This ratio varies among brood years in each 12-year simulation trial as determined by randomly choosing a year between 2002-2017 (brood year) and using the corresponding smolt-spawner ratio estimate for that year. The natural smolt-spawner ratio includes losses due to pre-spawning mortality, as well as variation in egg and fry survival. Note the model assumes no density-dependence in in-lake survival rates. This is a reasonable assumption given the current very low spawner abundances and the relatively short three-generation timeframe of the model. Freshwater mitigation is based upon decreasing the likelihood over time of the very low smolt-spawner ratios observed in the historical dataset, as detailed in the RPA.

The number of natural-origin spawners returning two years later, prior to fishery removals (adult recruits), is calculated based upon the number of predicted smolts and a randomly-drawn estimate of ocean survival rate for naturally-produced smolts (based upon a time series for brood years from 1999-2015). A fixed exploitation rate is applied to adult recruits to calculate the number of spawners that return to the fence. The number of fish at the fence taken for broodstock is simulated, and the remainder is the escapement to the lake.

The number of hatchery-produced smolts predicted by the model depends upon the simulated hatchery scenario, the number of hatchery- and naturally-produced adults predicted to return to the fence, and in-hatchery and in-lake survival rates. Scenarios include no hatchery production, smolt releases below the fence, parr releases into the lake, or both parr and smolt releases. Hatchery calculations begin with a prediction of the number of spawners taken at the fence each year for broodstock. We use a rule that no more than 50% of the total return to the fence can be taken for broodstock. In years when the total returns to the fence (hatchery- and naturally-produced) is at least twice as large as the broodstock requirement for the hatchery, the full requirement is taken. In years when total returns are not sufficient to meet the requirement, 50% of returns are taken for broodstock.

The number of fry or smolts produced from the hatchery each year depends upon the number of broodstock taken and a randomly drawn value for fry or smolts produced per female in the hatchery from the available time series (2002-2017). We assume 50% of the broodstock are females. Under the scenario where both parr and smolts are released, only smolts are released if the total number of broodstock is less than 38 (the minimum required to produced 50,000 smolts). When 38 or more broodstock are available, parr release numbers are based upon the available fish excess to what is required to produce 50,000 smolts.

The predicted number of smolts at the fence in the spring, produced from parr released from the hatchery the previous fall or winter, depends upon the number of parr released and a daily instantaneous mortality rate for hatchery-produced fry from the available time series of estimates (2002-2017). The value chosen is based upon the year selected for the choice of natural origin smolt/spawner ratio to maintain the covariation that exists between natural-origin and hatchery juvenile survival. The total in-lake survival rate from release to arrival at the fence depends upon the mortality rate and the assumed date of release. Fry released in the winter have a shorter period at large in the lake compared to fry released in the fall, and will therefore experience a higher overall survival rate from release to arrival at the fence. For these simulations we assume parr are released into the lake on December 15 each year as part of a strategy to avoid stressful environmental conditions encountered earlier in the year.

The number of hatchery-produced fish that return as adults prior to fishing depends upon a marine survival rate and the number of hatchery smolts produced from fry releases that are predicted to reach the fence in the spring as smolts, and the predicted number of smolts released downstream of the fence. In the case of fry releases, the predicted number of adult recruits depends upon the same randomly selected marine survival rate applied to natural-origin smolts described above. For smolt releases, a marine survival rate for hatchery smolts is randomly selected from the available time series (2007-2015 brood years). Hatchery-produced adult recruits are exposed to the same annual harvest rate that naturally-produced fish are exposed to.

In the code below a suite of performance measures are calculated for each scenario:

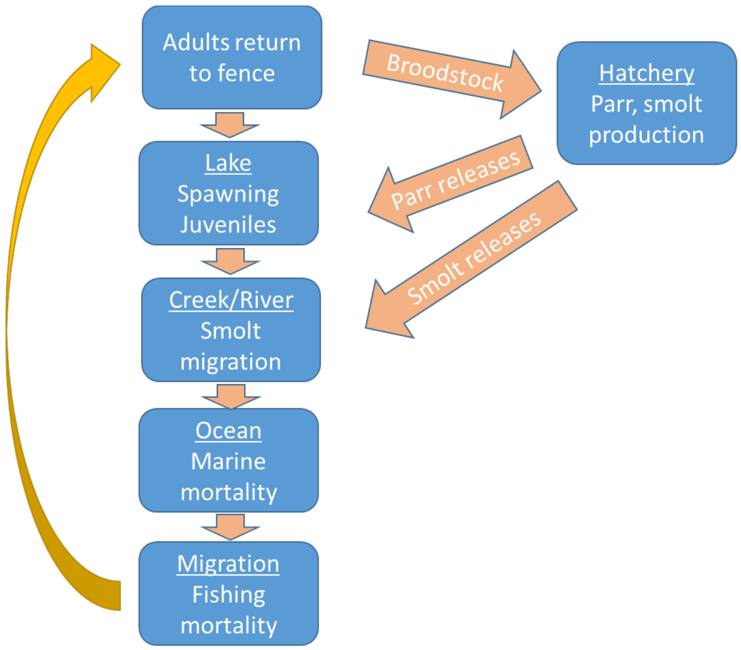
1. **Survival objective:** The proportion of years in each trial where the generational (4-year) arithmetic average abundance of spawners reaching the lake is ≥2500 and there are no less than 500 spawners in each of the four years used in the computation of the generational averages. We then compute the mean proportion of years when these conditions are met across 10000 trials.
2. **CSRT generational growth objective:** The proportion of years when the generationally-averaged spawner abundance increases over time and when increased abundance occurs for at least three of the four cycle lines. We then compute the mean proportion of years when these conditions are met across 10,000 trials.
3. The proportion of years when the escapement exceeds 7,000 spawners, averaged across 10,000 trials.

