A Cumulative Effect Assessment Using Scenario Analysis Methodology to Assess Future Cowichan River Chinook and Coho Salmon Survival

by

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We acknowledge with respect the Lekwungen peoples on whose traditional territory the university stands and the Songhees, Esquimalt and W̱SÁNEĆ peoples whose historical relationships with the land continue to this day.

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Abstract

This dissertation describes a proposed methodology for Cumulative Effects Assessment (CEA) with the purpose of improving the process by making it both more substantive and quantitative. The general principles of the approach include the following: use of effect-based analyses where selected Valued Component (VC) sensitivities are identified first and then effect pathways are determined building bottom-up linkages from VC sensitivities to potential stressors or combinations of stressors to effect drivers and forces behind the drivers. Models were developed based on statistical or historic trend analysis or literature review that predicted the responses of the VCs to changes in effect drivers. Further, scenarios of divergent futures were created that involved different developments of each effect driver or force, and finally the models were applied to each scenario to project the state of the studied VCs. A practical implementation was conducted to demonstrate the use of the proposed methods on future population trends of two anadromous salmon species from the Cowichan River, British Columbia, Chinook and Coho. The assessment was conducted for both early freshwater and marine phases of their life. For the freshwater phase, the assessment focused on two main factors affecting salmon survival, streamflow and stream temperature and established two main drivers affecting these stressors, land use and climate change, and two main forces behind these drivers, *Local* and *Global* human development driven change, respectively. Effects of stream temperature and streamflow on salmon freshwater survival were simulated using two models; one was based on Chinook freshwater survival correlations with stream temperature and was developed only for Chinook, and the other was based on literature-derived temperature and streamflow thresholds and was developed for both species. Connections between the stressors (stream temperature and streamflow) and drivers (land use and climate change) were established through a hydrologic model and stream temperature regression model. For the marine environment, models were created using Pearson correlation and stepwise regression analysis examining links between survival of Cowichan River Chinook and Strait of Georgia hatchery-raised and wild Coho and various environmental variables of the nearshore zone of Strait of Georgia and Juan de Fuca Strait. The models were applied to project future salmon survival under four future scenarios for 2050 that were created by combining two opposite scenarios of land use in the watershed, forest conservation and development, and two climate change scenarios, extreme and moderate. Scenario projections showed a decrease in overall (combined early freshwater marine) survival by 2050 for all three studied salmon populations. None of them are likely to survive in scenarios with extreme climate change, while scenarios with moderate climate change showed positive survival rates although lower than present-day baseline levels. Analysis also showed that land use management within the Cowichan River watershed can also affect freshwater survival of both Chinook and Coho and marine survival of Chinook through influence of river discharge on nearshore processes. However, our land-use management scenarios have considerably weaker effect than climate change on salmon survival. Therefore, we conclude that land use management alone is not sufficient to offset effects of climate change on salmon survival.

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Glossary

Term	**Definition**
Cumulative Effects	Effects caused by interactions of multiple human activities and natural processes that accumulate over space and time (CCME, 2014).
Drivers	Human or environmental activities or processes that generate or influence stressors (Nelson et al., 2006).
Effect	Change in environmental component's state or functionality caused by an action of a stressor (Judd et al., 2015).
Effect indicator	Measurable parameters of an environmental component that can be used to describe its state and functionality (BC EAO, 2013).
Environmental Component	An essential element of the natural environment. It can be an ecosystem, habitat, habitat, or a habitat property, physical or natural resource, species, group of species (guild) etc. (Hegmann et al. 1999).
Force	Human or natural superior phenomena behind drivers, that directly or indirectly cause large ecosystem changes (Laurent et al., 2015).
Scenario	Defined version of a possible future (Peterson et al., 2003)
Sensitivity	Characteristics of an environmental component (also termed vulnerability) that makes it susceptible to harm caused by exposure to a stressor (De Lange et al., 2010)
Stressor	Changes in environmental conditions that trigger an environmental component's physiological or behavioral responses and affect component's state or functionality (Selkoe et al., 2015)
Thresholds	A limit of exposure of an environmental component to environmental conditions beyond which even a small change in these conditions generates rapid change in component's state or functionality (Selkoe et al., 2015)
Valued Component (VC)	Environmental component that are of concern to the public, Aboriginal peoples, and/or government(s) and may be affected by projects, policies or other developments (BC EAO, 2013).

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Dedication

To my family, Aciemme and Deniza, who worked with me on this dissertation, and Archie, who cheered for me and patiently waited until I finish.

Chapter 1. Introduction

In Canada, environmental management of new projects over a certain size and complexity is primarily handled through the Environmental Impact Assessment (EIA) process. The EIA process is used as an instrument to protect the environment and public from any significant potential adverse effects; to influence the decision making of projects during planning stages so design of the projects mitigates adverse effects; and facilitate sustainable development (Barrow., 1995; Weaver et al., 2008).

The single-project EIA format has been shown to have low effectiveness at the policy and planning levels and in achieving sustainable development since the assessment is limited in space (extent of project-related effects) and time (life of the project) (Burris & Canter., 1997; Connelly 2011; Jay et al., 2007). Cumulative Effect Assessment (CEA) was developed and has been a mandatory part of EIA since 1979 in the USA and 1995 in Canada (Canter and Ross, 2010; Connelly., 2011).

CEA "is a systematic process of identifying, analyzing, and evaluating cumulative effects", which are defined as "changes in the environment caused by multiple interactions among human activities and natural processes that accumulate across space and time" (CCME, 2014). In other words, while an individual effect may be minor, when combined with other effects a significant environmental impact may be created. CEA normally conducts assessments over larger spatial (an ecological region, a bay, etc.) and temporal (beyond the life of the project) scales; evaluates all actions and projects within the assessment boundaries and their combined effects; and assesses significance of project effects in consideration of other effects (CEAWG, 2014; Hegmann et al., 1999). In other words, a proposed project has to be evaluated in the context of combined effects of all developments and processes on the ecosystem component under evaluation.

The term “cumulative effects” was first mentioned in 1973 (Canter & Ross, 2010) and initially was not widely used. There was no legal requirement for consideration of cumulative effects until 1979, when the importance of cumulative effect assessment was recognized, mainly due to failure of short-term impacts assessment to address objectives of sustainable development (Burris and Canter, 1997; Connelly, 2011;). Even after the introduction of the legal requirement for cumulative impacts assessment, also referred to as cumulative impact assessment, in the USA and Canada, proper attention was not paid to CEA until the late 1990s due to the absence of an acceptable framework or methodologies to implement these concepts (Burris & Canter, 1997; Canter & Ross, 2010; Connelly, 2011) and, simply, for lack of commitment from regulators (Burris & Canter, 1997).

Currently, CEAs in Canada mainly follow a *Cumulative Assessment Practitioners’ Guide* (Hegmann et al., 1999) published by the Canadian Environmental Assessment Agency (CEAA). This guide is similar to a guide published by the Council of Environmental Quality in the US a year earlier (Canter & Ross, 2010). Similar frameworks exist in other countries including, but not limited to, the European Union countries, Australia, and South Africa (Canter & Ross, 2010; Therivel & Ross, 2007). In general, the cumulative assessment framework can be condensed to the following steps:

- Initiate the CEA process by identifying direct and indirect effects of the proposed project on the selected valued components (VCs). VCs are biophysical, economic, social, heritage and health properties of the environment that are considered important by the proponent, public, First

Nations and government agencies, and the scientists involved in the assessment process and have the potential to interact with a project ((BC EAO, 2013; Milne & Bennett, 2016; Noble & Christmas, 2008).

- Identify other past, present, and reasonable foreseeable future actions within the space and time boundaries that could contribute to cumulative effects on the VCs.
- Assemble appropriate information for each VCs including their historic, current and potential future conditions.
- ‘Connect’ the proposed project and other projects or actions in the CEA study area to the selected VCs and their indicators.
- Assess the significance of the cumulative effects on each VC over the study temporal boundaries.
- Develop mitigation measures for each significant cumulative effect. Consideration should be given to multi-stakeholder collaboration to develop joint cumulative effect mitigation measures (Canter & Ross, 2010).

Ideally, CEA would be “an Environmental Impact Assessment (EIA) done well” (Hegmann et al., 1999), and the “best way” to achieve sustainable development (Senner, 2011) is the use of CEA in Sustainable Development Plans and Strategic Environmental Assessments (Canter & Ross, 2010; Connelly, 2011). It is recognized that CEA, when performed properly, can offer a means to evaluate the sustainability of alternative actions and their potential long-term environmental effects (Senner, 2011).

Unfortunately, current practice of CEA preparation, particularly in project-level EIA, mostly fail to assess cumulative effects properly and do not meet the goal of guiding sustainable development for several reasons. CEA in project-level EIA is, from the proponents' standpoint, a regulatory stepping stone. The main focus of the assessment, therefore, is to obtain project approval rather than to address sustainable development within the region of operation. As a result, CEA is often treated as a "rubber stamp" exercise and inadequate attention and resources are usually allocated to the assessment of cumulative effects (Handysides, pers. com., May 2016).

When preparing EIAs, practitioners tend to be narrowly focused on project-specific effects and, therefore, wider regional issues may be overlooked. CEAs are typically prepared to predict project-specific residual effects on VCs and in other cases, CEAs only assesses cumulative effects of other activities within the assessed region, which have effects similar to the residual effects determined for the project that prepares the CEA. Ecosystem components for which no project-specific residual effects are predicted, therefore, are not assessed in a context of cumulative effects from actions and developments other than those related to the project under review.

When assessing cumulative effect significance, project proponents usually evaluate effects generated by the project against the combined effects from all activities within the defined spatial and temporal boundaries. They rate project-specific effects as percentage of the combined cumulative effects and assign significance based on this percentage. Any cumulative effects are expected to be rated as "insignificant" and therefore ignorable (Sinclair et al., 2016).

Project-related EIAs typically also lack mechanisms to quantify the existing state of the environment especially at scales broader than project areas. This results in the assessment of potential effects on poorly characterized baseline conditions (Dube, 2003). Furthermore, often proponents have inadequate information about other projects in the region and their environmental impacts (Therivel et al., 1992).

Despite the shortcomings of CEA as practised in project-level EIAs, CEA has a high potential to be used as a development planning tool at larger geographic, administrative or ecosystem scales. This potential can be realized through initiatives that promote the use of CEA outside EIA process. These are usually CEAs conducted on a broader, regional environmental management level (Dube, 2003) with a focus on characterization of environmental effects from multiple stressors.

These initiatives usually use methods different from those used in project-based CEAs. Fisheries and Oceans Canada (DFO) recognizes four methods of CEA: activity-based, stressor-based, species- or habitat-based, and area-based (Murray et al., 2020). Activity- and stressor-based methods are primarily top-down approaches, species- or habitat-based are bottom-up approaches, while area-based assessment that can incorporate elements of both approaches.

CEAs within project-specific EIAs mainly use stressor-based (S-B; top-down) methods where the emphasis is on local, project-related stressors and their links with environmental indicators (or valued components (VCs)), and the potential for environmental effects is assessed through stressor-indicator interactions (Dube, 2003). One of the main deficiencies of the S-B method is that environmental effects may be underestimated if, as is often the case, project stressor/environment linkages are not fully understood (Drouinn & LeBlanc, 1994; Hegmann et al., 1999; Munkittrick et al., 2000).

When used at regional levels as a decision-making tool, CEA practitioners often use effects-based (E-B; bottom-up) methods. The E-B method identifies and assesses effects on a particular VC over broad spatial scales that may occur due to a potential stressor or interactions of multiple stressors (Cairns, 1986; Munkittrick et al., 2000). The effect endpoints or effect indicators in this approach are not stressor-dependent but are essential properties that respond to multiple stressors (Lowell et al., 2003).

Examples of regional initiatives are the British Columbia Cumulative Effects Framework (CEF, 2014), the Northern Rivers Ecosystem Initiative (Dube et al., 2006) and the Moose River Basin study (Munkittrick et al., 2000). These are multi-stakeholder research initiatives that were conducted for specific areas or watersheds on regional or national levels. In addition to geographic unit-focused approaches, DFO also conducts assessments of Species at Risk, e.g., the St. Lawrence beluga whale study (Williams et al., 2017) and Northeast Pacific resident killer whale populations study (Murray et al., 2019) which may or may not be regional in nature.

In British Columbia, the Cumulative Effects Framework (CEF) was initiated as an important part of the Integrated Decision-Making and the Natural Resource Sector Transformation initiative (CEF, 2014). CEF takes a strategic approach to assessing and managing cumulative effects and its intention is to conduct CEA in the areas where no projects are proposed that are reviewed under federal or provincial jurisdictions. The purpose of the Framework is to allow management of the resources not on project-by-project basis but on a regional basis. One of the key components of CEF is identification of priority values and assessment of their future conditions and making this information publicly available as a powerful decision support tool (CEF, 2014; MLNFO, 2014). CEF has several priority values that it focuses on, including forest ecosystem biodiversity, priority fish and wildlife species, water quantity and quality, cultural heritage resources, etc.

CEF identifies forecasting of the future and its implications for the values as a critical element of the assessment (CEF, 2014). The potential future conditions assessed under CEF include the foreseeable future (5-10 years) and the long-term future (50-100 years). Under CEF, CEAs are conducted for large regions by regional teams. The regional assessments conducted up to date include the Merritt Operational Trail CEA (Valdal & Lewis, 2015) and the Cariboo-Chilcotin Broad Scale CEA (Dawson et al., 2015).

Another example is the DFO's Beluga Whale study that assessed cumulative effects on a single species from multiple stressors, such as loss of prey, underwater noise and disturbance, and chemical pollution (Williams et al., 2017). The purpose of the study was to predict the response of the beluga population to cumulative changes in environmental conditions in St. Lawrence Estuary.

The regional based CEAs, however, have not become a keystone practice because they are mostly promoted by multi-stakeholder initiatives (Culp et al., 2000; Dube, 2006; Munkittrick et al., 2000). Unlike project-based studies, regional, species or ecosystem-based CEAs, with some exceptions (e.g., Species at Risk Act requires species-based CEA for certain species or ecosystem-based CEA applied to 'critical habitat' (Murray et al., 2020)), have no legislative mechanisms to make them compulsory (Culp et al., 2000; Dube, 2006; Munkittrick et al., 2000). The Canadian *Impact Assessment Act* of 2019 places a higher emphasis on regional impact assessments that the previous act, but no obligatory conditions or commitment are stated in the new *Act.*

Strategic Environmental Assessment (SEA) is another process that is aimed to conduct the EIA process at the policy or planning levels and increase its effectiveness on a larger scale (Pope et al., 2013). SEA is a strategic initiative assessment for policies, plans and programs usually initiated by governments to identify potential environmental concerns associated with proposed governmental or industry actions before EIA processes take place. Some SEAs focus on specific industry sectors (e.g. offshore wind or tidal production), a particular type of activity (e.g. offshore oil and gas exploration and development), or are focused on a range of different activities in a certain geographic area (Azcarate et al., 2013; Doelle et al., 2013; Lee & Walsh, 1992). The differences between CEA and SEA are often blurry (Pope et al., 2013) and they are usually interrelated; for instance, the Canadian Council of Ministers of Environment (CCME, 2009; Noble & Harriman, 2009) in the document outlining principles and guidance of the Regional SEA in Canada states that assessment of cumulative environmental effects is a component fully integrated into the SEA process.

Typically, CEAs tend to focus on a single scenario of future development based on conditions of the past, present or short-term future. However, these types of predictions of future effects based on one “most likely future” have a high potential to be wrong (Duinker & Greig, 2007). To address this issue, a scenario analysis methodology was proposed to shift assessment from a narrow-focused short-term future forecast towards longer-term perspective (beyond 5 to 10 years) and wider range of possible futures (Cornish, 2004; Duinker & Greig, 2006; Duinker & Greig, 2007; Greig et al., 2004). For example, the Northeast Pacific killer whale CEA (Murray et al., 2019) looks at various scenarios for different levels of shipping/noise in the Strait of Georgia, prey availability, etc., and projects these for 100 years into the future using population viability modelling.

In the context of assessing future impacts, a scenario is “a structured account of a possible future” and differs from a forecast because it takes into consideration uncertainties outside of the decision makers’ control (Peterson et al., 2003). The development of a scenario involves looking beyond the expected outcomes, both positive and negative, at the unexpected possibilities under different circumstances and defining the most suitable mitigation strategies in response to them. (Duinker & Greig, 2007). Scenario analysis must include the processes of creation and assessment of a number of alternative reasonable (not incredible) situations, distinctly different in causes and outcomes one from another (Schwartz, 1996). The scenario analysis should not be mistaken for a forecast. Assigning likelihood or probabilities to the scenarios should be avoided (Duinker, 2008).

Durance and Godet (2010) distinguish between two main kinds of scenarios, exploratory and normative. Exploratory scenarios use analysis of past and present trends to construct likely futures. Normative scenarios work from alternative pictures of the future, which may be both desirable and undesirable, and are formulated in a retro-projective way. Thus, exploratory scenarios are not based on societal values, whereas normative scenarios are. These two types of scenarios can be either highly similar or highly contrasted to one another, depending upon whether they are based on the most probable or the most extreme trends respectively.

The idea of different scenarios was first introduced by Herman Kahn at RAND Corporation who developed several prognoses for the directions the world was heading in the last quarter of the 20th century. He based these prognoses on various scenarios radically different in key events (Kahn & Weiner., 1967; Peterson et al., 2003). His work was further developed by researchers at Stanford Research Institute (Hawken et al., 1982) and analysts at Shell Oil corporation (Peterson et al., 2003). Scenarios have been used in the strategic decision-making process in business, politics, regional socio-economic and land use development, climate projections and various other institutional levels around the world.

Scenario analysis is used in environmental decision-making and strategic planning on global, large regional or sectoral scales. For instance, climate change projections, based on emissions scenarios, are used as plausible representations of future climate and used to investigate the potential impacts of climate change (Moss et al., 2010). It includes three phases: development of the Representative Concentration Pathways (RCPs) used to project the magnitude and extent of climate change (Taylor et al., 2012; Van Vuuren et al., 2011); development of RCP-based climate change projections and socioeconomic reference scenarios with quantification of population and income development; and integration of RCP and development of community-based scenarios (Van Vuuren et al., 2014).

CCME (2009) promotes evaluation of cumulative effects from multiple sectors under different scenarios within the Regional SEA process with the objective to inform a preferred development strategy for regional environmental management planning. A methodology of scenario development is however, not addressed in the document.

Duinker and Greig (2007) offer a rationale for using scenario-based methods in EIAs and CEAs based for forest management. In Canada, many public-land forest planners are required to project wood supplies based on forecasts of future forest conditions for 80 to 200 years. Some of these forecasts are based on sophisticated numerical models, which are, most of the time, driven by empirically-obtained knowledge of forest succession, response to treatment and natural disturbances, such as fire and storms. These models, however, omit the timber-market situation which can change rapidly. Neither do they consider climate change which can significantly alter patterns in tree reproduction and growth. Scenario-based approaches may offer a way of dealing with some of the uncertainties associated with the development of long-term predictions.