4. The proportion of years when the escapement exceeds 15000 spawners, averaged across 10,000 trials.
5. A quasi-extinction statistic, computed as the proportion of 10,000 trails where the number of spawners in four consecutive years is less than 50 fish.

6-8. Performance measures 1, 3, and 4 were also computed using the last simulated generation only. This quantifies the predicted state of the population at the end of the recovery period.

9. The Proportionate Natural Influence (PNI), that represents the potential degree of hatchery influence on the fitness of the population. This statistic is computed as the ratio of the proportion of natural-origin spawners in the broodstock (pNOB) to the sum of pNOB and the proportion of hatchery-origin fish spawning in the lake (pHOS). That is, PNI=pNOB/(pNOB+pHOS). PNI is computed annually, averaged across years in a trial, and then averaged across 10,000 trials.
10. PNI for the last generation of each trial.

In the document we report on performance measures 5, 6, 7, and 10 only.



<u>Fixed parameters</u>

- Sex ratio, age structure
- In-hatchery survival
- Broodstock removal rates
- Fishing mortality

<u>Varying parameters (resampling 1999+)</u>

- Natural-origin smolts/spawner
- In-lake hatchery parr survival
- Ocean survival, lake smolts
- Ocean survival, hatchery smolts

<u>Simulation settings</u>

- Initialize with 2015-2018 data
- 12-year simulations
- 10,000 MC trials
- Summary stats for last generation

Figure A.1. Flowchart for the Cultus Lake Sockeye Salmon model.