Climate change can be a significant factor in determining the direction which various large-scale projects today may take going forward. A scenario-based approach may offer the possibility to develop an appropriate mitigation strategy to address such impacts. Duinker and Greig (2007) stress the importance of considering a climate change scenario in an example of planning a hydroelectric project with design life-time of 50-100 years proposed in northern Manitoba. Climate change may completely change the region's annual rainfall periodicity and distribution, thus seriously affecting viability of the project.

There are different approaches to the number of scenarios to be developed. Cornish (2004) suggests that the ideal number of scenarios considered is five, including optimistic, pessimistic, surprise-free (continuation), disastrous, and transformation (miracle) scenarios. Creed and Laurent (2015), Duinker (2008) and Laurent et al. (2015) propose an approach where scenarios are built on a futures plane defined by two orthogonal axes, which represent two major forces, one defined by environmental (or environment-economy) changes, the other by human attitudes or values.

The present research proposes an alternative approach to CEA by combining several methods discussed above with the purpose of making the process more substantive and quantitative. The main approach of this methodology is the application of quantitative modeling on scenario assessment. A quantitative approach is valuable because it provides a more reliable and repeatable process for assessing the impacts of multiple stressors on VCs. Since each scenario outcome is quantitative, e.g., projected probabilities of effects on the VC, numeric effect indicators, etc., they are comparable to each other or to the base scenario representing present-day conditions (baseline condition) and the rating for each scenario can be based on an overall effect size. At the same time the approach must be simple enough so it can be used by a practitioner without specialized knowledge in various disciplines. In this dissertation this methodology is tested on an example of the Cowichan River watershed with two salmon species selected as VCs. The objective of the case study is to demonstrate whether the CEA process of building and application of simplistic modeling and scenario assessment approach works on VCs with a complex life history, Pacific salmon. The following are the main elements of our study:

- The assessment is effect-based. It first identifies effect pathways and effect stressors for two anadromous salmon species native to Cowichan River, fall Chinook (*Oncorhynchus tshawytscha*) and Coho (*O. kisutch*), and based on that recognizes effect drivers and forces behind the drivers.
- The effects pathways and effects are studied in both freshwater and marine environments.
- We develop pathway models that predict future of each of our VCs.
- Scenario analysis is used to assess effects from a range of alternative futures that are logical projections of our selected forces.
- The assessment is quantitative or semi-quantitative and allows for numerical comparison between different scenarios.

The scenario analysis is aimed to detach the assessment from trying to predict the most probable future and shift it towards developing responses to the question “what if?” applied to a wide range of plausible alternative futures and motivating preparedness for uncertainties outside our control rather than confidence in a given forecast based on a single future.

The remainder of the dissertation is organized as follows: Chapter 2 will use the methodology to assess impacts of climate change and land cover change on survival of the two salmon species during the early life stages in the freshwater environment. Chapter 3 will provide a similar assessment of salmon survival using the same methodology but for the marine environment phase of the species life cycle and chapter 4 will provide the description of the methodology and will show how the methodology can be used to combine these models into a scenario analysis and more complete CEA. Chapter 5 will present a conclusion.

Chapter 2. Modeling Future Scenarios of Cowichan River Chinook and Coho Early Life Freshwater Survival

Article Information

Chapter 2 has been prepared as a manuscript for submission to a journal.

Abstract

Our study conducted cumulative effects assessment on freshwater survival of two Cowichan River anadromous salmon species, Chinook and Coho using scenario analysis. The assessment was focused on impacts from land use and climate change through two physical properties of water: stream temperature and discharge that were deemed the most influential factors for salmon freshwater survival. Four future scenarios for 2050 were created by combining two opposite scenarios of land use in the watershed, forest conservation and development, and two climate change scenarios, more extreme and moderate. Discharge and stream temperature conditions were projected using hydrologic and regression models developed using historical discharge, stream temperature and weather data. Salmon survival was projected using two models: a statistical model using Pearson correlation and stepwise regression based on historic Chinook data that links freshwater survival to changes in temperature and discharge, and a literature-based temperature and discharge threshold model. Chinook survival was projected using both models, while Coho survival was estimated using the threshold-based model only, because no Cowichan River-specific data on Coho survival was available. All four future scenarios showed a decrease in Chinook freshwater survival from the baseline level of 5.58%. Chinook future freshwater survival ranged from 1.64% in the most pessimistic scenario to 4.38% for the most optimistic scenario. Coho projected freshwater survival ranged from 1.98% to 3.01% as compared to the 2.75% literature-based baseline. Scenarios with extreme climate change resulted in more negative impacts on salmon survival compared to scenarios with

moderate climate change; scenarios with development-oriented land use resulted in more negative effect on salmon freshwater survival than conservation-oriented land use scenarios. At the same time land use showed a weaker effect on salmon freshwater survival compared to climate change, indicating that land use management alone would not be sufficient to mitigate effects from climate change on salmon freshwater survival.

2.1 Introduction

This study aimed to develop and apply a predictive model for assessing cumulative effects using scenario analysis on the early stages of two Cowichan River watershed anadromous salmon populations: fall-run Chinook (*Oncorhynchus tshawytscha*) and Coho (*O. kisutch*). We developed plausible different future scenarios that combined global effects (climate change) and local changes (watershed management), and predicted the likely impacts resulting from consequences of these effects on the survival of the two populations. The purpose of applying different scenarios is to provide new insights into the interaction between global and local effects that can be used by policy makers, to enable strategies and planning that will help to increase salmon survival rates towards desired outcomes.

Water discharge and temperature are considered to be the most important factors in freshwater success and survival of anadromous salmonids (Sandercock, 1991). Salmon metabolism, feeding rates, growth, embryo and larvae development, timing of migration, spawning, freshwater rearing, seaward migration and food availability are all influenced by ambient water temperature. High temperatures can block salmon migration, impede growth and reproduction, inhibit smoltification, increase risk of diseases, cause physiological stress and mortality (Carter, 2005; USEPA, 2001; Richter & Kolmes, 2005). Therefore, changes in stream temperature may be detrimental to salmon freshwater survival, particularly in early life stages.

River discharge fluctuations are also reported to correlate with overall salmonid success (Smoker 1953; Groot and Margolis 1995). Low summer flows are shown to reduce rearing habitat causing stranding of juvenile fish in isolated pools, thereby increasing their vulnerability to diseases and predation (Cederholm & Scarlett, 1981). Extreme winter floods have negative effects on the survival of salmon eggs and juvenile salmon (Burt, 2002; Greene et al., 2005; McKernan et al., 1950; Narvel 1978, as in in Sanderkock, 1991; Seiler et al., 1998, 2003), as excessive flooding can cause scouring of redds, crushing of eggs by gravel, and sediment deposition on eggs (Holtby & Healey, 1986; Montgomery et al., 1996; DeVries, 1997; Lotspeich & Everest, 1981). High floods reduce the availability of of slow-water habitats and cause displacement of juveniles downstream from their rearing habitats (Latterell et al., 1998). Habitat disruption by flooding also causes loss of food in the longer-term since it dislodges stream insects from gravel (Mundie, 1969).

At the same time there is compelling evidence that anthropogenic changes on both global and local scales impinge upon river streamflow and temperature (e.g., IPCC, 2013), thereby indirectly influencing salmon reproductive success and survival. At the global scale, streams are affected, to varying degrees, by changes in atmospheric temperature and precipitation, while on the local scale changes are caused through watershed management, such as land use and land cover change. Therefore, future survival and success of freshwater fish populations are dependent on the combined impacts of global-scale climate change and local-scale management and human behaviour.

In our scenarios we used combinations of opposing scenarios of climate change as a global driver and opposing scenarios of land use as a local driver. We used a hydrological model developed for the Cowichan River and statistical analysis to predict the influence of each scenario on river discharge and stream temperature and, consequently, on early-stage survival of the two salmon populations in the freshwater environment.

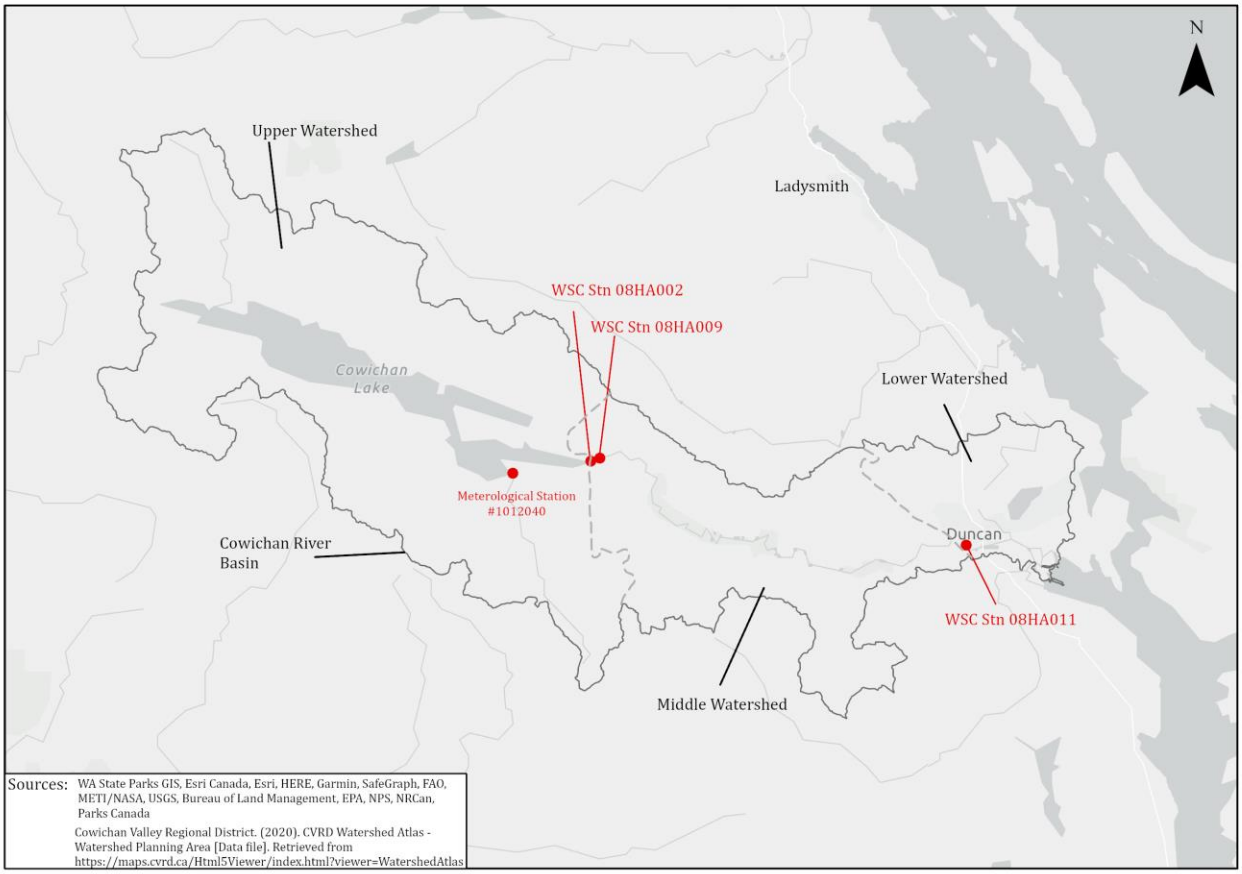
Many different factors potentially affect salmon survival and success, including stream management, habitat restoration, population enhancement, etc. (Burt & Roberts, 2002; V.Komori & Assc., 2010). However, given the constraints imposed by data availability and compatibility, for this study we only focused on mechanisms that affect the two physical properties of water deemed the most influential in salmon early-stage survival, i.e., discharge and temperature. The decision to limit the number of physical factors to be investigated was also made for simplicity and practicality. In practice, practitioners of environmental assessments are more likely to undertake models that focus on a few important factors than a suite of many factors. Also, decisions and human drivers that influence salmon populations directly, such as fishing, and fisheries management and conservation measures (fishing restrictions or habitat restoration) were deliberately not considered in this assessment but could be added to the analysis in the future.

2.2 Materials and Methods

2.2.1 Study Area and Populations

2.2.1.1 Study Area

The Cowichan River runs in the southeastern part of Vancouver Island, British Columbia and discharges into the Strait of Georgia. The total watershed area of the river is 930 km^2. The headwaters are in a mountainous area in the western part of the watershed with a maximum elevation of 1483 m. At the head of the river there is Cowichan Lake at an elevation of 162-165 m above the sea level. The surface area of Cowichan Lake is approximately 62 km^2 and its length from west to east is approximately 31 km. The river flows from Cowichan Lake for approximately 45 km and discharges into Cowichan Bay on the eastern shore of Vancouver Island.



Sources: WA State Parks GIS, Esri Canada, Esri, HERE, Garmin, SafeGraph, FAO, METI/NASA, USGS, Bureau of Land Management, EPA, NPS, NRCan, Parks Canada

Cowichan Valley Regional District. (2020). CVRD Watershed Atlas - Watershed Planning Area [Data file]. Retrieved from https://maps.cvrd.ca/Html5Viewer/index.html?viewer=WatershedAtlas

Figure 1 Cowichan River Watershed Showing Watershed Divisions with Three Water Survey Canada (WSC) Hydrometric Stations.

The river flow is regulated through the weir at Cowichan Lake owned by Catalyst Paper. The purpose of the weir, as stated in the water license, is to hold water in the lake to maintain a minimum flow of 7.08 m^3/s in summer, while allowing water to overflow it freely in winter. Normally, storage and controlled release of water from the lake begins some time between late March and early May when water stops passing over the top of the weir. After that, water is released through the weir gates in a controlled manner to allow water storage to last through the summer and maintain the minimum required flow. The weir discharge level below which water from the lake is pumped into the downstream river to provide enough fish habitat is set by

Fisheries and Ocean Canada (DFO) at 4.5 m^3/s, even though historically river discharge has fallen as low as 3 m^3/s (B. Houle, pers. com., January 29, 2020). The water license also allows Catalyst Paper to withdraw 2.83 m^3/s for the Crofton Pulp Mill and drinking water for the town of Crofton.

For the purpose of this study, the entire watershed was divided into three areas: the upper, middle and lower regions. The upper watershed included areas that drain into Cowichan Lake; the middle watershed included the basin of Cowichan River from below the lake dam to a hydrographic station at the City of Duncan (08HA011); the lower watershed encompassed areas below the hydrographic station to the river estuary.

2.2.1.2 *Salmon Populations and Their Resource Needs*

Anadromous salmonid populations in Cowichan River mostly consist of fall Chinook (*O. tshawytscha*), Coho (*O. kisutch*), chum (*O. keta*), and winter-run steelhead (*O. mykiss*) salmon, and smaller presence of sea-run cutthroat trout (*O. clarki*) (Burns et al., 1988). There are also rarer populations of summer-run Chinook, as well as sockeye (*O. nerka*) and pink salmon (*O. gorbuscha*) with the latter occurring in the lower Cowichan River. Resident freshwater salmonids include indigenous populations of rainbow trout (*O. mykiss*), cutthroat trout (*O. clarki*), Dolly Varden char (*Salvelinus malma*), landlocked sockeye salmon (kokanee) in Cowichan Lake (Burt & Wightman, 1997) and brown trout (*Salmo trutta*) that was successfully introduced in the 1930s (Lill et al., 1975). Other introduced species in the watershed include three-spine stickleback (*Gasterosteus aculeatus*), prickly sculpin (*Cottus asper*), pumpkinseed (*Lepomis gibbosus*), and various lamprey species (*Lampetra* spp.) (Hanelt, 2002, as in V.Komori and Assc., 2010).

The two anadromous salmon populations that we considered in our study, fall Chinook and Coho, have slightly different freshwater adaptation strategies. Both start their major spawning migration in mid-October when a large increase in streamflow occurs (to approximately 15 m^3/s) with spawn taking place mostly in November through December (Lill et al., 1975; Neave, 1943; Tompkins et al., 2005). Both species lay eggs in gravel beds (redds) in the middle watershed, particularly in the upper 12 km of the river below the lake, which is also the location where most juvenile rearing occurs (Burt & Robert, 2002; Bert et al 2005; Lister et al. 1979; Nagtegaal and Riddell 1998; Pellet, 2017).

Chinook egg incubation, hatching, and larvae (alevin) stages in Cowichan River continue through the winter until the end of February with the main juvenile (fry) emergence occurring in March, although some (later group) emergence may continue until May (V. Komori and Assc., 2010). Cowichan Chinook fry spend a relatively short time (less than 90 days; Craig, 2015) in the river and the majority (early group; 85%) migrate to the lower river/ estuary from April through May. The second, much smaller group (15%) migrate to the estuary in May/ June (Candy et al., 1995; Healey, 1991; Nagtegaal et al., 2004). Chinook smoltification (adaptation to ocean life) occurs in the estuary where Chinook first rear in the shallows (April and May) and then in deeper sections (June to August) before migrating to nearshore marine areas of the Gulf Islands in the Strait of Georgia in June to September (Atkinson & Pellett, 2018; Thakur et al., 2018;).

Coho spend their early stages from egg fertilization through emergence through the winter months, with slightly shorter incubation and alevin periods compared to Chinook (Atkinson & Pellet, 2018; Craig, 2015; Pearce et al., 2020). Unlike Chinook, Coho juveniles, first as fry, then in stages called parr, spend a full year in the freshwater, from March of the emergence year to April of the following year with smoltification and outmigration peaking a month later in May.

2.2.2 Physical Modeling

2.2.2.1 Hydrological Model

We developed streamflow predictions for our future scenarios using a daily time-step hydrologic model built using Microsoft Excel software that uses basic water balance methodologies (Feddema et al., 2013; Mather, 1978; Savage et al., 1996; Thornthwaite 1948). The model estimated streamflow using meteorological input data (air temperature and precipitation) by partitioning overland runoff from precipitation (Mather, 1978; SCS, 1972), estimating potential evapotranspiration (PET; Thorntwaite, 1948), snow accumulation, snowmelt (Willmott et al., 1985), soil moisture conditions, actual evapotranspiration (AET), moisture surplus and deficit conditions. The model incorporated Soil Conservation Service (SCS) curve number (CN) developed to calculate the proportion of precipitation that becomes overland runoff (Mather, 1978; SCS, 1972). Higher curve numbers represented higher runoff conditions, which depended on land cover type and antecedent rainfall conditions, with wetter conditions resulting in higher runoff. Standard CNs used were 60/78/90 for CN1/CN2/CN3 (Mather 1978; SCS, 1972); these numbers could be changed upward or downward depending on soil type and thickness, land use (e.g., forest vs urban) and other land cover and climatic conditions (Feddema et al., 2013). To simulate water flows for the entire watershed, the watershed was subdivided into three regions with each having soil water holding capacity and CNs based on topographic, land cover and soil conditions representative of each area. Other assumptions and considerations in the model included: adjusted proportions and time lags for both surface and groundwater flows that contributed to streamflow after a rainfall event; inclusion of a reservoir and lag of water flow across Lake Cowichan; and incorporation of seasonal human flow controls at the weir on Lake

Cowichan during the summer period (as specified in the water management plan). The model also allowed for representation of global and local climate scale temperature and precipitation projections that modified the daily input conditions and allowed for simulation of various climate related scenarios.

The model was calibrated by running it for a 31-year period (January 1st, 1980 to December 31st, 2010) using the daily observed maximum and minimum temperatures and precipitation from meteorological station Cowichan Lake Forestry (#1012040) located at the eastern end of Cowichan Lake, at an elevation of 176.8 m (https://data.pacificclimate.org/portal/pcds/map/). Elevation adjustments for temperature (lapse rate) and precipitation (percent change) inputs for the upper watershed were based on comparisons of data from station Jump Creek (1160 m). The model was validated by comparing the results to data from three Water Survey Canada (WSC) hydrometric stations that measure Cowichan Lake level (08HA009), discharge from Cowichan Lake to Cowichan River (08HA002) and Cowichan River discharge near Duncan (08HA011).

2.2.2.2 Water Temperature Model

Factors influencing maximum and mean water temperature in the Cowichan River were examined through correlation analysis against a number of weather and hydrologic variables. Cowichan River daily water temperature data from August 2000 to July 2012 were estimated from hourly data recorded by Catalyst Paper at a monitoring station near Duncan (B. Houle, pers. com., June 5, 2019). To estimate the water temperature, the same climate and discharge data used by the hydrological models were used as predictor variables. First, a Pearson correlation analysis was conducted between climate and discharge variables and water temperature and variables that showed higher correlation (R<-0.4 and R>0.4) with water temperature were used for further analysis. Further, variables that were likely to cause multicollinearity were detected using variance inflation factor (VIF) analysis and removed (maximum value for VIF cutoff was 10). In the final step, a backward elimination reverse stepwise linear regression analysis was used to determine the most statistically significant independent variables influencing water temperature. Backward elimination was chosen over the forward selection because in forward selection there is a potential that two or more variables that work best with each other will not be selected in the final model, or a regressor added at an early step may become redundant because of its relationship with regressors added later (Burt et al., 2009).

2.2.3 Biological Model

2.2.3.1 Chinook Survival Model

Data for Cowichan Chinook egg-to-fry survival rates in the Cowichan River were available for the period from 1990 to 2001 (Nagtegaal et al., 2004). This information formed the basis for determining a relationships between Cowichan River physical variables, such as discharge and stream water temperature, and Chinook freshwater survival. Egg-to-fry survival rates were calculated as a ratio of naturally-reared Chinook fry abundance in the river to an estimated number of eggs produced. The number of produced eggs was derived from the estimated number of Chinook female spawners (assuming a 1:1 ratio of female to male spawners) multiplied by an average fecundity of 4,024 eggs per female (Nagtegaal et al., 2004). We assumed that Chinook egg-to-fry survival is density independent (independent of egg/alevin density).

The examined physical variables expected to impact salmon survival included discharge data from the two hydrographic stations and stream temperature values obtained from the hydrologic model. The data investigated included monthly, annual, summer, winter and spring mean, maximum and minimum values for each parameter. Linkages between stream physical variables and Chinook survival rates were first evaluated using a Pearson correlation analysis and variables that showed higher correlation (R<-0.4 and R>0.4) with Chinook survival rates were used for further analysis. Variables were then tested for multicollinearity using variance inflation factor (VIF) analysis and were removed as appropriate (maximum VIF used for cutoff is 7). In the final step, a backward elimination reverse stepwise linear regression analysis was used to determine the most statistically significant independent variables influencing Chinook egg-to-fry survival. These variables were used for future survival modeling.

2.2.3.2 Environmental Thresholds

To simulate environmental impacts on salmon, we used the concept of environmental thresholds similar to climate envelope modeling (Feddema et al., 2013; Hijmans & Graham, 2006; Pearson & Dawson, 2003). We applied temperature and discharge thresholds to each phase of the two salmon species freshwater residence to determine their freshwater survival.

We defined two main phases of Chinook development in Cowichan River once spawning has occurred, incubation which occurs during winter (December to February), and fry rearing occurring mainly in March and April. We determined six phases in Coho freshwater residence from the first winter (egg incubation) to the second spring (smoltification).

The USEPA (2001) reports that there is little variation in salmonid temperature adaptation among different stocks regardless of their geographic locations due to insignificant genetic variations in this trait. Therefore, temperature thresholds found in literature are considered applicable for Cowichan River salmon stocks.

The first environmental criterion used in this study was maximum weekly maximum temperature (MWMT), which is one of the most commonly used metrics for assessing chronic and acute temperature exposure of salmonids (Carter 2005). The MWMT can be used for both sub-lethal and lethal effects; it is also known as the seven-day average of the maximum daily temperatures (7-DADM; Carter 2005).

We conducted a literature-based review of normal temperature ranges and thresholds for each life stage of freshwater residence of Chinook and Coho (Beacham & Murray, 1985; Bell, 1986; Brett, 1952; Brett et al., 1982; Burck 1993; Carter 2005; Flett et al., 1996; Hicks, 2000; Lill et al., 1975; McCullough et al., 2001; Murray & McPhail, 1988; Raleigh et al., 1986; Richter & Kolmes, 2005; Spence et al., 1996; Sullivan et al., 2000). Based on the review we develop Cowichan River-specific temperature thresholds for each stage of the two species (Table 1).

Table 1 Cowichan River Coho and Chinook freshwater normal development and survival thresholds.

Stage	**Timing**	**Temperature range (° C)**		**Discharge range (m^3/s)**	
		Lower limit	**Upper limit**	**Lower limit**	**Upper limit**
Chinook					
Incubation	December - February	2.0	12.0	4.5	212.0
Fry rearing	March - April	5.0	16.0	4.5	212.0
Coho					
Incubation	December-February	2.0	12.0	4.5	212.0
Emergence/ fry	March - May	4.4	16.0	4.5	212.0
Summer parr	June - September	4.4	24.0	4.5	212.0
Fall parr	October - November	4.4	24.0	4.5	212.0
Second winter parr	December - February	4.4	24.0	4.5	212.0
Second spring/ smolt	March - April	4.4	24.0	4.5	212.0

The second environmental variable used was river flow rates. The current minimum discharge level of 4.5 m^3/s set by DFO for Cowichan River was used as lower threshold for discharge for both species. It should be noted however that, due to the weir management, discharge from the lake into the river below was not expected to fall below the threshold level from April to October (Craig, 2015).

Flood volumes that were considered adverse for freshwater survival are not well documented in the literature compared to temperature-based thresholds. Discharge volumes that were adverse to early salmon survival seem to be watershed- and population-specific, probably due to differences in spawning and rearing ground morphology from one watershed to another. Beamer and Pess (1999) found that the impact on Skagit and Stillaguamish River Chinook juveniles was significant when peak flow was equal to or exceeded the 20-year flooding event. McKernan et al. (1950) stated that winter flooding had an impact on Coho spawning areas in Siletz and Coquile rivers in Oregon when the flow was 50% higher than the average flood. Effects of winter floods on Cowichan River eggs and juvenile salmon were not studied due to inaccessibility of spawning and rearing grounds in winter (V. Komori and Assc., 2010); however, Burt and Robert (2002) used 400% of the mean annual discharge (MAD) of 53 m^3/s, or 212 m^3/s, as a threshold for Cowichan River Chinook egg-to-fry survival. We assumed that Coho was not less vulnerable to winter floods than Chinook. Therefore, we used the same value as the upper discharge threshold in our study.

We assumed that exceedance of the discharge or temperature survival thresholds reduced salmon survival. We used a 31-year long model simulation of daily discharge and water temperature as input variables to estimate a survival probability. The probability of exceedance of the threshold at any stage was estimated as a ratio of the number of days when thresholds were exceeded to the total number of days of the stage over which the simulation is run. We used the term *survival* as a probability of simulated favourable environmental conditions (conditions within the thresholds) for each stage, estimated as follows:

$$Survival = \frac{Days\ within\ thresholds}{Total\ days},$$

or $Survival = \frac{Total\ days - Exceedance\ days}{Total\ days}$

Overall freshwater survival was calculated as the product of survivals of all freshwater stages.

We assumed that there are intrinsic mortality/survival rates for each stage of the salmon life cycle even if discharge and water temperature conditions are within the “normal” survival thresholds. Therefore, we applied our simulated survival rates based on environmental thresholds to these intrinsic survival rates.

In the case of Chinook, we used the survival rates predicted by the regression as the “intrinsic” rates and multiply them by the survival based on the thresholds. We do this because we assume that the observed independent variables used in the regression analysis of Chinook freshwater survival are within the normal survival thresholds and, therefore, the regression does not account for potential future threshold exceedances.

There was no long-term data available on Cowichan River Coho freshwater survival. Therefore, we used an average survival rate of 3.4% estimated from literature (Bradford et al., 2000) as an “intrinsic” Coho freshwater survival on which the estimated threshold-based survival rates are applied. The average literature-based survival rate was used for Coho to be consistent with Chinook for which threshold-based survival was applied to the regression-predicted average survival.

2.2.4 Scenario Simulations

Future mean Chinook and Coho freshwater survival rates were projected for 2050s by running the entire 31-year long hydrological and temperature models and applying the mean simulated discharge and temperature values to the survival models. The models were run for the existing baseline data (base scenario) and for each of the four future scenarios of projected climate and watershed management changes described in this section.

2.2.4.1 General Approach

The approach to scenario development was similar to that described in Duinker (2008), Creed and Laurent (2015) and Laurent et al (2015). Four scenarios were developed by combining two divergent scenarios for each of two forces. A local forcing driver was represented by land use management, and a global driver was represented by climate change (Figure 2). The local force, land use management, is related to demographic and socio-economic conditions that determine land development. Land use directly affects local hydrologic conditions, such as surface runoff and groundwater partitioning. The two opposing scenarios for local land use were conservation and forest restoration on the one side, and land development for logging, urbanization and agricultural uses on the other. The second force is climate change, which affects air temperature, precipitation, evaporation, runoff, and water temperature. The two opposing climate change scenarios depicted were a moderate and a more extreme changes in climate conditions, based on opposite extremes of the Representative concentration pathway (RCP) 8.5 Intergovernment Panel on Climate Change (IPCC) climate change projection (IPCC, 2014).

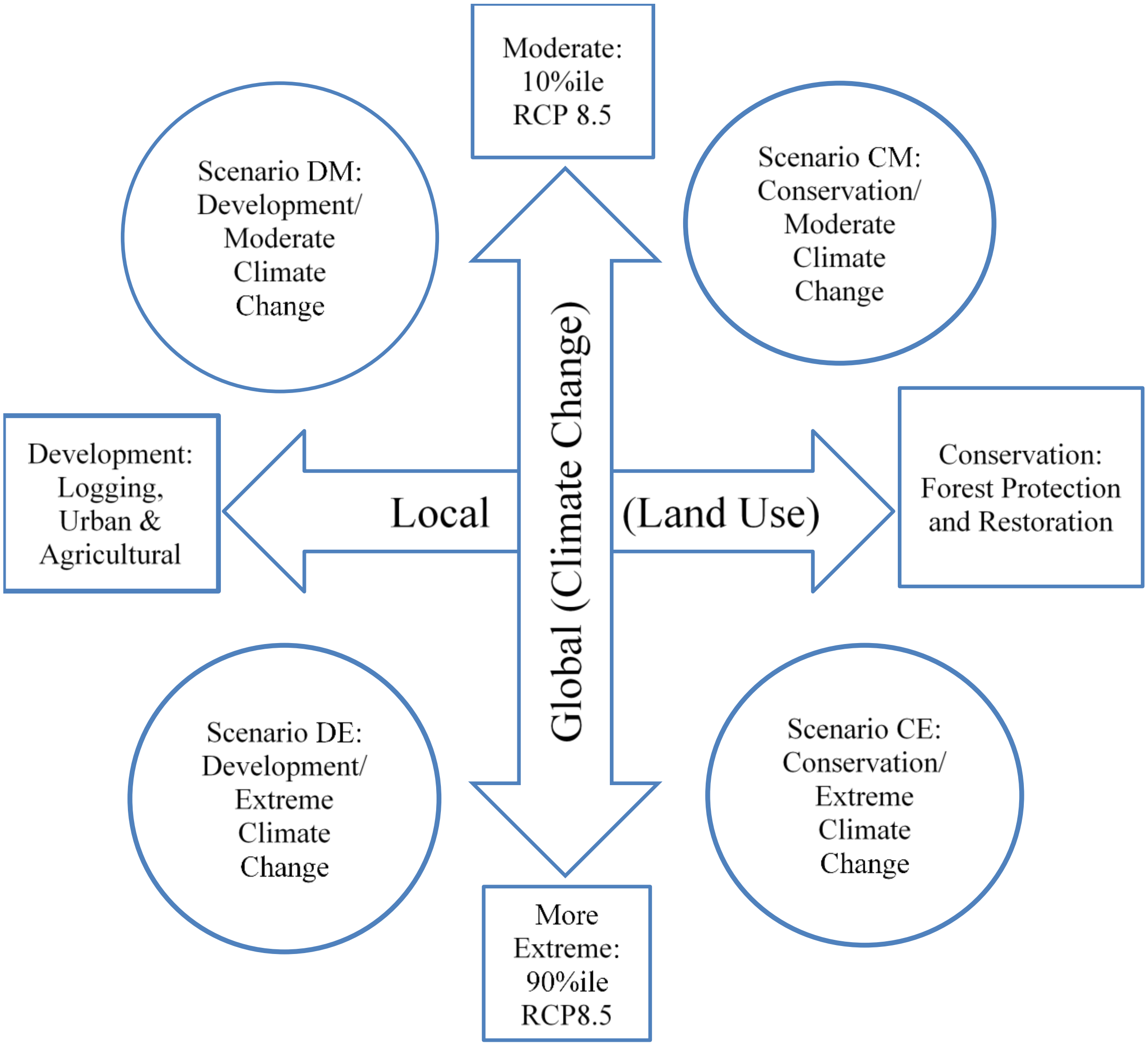


Figure 2. Future Watershed Development Scenarios

Thus, the four scenarios were forest conservation in combination with moderate climate change (Scenario CM), forest conservation and more extreme climate change (Scenario CE), land development and more extreme climate change (Scenario DE), and land development with moderate climate change (Scenario DM). Detailed description of the scenarios is provided in the following subsections.

2.2.4.2 Global (Climate Change) Scenarios

Climate change scenarios were based on Global Climate Models (GCM) projections using RCP 8.5 greenhouse gas emission scenario (Collins et al., 2013). For the *moderate* climate change scenario (the upper end of the Y axis in Figure 2), we used the 10th percentile values of 2050 climate projections based on the high-emission climate change scenario RCP 8.5, while the 90th percentile 2050 projections of the same RCP scenario were used for the more *extreme* scenario (the lower end of the Y axis). Projections representing two extremes of the same RCP scenario were selected because differences between the projected changes for two different RCPs (e.g., between RCP 8.5 and RCP 4.5 or RCP 2.6) present less variation compared to differences projected from the different models for the same scenario (e.g., Ishizaki et al., 2012; Loder & van der Baaren., 2013). The RCP 8.5 was selected because it represents the more realistic, "business-as-usual", scenario (IPCC, 2014).

Projected temperature and precipitation changes in 2050 were taken from the Pacific Climate Impact Consortium (PCIC; https://www.pacificclimate.org/) projections for British Columbia (Table 2). With one exception, 10th percentile projections of changes in temperature and precipitation were used for the moderate scenario of climate change, while for the extreme scenario we use the 90th percentile values. The exception was the projection for summer-time precipitation changes, the values for summer were reversed: the calculated 90th percentile projected change of 4.2% increase is a moderate change whereas the estimated 10th percentile change of 42% decrease is associated with warmer temperature and a more extreme scenario (PCIC, pers. com., August 11, 2020).

Table 2. Scenarios of changes in temperature and precipitation for Cowichan River valley for 2050 (PCIC).

Season	**Moderate Scenario (10%ile)**		**Extreme Scenario (90%ile)**	
	ΔT° C	**ΔP, %**	**ΔT° C**	**ΔP, %**
Winter (D-F)	1.8	-0.71	3.3	8.1
Spring (M-M)	1.7	-5.3	4.3	6.5
Summer (J-A)	2.0	2.8	4.2	-42.0
Autumn (S-N)	1.7	-6.4	3.8	12

2.2.4.3 *Local Management (Land Use) Scenarios*

The two local forces scenarios, *Conservation* and *Development*, represented two different directions for land use management. The former was directed towards forest restoration and an increase in forested land cover, and the latter leading to a decrease in forest cover due to increase in logging, as well as an increase in urban and agricultural land uses.

Currently, forest and dense vegetation occupy approximately 66% of the entire watershed area (Table 3; Foster & Allen, 2015). Most of the forest and densely vegetated areas (70%) are in the upper watershed (Table 4). The upper watershed also has most of the clear-cut areas of the entire Cowichan River watershed. In total, non-forested areas including clear-cuts, roads, urban/residential and agricultural areas make up approximately 27% of the entire watershed. Approximately 75% of the urban/residential areas are located in the lower watershed, while the middle and upper watersheds contain 21% and 4% of the urban/residential areas respectively (Tables 4 to 6). Agricultural lands currently occupy approximately 3.8% of the total watershed area and are mostly concentrated in the lower and middle watersheds (CVRD, 2016).

The Conservation Scenario

In this hypothetical scenario we envisioned a decrease in non-forested areas (urban/residential and roads) to a plausible minimum of 5% and an increase in forested land to a maximum of 87.8%, with the remaining 7.2% occupied by water. While the choice in land purpose transformation was purely arbitrary (e.g., conversion of all agricultural land into forest), we felt that this scenario was achievable without population relocation, e.g., through application of “green infrastructure” initiatives (Brears, 2018) that include measures to reduce surface runoff and increase groundwater recharge. More detailed land use distribution for this scenario and its comparison with the baseline conditions and the *Development* scenario is shown in tables 3 through 6.

The Development Scenario

The *Development* scenario for land use envisaged a maximum possible development of land within the watershed for logging, urban cover and agriculture. This meant a decrease in forest area to a minimum of less than one-third of the entire watershed area localized in the mountainous, hard to develop, areas in the upper watershed (Tables 3 through 6), and a greater extent of agricultural and urban areas in the lower portions of the watershed.