A.1. SOURCE CODE FOR CULTUS LAKE SOCKEYE SALMON POPULATION DYNAMICS MODEL

Text highlighted in green are comments (statements that start with a #).

```
##### Define Data Series of Survival Rates that will be randomly sampled as defined in Cultus input data
for model v3.xlsx ##########

#Natural (lake) smolts/spawner
#LSpS=c(5.0,3.0,20.8,22.5,33.7,59.6,85.8,38.6,130.3,1.4,106.9,20.8,1.7,2.3,29.3,4.7,1.0,1.1)
#Remove 1st 3 estimates so have same number as for Hmd, then can pick the same years in simulation to
#account for correlation
LSpS=c(22.5,33.7,59.6,85.8,38.6,130.3,1.4,106.9,20.8,1.7,2.3,29.3,4.7,1.0,1.1,7.2)
Nlsps=length(LSpS)

#Daily instantaneous survival rate for from lake release of fry to fence as smolt
Hmd=c(.0173,.0141,.0094,.0093,.0059,.0057,.0086,.0079,.0091,.0106,.0120,0.0122,0.0185,0.0172,0.0195,0.0155)
Nhmd=length(Hmd)

#Ocean survival rate applied to naturally produced smolts (from lake) as well as hatchery fry that survived
#to fence
Lms=c(0.042,0.011,0.011,0.035,0.014,0.012,0.024,0.030,0.056,0.012,0.023,0.018,0.035,0.049,0.009,0.041)
Nlms=length(Lms)

#Ocean survival rate for hatchery smolts released downstream of fence
Hms=c(0.0318,0.0052,0.0092,0.0083,0.0095,0.0050,0.0023,0.0067)
Nhms=length(Hms)



##### Define Constants and State Variable Arrays #####

Nsims=1000
Ngens=3

AgeAtReturn=4;Nyrs=Ngens*AgeAtReturn
#Lyr (last brood year) is 2026, but will simulate escapement through 2030 (prediction for last brood year
#iyr is for iyr+4)
Fyr=2015;Lyr=Fyr+Nyrs-1
Yr=c(seq(Fyr,Lyr,by=1),Lyr+1,Lyr+2,Lyr+3,Lyr+4) #2015-2030 total years if Ngens=3.
```

```
Sp=matrix(nrow=Nyrs+AgeAtReturn,ncol=Nsims)     #spawners
Sp_Nat=Sp;Sp_Hatch=Sp;pNOB=Sp;pHOS=Sp;PNI=Sp
Sp_Nat_A=Sp; Sp_Hatch_A=Sp; Sp_A=Sp   #Spawner series used for assessments
Sm_Nat=Sp;Sm_Hatch=Sm_Nat                       #smolts
Ret=Sp;Ret_Nat=Ret;Ret_Hatch=Ret                #adult returns to fence

#hatchery-produced fry released in lake, hatchery-produced smolts released downstream of fence
HatFry=Sp;HatSmolt=Sp;Brood=Sp
Brood=matrix(nrow=Nyrs+AgeAtReturn,ncol=Nsims)  # # of spawners taken for broodstock

#State variable initialization

#indexed by calender year (iyr). First 4 years are initialized based on observations
Sp[1:4,1:Nsims]=rep(c(1113,2554,670,330),times=Nsims)

#First year is 2015 so this is smolts two years later in 2017-2019
Sm_Nat[3:5,1:Nsims]=rep(c(1089,2722,4793),times=Nsims)

#Fry in 2017-2020 (1st 3 numbers are survived to fence, last number is releases )
HatFry[3:6,1:Nsims]=rep(c(2735,3165,7070,194000),times=Nsims)
HatSmolt[3:6,1:Nsims]=rep(c(24747,26146,50750,50000),times=Nsims) #smolts in 2017-2020 released below fence
PNI[1:4,1:Nsims]=rep(c(0.19,0.08,0.54,0.69),times=Nsims) #observed PNI values (2015-2018) for plotting

#### Policy Parameters ##############
ErMult=0 #multiplier of existing exploitation pattern; use 1 for existing ER
fnout="stats.out"
Uadams=0.5*ErMult; Ureg=0.2*ErMult              #ER in Adams yesr (2018, 2020, etc.) and non-Adams (reg)
years
Hscen=4                             #Hatchery scenario (1 = no hatchery, 2=smolts, 3=fry, 4=mixed)
MaxBrood=c(0,68,202,160)            #required broodstock for Hscen 1-4
HSmPerFem=c(0,2584,2476,NA)         #hatchery smolts or fry-smolts produced per female
pBrood=0.5                          #maximum prop of adult at fence that can be taken for broodstock

#Number of days from fry release in lake to smolt migration at fence (192=fall release, 120 for winter)
Hdur=120
```

```
#Mitigation of smolt production: HabMax is the minimum smolts/spawner value reached by by #HabMaxYr
HabMax=1;HabMaxYr=10
#Setup the year-specific sequence of mitigations. First 5 brood years (2015-2019) are not affected
HabMult=c(1,1,1,1,seq(1,HabMax,length.out=HabMaxYr))

#Set additional HabMults at HabMax for years after HabMaxYr
if(length(HabMult)<Nyrs) HabMult=c(HabMult,rep(HabMax,times=Nyrs-length(HabMult)))

#### Performance measures #####################

Nobj=7
Obj=matrix(data=0,nrow=Nobj,ncol=Nsims)
ObjStats=matrix(nrow=Nobj,ncol=3)         #LCL, mean, and UCL stats for Obj values across sims

LG_Obj=matrix(data=0,nrow=4,ncol=Nsims)   #Some stats for last generation
LG_ObjStats=matrix(nrow=4,ncol=3)

perc=c(0.1,0.9)                     #percentiles for plotting and uncertainty bound on performance measures

######## Model ############################

#Set random  seed so we always get the same set of random numbers for each policy (across a set of sim
#trials and years). Comment this out when determing how many Nsims are needed to get a stable result. Need
#big Nsims for stable Obj[2,]
set.seed(10)

for(isim in 1:Nsims){         #trials loop

      cycle_cnt=0
      for(iyr in 1:Nyrs){     #year loop

            #Set exploitation rate in adams ('22, '26, '30) and non-adams years ('19-'21, '23-25, '27-29)
            cycle_cnt=cycle_cnt+1
            #iyr=1 is 2015, so in 2018 (adams year) you are on cycle_cnt=4. Apply greater (Uadams) ER
            if(cycle_cnt==4){
                  U=Uadams
                  cycle_cnt=0
```

```
} else {
      U=Ureg              #non-adams year, apply lower ER
}


#### Natural production ########
#Predict naturally-produced smolts exiting lake given escapement and random pick from lake
#smolts/spawner data series
#Smolt data series is shortened to include only values > HabMult to reflect lake mitigation
if(iyr>3){
#Sm_Nat already defined for iyr=1-3 given values for Sm_Nat[1+2,] Sm_Nat[2+2,], Sm_Nat[3+2,]
#(See initial conditions above)
LSpS2<-LSpS[LSpS>HabMult[iyr]];Nlsps=length(LSpS2) #Truncate Sm/Sp vector to values > HabMult
j=runif(n=1,min=SurvStart,max=Nlsps)                  #random pick of element in LSpS2
Sm_Nat[iyr+2,isim]=Sp[iyr,isim]*LSpS2[j]  #Use picked value of LSpS2 to compute smolts
}

#Predict returns to fence two years later from natural production in lake based on smolts
#produced and ocean survival
k=runif(n=1,min=1,max=Nlms)   #pick of element in marsurv survival for smolts produced inlake
Ret_Nat[iyr+4,isim]=Sm_Nat[iyr+2,isim]*Lms[k]*(1-U)


#### Hatchery production #######
#HatFry and HatSmolts for iyr=1:4 defined by initial conditions so doesn't need to be
#calculated

#hatchery production depends on brood take. First year this is computed is in year 5 (2019)
if(iyr>4){
      if(Hscen==1){           #no hatchery
            HatFry[iyr+2,isim]=0; HatSmolt[iyr+2,isim]=0

      } else if (Hscen==2){   #smolt release only
            HatFry[iyr+2,isim]=0
            HatSmolt[iyr+2,isim]=Brood[iyr,isim]*0.5*HSmPerFem[Hscen]

      } else if (Hscen==3){   #fry release only
            HatFry[iyr+2,isim]=Brood[iyr,isim]*0.5*HSmPerFem[Hscen]
            HatSmolt[iyr+2,isim]=0
```

```
        } else {          #combined fry and smolt release
              if(Brood[iyr,isim]>38){ #enough broodstock to produce both fry and smolts
                    #need 19 females (38*0.5) to produce 50,000 smolt limit (19*HsmPerFem[3])
                    HatSmolt[iyr+2,isim]=38*0.5*HSmPerFem[2]

                    #remaining non-smolt destined brood goes to producing fry
                    HatFry[iyr+2,isim]=(Brood[iyr,isim]-38)*0.5*HSmPerFem[3]

        } else {    #not enough brood so produce only smolts
                    HatSmolt[iyr+2,isim]=Brood[iyr,isim]*0.5*HSmPerFem[2]
                    HatFry[iyr+2,isim]=0
              }
        }
  }


  #Calculate returns to fence from hatchery fish at fence two years ago