Table 3. Land Use Scenario Comparison for the Entire Watershed

	Baseline		**Conservation scenario**		**Development scenario**	
Type of land cover	**Area (km^2)**	**% of total**	**Area (km^2)**	**% of total**	**Area (km^2)**	**% of total**
Total watershed	930.0	100.0	930.0	100.0	930.0	100.0
Open water bodies	67.0	7.2	67.0	7.2	67.0	7.2
Urban areas	58.5	6.3	37.2	4.0	144.0	15.5
Clear-cut areas and roads	159.6	17.2	9.5	1.0	174.5	18.8
Agriculture	35.0	3.8	0.0	0.0	249.5	26.8
Forest and dense vegetation	609.9	65.6	816.3	87.8	295.0	31.7

Table 4. Land Use Scenario Comparison for the Upper Watershed

Type of land cover	Baseline		Conservation scenario		Development scenario	
	Area (km^2)	% of total	Area (km^2)	% of total	Area (km^2)	% of total
Total watershed	594.0	100.0	594.0	100.0	594.0	100.0
Open water bodies	62.5	10.5	62.5	10.5	62.5	10.5
Urban areas	2.5	0.4	1.6	0.3	42.0	7.1
Clear-cut areas and roads	102.1	17.2	6.0	1.0	120.0	20.2
Agriculture	3.3	0.6	0.0	0.0	159.5	26.9
Forest and dense vegetation	423.6	71.3	523.9	88.2	210.0	35.4

Table 5. Land Use Scenario Comparison for the Middle Watershed

Type of land cover	Baseline		Conservation scenario		Development scenario	
	Area (km^2)	% of total	Area (km^2)	% of total	Area (km^2)	% of total
Total watershed	232.0	100.0	232.0	100.0	232.0	100.0
Open water bodies	0.5	0.2	0.5	0.2	0.5	0.2
Urban areas	12.0	5.2	7.6	3.3	42.0	18.1
Clear-cut areas and roads	41.5	17.9	2.5	1.1	39.5	17.0
Agriculture	13.7	5.9	0.0	0.0	70.0	30.2
Forest and dense vegetation	164.3	70.8	221.4	95.4	80.0	34.5

Table 6. Land Use Scenario Comparison for the Lower Watershed

Type of land cover	Baseline		Conservation scenario		Development scenario	
	Area (km^2)	% of total	Area (km^2)	% of total	Area (km^2)	% of total
Total watershed	104.0	100.0	104.0	100.0	104.0	100.0
Open water bodies	4.0	3.8	4.0	3.8	4.0	3.8
Urban areas	44.0	42.3	28.0	26.9	60.0	57.7
Clear-cut areas and roads	16.0	15.4	1.0	1.0	15.0	14.4
Agriculture	18.0	17.3	0.0	0.0	20.0	19.2
Forest and dense vegetation	22.0	21.2	71.0	68.3	5.0	4.8

The parameters modified in the hydrologic model to represent the two land use scenarios were: SCS curve number, modifying the partition of infiltrated water to the soil or overland flow; water holding capacity, the ability of soil to hold water which changes with soil erosion, fractions of overland runoff and groundwater contributing to stream flow over time (days) from a precipitation event, rates of partitioning of water surplus to groundwater and the duration of these flows to the stream. These changes, in general, resulted in higher surface water runoff during precipitation events for the *Development* scenario and in higher rates of precipitation contribution to groundwater and longer water holding in the watershed for the *Conservation* scenario.

2.3 Results

2.3.1 Modeling

Calibration results of the hydrologic and water temperature regression models showed that both models had high explanatory power. Validation statistics based on Legates and McCabe (1999) and Willmott et al. (1985, 2012) are shown in Table 7. The lake level and river discharge calibration results were similar to those of a previous modelling conducted for the watershed (Foster & Allen, 2015).

The stepwise temperature regression analysis showed that both mean and maximum daily stream temperatures were highly dependent ($p < 0.05$) on 20-day average air temperature (direct correlation) and average daily discharge (inverse correlation). Regression analysis coefficients and P-values are shown in Table 8.

The stepwise linear regression selected maximum water temperature in December and mean annual monthly maximum water temperatures of the brood year as factors significantly affecting Chinook egg-to-fry survival (Table 8). The regression shows high explanatory power ($R^2 = 0.74$; Table 7).

Table 7. Hydrological, stream temperature and Chinook egg-to-fry survival model calibration and goodness-of-fit statistics (Legates and McCabe (1999); Willmott et al. (1985, 2012)).

Modeled parameter	**Obs. mean**[1]	**Obs. MAD**[2]	**Pred. mean**[3]	**Pred. MAD**[4]	**MBE**[5]	**MAE**[6]	**d_r**[7]	**R^2**[8]
Cowichan Lake level	155.9	6.30	162.50	0.40	6.58	0.21	0.98	0.76
Cowichan Lake discharge	44.30	33.5	44.60	35.60	0.26	10.91	0.87	0.85
Cowichan River discharge at Duncan	52.40	43.00	54.80	46.30	2.39	14.62	0.87	0.85
Mean daily stream temperature	11.90	4.80	11.90	4.60	0.00	0.99	0.91	0.94
Maximum daily stream temperature	12.50	5.00	12.50	4.90	0.00	1.07	0.91	0.94
Chinook egg-to-fry survival	6.58	3.73	6.58	3.32	0.00	0.02	0.79	0.74

Table 8. Stream temperature and Chinook egg-to-fry survival regression coefficients and P-values.

Descriptor	**Coefficient**	**P-value**
Mean daily stream temperature		
Intercept	3.052	0.000
20-day average air temperature (°C)	0.902	0.000
Cowichan River Discharge at Duncan (m^3/s)	-0.002	0.0001
Maximum daily stream temperature		
Intercept	3.422	0.000
20-day average air temperature (°C)	0.934	0.000
Cowichan River Discharge at Duncan (m^3/s)	-0.004	3.63E-13
Chinook survival		
Intercept	0.371	0.099
Brood year maximum water temperature in December (°C)	0.034	0.003
Brood year mean monthly maximum water temperature (°C)	-0.041	0.018

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[1] Obs. Mean – mean of observed values.

[2] Obs. MAD – mean absolute deviation of observed values.

[3] Pred. mean – mean of predicted values.

[4] Pred. MAD – mean absolute deviation of predicted values.

[5] MBE – mean bias error.

[6] MAE – mean absolute error.

[7] d_r – index of agreement.

[8] R^2 – coefficient of determination.

2.3.2 Scenario Simulations

2.3.2.1 Discharge

The river discharge scenario simulations showed an increase in winter discharge and a decrease in summer discharge for most of the future scenarios (Figure 3). The exception was Scenario CM (conservation/restoration of forest and moderate climate change) that had lower discharge in winter and higher discharge in summer. Scenario CM was closest to the baseline (1980 to 2010) conditions while Scenario DE (development of land and more extreme climate change) manifested in the highest changes from the baseline with highest discharge in winter and lowest in summer. The land use scenarios showed influence on river discharge with the conservation scenario moderating the influence of climate change, while land development exacerbated climate change effects on discharge. However, overall the influence of selected changes in land use management on stream conditions were smaller compared to those resulting from changes due to climate change.

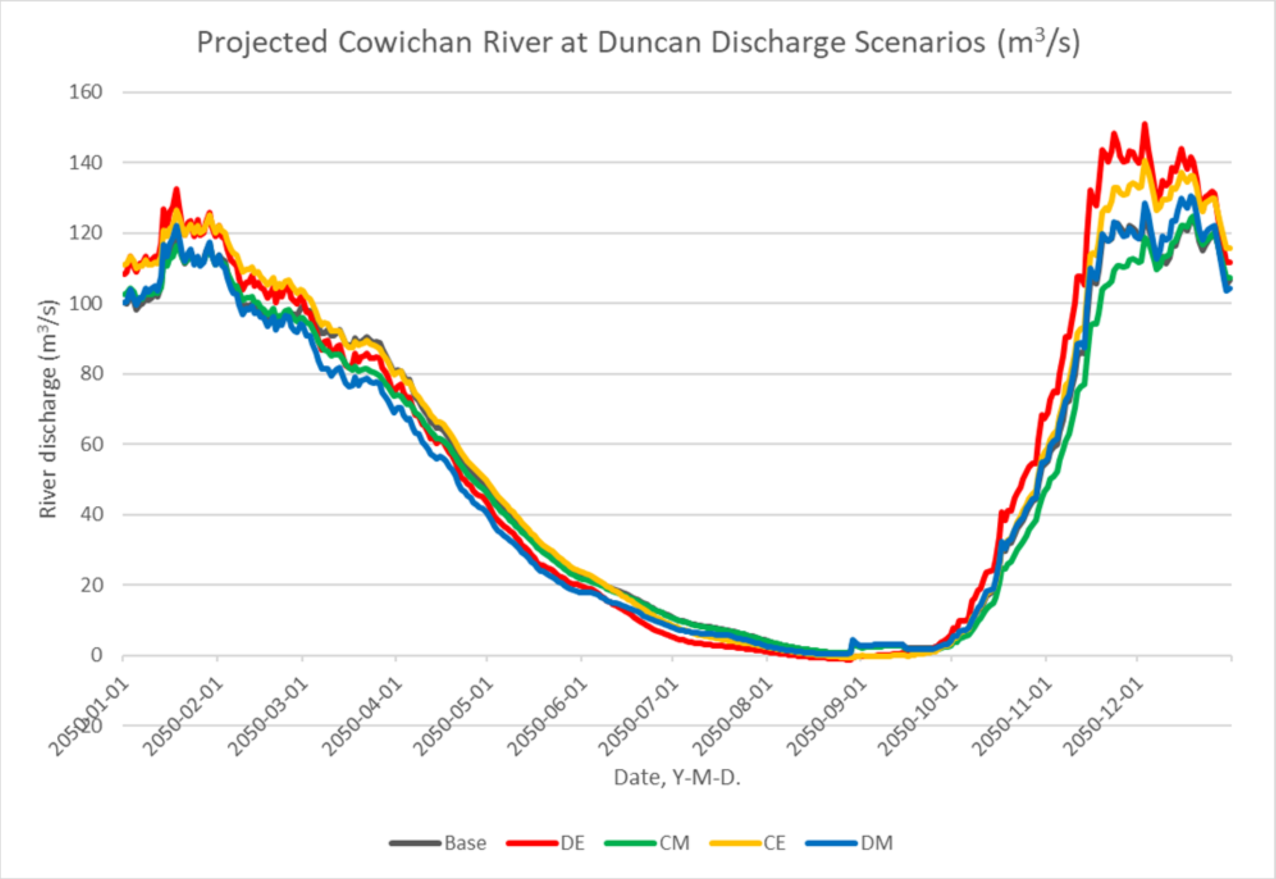

Figure 3. Average Scenario Projections for Cowichan River Discharge at Duncan

2.3.2.2 Water Temperature

The water temperature projections showed an increase in stream temperature for all scenarios (figures 4 and 5). In comparison to 1980-2010 levels, the most extreme scenario (Scenario DE) had an average increase of 3.7°C in annual mean water temperature (3.3°C increase in winter and 4.0°C in summer) and of 3.9°C in annual maximum temperature (3.5°C in winter and 4.2°C in summer). The most moderate scenario (Scenario CM) projected an average increase of 1.5°C in annual mean water temperature (1.5°C in winter and 1.7°C in summer) and of 1.6°C in annual maximum temperature (1.6°C in winter and 1.8°C in summer). Variation in land use changes showed only weak (<0.32°C) moderating effects on water temperature. The highest water temperatures for all scenarios were projected in August. The lowest temperatures for all scenarios were projected at the end of December – beginning of January.

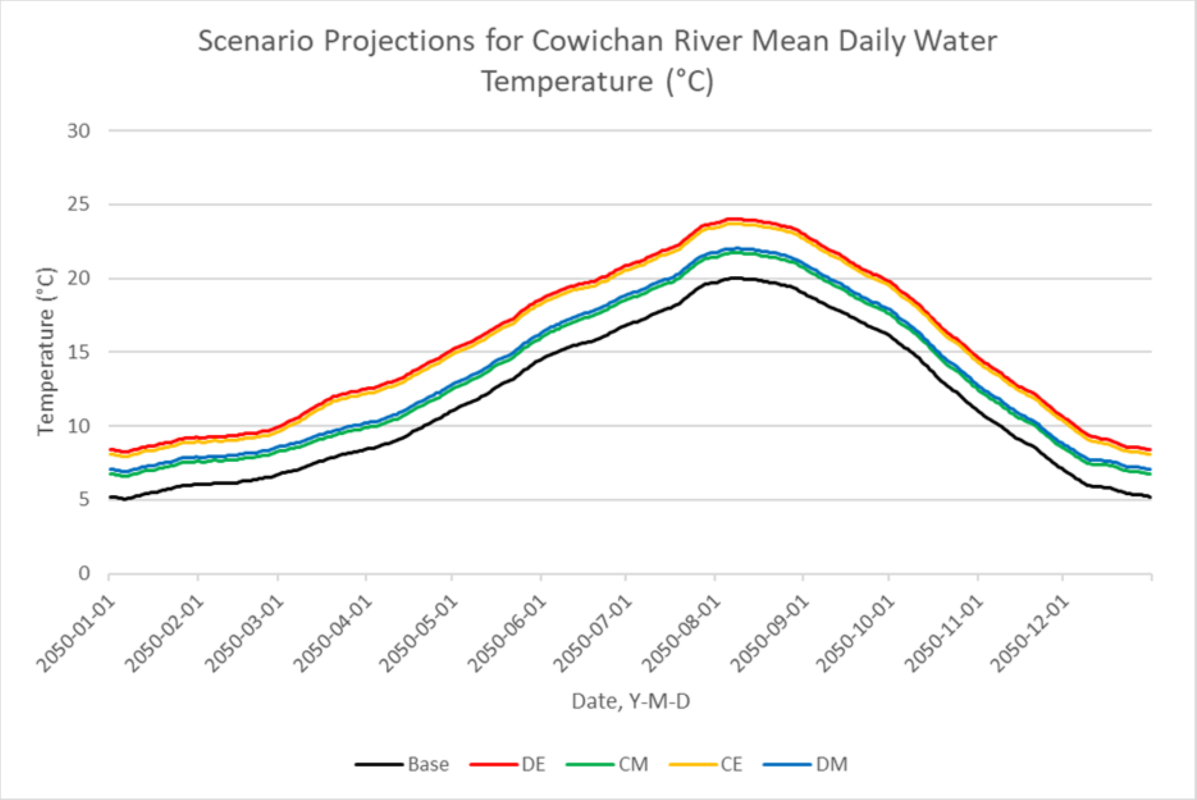

Figure 4. Average Mean Daily Water Temperature Scenario Projections for Cowichan River

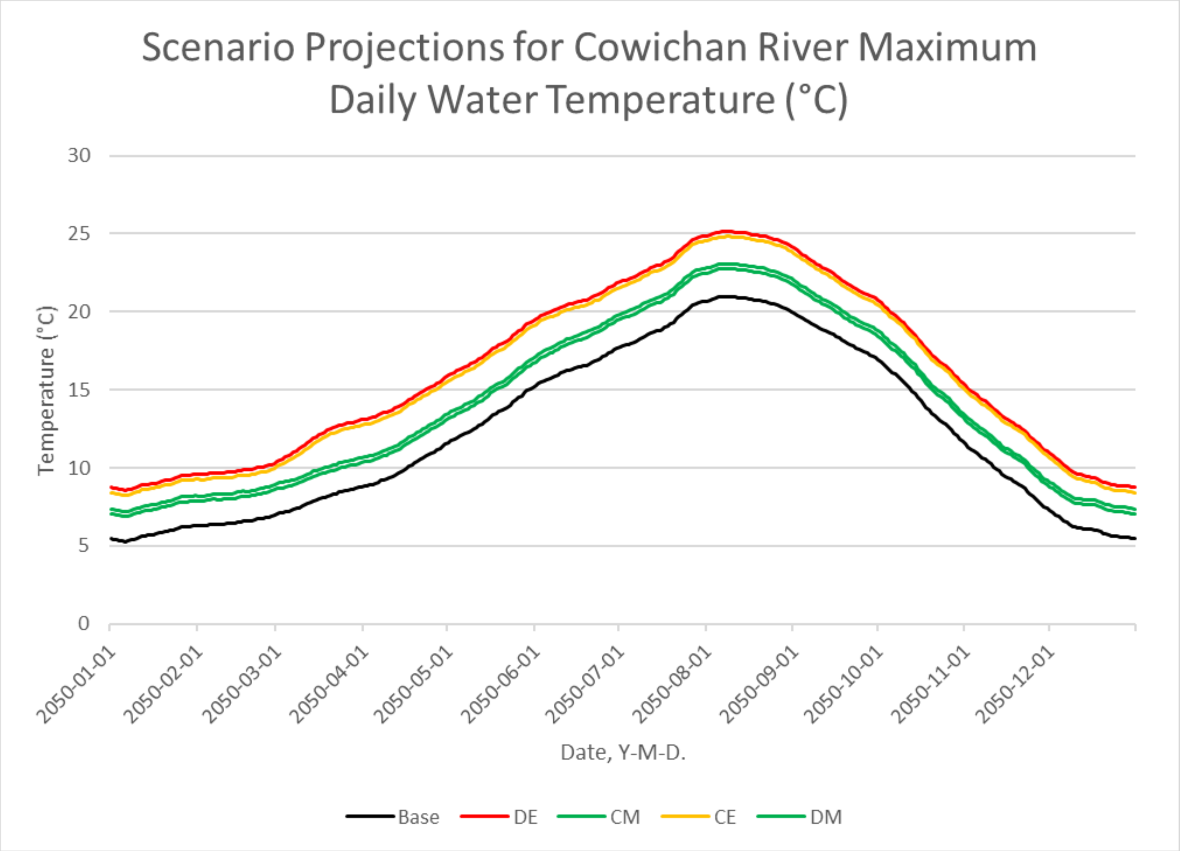

Figure 5. Average Maximum Daily Water Temperature Scenario Projections for Cowichan River)

2.3.2.3 Chinook Survival

Future scenario projections showed a decrease in Chinook egg-to-fry survival from the estimated 1980 – 2010 baseline for all four scenarios (Table 9). The estimated mean baseline survival value of 5.6% was reasonably close to the observed 1990 to 2001 mean value of 6.58% (Nagtegaal et al 2004). Predicted future survival rates based on the regression methodology showed a wide variation between scenarios, ranging from 1.6% (Scenario DE) to 4.1% (Scenario CM) survival, or overall decreases in survival relative to the 5.6% baseline by about one fourth under the most moderate scenario (CM) to about three fourths below current rates for the more extreme scenario (DE). The projected changes in survival mainly resulted from the influence of annual mean water temperature on the regression model predictions, while survival estimates based on thresholds showed only marginal variations. The threshold-based projected changes in survival were much smaller because even with year-round increases in water temperature and winter discharge, these increases during Chinook's early life residence time (winter and early spring) were still mostly within the thresholds used.

Table 9 Projected Cowichan River water temperature and Chinook egg-to-fry survival.

Scenario	Brood year maximum water temperature in December (°C)	Brood year mean monthly maximum water temperature (°C)	Survival Estimates using regression (%)	Survival probability based on thresholds (%)	Overall freshwater survival estimate (%)	Production (smolts) per spawner (individ.)
Baseline	7.74	14.04	5.79	96.35	5.58	112.00
DE	11.30	17.96	1.85	88.92	1.64	33.00
CE	11.02	17.65	2.20	92.92	2.04	41.00
DM	9.60	15.98	4.17	98.39	4.10	83.00
CM	9.39	15.75	4.42	98.98	4.38	88.00

2.3.2.4 Coho Survival

Simulated Coho egg-to-smolt survival ranged from 2.1% (Scenario DE) to 3.1% (Scenario CM; Table 10). The moderate climate change scenarios (DM and CM) showed improvement in projected survival relative to the Baseline Scenario (2.9%) because of increases in winter water temperature to more favourable levels.

Projected survival in scenarios DE and CE was mostly affected by high summer temperatures, particularly in August. Projected August water temperatures exceed the upper normal juvenile Coho survival limit of 24°C MWMT (Lusardi et al 2020) 76% of the time in Scenario DE and 65% of the time in Scenario CE. At the same time, projected discharges did not show any exceedances of the lower or upper limits used.

Table 10. Projected Cowichan River Coho egg-to-smolt survival.

Scenario	**Survival estimates based on literature (%)**	**Survival probability based on thresholds (%)**	**Overall freshwater survival estimate (%)**	**Production (smolts) per spawner (individ.)**
Baseline	3.40	81.02	2.75	34.00
DE	3.40	58.36	1.98	25.00
CE	3.40	66.34	2.26	28.00
DM	3.40	86.40	2.94	37.00
CM	3.40	88.52	3.01	38.00

2.4 Discussion

The analysis suggests Cowichan Chinook freshwater production is affected by physical variables, such as water temperature and discharge, which, in turn, are dependent on climate factors such as air temperature and precipitation and local watershed management. Maximum water temperature in December and mean monthly maximum water temperature in the brood year can explain 75% of the variability in Chinook egg-to-fry survival (Table 7 and 8).

When investigating temperature thresholds for both Chinook and Coho, our assumed durations and timing window for incubation and fry development were slightly shorter than those observed naturally during the baseline period. For instance, Chinook and Coho incubation was reported to last through March (Atkinson & Pellet, 2018; Craig, 2015; Pearce et al., 2020), while we used December through February average conditions. Incubation and emergence have lower upper temperature thresholds than the next stage, fry, therefore the exposure of eggs and alevin to higher temperatures in March may decrease salmon survival. However, we assumed that warmer water temperatures would accelerate egg hatching and fry emergence so that in the future December through February would be the relevant period for these life stages. Using Murray & McPhail's (1988) growing degree day models for emergence for Chinook (920) and

Coho (872) in Scenario DE with projected mean water temperatures of 8°C we estimated 50% emergence of Chinook and Coho fry on March 9th and March 5th respectively (compared to April 17th and April 12th for baseline conditions) assuming egg fertilization occurred on December 1st.

The models showed that Coho had higher survival variability and, generally, lower survival rates based on temperature and discharge thresholds than Chinook. This is mainly because Coho in the Cowichan River have longer freshwater residence times that includes the critical summer rearing period when stream temperatures may reach or exceed upper limits of tolerance for normal development and discharges may drop below the minimum levels necessary to sustain rearing habitat. This makes Coho potentially more vulnerable than Chinook to future changes in stream conditions related to climate change and local management. Coho freshwater residence also includes the following winter rearing period, which is also critical for survival due to vulnerability of juvenile fish to cold temperature and floods (Lawson et al 2004). The models projected that future temperature increases may improve chances for second winter survival, while projected frequencies of detrimental floods in the Cowichan River would still be low.

The statistical analysis showed that Chinook survival was sensitive to stream temperature even when temperatures were within the established thresholds. For Chinook, regression-based survival projections showed higher variability than threshold-based projections. Similarly, high sensitivities to temperature (and discharge) may exist for Coho, and the range of projected survival among the scenarios could be greater if we had enough historical data to derive survival-physical factors relationships. Our predicted range of Coho survival is smaller than observed ranges available in the literature (Bradford et al., 2000; Lawson et al., 2004).

Environmental thresholds and, subsequently, survival estimates, may change depending on available data on the use of different physiological and adaptational tolerances that have been suggested in the literature. For instance, we used a MWTM value of 24 °C from Lisardi et al. (2020) as the upper temperature threshold for summer Coho fry, although earlier studies reported considerably lower tolerance maximums (e.g., 20.3 °C (Bret, 1952); 23 °C (Spence et al., 1996); 22.5 °C (Sullivan et al., 2000); 22 °C USEPA 1999, as in Carter 2005). Differences among the various studies could be a function of adaptation of various stocks to local conditions or adaptation to observed increases in temperature or could suggest that there are other mechanisms in the natural environment that help adapt to higher temperatures such as increased ecosystem productivity and prey availability (Lisardi et al. 2020).

Another factor to consider when assessing potential effects of threshold exceedance by modeled temperature is behavioral adaptation of juvenile salmon to mainstream temperature increases. Juvenile Coho in summer use thermal refugia, for example water pockets or pools cooled by spring-fed tributaries or groundwater seepage (V.Komori and Assc., 2010; T. Rutherford, pers. com., November 20, 2021), which is a known strategy of juvenile salmon during freshwater rearing when mainstream temperature becomes too high (Beechie et al., 1994; Reeves et al., 1989).

River discharge in our study had less of an impact on salmon survival than stream temperature. This could be either because the streamflow in Cowichan River is regulated and, therefore effects from extreme drought are mitigated, or because we are underestimating effects of low and high discharges because of lack of watershed-specific data (V. Komori and Ass., 2010). However, in our study the role of streamflow is twofold. Beyond direct impacts it also helps to regulate stream temperature. Through these two mechanisms it plays a significant role in determining salmon freshwater survival.

Our study suggests that water flow and temperature management are important factors in maintaining salmon stocks. Discharge and temperature management can be achieved through land use and land cover management in the watershed. Possible strategies include Cowichan Lake discharge and storage management, groundwater exchange management through increasing alluvial system complexity, increase in riparian shading, channel management including removal of stream impoundments (debris), reduction of water withdrawal, etc. (Beschta, 1997; Norton & Bradford, 2009; Poole & Berman, 2001a, b).

Manipulation of Cowichan River flow through discharges from Cowichan Lake already plays a major role in juvenile salmon survival by storing some excess water in the winter and providing enough water flow in the river through the summer and early fall (Craig, 2015). However, it has been reported that the dam design is no longer adequate to provide even the minimum discharge level of 4.5 m^3/s through the summer, due to increasingly frequent drought conditions observed in the last two decades (Compass, 2018). In some recent years, discharge from the lake had to be reduced to as low as 4 m^3/s to allow streamflow to last through the summer (Brian Houle, pers. com., January 31, 2020). Even though historically river discharge has fallen as low as 3 m^3/s (Brian Houle, pers. com., January 31, 2020) frequent low discharges in combination with higher stream temperatures, in part resulting from low flow rates, may have detrimental effects on juvenile salmonids. Therefore, a Public Advisory Group (PAG) for a Cowichan Water Use Plan has been considering alternative strategies that include a proposal to increase weir height by 0.7 m and to start outflow controls one month earlier than currently (Compass 2018). This increase in weir height will reportedly provide sufficient water storage to augment summer and fall flows for salmonids. Even though the measure is aimed to provide enough water to sustain fish habitat, it will also lead to a decrease in summer water temperature as an inverse correlation between discharge and temperature is found in this study.

Other factors influencing survival and success of salmonids in Cowichan River include availability and quality of spawning habitats, unrestricted passage to spawning habitat, water quality (suspended sediment load, pollutants), and quality of riparian habitat. It has been reported that survival of salmon eggs and alevins was reduced in some areas of Cowichan River affected by elevated rates of natural sedimentation and accelerated bedload due to decreased bank stability and increased erosion (V.Komori and Assc., 2010).

Other measures that can contribute to improvement of salmonid survival in Cowichan River besides streamflow and temperature management include habitat restoration, improvements to access/habitat quality and quantity in off channel sites, bank protection, erosion control, debris removal etc. (LGL 2005, as in V.Komori and Assc., 2010).

We only investigated freshwater survival of two salmon species in their early life stages from egg fertilization to smolt migration to the marine/estuarine environment. Another critical stage of anadromous salmon freshwater residence is adult return and spawning, which for both our species occurs in the fall. Stream flow and temperature also play an important role in spawner survival and success (Bell, 1986; Brett, 1952; Burck, 1993; Carter, 2005, Hicks 2000; Neave, 1943; Tompkins et al., 2005). For instance, delayed fall discharge may delay salmon runs into the river resulting in fish accumulation in the estuary and increased death from predation. Also, a greater proportion of adult spawners spawn in the lower reaches of the Cowichan River, as low as downstream Duncan in years of low flow during the upstream migration period (Nagtegaal & Riddel, 1998). Higher water temperature during migration and spawning may interrupt normal processes, increase the risk of disease, disrupt physiological functions, and cause early death (Brett, 1952; Burck, 1993). Therefore, further assessment of scenario effects on upriver migration and spawning, as well as assessment of marine survival, will be useful to understand a full life-cycle success of a salmon generation. With improved information on how stream flow and temperature impact spawning a similar model to the one described here could provide insights on salmonid survival under different scenarios.

2.5 Conclusion

In our study we projected four future scenarios of freshwater survival of two anadromous salmon species, Chinook and Coho, native to Cowichan River. The projections used hydrologic and statistical models linking salmon survival to projected climate and land use impacts on physical river conditions including streamflow (discharge) and stream temperature. The future scenarios were combinations of watershed land use and climate change conditions.

Our study demonstrated how a simple hydrologic model could be used to assess the interacting impacts of local land use change and global climate change on river conditions, and subsequently the survival rates of juveniles of two salmon species. All four scenarios considered combinations of watershed conservation efforts vs increased development and high vs low climate change ranges from the 8.5 IPCC RCP for the region by 2050. Results projected 25% (conservation with lower climate change conditions) to 75% (development with high climate change conditions) decreased survival rates relative to current conditions. Survival was most impacted by changes in water temperature conditions which we estimated based on river flow and 20-day average air temperature values. We also found that a regression-based survival model was more sensitive to changes in climate conditions and land use compared to survival rates estimated using temperature and flow rate threshold values. Changes in land use and land cover such as forest restoration and other measures to decrease overland runoff would help to improve chances of freshwater salmon survival. However, these changes are insufficient to offset the projected impact of globally driven climate change projection. Land use management, stream regulations, water temperature management and other habitat improvement measures will be crucial to improve salmon chances of success in the future.

Chapter 3. Future Marine Survival Scenarios of Two Strait of Georgia Pacific Salmon Species, Chinook and Coho.

Article Information

Chapter 3 has been prepared for publication in a journal.

Abstract

This study provided a cumulative effects assessment on marine survival of three anadromous Pacific salmon populations in British Columbia, Cowichan River Chinook and Strait of Georgia hatchery-raised and wild Coho, using scenario analysis. The assessment was focused on impacts from local land use management and climate change on salmon marine survival through various environmental variables, such as sea surface temperature (SST), sea surface salinity (SSS), air temperature, precipitation, wind gust speed, and Cowichan and Fraser river discharges, in the first year of the salmon marine residence. These linkages were investigated through Pearson correlation and stepwise regression analysis of historic data on the long-term salmon populations marine survival and the above environmental factors. The analysis showed that the marine survival of both Chinook and Coho is highly correlated to environmental conditions during the first year of marine residence, explaining at least 75% of survival variability for Chinook and wild Coho and 70% survival variability for hatchery-raised Coho. The regression analysis showed that Chinook marine survival was negatively related to SST in Strait of Georgia in July and mean Cowichan River discharge in October, and positively correlated to mean minimum daily air temperature in the Strait of Georgia in October. Both Strait of Georgia hatchery-raised and wild Coho marine survival showed positive correlation to SSS in the Juan de Fuca Strait, and negative correlations to mean June to September air temperature and to mean annual extreme monthly wind gust speeds. The regression equations were used as predictive models for future survival of the three salmon populations applied on the future scenarios for 2050. Four future

scenarios created by combining two opposite scenarios of land use in the Cowichan River watershed, forest conservation and development, and two climate change scenarios, more extreme and moderate, were applied to Cowichan Chinook. Two future climate change scenarios, extreme and moderate, were applied to both Coho populations. The scenario projections showed decline in marine survival for all three salmon populations under all scenarios. Under the moderate climate change scenario estimated marine survival rates were 0.56% and 0.63% for Chinook for scenarios with development and conservation land use respectively, and 0.88% and 4.77% for hatchery-raised and wild Coho, respectively. In the more extreme scenarios, juvenile salmon entering the marine environment may not survive through the first year at sea at all. Also, the assessment showed that wild Coho had better marine survival than hatchery-raised Coho both historically and in the projected scenarios.

3.1 Introduction

This study aimed to assess future climate impacts and ocean conditions on populations of two Pacific salmon species, Cowichan River Chinook (*Oncorhynchus tshawytscha*) and Strait of Georgia Coho (*O. kisutch*). The focus was on projecting future marine survival scenarios of these two species as a component of Cowichan River salmon future survival and success within a cumulative effects assessment. The first part of the assessment was conducted on the freshwater phase of the early development stages of each species (Ospan et al., unpublished, Chapter 2). The purpose of the overall cumulative assessment was to examine how different scenarios of land use within the Cowichan River watershed, in combination with different scenarios of climate change, could affect the future survival of anadromous salmon species native to the river. The temporal boundary of the assessment was 2050, or approximately 30 years from now. This temporal boundary was within a planning time scale that is practically foreseeable for decision makers at a local scale.

Anadromous salmon have complex life histories. A significant portion of their adult life is spent in the open ocean, which is highly complex in terms of the number of potential factors affecting salmon survival, and the mechanisms by which these factors influence survival are not fully understood (Clark et al., 2016). However, the nearshore ocean appears to have a strong influence on salmon success, and the first few months spent by juvenile salmon at sea are the most critical for their overall marine survival. Survival during this initial period is strongly correlated with their return as spawning adults to the river habitats (Beamish & Mahnken, 2001; Beamish et al., 2004; Beamish et al., 1999; Beamish et al., 2008; Beamish et al., 2010; Chittenden et al., 2018; Brodeour et al., 2011). Furthermore, Chinook and Coho smolts from streams and rivers on the east coast of Vancouver Island and from the Fraser River travel to, or through, the Strait of Georgia and are thought not to migrate too far in the open ocean, further suggesting near shore water conditions could be a likely factor in their survival.

A number of studies indicate that salmon survival in the marine environment is strongly correlated with water temperature and salinity (Pearcy, 1992; Blackbourn 1985, 1990). Michel (2019) found that riverine streamflow during smolt outmigration has a higher correlation with Chinook marine survival than marine conditions. This may be explained by the influence of riverine discharge on nearshore marine physical conditions. It is likely, therefore, that nearshore marine physical conditions play a major role in salmon survival. Beamish et al. (2010) found strong correlation between water temperature and wind speed in Strait of Georgia and Coho survival during the first four months in the marine environment.

Many factors influencing marine temperature and salinity are outside the direct control of human management decisions at the local and regional levels. However, since marine physical conditions, particularly in Strait of Georgia, are largely dependent on freshwater runoff among other factors (Masson, 2006) it is possible that stream hydrologic conditions play an important role in salmon marine survival. Therefore, factors affecting stream hydrology, among them human watershed management and climate change may also affect salmon survival and success during their entire life cycle (freshwater and marine).

This study aimed to develop and apply predictive models for assessing cumulative effects using scenario analysis on the marine survival of Cowichan River Chinook and Coho. The models linked marine physical factors (e.g., temperature, salinity, wind speed, riverine discharge etc.) affecting Chinook and Coho marine survival and are applied on four scenarios of watershed management choices and severity of global climate change to project how changing near shore conditions might impact salmon survival. The purpose of applying different scenarios was to provide new insights into the interaction between global and local effects that could be used by policy makers, to enable strategies and planning that would help to increase salmon survival rates towards desired outcomes.

3.1.1 Study Area and Populations

The Cowichan River runs in the southeastern part of Vancouver Island and discharges into the Strait of Georgia between the island and mainland of British Columbia (Figure 6). The Strait of Georgia is connected to the open ocean through Juan de Fuca Strait in the south and Johnstone Strait in the north. Oceanography of the strait is characterized by an estuarine-type circulation heavily influenced by discharge from Fraser River on the mainland that reaches a maximum in June as the winter snowpack melts (Thomson, 1981).

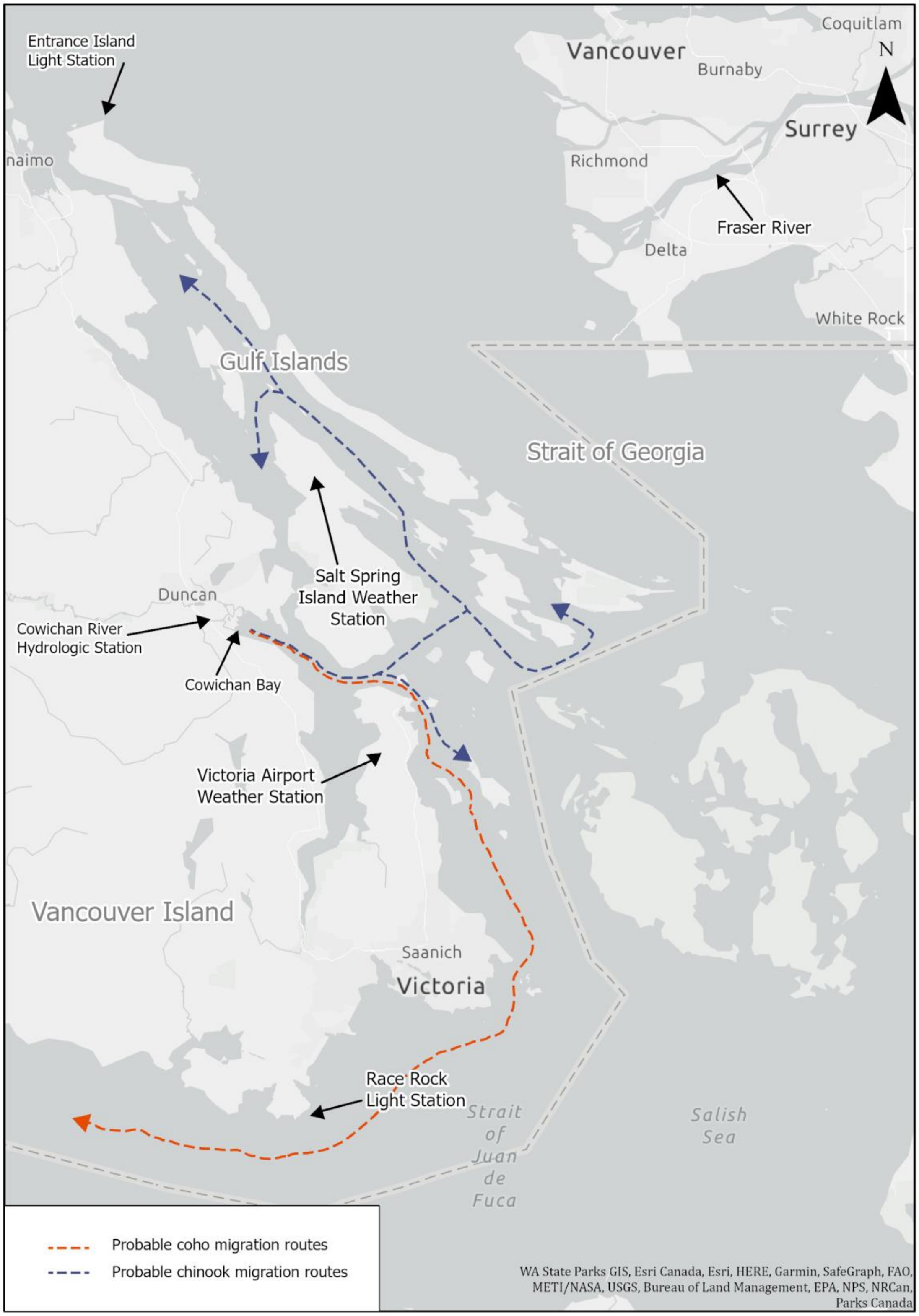

Figure 6. Study Area. Solid arrows show sources of physical data used in the assessment; dashed lines show salmon early migration pathways in the marine environment.