  #note that random picks for MS values for naturally-produced smolts (Lms[k] vs. hatchery-
  #produced smolts (Hms[m] are not correlated in sim (r2 in data = 0.15)

  #random pick of element in marine survival for hatchery smolts released below fence
  m=runif(n=1,min=1,max=Nhms)

  if(iyr>3){
        #random pick of element in instantaneous mortality for fry-smolt for hatchery fry
        #releases
        l=j                           #Use same year as picked for natural Sm/Sp

        #translate to survival for release-smolt interval
        HatFrySurv=exp(-Hmd[l]*Hdur)

        #For plotting only. Total hatchery production making it to fence as smolts, which is just
        #smolts and survived fry
        Sm_Hatch[iyr+2,isim]=HatSmolt[iyr+2,isim] + HatFry[iyr+2,isim]*HatFrySurv
```

```
#Predict fence returns from hatchery production which includes fry releases and smolt releases
#Note that marine survival for fry releases is same as for naturally-produced smolts, but smolt
#releases below fence use a separate ocean survival rate
      Ret_Hatch[iyr+4,isim]=(HatSmolt[iyr+2,isim]*Hms[m] +
      HatFry[iyr+2,isim]*HatFrySurv*Lms[k])*(1-U)

} else {    #special treatment for 1st 3 years where survival of hatchery fry releases to fence
            #is already known (so HatFry = smolts at fence from fry release)
      Sm_Hatch[iyr+2,isim]=HatSmolt[iyr+2,isim] + HatFry[iyr+2,isim]
      Ret_Hatch[iyr+4,isim]=(HatSmolt[iyr+2,isim]*Hms[m] + HatFry[iyr+2,isim]*Lms[k])*(1-U)
}

#Total returns to fence is sum of natural and hatchery returns
Ret[iyr+4,isim]=Ret_Nat[iyr+4,isim] + Ret_Hatch[iyr+4,isim]

#### Broodstock Collection #####

# # of fish taken for brood can be no more than 50% of fence returns (pBrood)
if(Hscen==1){
      Brood[iyr+4,isim]=0
} else {
      #returns are >= 2*broodstock requirement (pBrood=0.5)
      if(Ret[iyr+4,isim]>=MaxBrood[Hscen]/pBrood){
            Brood[iyr+4,isim]=MaxBrood[Hscen]         #take full broodstock requirement
      } else {
            #Not enough returns for full broodtake. Take 1/2 of the return to fence
            Brood[iyr+4,isim]=Ret[iyr+4,isim]*pBrood                     }
}


#Compute # of natural and hatchery-origin returns taken as brood to determine number of
#spawners making it to lake to spawn and for PNI computation. Proportion of hatchery and
#natural spawners at fence taken for brood is in proportion to the composition of returns to
#fence
NatTaken=Brood[iyr+4,isim]*Ret_Nat[iyr+4,isim]/Ret[iyr+4,isim]
HatTaken=Brood[iyr+4,isim]-NatTaken

#Compute # of spawners into lake after removing broodtake from fence returns
Sp_Nat[iyr+4,isim]=trunc(Ret_Nat[iyr+4,isim]-NatTaken)

Sp_Hatch[iyr+4,isim]=trunc(Ret_Hatch[iyr+4,isim]-HatTaken)
```

```
Sp[iyr+4,isim]=trunc(Sp_Nat[iyr+4,isim]+Sp_Hatch[iyr+4,isim])
##Second set of spawner abundances, includes broodstock-- to be used for assessment and plots
Sp_Nat_A[iyr+4,isim]=trunc(Ret_Nat[iyr+4,isim])
Sp_Hatch_A[iyr+4,isim]=trunc(Ret_Hatch[iyr+4,isim])
Sp_A[iyr+4,isim]=trunc(Sp_Nat_A[iyr+4,isim]+Sp_Hatch_A[iyr+4,isim])


#PNI and pHOS computations
#Note that pNOB=PNI in Cultus sim becaue we assume proportion of nat and hatch taken for brood
#is exactly the same as proportion arriving at fence
#(PNI=pNOB/(pNOB+pHOS), pHOS=SP_Hatch/(Sp_Nat + Sp_Hatch). Say 30% of fish at fence are
#natural, so PNI=0.3/(0.3 + (1-0.3)) = 0.3
#But keep the equations below so they are consistent with equations in hatchery review lit.

if(Brood[iyr+4,isim]==0){
      PNI[iyr+4,isim]=1
} else {
      pNOB[iyr+4,isim]=NatTaken/Brood[iyr+4,isim]
      pHOS[iyr+4,isim]=Sp_Hatch[iyr+4,isim]/Sp[iyr+4,isim]
      PNI[iyr+4,isim]=pNOB[iyr+4,isim]/(pNOB[iyr+4,isim]+pHOS[iyr+4,isim])
}


######### Calculate Performance Measures for Objectives #################

#model initialized with escapements from 2015-2018 (iyr=1-4) and 2019 (iyr=5) is first year
#with a prediction for escapement so this is when objective calculations start.
#Note that since last iyr (brood) is 2026, last spawner prediction is 2026+4=2030
#The way generational stats are laid out below, last spawner prediciton used is iyr+3=2029

if (iyr>4){

      #Generational abundance objective (I). Gen avg>=2500 and no years with <500 fish
      GenAvg=mean(Sp[iyr:(iyr+3),isim])
      fail=length(which(Sp[iyr:(iyr+3),isim]<500))
      if(GenAvg>=2500 & fail==0) Obj[1,isim]=Obj[1,isim]+1  #objective met for this trial

#Generational growth objective (II). Growth across generational averages and for 3 of 4 cycles.

      GroGen=mean(Sp[iyr:(iyr+3)],isim)-mean(Sp[(iyr-4):(iyr-1),isim])
```

```
                    GroCyc=c(Sp[iyr+3,isim]-Sp[iyr-1,isim],Sp[iyr+2,isim]-Sp[iyr-2,isim],Sp[iyr+1,isim]-
                    Sp[iyr-3,isim],Sp[iyr,isim]-Sp[iyr-4,isim])


                    if(GroGen>0 & length(which(GroCyc>0))>=3) Obj[2,isim]=Obj[2,isim]+1

                    #natural spawners greater than WSP lower limit
                    if(Sp[iyr,isim]>=7000) Obj[3,isim]=Obj[3,isim]+1
                    if(Sp[iyr,isim]>=15000) Obj[4,isim]=Obj[4,isim]+1     #natural spawners >= gen value

                    #Has quasi-exinction limit been reached in four consecutive years
                    if(Sp[iyr,isim]<50 & Sp[iyr+1,isim]<50 & Sp[iyr+2,isim]<50 & Sp[iyr+3,isim]<50)
                    Obj[5,isim]=1     #did quasi-extinction occur at any point in the simulation

                    #Some stats for last generation
                    if(iyr==Nyrs) {
                          Obj[7,isim]=GenAvg      #generational average abundance at end of simulation

                          if(GenAvg>=1000 & fail==0) LG_Obj[1,isim]=LG_Obj[1,isim]+1
                          if(GenAvg>=7000) LG_Obj[2,isim]=LG_Obj[2,isim]+1
                          if(GenAvg>=15000) LG_Obj[3,isim]=LG_Obj[3,isim]+1
                          LG_Obj[4,isim]=mean(PNI[iyr:(iyr+3),isim])
                    }
              }

        } #next iyr

        #proportion of years when objective was met for current trial
        for(i in 1:4) Obj[i,isim]=100*Obj[i,isim]/(Nyrs-4)

        #average PNI over simulation period for current trial (as a %)
        Obj[6,isim]=mean(PNI[5:Nyrs,isim],na.rm=T)
} #next trial simulation


#Summarize performance measures across sim trials and dump to file and screen
for (i in c(1,2,3,4,6,7)){

        #Average performance measure values across simulations
        ObjStats[i,2]=mean(Obj[i,1:Nsims])
```

```
      #10th and 90th percentile or whatever perc is set to.
      ObjStats[i,c(1,3)]=as.double(quantile(Obj[i,1:Nsims],prob=c(perc[1],perc[2]),na.rm=T))
}
ObjStats[7,2]=median(Obj[7,1:Nsims])      # take median value of last generation abundance
ObjStats[5,2]=100*sum(Obj[5,1:Nsims])/Nsims     #% of trials where quasi-extinction occurred

#can't compute credible interval for extinction stat. Only one value possible across trials.
ObjStats[5,c(1,3)]=c(NA,NA)

#Finish last generation stats
for(i in 1:4){
      if(i<4){
            LG_ObjStats[i,2]=sum(LG_Obj[i,1:Nsims])/Nsims   #Proportion of sims that met criteria
            LG_ObjStats[i,c(1,3)]=c(NA,NA)
      } else {
            LG_ObjStats[i,2]=median(LG_Obj[i,1:Nsims])      #median PNI
            LG_ObjStats[i,c(1,3)]=as.double(quantile(LG_Obj[i,1:Nsims],prob=c(perc[1],perc[2]),na.rm=T))
      }
}


#Dump results to file
objnm=c("ObjI","ObjII","WSP_7k","WSP_15k","Ext","PNI","EndGenAvg")
write.table(file=fnout,round(ObjStats,digits=1),row.names=objnm,col.names=c("LCL","MU","UCL"))
```