Cowichan River supports several populations of anadromous salmon species, among them are fall-run Chinook and Coho. They have slightly different life histories. Both species make their spawning runs up-river in mid-October through December (mostly in November) and lay eggs in the upper reaches of the river below Cowichan Lake (Neave, 1943; Lill et al., 1975; Tompkins et al., 2005; Lister et al., 1981; Nagtegaal & Riddell, 1998; Pellet, 2017). Egg incubation of both species occurs during winter and juvenile fish (fry) emerge mainly in the spring of the following year.

Chinook fry spend less than 90 days in the Cowichan River and migrate to the estuary from April through June (Craig, 2015; Nagtegaal et al., 2004; Healey, 1991; Candy et al., 1995). Chinook then spend two to four months in the estuary where smoltification (physiological adaptation to marine life) and rapid growth occur (Pearcy, 1992). Juvenile Chinook first rear in shallow (April and May) and then in deeper sections (June to August) of the Cowichan River estuary before migrating to nearshore marine areas of the Gulf Islands in the Strait of Georgia from June to September (Thakur et al., 2018; Atkinson & Pellett, 2018). Although Chinook salmon are known to embark on extensive ocean migrations, the majority of Cowichan River Chinook population most likely remains in the Strait of Georgia for the first several months of their marine growth phase (Beamish et al., 2011; Neville et al., 2015); even though a minority of Cowichan Chinook is found to migrate as far north as Queen Charlotte Strait, to the west coast of Vancouver Island and as far south as Washington and Oregon (W. Luedke pers. com., as in V. Kommori and Assc., 2010). Marine residence of Cowichan Chinook lasts from 1.5 to 4.5 years and the age composition of returning spawners consists primarily of sexually mature 3- and 4-year-old fish with varying contributions of age-2 males (jacks) that may vary from 20% to 73%

of total returners (Tompkins et al., 2005). The proportion of age-5 adults is considerably smaller and is usually less than 2%.

Unlike Chinook, Coho juveniles spend a full year in fresh water, from the March of emergence to April of the following year with smoltification and outmigration peaking in May (Atkinson & Pellet, 2018; Craig, 2015; Pearce et al., 2020). Coho smolts spend only a brief period in the estuary (Pearcy 1992) and enter the Strait of Georgia in May. Until the last few decades, Coho was believed to remain in the Strait of Georgia for their entire marine life, but this pattern of behavior has increasingly shifted to an outmigration from the Strait of Georgia through the Juan de Fuca Strait to the open Ocean from in October to December for their first year of marine residence. This shift in marine residence is thought to be related to changes of physical conditions in the strait due to climate change (Beamish et al., 1999; Chittenden et al., 2009). Coho spend a maximum of 1.5 years in the marine environment (Pearcy 1992) returning to the native stream as jacks or 3-year-old mature adults (Sandercock, 1991; Pearce et al., 2020).

From the literature there is evidence that the ocean environment is changing and impacting salmon survival (e.g., Beamish et al., 1999; Beamish et al., 2010; Chittenden et al., 2009). However, while anthropogenic climate change might be an underlying factor in driving these changes, there are other potential human impacts that can also affect nearshore and Georgia Strait conditions. One potential major influence is changes in regional runoff conditions based on human and climate change impacts on river runoff into these environments. The aim of this study was to assess to what extent climate change and river runoff conditions impact salmon survival during the marine phase of their life cycle.

3.2 Materials and Methods

The main objective of this study was to develop predictive models of marine survival for Coho and Chinook salmon, based on an analysis of the linkages between survival rates and physical ocean conditions. To assess potential future impacts of climate change and human development on ocean survival, four scenarios combining projected climate and watershed management changes were developed and their impact on the variables affecting survival is projected and used to simulate potential future survival rates.

3.2.1 Statistical Analysis

Marine survival discussed in this study referred to natural survival in the marine environment that does not include fishing-related mortality. Marine survival was estimated using coded wire tags (CWT) that are inserted in hatchery raised juvenile fish prior to their release. Survival rates were then estimated by dividing the number of fish with CWTs that survive to age 2 (pre-fishery recruitment) to the total number of CWT released (Tompkins et al., 2005). Age-2 pre-fishery recruitment was estimated through annual CWT recovery from commercial and sport fisheries and fish returned to the river. Marine survival rates for Chinook released from the Cowichan hatchery for smolt years 1986 to 2013 (brood years 1985 to 2012) was provided by DFO (Figure 7). Data for 1989 to 1991 smolt years were deemed outliers using a Box-plot method (Walfish, 2006) and were removed from the analysis as outliers.

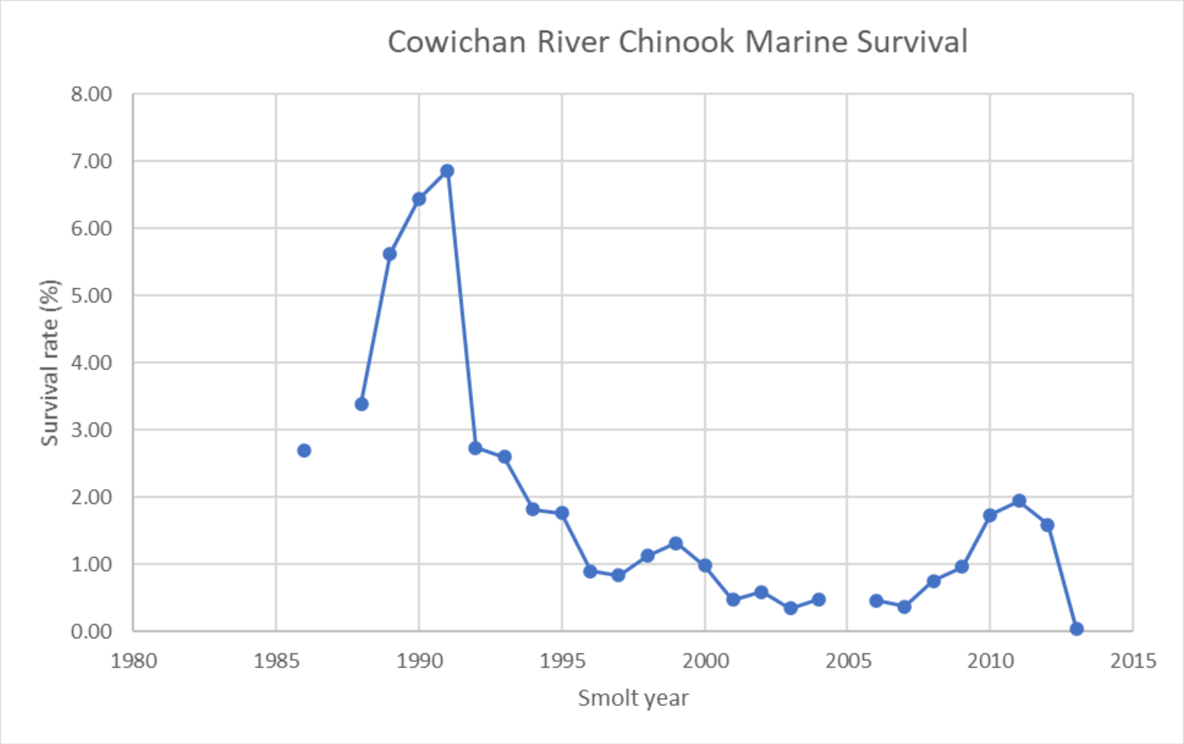

Figure 7. Cowichan River Chinook Marine Survival (DFO, pers. com.).

CWT tagging of hatchery-released Coho in Cowichan River started in 2018 (Pearce et al., 2020), therefore, no marine survival estimates were available for the Cowichan River Coho population specifically. Instead, overall Strait of Georgia hatchery and wild Coho survival rates based on CWT programs were used in this analysis; hatchery data consisted of combined CWT-based estimates for Inch, Big Qualicum, Chilliwack, and Quinsam hatcheries; wild Coho survival estimates were based on CWT-based studies on Black and Myrtle creeks and Salmon River wild Coho stocks (Irvine et al. 2013). Survival data for both hatchery and wild Coho was provided by DFO for 1985 to 2016 smolt years (Figure 8). Smolt year 1987 was removed from both hatchery and wild Coho analysis as outliers based on Box-plot method (Walfish, 2006).

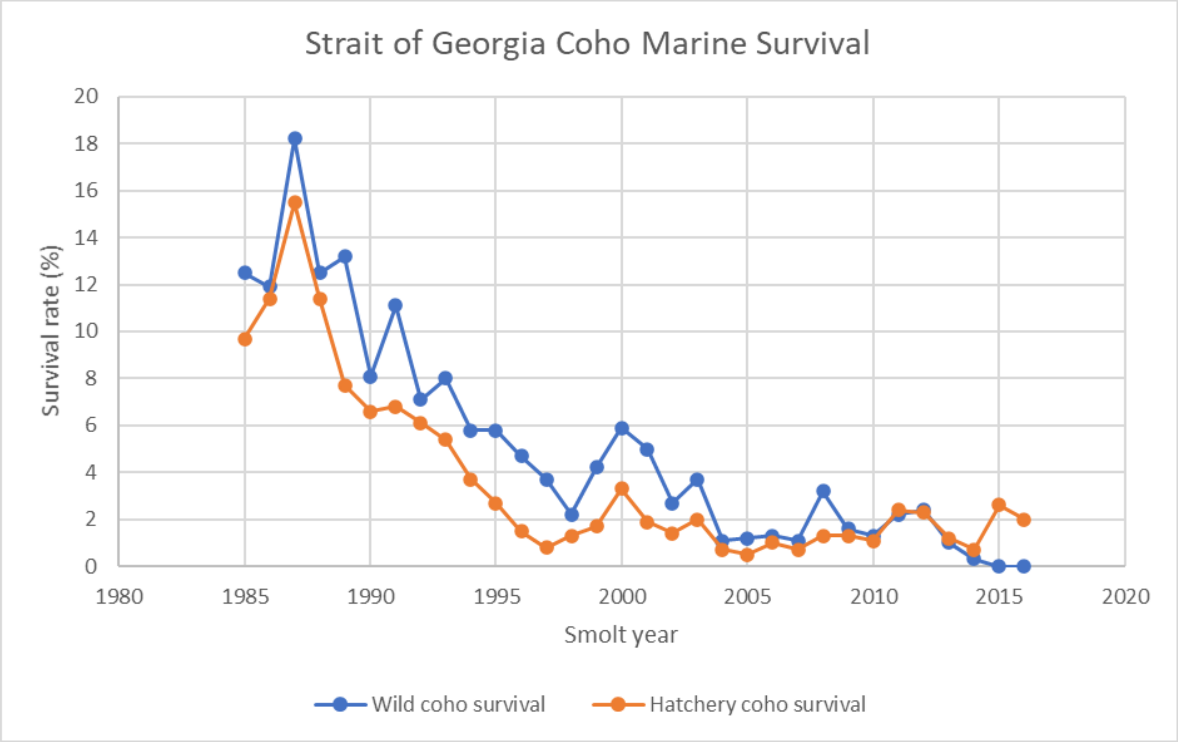

Figure 8. Strait of Georgia Coho Marine Survival (DFO, pers. com.)

The physical ocean data examined included a number of physical variables, such as mean, minimum and maximum monthly, seasonal and annual values for Cowichan and Fraser river flows, sea surface temperature (SST) and sea surface salinity (SSS) in the Strait of Georgia and Juan de Fuca Strait, air temperature, precipitation, monthly extreme gust speed, and open ocean SST. Criteria for data source selection included physical proximity to assumed habitats and migration pathways of the studied salmon populations and availability of continuous data for the period between 1985 and 2016. Table 11 provides a summary of data used in this analysis.

Temporally, the physical ocean data were matched to correspond to the Chinook and Coho smolt year, as the first several months determine the most critical in marine survival (Beamish & Mahnken, 2001; Beamish et al., 2010; Chittenden et al,. 2018; Brodeour et al. 2011); however, longer-term (2-year and 3-year mean) estimates were also used. A total of 296 physical variables were selected for this analysis to find correlations between the variables and survival outcomes.

Table 11. Physical data used in the analysis.

Data	Source	Location	Coordinates
Cowichan River discharge	Water Survey Canada (WSC) hydrometric station #08HA011	Duncan	48°46'23''N 123°42'52''W
Fraser River discharge	WSC hydrometric station #08MF005	Hope	49°23'09"N 121°27'15"W
Sea surface temperature (SST) and Sea surface salinity (SSS)	Race Rocks Lightstation Fisheries and Oceans Canada (DFO)	Juan de Fuca Strait, south of Vancouver Island	48°17'53"N 123°31'53"W
SST and SSS Strait	Entrance Island Lightstation (DFO)	Strait of Georgia near Nanaimo	49°12'33"N 123°48'30"W
SST open ocean	National Oceanic and Atmospheric Administration (NOAA) buoy station #460001	North-east Pacific Ocean, south of Gulf of Alaska	56°18'16"N 147°55'13"W
Air temperature, precipitations, maximum monthly gust speed	Victoria International Airport Environment Canada (EC) weather station #1018620	North end Saanich Peninsula, Vancouver Island, 18 km southeast of Cowichan River estuary	48°38'50"N 123°25'33"W
Air temperature, precipitations	Salt Spring St. Mary's Lake EC station #1016995	North end Salt Spring Island, 16 km north of Cowichan Bay	48°53'24"N 123°32'60"W

Linkages between physical environmental factors and salmon survival were first evaluated using a Pearson correlation analysis. Factors that showed higher correlation (R<-0.5 and R>0.5) with salmon survival are selected for further analysis. Next, variables that were likely to cause multicollinearity were eliminated using a variance inflation factor (VIF) analysis. Those with a value greater than 10 were removed. In the final step, a backward elimination stepwise regression analysis was used to determine the most statistically significant independent variables influencing salmon marine survival. We have selected backward elimination over the forward selection because in forward selection there is a potential that two or more variables that work best with each other will not be selected in the final model, or a regressor added at an early step may become redundant because of its relationship with regressors added later (Burt et al., 2009).

3.2.2 Future Scenarios

The future scenarios for marine survival were consistent with those used for the freshwater phase of salmon survival (described in detail in Ospan et al., unpublished, Chapter 2), using an approach similar to that in Duinker (2008), Creed and Laurent (2015) and Laurent et al. (2015). Four scenarios were created by combining a global forcing factor, two extremes of climate change outcomes for the IPCC RCP 8.5 scenario, and a local forcing factor, watershed conservation vs. development.

The two opposing climate change scenarios are the upper and lower 10 percentiles of projected changes for climate variables (e.g., temperature, precipitation or wind speed) under the IPCC RCP 8.5 scenario for the region (Ospan et al., unpublished, Chapter 2; PCIC, 2020; Collins et al., 2013). Projections representing two extremes of the same RCP scenario were selected because differences between the projected changes for two different RCPs (e.g., between RCP 8.5 and RCP 4.5 or RCP 2.6) were less than differences among the projected changes from the different models for the same scenario. This was observed in other studies (e.g., Loder & van der Baaren 2013; Ishizaki et al., 2012). We selected the RCP 8.5 scenario because it represented the more realistic, “business-as-usual”, scenario (IPCC, 2014).

The two opposing land management scenarios were created by altering present day land cover/land uses in the Cowichan watershed and projecting a conservation scenario where reforestation and green space development was prioritized, which was contrasted to a development scenario with expanded urban areas, farmland development and intensive wood harvesting (Ospan et al., unpublished, Chapter 2). The final four scenarios combined the climate and land management projections as follows: forest conservation in combination with moderate climate change (Scenario CM), forest conservation and more extreme climate change (Scenario CE), land development and more extreme climate change (Scenario DE), and land development with moderate climate change (Scenario DM).

Within these scenarios we recognized that the climate change scenarios affected all physical variables used in the marine survival models, while land use scenarios affected only Cowichan River discharge and water temperature. Our analysis also assumed that changes in the Cowichan watershed reflected expected changes for all watersheds in the region. Therefore, relative changes in water discharge and water temperatures in the Cowichan watershed would be representative of the cumulative discharge changes into the Strait of Georgia from all watersheds in the region. In other words, correlations based on scenarios impacting the Cowichan watershed discharge would be representative of development in all watersheds discharging into the Strait.

Excepting the extreme gust speed projections (which were based on two historic extremes), selected scenario values for each physical factor representing global forces, such as air temperature, SST and SSS, are based on model projections of the high-emission IPCC climate change scenario RCP 8.5. For air temperature and SST, the lower 10th percentile model projections were used for the moderate scenario, while the upper 90th percentile projections are used for extreme scenarios. For SSS we reversed the projections, with the optimistic scenario represented by the upper 90th percentile projection and the pessimistic scenario with the lower 10th percentile values. Values for summer-time precipitation changes were reversed: 90th percentile projected change is used for the moderate scenario and 10th percentile change is used for the more extreme scenario because the 10th percentile projection for changes in summer precipitation of 42% decrease represents a more extreme outcome associated with warmer temperature (PCIC, pers. com., August 11, 2020).

Local air temperature projections for the 2050s (2040-2069) relative to the 1961-1990 base period were downloaded from the Pacific Climate Impact Consortium (PCIC) Climate Explorer (PCIC, 2019) model PCIC 12 for the RCP 8.5 future climate scenario. Climate Explorer uses downscaled outputs from Global Climate Models (GCMs) from the fifth phase of the Global Model Intercomparison Project (CMIP5). The projections used were computed from daily statistically downscaled scenarios developed using the Bias Correction with Constructed Analogues and Quantile mapping, Version 2 (BCCAQv2) method (PCIC, 2019).

SST and SSS projections were computed using projected changes in SST and SSS off the Vancouver Island coast from 1986-2005 to mid-century (2046-2065) from six earth System Models (ESMs) running the CMIP5 RCP 8.5 scenario (Lodder & van der Baaren, 2013). The projected 10th percentile and 90th percentile changes were applied to the mean 1996-2005 SST and SSS at Entrance Island and Race Rocks light stations respectively.

There are no conclusive projections of wind speed for the Vancouver Island area. Large and small-scale wind reports include increasing trends (Young et al., 2011), decreasing trends (McVicar et al., 2012) or no significant trends (Merryfield et al., 2009; Morrison et al., 2014; Wang et al., 2016) in wind speed and frequency. Gust speed for this study scenarios were selected as 10th percentile (moderate scenario) and 90th percentile (extreme scenario) of 54-year (from 1964 to 2017) long-term mean annual extreme monthly gust speeds observations from the Victoria International Airport meteorological station (Figure 9).

Cowichan River discharge values are taken from the Cowichan River freshwater model outcomes (Ospan et al., unpublished, Chapter 2).

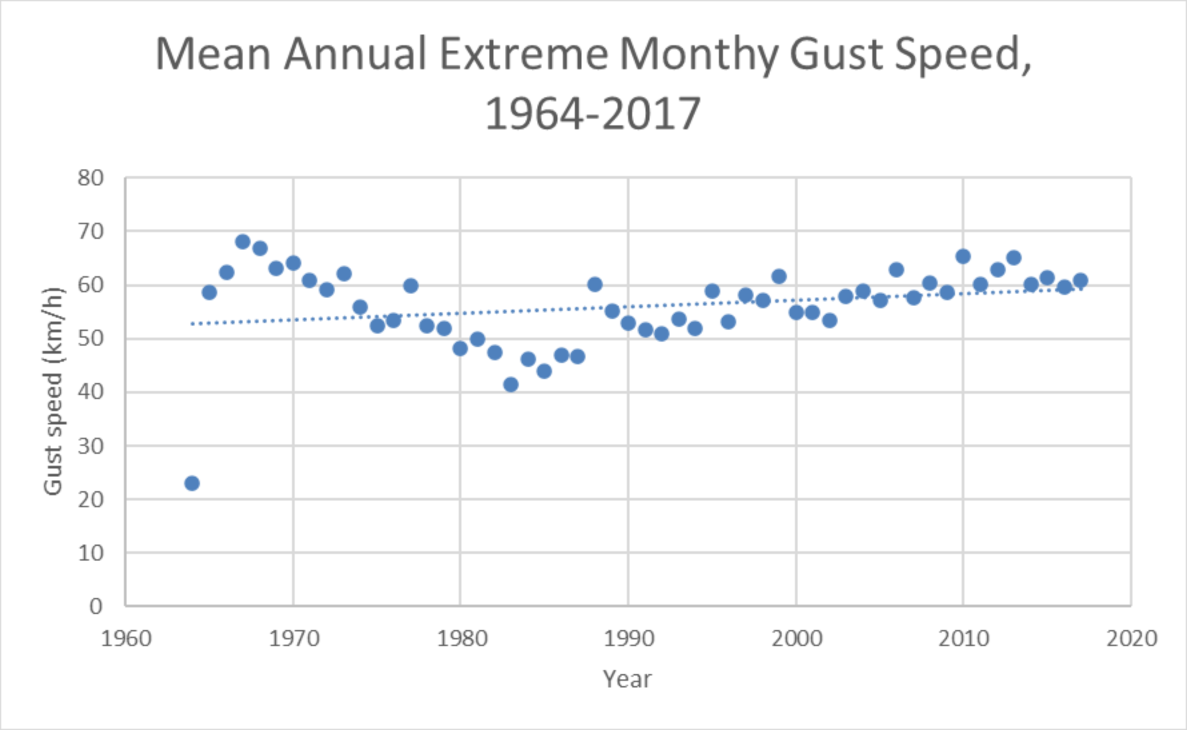

Figure 9. Mean Annual Extreme Monthly Gust Speed, Victoria International Airport, 1964 to 2017.

3.3 Results

3.3.1 Statistical Analysis

Results suggested that salmon marine survival rates correlated well with several physical environmental variables. Cowichan Chinook marine survival showed negative correlations (r < -0.4) with Cowichan River discharge in October, SST at Entrance Island in July and at Race Rock in January and October, and air temperature at Salt Spring Island and Victoria Airport in summer, all physical variables for the year of smolt migration; and survival is positively correlated (r> 0.5) with air temperature at Salt Spring Island in October of the smolt year.

Both hatchery-raised and wild Coho survival showed negative correlations ($r < -0.5$) with SST at Race Rock from October through February, summer air temperature at Victoria Airport, and July and mean annual maximum wind gust speed, all in the year of smolt migration. Coho survival rates positively correlated with summer salinity ($r > 0.5$) in the smolt year.

Stepwise regression analyses resulted in regression models with high explanatory power for Chinook and both hatchery-raised and wild Coho marine survival rates. Model goodness-of-fit analysis results are shown in Table 12.

The regression analysis for marine survival of Cowichan River Chinook showed it was highly dependent ($p < 0.05$) on three variables (Table 13). Chinook marine survival was negatively related to SST at Entrance Island in July and mean Cowichan River discharge in October, and was positively correlated to mean minimum daily air temperature at Salt Spring Island in October. Regression coefficients and their *P*-values are presented in Table 13.

Both Strait of Georgia hatchery-raised and wild Coho marine survival regression analyses showed their strong dependence ($R^2 \geq 0.70$, adjusted $R^2 \geq 0.67$) on environmental attributes with a positive correlation to SSS at Race Rocks (two-year mean for hatchery-raised and mean summer for wild), and negative correlations to mean June to September air temperature (mean minimum monthly for hatchery-raised and mean for wild) and to mean annual extreme monthly wind gust speeds observed at the Victoria International Airport. Regression coefficients for both equations and their *P*-values are presented in Table 13.

In addition to goodness-of-fit tests shown in Table 12, our models were validated using a splitting technique (Snee, 1977): for each model the data was randomly split into two sets with roughly equal number of datapoints; the regression analysis was conducted on one dataset and the resulting coefficients are applied onto the second dataset to test the prediction accuracy of the model. The results showed a high degree of fitness ($R^2 > 0.75$) for all the regression models.

Table 12. Regression Models Goodness-of-Fit Results (Legates and McCabe (1999); Willmott et al. (1985, 2012)).

Regression model	**Obs. mean**[9]	**Obs. MAD**[10]	**Pred. mean**[11]	**Pred. MAD**[12]	**MBE**[13]	**MAE**[14]	**d_r**[15]	**R^2**[16]
Cowichan Chinook marine survival	0.013	0.007	0.013	0.006	0.000	0.003	0.80	0.75
Strait of Georgia hatchery Coho marine survival	0.033	0.025	0.033	0.021	0.000	0.01	0.78	0.70
Strait of Georgia wild Coho marine survival	0.050	0.032	0.050	0.030	0.000	0.02	0.81	0.77

Table 13. Cowichan Chinook and Strait of Georgia Coho Marine Survival Linear Regression Coefficients.

Variable	**Coefficients**	**P-value**
Cowichan Chinook marine survival		
Intercept	0.05069	0.14151
SST Entrance Island, July (T° C)	-0.00608	0.00138
Cowichan River Discharge, October (m^3/s)	-0.00013	0.00209
Mean minimum monthly air T, Salt Spring Island, October (T° C)	0.00945	4.083E-05
Strait of Georgia hatchery Coho marine survival		
Intercept	-0.87789	0.06598
2-year mean SSS, Race Rocks light station (PSU)	0.03965	0.00718
June - Sept mean minimum monthly air T, Victoria Airport (T° C)	-0.01969	0.00383
Mean annual extreme monthly gust speed, Victoria Airport (m/s)	-0.00205	0.011995
Strait of Georgia wild Coho marine survival		
Intercept	-0.25131	0.52098
Mean summer SSS, Race Rock light station (PSU)	0.03406	0.00404
June - September mean air T, Victoria Airport (T° C)	-0.03665	7.350E-05
Mean annual extreme monthly gust speed, Victoria Airport (m/s)	-0.00318	0.00082

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[9] Obs. Mean – mean of observed values.

[10] Obs. MAD – mean absolute deviation of observed values.

[11] Pred. mean – mean of predicted values.

[12] Pred. MAD – mean absolute deviation of predicted values.

[13] MBE – mean bias error.

[14] MAE – mean absolute error.

[15] d_r – index of agreement

[16] R^2 – coefficient of determination.

3.3.2 Scenario Projections

The regression equations (Table 13) were used to estimate Chinook and Coho marine survival rates for the 2050 scenarios. While Strait of Georgia Coho marine survival was not shown to be affected by Cowichan River discharge, Cowichan Chinook marine survival was. Therefore, only two scenarios were developed for Coho and four for Chinook.

Future projections showed that in all the scenarios considered, a decrease in marine survival should be expected. None of the three studied populations of salmon are likely to survive in scenarios with extreme climate change, while scenarios with moderate climate change showed positive survival rates albeit at lower rates compared to base levels.

Results of the mean predicted marine survival rates for Chinook and Coho for each scenario were presented in tables 14 through 16. Mean Cowichan River Chinook marine survival rates ranged from as low as -0.16% for Scenario DE (Development of land and extreme climate change) to as high as 0.63% for Scenario CM (Conservation of forest and moderate climate change), where negative values indicated an unsustainable population.

Hatchery-raised Coho marine survival projections showed a -8.73% survival rate for Scenario E (extreme climate change) and a 0.88% survival rate for the Scenario M (moderate climate change). Projected wild Coho marine survival ranged from -6.3% for Scenario E to 4.77% for Scenario M. Negative survival rates essentially mean that there was no survival for these scenarios, but the negative values were used to indicate the severity of impacts relative to baseline conditions.

Table 14. Cowichan River Chinook marine survival: historic and projected 2050 scenarios

Scenario	Input Parameters			Estimated Survival (%)
	SST Entrance Island -July (°C)	Cowichan R Discharge - October (m^3/s)	Mean minimum air T - October (° C)	
Base 1986-2013	18.1	29.4	8.0	1.30
Scenario DE	22.2	33.5	9.2	-0.16
Scenario CE	22.2	26.8	9.2	-0.08
Scenario DM	19.6	26.5	8.2	0.56
Scenario CM	19.6	21.1	8.2	0.63

Table 15. Strait of Georgia hatchery-raised Coho marine survival: historic and projected 2050 scenarios

Scenario	Input Parameters			Estimated Survival (%)
	2-year mean SSS, Race Rock (PSU)	June-September mean monthly minimum air T (° C)	Annual mean extreme monthly gust speed (km/h)	
Base 1985-2016	31.1	10.4	57.0	3.32
Scenario E	30.0	13.7	63.1	-8.73
Scenario M	31.3	13.1	47.1	0.88

Table 16. Strait of Georgia wild Coho marine survival: historic and projected 2050 scenarios

Scenario	Input Parameters			Estimated Survival (%)
	Summer mean SSS, Race Rock (PSU)	June - September mean air T (°C)	Annual mean extreme monthly gust speed (km/h)	
Base 1986-2014	31.1	15.78	56.8	5.0
Scenario E	30.0	17.3	63.1	-6.32
Scenario M	31.3	16.9	47.1	4.77

3.4 Discussion

Marine survival of the two Strait of Georgia salmon species showed notable declining trends over the observed 30-year period (1985 to 2016). Our study supports the idea that these declines are related to changes in air and sea surface temperature, and sea surface salinity related to climate change as has been observed previously (Nickelson, 1998; Fisher & Pearcy, 1988; Holtby et al., 1990; Pearcy 1992; Beamish et al. 2004; Beamish et al., 2010).

Our study also showed that the marine survival of both Chinook and Coho was highly correlated with environmental conditions during the first year of marine residence, explaining at least 75% of survival variability for Chinook and wild Coho. These findings support the critical period hypothesis (Beamish & Mahnken, 2001) that juvenile salmon development within the first year at sea determines their survival through adulthood and overall strength of the cohort, and that environmental conditions within this period are the most critical in defining the overall salmon marine survival (Beamish & Mahnken, 2001; Beamish et al., 2010).

Our study also supports a previous observation by Mitchel (2019) that riverine streamflow during early marine residence has an influence on Chinook marine survival. The negative correlation of Cowichan Chinook with Cowichan River October discharge can be explained by the influence of overall regional October river discharge on conditions of nearshore marine environment (e.g., salinity, surface temperature, turbidity, nutrient flows, water column structure, etc.), a critical habitat for some salmon life cycle phases. Therefore, processes that influence the character, quantity and quality of riverine discharges have an impact of Chinook marine survival. This means that the local management within the watershed (e.g., land use) in combination with global forcing (climate change) has an effect not just on freshwater conditions, but also on Chinook marine survival. Dependence of Chinook survival on the native stream discharge shows that land-use management within the river watershed that affects stream hydrology (Ospan et al., unpublished, Chapter 2) affects not only freshwater survival but also survival in the marine ecosystem. Therefore, it is possible that measures to mitigate climate change effects within the river watershed can also improve chances of Chinook survival in the marine environment.

Our study also indirectly confirmed previous observations and studies of Chinook and Coho early marine residence and migration routes. Higher correlation of Chinook survival with SST at Entrance Island, Cowichan River discharge, and air temperature at Salt Spring Island confirmed the observations that Chinook spend at least several months of their early marine life in the Strait of Georgia, particularly in the nearshore areas of the Gulf Islands (Atkinson & Pellett, 2018; Beamish et al., 2011; Neville et al., 2015; Thakur et al., 2018). At the same time higher correlation of Coho survival with salinity at the Race Rock Islands and summer air temperature at the Victoria Airport may support the conclusion that Coho embark on earlier migrations southward to or through the Juan de Fuca Strait than was previously reported by Beamish et al. (1999) and Chittenden et al. (2009).

A negative relationship between Coho marine survival and wind speed was previously reported by Beamish et al., (2010). They found that the decline in Coho marine survival in the Strait of Georgia coincided with an increase in days when wind speeds exceed 25 km/h. They suggested that high wind speed may impede the availability of prey resources for juvenile salmon by increasing the mixing of surface water, speculating that the winds affect zooplankton production (Beamish et al., 2010). Other possible mechanisms can include wind driven mixing of surface water that increase the energy demand from juvenile Coho to swim and chase their prey and therefore increase their mortality. This vulnerability to the wind speed combined with increased outmigration from the Strait of Georgia over the last decades is likely linked to climate change potentially indicating juvenile Coho are increasingly susceptible to climate-related changes. It is unclear whether the wind speed is going to increase or decrease in the future; historically, it showed a trend of a slight increase over 54 years (Figure 9); however, in the extreme climate scenario the increased wind speed is going to negatively impact Coho survival.

Wild Coho exhibited better marine survival than hatchery-raised Coho both historically and in the projected scenarios. This trend has been previously reported (Beamish et al., 2010; Irvine et al., 2013) and it has been suggested that hatchery-raised fish have lower survival in a stressful environment and that wild salmon may be better adapted to the Strait of Georgia ecosystem. Therefore, efforts to maintain salmon stocks through increased hatchery production may not be successful in addition to the concern that hatchery enhancement may be negatively affecting wild stocks mainly through overfishing of the mixed stocks, genetic impact, competition for resources due to limited carrying capacities of both freshwater and marine habitats (Gardner et al., 2004; Jones et al., 2018).

Based on the above comparison between the wild and hatchery raised Coho marine survival it is possible that the wild population of Cowichan River Chinook also have higher survival rates compared to the hatchery-raised Chinook assessed in our study. Beamish et al. (2012) reports that early marine survival of wild Chinook in the Strait of Georgia during their study in 2008 was found to be six to 24 times as high as that of hatchery-raised Chinook. It is possible that marine survival of wild Cowichan River Chinook is also higher than the projected survival rates of hatchery-raised Chinook used in this study. Therefore, obtaining long-term information on wild Cowichan River Chinook marine survival would be necessary to produce more accurate projections of Cowichan Chinook marine survival.

Our analysis showed that, under the current climate trends, the decreases in salmon marine survival is expected to continue further in all our scenarios. In the more extreme scenarios, juvenile salmon entering the marine environment may not survive through the first year at sea. Since our two opposite scenarios of climate change are just two ends of the same "business-as-usual" climate change scenario, our projections may be interpreted as showing the possible range of outcomes in the next 30 years.

Detrimental effects of climate change on Pacific salmon populations, particularly Chinook and Coho, has been a growing concern (Beamish et al., 2004; Beamish et al., 2010; Irvine & Fukuwaka, 2011; Muñoz et al. 2015; Wainwright & Weitkamp, 2013). Our analysis shows that salmon production in the Strait of Georgia in general and Cowichan River, in particular, may stop by mid-century due to very poor marine survival, and that the decline may not be stopped or reversed unless climate change is stopped or, at they very least, slowed down. Otherwise, potential coping strategies to climate change may include adaptation to new environmental realities and shifting in species distribution including reorientation of fisheries to new species that may occupy the historic salmon habitats and ranges (Cheung et al., 2011).

Chapter 4. Cumulative Effects Assessment Using Scenario Analysis on Two Cowichan River Pacific Salmon Species, Chinook and Coho

Chapter Information

Chapter 4 has been prepared for publication in a journal.

Abstract

This paper describes a proposed methodology for Cumulative Effects Assessment (CEA) with the purpose of improving the process by making it both more substantive and quantitative. The general principles of the approach include the following: use of effect-based type of analyses where selected Valued Component (VC) sensitivities are identified first and then effect pathways are determined building bottom-up linkages from VC sensitivities to potential stressors or combinations of stressors to effect drivers and forces behind the drivers. Quantitative models were developed based on statistical or historic trend analysis or literature review that predicted response of the VCs to pressure from effect drivers. Further, scenarios of divergent futures were created that involved different developments of each effect driver or force, and finally the models were applied to each scenario to project the state of the studied VCs in each scenario. For a practical implementation, the methodology assessed future population trends of two anadromous salmon species from the Cowichan River, British Columbia, Chinook and Coho. The assessment was conducted for both early freshwater and marine phases of their life. In fresh water, the assessment focused on two main factors affecting salmon survival, streamflow and stream temperature and established two main drivers affecting these stressors, land use and climate change, and two main forces behind these stressors, *Local* and *Global*, respectively. In the marine environment, linkages were examined using Pearson correlation and stepwise regression analysis between marine survival of Cowichan River Chinook and Strait of Georgia hatchery-raised and wild Coho and environmental factors including sea surface salinity (SSS),

sea surface temperature (SST), Cowichan River discharge, air temperature and wind gust speed in the nearshore areas of the Strait of Georgia and Juan de Fuca Strait during the first year of marine residence. Predictive models were developed based on regression analysis for Chinook freshwater survival and marine survival of all three populations based on effects of few stressors. These models explained 75% and at least 70% of variability in salmon survival in freshwater and marine environments, respectively. The models were applied to project future salmon survival in 2050 under four scenarios created by combining two opposite scenarios of land use in the watershed, forest conservation and logging, urban and agricultural development, and two climate change scenarios, more extreme and moderate. Scenario projections showed a decrease in overall (combined early freshwater marine) survival by 2050 for all three studied salmon populations. None of them were likely to survive in scenarios with extreme climate change, while scenarios with moderate climate change showed positive survival rates although lower than present-day baseline levels. Analysis also showed that land use management also influenced freshwater survival of both Chinook and Coho and marine survival of Chinook through influence of river discharge on nearshore processes. However, our land-use management scenarios have considerably weaker effect than climate change on salmon survival.

4.1 Introduction

Cumulative effects assessment (CEA) is done to assess combined environmental effects of development from all sources including human activities and natural changes. CEA is conducted as part of Environmental Impact Assessment (EIA) required for permitting of new projects under both federal and provincial jurisdictions. Also, CEA is conducted on a strategic level by various governmental institutions and public initiatives, such as Fisheries and Oceans

Canada (DFO) (Murray et al., 2020) or the BC Cumulative Effects Framework (BC Government, 2014).

The purposes of CEA may include promotion of stakeholder awareness and triggering a response among key planners and decision makers, fostering of understanding of main effect drivers, inciting creative thinking and innovative solutions, and facilitate strategic planning.