APPENDIX B. GLOSSARY OF TERMS & ACRONYMS

Term	Definition
A	
Aerobic Microbial Decomposition	Decomposition of organic matter via aerobic pathways, requiring the consumption of ambient dissolved oxygen as an electron acceptor
Anaerobic Microbial Decomposition	Decomposition of organic matter via non-aerobic pathways when dissolved oxygen concentrations are limiting for aerobic decomposition, requiring other electron acceptors other than oxygen
Airshed	Region of the atmosphere, relative to the underlying landscape, where the movement of air and pollutants can be hindered by local geographic features such as mountains, and by weather conditions. (e.g. Fraser Valley Airshed)
Algae	Diverse group of unicellular and/or colonial photosynthetic eukaryotic organisms contributing to primary production in aquatic ecosystems.
Allowable Harm – *SARA*	Harm to a wildlife species that will not jeopardize its recovery or survival
Anadromy – *Pacific salmon*	Migratory fish (i.e. Pacific salmon) life history involving hatching and rearing of juveniles in freshwater, followed by migration to and maturation in saltwater (i.e. Pacific Ocean), returning to freshwater for reproduction
Alevin – *Pacific salmon*	Emergent larval fish (i.e. Pacific salmon), reliant upon attached yolk sack
Amphipod	Crustacean invertebrate typically of the order *Amphipoda*
Anoxia - *water*	An absence of dissolved oxygen in water
Anthropogenic	Of, relating to, or resulting from the influence of human beings on nature
B	
Bacterial Kidney Disease (BKD)	Chronic disease caused by the bacterium *Renibacterium salmoninarum* largely infesting salmonids, responsible for significant mortality
BATHTUB Model	US Army Corps of Engineers steady-state water quality model for lakes and reservoirs designed to assess and predict eutrophication
Benchmark - *Pacific salmon*	Biological reference point for a Pacific salmon population, against which the attributes of a stock (i.e. abundance, survival, exploitation) can be measured in order to determine its status

Term	Definition
Benthic zone – *lakes*	The bottom of lakes and other aquatic habitats, including the substrate surface and some sub-surface layers
Biological Oxygen Demand (BOD)	The amount of dissolved oxygen that must be present in water in order for microorganisms to decompose organic matter *syn.* Biochemical oxygen demand
Biomass	The total mass of organisms in a given area or volume aggregated at the species, population, community or ecosystem level
Broodstock - *Pacific salmon*	A group of mature individuals used in aquaculture for breeding purposes
Broodstock Enhancement - *Pacific salmon*	Augmentation of wild or hatchery salmon populations through the use of hatchery aquaculture to propagate juveniles released to the environment
C	
Captive Broodstock - *Pacific salmon*	Hatchery broodstock enhancement where the entire life cycle serially occurs in captivity
Cetacean	Marine mammal of the order *Cetacea*, (i.e. whale, dolphin, porpoise)
Climate Change	A change in global or regional climate patterns, specifically a change apparent from the mid- to late-20th century onwards, attributed largely to increases in atmospheric carbon dioxide resulting from fossil fuel use
Climate Variability	Variations in the mean state and other characteristics of climate on spatial and temporal scales beyond individual weather events
Committee on the Status of Endangered Wildlife in Canada (COSEWIC)	An independent advisory panel to the Minister of Environment and Climate Change Canada that meets twice a year to assess the status of wildlife species at risk of extinction
Conservation unit (CU) - *Pacific salmon*	A group of wild salmon sufficiently isolated from other groups that, if extirpated, is very unlikely to re-establish naturally within an acceptable timeframe, such as a human lifetime or a specified number of generations
Competition	An interaction between organisms or species in which both requires a resource that is in limited supply (i.e. food web resources)
Crepuscular - *period*	Pertaining to twilight at dawn and/or dusk
Critical Habitat - *SARA*	The habitat that is necessary for the survival or recovery of a listed wildlife species and that is identified as the species' critical habitat in the recovery strategy or in an action plan for the species

Term	Definition
D	
Decapod	A crustacean of the order *Decapoda*
Deep Chlorophyll Maximum (DCM) - *Lakes*	The region below the water surface, typically with the maximum concentration of chlorophyll associated with deep. Syn. Subsurface chlorophyll maximum
Deme	A subdivision of a population consisting of closely related organisms, breeding mainly within the group.
Density Dependence	An effect in which the intensity changes with increasing population density
Depensatory Mortality - *Pacific salmon*	Mortality in a population, the rate of which increases as the size of the population decreases
Designatable unit (DU)	A wildlife species, native to Canada, wild by nature, possibly including captive individuals with recent wild ancestors
DFO	Fisheries & Oceans Canada (formerly Department of Fisheries & Oceans)
Dissolved Oxygen (DO)	The concentration or percent saturation of oxygen molecules dissolved in water
Domestication Selection - *Pacific salmon*	Artificial genetic selection within organisms and/or populations (i.e. Pacific salmon) arising from propagation within hatchery environments
E	
Effective Female Spawner(s) (EFS) – *Pacific salmon*	An estimate of the female spawner(s) that is adjusted for the proportion of eggs that were not spawned, as determined by sampling. This estimate reflects a female reproductively-successful cohort of the overall return
Egg – *Pacific salmon*	Female reproductive product. Unfertilized eggs are deposited and fertilized by the male through milt
El Niño-Southern Oscillation (ENSO)	Quasi-periodic variation in winds and sea surface temperatures over the tropical eastern Pacific Ocean, oscillating between warm (El Niño) and cold (La Niña) states, with climatic influences on the tropics subtropics
Emergence	Abandonment of interstitial gravel habitats following utilization of the egg sac (alevin), transitioning to the free swimming rearing life history stage (fry)
Endangered - *SARA status*	A wildlife species facing imminent extirpation or extinction
Endemic	Native and restricted to a certain place

Term	Definition
Epigenetic Effects	Upregulation or downregulation of gene expression in relation to organismal behavior or the environment
Epilimnion	The typically warmer surface water column layer in a thermally stratified lake overlying the deeper, typically colder hypolimnion
Euphasiid	Marine crustacean of the order Euphasiacea
Euphotic Zone	The biologically-productive, uppermost water layer in a lake that receives sunlight, permitting photosynthesis *syn.* Photic zone, trophogenic zone
Eutrophication	Excessive nutrient enrichment of aquatic ecosystems (i.e. lakes) inducing excessive algal and macrophyte growth. *syn.* Cultural eutrophication, dystrophication
Estuary	A partially enclosed coastal body of brackish water receiving freshwater from one or more river systems, with free hydrological connection to the open ocean
Eurasian Watermilfoil (EWM)	A perennial invasive aquatic plant that established in British Columbia in the 1970's, forming dense submergent stands *syn. Myriophyllum spicatum*
Exploitation - *fisheries*	Capture of fish in an recreational, commercial and/or indigenous fishery
Exploitation Rate (ER) - *fisheries*	The proportion of the numbers or biomass removed by fishing over a defined period of time.
Extirpated - *SARA status*	Species which no longer exist in the wild in Canada, but exist elsewhere in the wild
F	
Fecundity - *Pacific salmon*	Physiological maximum potential reproductive output of a female over its lifetime
Fence – *enumeration*	Weir structure used to constrain the swim path of fish for the purposes of population estimation
Fitness - *Pacific salmon*	The reproductive success of a genotype, typically measured as the number of offspring produced by an individual that survive to reproductive age
Floc - *lake*	Aggregative generation and sedimentation of particles in the water column
Food web - *aquatic*	A network of interlinked and interdependent food chains within an ecosystem

Term	Definition
Fry - *Pacific salmon*	Free swimming larval fish rearing in lakes and streams
G	
Generation - *Pacific salmon*	A single cohort of fish within a population, typically defined annually in Pacific salmon
Genomic	Pertaining to the complete set of genes in a cell or organism
Groundwater	Water held or flowing underground in the soil or in pores and crevices in bedrock or sedimentary deposits
H	
Hatchery supplementation - *Pacific salmon*	Propagation of fish from a specific population within an artificial rearing environment to supplement wild stocks
Holomixis - *lake*	Lakes where the whole water column mixes seasonally from surface to bottom
Hydroacoustics - *juvenile Pacific salmon*	Use of sound in water (i.e. sonar) to enumerate fish targets in a water column
Hydroacoustic & Trawl Survey - *Pacific salmon nursery lakes*	Surveys of Pacific salmon nursery lakes applying downward-facing hydroacoustic sonar to estimate and enumerate fish targets, coupled with collapsing mid-water trawling for target apportionment to species
Hyphoreic Zone - *groundwater*	The region of sediment of porous space beneath or alongside a body of water where exchange between groundwater and surface water occurs
Hypolimnion - *lake*	The typically colder bottom layer in a thermally stratified lake water column underlying the shallower, typically mixed epilimnion
Hypoxia/Hypoxic - *water, fish*	Oxygen deficiency in a biotic environment and/or fish tissues
I	
Incidental harvest – *fisheries*	Untargeted lethal retention of Cultus Lake Sockeye Salmon
Incubation - *Pacific salmon*	Development of a fertilized embryo within an egg
Infectious Hematopoietic Necrosis Virus (IHNV)	The causative agent for infectious hematopoietic necrosis, a pathology within salmonids potentially leading to mortality
Integrated Fisheries Management Plan (IFMP) - *Pacific salmon*	A fisheries management tool involving stock assessment, industry and interested party consultation, priority setting, and guidance intended to promote sustainable fisheries
In-season	Pertaining to the period during a fishing season or fishery

Term	Definition
- fisheries management	
Internal Loading – *lakes*	Introduction of sediment constituents (i.e. nutrients, toxicants) into the overlying water column, often occurring under reducing conditions at the sediment-water interface (i.e. redox)
Interstitial – *substrates*	Voids between sediment particles or cobbles
Invasive Species	A non-native, introduced species that spreads from a point of introduction to become naturalized, with negative impacts on its new environment
Isothermal - *lakes*	A lake condition involving a constant temperature from surface to sediments permitting wind-driven mixing, where it occurs
J	
-	-
K	
-	-
L	
Life History	The series of changes undergone by an organism during its lifetime
Limiting Factor - *SARA*	Biotic or abiotic natural factors negatively affecting Cultus Lake Sockeye Salmon productivity
Limnology	The study of the physical, chemical and biological features of lakes and other bodies of freshwater
Littoral Zone – *lake*	The nearshore zone in a lake defined from the shoreline to the depth at which 1% of incident light is attenuated
M	
Macrophyte	A macroscopic aquatic plant that is large enough to be visible to the eye
Metalimnion - *lake*	The water column layer which lies beneath the epilimnion and above the hypolimnion, where temperature decreases rapidly with increasing depth *Syn.* thermocline
Mitigation – *stressor*	The action of reducing the severity, seriousness, or painfulness of a stressor on an aquatic habitat or species
Mixis - *lake*	Circulation of the water column within a lake, typically referring to seasonal overturn during the period when the lake not thermally stratified
Monomictic - *lake*	Lakes where the entire water column mixes (i.e. holomixis)

Term	Definition
Morphometry – *lake*	The unique bathymetric shape of a lake
Mortality	The state of being subjected to death for an organism
Mortality Rate	The number of deaths within a population across a given period of time
N	
Natal Habitat - *Pacific salmon*	Freshwater habitat (i.e. lake, river, stream) where an organism is born
Nursery Lake - *Pacific salmon*	Freshwater rearing habitat typically used by rearing Sockeye Salmon
O	
Outmigration – *Pacific salmon*	Action of leaving natal freshwater habitat(s) for the Pacific Ocean
Olfactory Imprinting - *Pacific salmon*	Biologically-relevant learning during a sensitive (i.e. juvenile) period defined by a particular developmental stage or physiological state
Oxic - water	Sufficient dissolved oxygen in a biotic environment and/or fish tissues
P	
Pacific Decadal Oscillation (PDO)	A robust, recurring pattern of ocean-atmospheric climate variability centered over the mid-latitude Pacific basin, with synoptic climate influences on regional marine and continental ecosystems
Paleolimnology	The study of lakes and lake sediments to reconstruct past limnological, climatic, and environmental changes
Parvicapsula minibicornis	Myxosporean parasite common to adult Cultus Lake sockeye salmon
Population	A number of all the organisms of the same group or species that live in a particular geographical area and are capable of interbreeding
Post-season – *fisheries management*	Pertaining to the period following the fishing season or a fishery
Predation/Predator/Prey	A biological interaction where one organism (i.e. predator) kills and eats another organism (i.e. prey)
Pelagic Zone - *lake*	The open-water zone of a lake ecosystem
Periphyton	Attached algae, cyanobacteria, and bacteria, attached to submerged surfaces within aquatic ecosystems
Phenology	Of or pertaining to the timing of seasonal and/or cyclical natural phenomena that are ecologically influential (i.e. food web development)

Term	Definition
Photosynthesis	A process used by plants and other autotrophic organisms to convert light energy into chemical energy that can be released to support physiological function(s)
Phytoplankton	Autotrophic components of the plankton community (e.g. algae, cyanobacteria) within a freshwater ecosystem (e.g. lake)
Piscivore	A carnivorous animal that that eats primarily fish
Pre-season *- fisheries management*	Pertaining to the period prior to the fishing season or a fishery
Production/Productivity *- aquatic ecosystem*	The creation of new organic matter (i.e. biomass), usually expressed as a rate
Production/Productivity *- fish and fisheries*	The relationship between the quantity of fish produced and the amounts of inputs used to harvest the fish.
Profundal zone - *lake*	The deepest, vegetation-free zone of a lake benthic zone with substrates characterized by silts and muds
Q	
-	-
R	
Rearing/Rearing Habitat *- Pacific salmon*	The process and/or habitat for growth of juvenile Pacific salmon in freshwater before outmigration to the Pacific Ocean
Recovery – *SARA*	A return to a state in which the population, distribution characteristics, and the risk of extinction are all within the normal range of variability for the wildlife species.
Recovery potential assessment (RPA) - *SARA*	Assessment process including the current status of the designatable unit, the threats to its survival and recovery, and the feasibility of recovery, to advise the Minister in response to COSEWIC recommendations
Recruitment - *population dynamics, Pacific salmon*	The process by which new individuals are added to a population by birth, maturation, and/or immigration.
Redd – *Pacific salmon*	A nest built to receive, and incubate eggs following fertilization
Redox – *water, lakes*	A chemical reaction in which the oxidation states of atoms are changed through oxidation (loss of electrons increasing oxidation state) or reduction (gain of electrons decreasing oxidation state); *Syn.* oxidation-reduction

Term	Definition
Remotely Operated Underwater Vehicle (ROV)	Tethered underwater mobile device capable of image acquisition and/or other tasks at depth within aquatic systems
Reproduction – *fish*	Biological process whereby new individual organisms (e.g. offspring) are produced from sexual interchange of gametes. *Syn.* breeding
Reproductively-isolated - *fish*	Inability for sexually-compatible populations to interbreed due to behavioural, physiological or environmental impediments
Residence - *SARA*	A dwelling-place, such as a den, nest or other similar area or place, that is occupied or habitually occupied by one or more individuals during all or part of their life cycles, including breeding, rearing, staging, wintering, feeding or hibernating
Run timing group - *Pacific salmon*	Pacific salmon fisheries management population aggregations (i.e. early Stuart run, early run, summer run, late run) defined by the similar spawning adult return timing of differing stocks within the Fraser River Sockeye Salmon complex
S	
***Salmonicola* spp.**	Largely freshwater parasitic copepods of the genus *Salmonicola*, that feed on the blood and epithelial cells of salmonid fishes, typically infesting the gill filaments, opercula, mouth cavity tissues, and fins, and capable of causing sub-lethal to lethal stress
Schmidt Stability - *lake*	The resistance to mechanical mixing of a thermally-stratified lake water column due to a thermally- induced density differential, and represented by the Schmidt Stability Index (J/m^2)
Semelparity – *Pacific salmon*	A reproductive strategy characterized by a single reproductive episode before death
Senescence – *lake, seasonal*	The end-of-growing-season decreases in aquatic production and organismal biomass associated with procession into fall and winter
Smolt – *Pacific salmon*	A juvenile salmon following the parr stage, undergoing physiological preparations and/or outmigration to the Pacific Ocean
Smolt-recruit survival – *Cultus Lake Sockeye Salmon*	Survival from the enumeration fence to recruitment, defined as the sum of the number of mature fish reaching the lake and those caught in fisheries
Smolt-spawner survival – *Cultus Lake Sockeye Salmon*	Survival of fish between lake departure (smolts counted at the enumeration fence) and their escapement to the enumeration fence (lake) as adults
Sockeye Salmon	An anadromous and semelparous species of the Pacific salmon guild (*Oncorhynchus* spp.) that typically rear their juveniles in nursery lake environments; *syn. Oncorhynchus nerka*

Term	Definition
Smolt/spawner – *Pacific salmon*	The mean number of outmigrating smolts produced per effective female spawner
Spawner – *Pacific salmon*	Sexually mature Pacific salmon reaching its natal environment
Special concern (*status*)	Species which may become threatened or endangered because of a combination of biological characteristics and identified threats
Species at Risk Act - *SARA*	Federal legislation governing the identification, conservation, and recovery of wildlife species at risk of extinction in Canada
Spring bloom - *lakes*	A strong increase in phytoplankton abundance that typically occurs in the early-spring, lasting through late-spring and early-summer
Stratification - *lakes*	*syn*. thermal stratification; density stratification
Substrate - *lakes*	Of or pertaining to bottom environments underlying a lake water column (i.e. sediments, nearshore bottom)
Survival – *SARA*	The achievement of a stable or increasing state where a wildlife species exists in the wild in Canada and is not facing imminent extirpation or extinction as a result of human activity
T	
Taxonomy	Biological classification of organisms and the identification of same
Thermocline	The water column layer which lies beneath the epilimnion and above the hypolimnion, where temperature decreases rapidly with increasing depth; *Syn.* metalimnion
Threat - *SARA*	A threat is defined as any human activity or process that has caused, is causing, or may cause harm, death, or behavioural changes to a wildlife species at risk, or the destruction, degradation, and/or impairment of its habitat, to the extent that population-level effects occur. A human activity may exacerbate a natural process
Threatened – *SARA status*	Species which are likely to become endangered if nothing is done to reverse the factors leading to their extirpation or extinction
Trophic	Relating to feeding and nutrition
Trophic Level	Each of several hierarchical levels in an ecosystem, comprising organisms that share the same function in a food chain or web, and the same nutritional relationship to the primary sources of energy (e.g. primary producers, primary consumers, secondary consumers)
Trophic Status – *lakes*	Productivity of a lake ecosystem, in terms of organic carbon produced per unit of space and time

Term	Definition
Turnover - *lakes*	The phenomenon whereby the entire volume of water in a lake is mixed by wind when the vertical temperature-density gradient of the water column is minimal (i.e. isothermal)
U	
-	-
V	
-	-
W	
Water Column - *lake*	The vertical column of water from surface to bottom sediments within a lake
Watershed	An area of land that drains all the channelized (i.e. streams, rivers), and unchannelized water inputs (i.e. overland flows, groundwater flows) to a body of water (i.e. lake)
Wild Salmon Policy (WSP)	Federal policy guiding conservation of wild Pacific Salmon in Canada in relation to societal values *Syn.* Canada's Policy for the Conservation of Wild Pacific Salmon
X	
-	-
Y	
-	-
Z	
Zooplankton – *lakes*	Motile plankton (i.e. nekton), consisting of small animals and immature stages of larger animals