CEAs conducted within the EIA processes are often criticized for being aimed at project approval and narrowly focusing on project-specific stressors and their links to effect indicators (Clarke Murray et al., 2014) within restricted geographic and temporal limits, thereby potentially overlooking wider regional issues or valued components (VCs) for which project-specific effects are not predicted. Strategic-level CEAs are designed to conduct assessments on a broader, regional environmental management level (Dube, 2003) with a focus on characterization of environmental effects from multiple stressors that are aimed to inform development of strategic initiatives, policies, plans or programs on a regional basis (CCME, 2009). Strategic-level CEAs, however, lack consistency in methods because they often have different purposes or different legal frameworks, or no legislative frameworks at all (Culp et al., 2000; Dube, 2006; Munkittrick et al., 2000; Murray et al., 2020).

This study proposes, develops and demonstrates a new methodology for CEA processes to facilitate its use and improve its reliability. By combining several methods, we propose the CEA process can be made both more substantive and quantitative. We also, propose a simple assessment methodology/model that can be used by a practitioner without deep knowledge in specialized disciplines, such as animal physiology, hydrology, physical oceanography, or modeling.

The following are the main proposed principles of our methodology:

- Use of an effect-based method (bottom-up) as opposed to the stressor-based (top-down) method traditionally used in project-oriented CEAs. The effect-based method, also known as Species or Habitat – Based Method (Murray et al. 2020), identifies and assesses multiple effects on a particular ecosystem component or VC, (e.g., salmon species, killer whale, water resources, or lake level, etc.) that may occur due to a potential stressor or interactions of multiple stressors (Dube 2003). By contrast, the stressor-based method emphasizes local, project-related stressors and their links with VCs (Clarke Murray et al., 2014).
- The assessment involves consideration of ecological sensitivities of selected VCs during different life stages and identify the most critical environmental and human factors (stressors) that influence these sensitivities and, therefore, affect the VCs.
- Use of scenario analysis (Webber et al., 2012). This approach involves creation of several alternative future, current or past scenarios and an analysis of their outcomes. It can be used to evaluate changes in VCs in response to changes in stressors and key drivers. The outcome of each scenario is assessed using a quantitative or semi-quantitative model.
- The assessment of each scenario includes quantitative or semi-quantitative evaluation of the various effects of environmental and anthropogenic stressors on the VC's sensitivities at each life stage. This also involves determination of effect indicators and/or effect criteria, such as survival rates correlated to certain drivers, numeric thresholds, etc. The effects are assessed using

predictive models that are applied to each scenario, which results in a range of projections or probabilities that indicators or criteria consistent with an effect on the VC meet (e.g., on survival of the population, or sub-lethal effects).

- Since, each scenario outcome will be numeric, e.g., projected probabilities of effects on the VC, they will be comparable to each other or to the base scenario representing present-day conditions (baseline condition). Significance ratings for each scenario will be based on an overall effect size, such as a percent change or by using a normalized index to indicate relative differences (e.g., between –1 and 1).

The application of this methodology will be demonstrated using scenarios driven by a global (climate change) and a local (land use) to assess the cumulative effects on two salmon populations (VCs).

4.2 Methodology

The proposed approach and methodology consist of the following steps, which will be described in more detail below:

1) Definition of the focus and scope of the assessment (Scoping);
2) Identification of the main drivers and effect pathways;
3) Scenario development for the most important drivers and description of scenario assumptions;
4) Scenario analysis including future projections for each scenario and assessment of each scenario’s effects;
5) Review of assessment is intended to inform future development strategies and plans and to make recommendations for addressing uncertainties and gaps in knowledge.

The main purpose of CEA is to define how future developments and/or management decisions within the geographic area may affect specific environmental issues. The pragmatic focus of an assessment is focus on human developments that can be controlled within the study area to mitigate potential harm, and therefore are amenable to management. For example, human developments affecting land use can affect a watershed hydrology and coastal physical parameters such as salinity and temperature and subsequently influence biological processes. However, local environmental effects occur within patterns and processes at regional or global spatial scales, e.g., climate change. The interconnection of processes at different spatial scales will often need to be included to identify the true impacts of the combined effects and how local management change can play a mitigating role.

4.2.1 Definition of Focal Questions (Scoping)

The purpose and scope of this work is to develop a methodology that can identify and assess the effects of human and/or natural stressors over a selected spatial scale. Therefore, the assessment begins with determination of relevant spatial and temporal boundaries and VC selection. This step is required for all environmental and impact assessments (Hanna, 2016; Kominkova, 2008; Milne and Bennett, 2016).

The study area, or geographic limits within which the effects on the environment are assessed, needs to be clearly defined. For the purpose of CEA, the study area may be based on specific geographic units (e.g., for aquatic and marine resources, a study area could be a water body, such as a bay or strait, an estuary, a river basin, a watershed, wetland, etc.) or ecological boundaries (e.g., spatial range) of a VC. The study area will also take into account the spatial scale on which policy decision making must occur. A study area may also be determined by the potential for interactions of several projects and developments.

The temporal scale should be defined at a pragmatic level to limits within which current and future policies and management strategies could influence environmental resources, considering both predictability and uncertainty (Duinker & Greig, 2007). At the same time the temporal scales should be long-term enough for policies to be set as guidance for future plans and proposals.

The environment is assessed through use of a VC (BC EAO, 2013; Milne & Bennett, 2016; Noble and Christmas, 2008). VCs are environmental resources that are of concern to the public, Aboriginal peoples, and/or government(s) and may be affected by projects, policies or other developments. A VC may be a biological unit (population, species, a group of species such as a guild, a functional group or community), habitat, or a habitat property or ecological attribute, such as water or sediment quality. A VC can also represent a large group of species of organisms belonging to different functional groups but combined by classification and/or habitat, such as *marine mammals*, or *marine birds*, or an attribute partially based on aesthetic value, such as *visual quality*. There is a large literature on selection of VCs, however, our emphasis is on other components of the CEA methodology, so an extended discussion of VC selection is outside of the scope of this study.

Finally, effect indicators should be determined for VCs. Effect indicators are measurable variables that can be used to describe the state of the VC. An effect indicator can be a measure of success of a biological unit (e.g., abundance, survival rate, fecundity, growth rate, etc.), an area of a habitat, or an environmental index.

4.2.2 Identification of Key Drivers and Effect Pathways

To determine the main drivers affecting the selected VCs we need to determine the main potential pathways through which the VCs can be affected. Pathways include the following elements (from bottom up): VC survival/success, sensitivities, stressors, key drivers and, if necessary, main forces (demography, economy, etc.). Relationships among these elements are shown further in Section 3.2.

First, a detailed VC profile is prepared that includes information on the VC to determine conditions required for its survival/success. In the case of a biological VC, such as a species, the profile includes life history and characteristics of each life stage such as habitat requirements, duration of certain conditions, physiological conditions, growth rates, survival rates, food resources, predators, physical conditions of the environment, seasonality, and other critical factors. The profile should be as specific to the population resident in the assessment area as possible because often populations of the same species living in different geographic areas have different life history characteristics, such as timing of spawning, migration periods, etc. In the case of the VC being a habitat or ecological attribute, or an aesthetic value, the profile would include characteristics of VC users, such as species, communities and or social groups.

Second, effect pathways are determined for each life stage of the VC. The most important part of the effect pathway selection is determination of sensitivities and stressors. Sensitivities and stressors are directly linked to each other. Sensitivities are thresholds of normal physiological or behavioral response of the VC to environmental attributes of the habitat, and stressors are changes in these attributes that trigger the VC's physiological or behavioral responses and affect survivorship, reproduction or development at each life stage of the VC (Selkoe et al., 2015). Sensitivities can be to physical attributes of the environment or habitat, such as ranges of temperature or salinity, or biological, such as predation or prey availability. A stressor can be a change in a normal attribute of the environment, such as temperature, or can be an introduced factor, such as a pollutant or invasive species. It is understood that there can be a large number of environmental attributes that may affect organism survivorship at each stage, however, for the purpose of simplicity and efficiency, the most critical attributes are selected (Pecl et al., 2014).

There could be several potential ways for sensitivity and effect pathway determination, for example, those based on:

- well understood physiological and/or behavioral responses of the VC to environmental changes and physical/biological relationships (for responses that are well documented in the scientific literature)
- known links between physical and biological factors and effect indicators that can be verified through correlation analysis of data
- established sensitivity thresholds with effects determined through simple threshold exceedances (binary) (derived from the scientific literature)
- pathways when there are less understood complex dependencies of VC survival and wellbeing on environmental variables can be derived through "grey box" models, such as step-wise regression analysis, complex statistical models, artificial intelligence/machine learning (principal component analysis (PCA), Bayesian analysis, neural networks etc.) of data

Since some VCs can have complex life histories with each life stage having its own specific sensitivities and, effect pathways for different life stages. Accounting for these life stages may require different methods or combinations of methods to assess overall impacts.

Third, effect drivers need to be identified. Effect drivers are activities or processes that generate or influence stressors (Nelson et al., 2006; Oesterwind et al., 2016). Key drivers can be a process/ factor or a combination of factors that affect selected sensitivities directly. Key drivers can also be combined under major forces, if feasible. Major forces are logical combinations of key drivers that dictate directions and the extent of effect drivers. For example, a fishery can be a key driver causing overfishing stress on a certain fish population, while a major force behind it can be a socio-economic, demographic, or political situation that generates the demand for food (Zondag & Borsboom, 2009).

Effect drivers and stressors should be selected so that they can be assessed in the context of scenarios, meaning that it is possible to project changes in stressors based on scenarios or projections of major forces for the selected geographic limits. Furthermore, the study needs to be constructed in such a way that changes among all the scenario projections can be translated into changes in stressors that relate to VC responses.

The fourth and final step reviews how changes in stressors from one or multiple drivers combine to effect the selected sensitivities. At this stage a predictive model can be developed that can then be used to assess impact from the combination of drivers on each life stage of the VC.

4.2.3 Scenario Development

Once the scope of assessment and key drivers are determined, the scenarios are developed. Each scenario is a logical inference of future conditions, which involves determination of the direction and extent of the drivers. By using scenario analysis, we hope to reduce uncertainties related to expectations from the future and improve our understanding of and preparedness for potential outcomes (Carlson et al., 2011).

A scenario analysis involves looking at various outcomes of development under different circumstances and defining the most suitable mitigation or adaptation strategies (Duinker & Greig, 2007). Scenario analysis includes the process of creation and assessment of a number of alternative reasonable (not incredible) situations; and, each situation is distinctly different from another (Schwartz, 1996). The scenario analysis shouldn't be mistaken for a forecast, and assigning likelihood or probabilities to the scenario analysis should be avoided (Duinker, 2008).

Methods for scenario creation may vary from "an imaginative exercise by a single individual" to a group process that involves stakeholders of various interests and expertise (Peterson et al., 2003; Duinker and Greig 2007). Methods may also differ in the analytical techniques, often contrasting: backcasting versus forecasting; descriptive versus normative; quantitative versus qualitative; trends versus peripheral; and inductive versus deductive reasoning (Duinker and Greig 2007). Scenario-development methods and techniques are described by Bishop et al. (2007) and Muscat et al. (2012).

4.2.4 Scenario Assessment

The impact of each scenario on each of the VC's life stages or habitats is assessed using quantitative or semi-quantitative models. One of the objectives of models is to predict the effect on the VC through changes in effect indicators.

Statistical relationships between effects indicators and stressor variables, such as a regression analysis, can be used as a model. If there is not enough data to derive such relationships, the assessment may use effect thresholds to predict effects from stressors on sensitivities. Effect thresholds can be used for different life stages of the VCs. Effect thresholds may be values of physical properties (e.g., temperature threshold) whose exceedance will impact effect indicators. Thus effect thresholds can be used in a similar way as to the concept of climate envelopes (Pearson & Dawson, 2003; Hijmans & Graham, 2006; Feddema et al., 2013).

In cases where effect thresholds are used, effect indicators (e.g., survival) for each life stage for each scenario can be estimated using the following equation:

$$E_i = E_{i-1} \times x_i \times (1 - y_i)$$

Where:

E_i - effect indicator (e.g., survival) of the VC during the life stage i;

x_i – baseline (natural) effect indicator value (survival) or hypothetical indicator value of the VC during the life stage i;

y_i – probability of effect from the scenario on the indicator of the VC during the life stage i calculated as the probability of the effect threshold being exceeded.

Once effects on each life stage have been assessed, overall projections for the entire life cycle of the VC are produced by combining results for all life stages. The overall effect can be calculating by adding effects of each life stage or by multiplying. For instance, when we use survival rate (as percentage) and an effect indicator, the overall results for each scenario can be calculated as follows:

$E = E_1 \times E_2 \ldots \times E_n$ (*Equation 1*)

Where:

E – overall VC's survival

n – the last life stage of the VC.

Where effect thresholds are used as effect indicators the overall results can be calculated as follows:

$E = x_1 \times (1 - y_1) \times \ldots \times x_n \times (1 - y_n)$ (*Equation 2*)

Results from the scenario assessments are compared among the future scenarios and to baseline conditions. To determine relative significance of effects, results from different scenarios can be compared as a percent change from a baseline or by using a normalized index to indicate relative differences (e.g., an index with values ranging from –1 to 1 where 0 equals ‘no change’, similar to the relative moisture index developed by Willmott and Feddema (1992).

4.2.5 Conclusions and Recommendations

As an outcome of the assessment, multiple different future projections can be evaluated ranging from the “most positive” to “most negative”. It is possible that the “positive” scenarios will result in more positive changes compared to baseline conditions if, for example, effect mitigation or protection measures have stronger effect on the VC than detrimental drivers. However, it is also likely that all scenario outcomes will show decrease in effect indicators relative to the baseline, and in this case scenario outcomes will range from “least negative” to “most negative”. In any case, the assessment will show potential management decisions that can be made to steer the future towards more desirable outcomes.

4.3 Practical Implementation

For an example of practical implementation, we used our methodology to assess future survival rates for two anadromous Pacific salmon species, Chinook (*Oncorhynchus tshawytscha*) and Coho (*O. kisutch*) native to Cowichan River, British Columbia. Our assessment focused on the Cowichan River watershed with the two anadromous salmonids, Chinook and Coho, that are native to the river selected as VCs. However, the effects are assessed beyond the watershed to include conditions in the Strait of Georgia, Juan de Fuca Strait, and the marine environment with undefined boundaries where the two populations spend parts of their life.

The focus of the assessment was on processes that affected the VCs and could be managed within a certain geographic area, in our case the Cowichan River watershed. In our example, we conjectured that human activities within a watershed could affect physical properties (streamflow and temperature) in the river and also physical and biological processes in the coastal marine environment, such as water salinity, temperature and biological productivity through altered hydrology and outflows of the Cowichan River that discharges into this environment. Therefore, processes within the watershed were speculated to affect both the freshwater and marine stages of our VCs at least in the near coastal areas.

Anadromous salmon have complex life histories and spend their life cycle in both freshwater and marine environments. During their early life stages in freshwater, they are particularly vulnerable to changes in water temperature, water flow, water quality and other environmental factors.

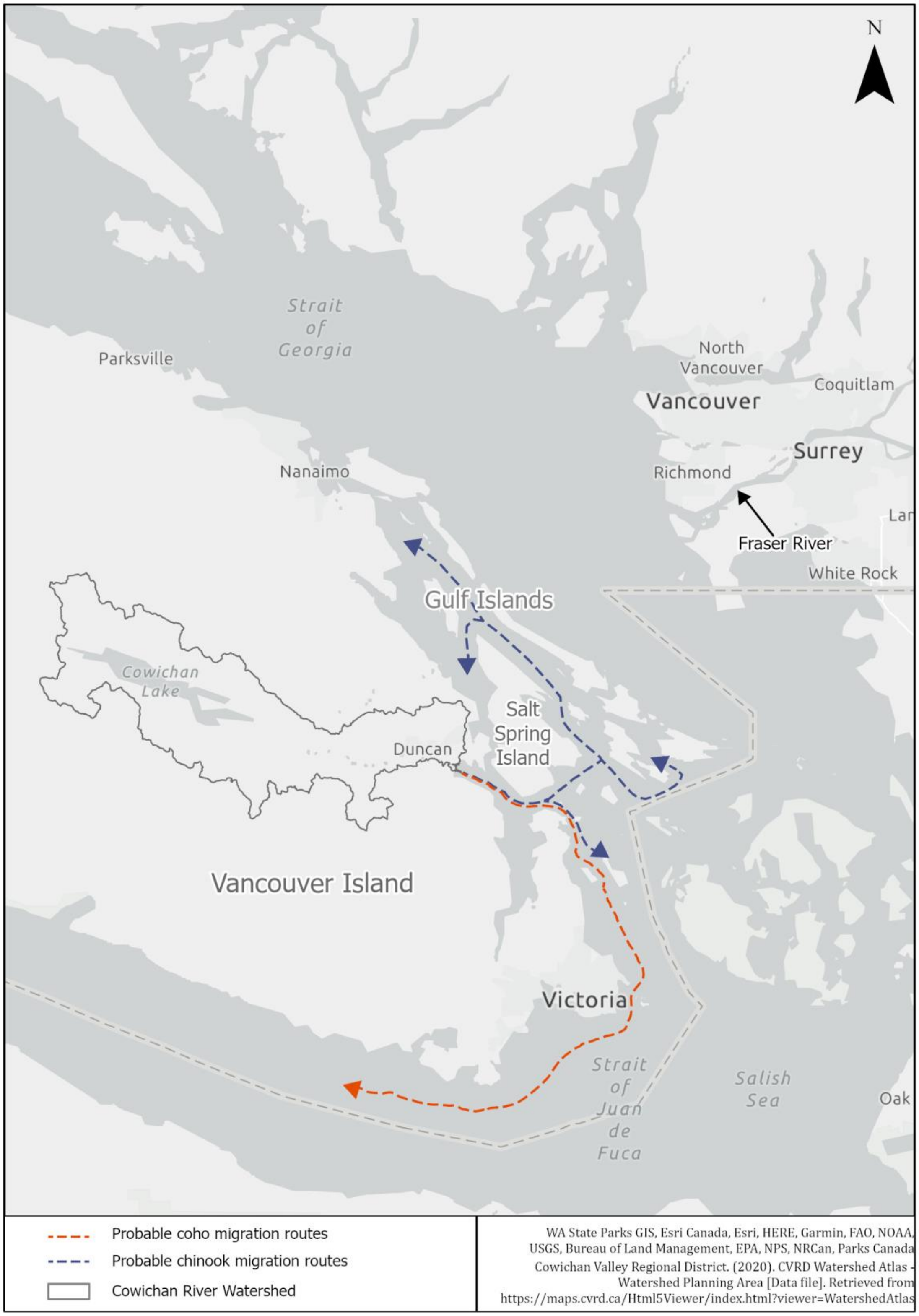
Many factors that affect salmon survival and development in the open ocean (ocean water temperature, salinity, currents, wind, upwelling, decadal oscillations, harvest outside the Exclusive Economic Zone, etc.) are outside the influence of management decisions on the local or regional scales. However, there are strong indications that survival of salmon in the marine environment is at least partially dependent on physical characteristics of freshwater runoff, particularly during the vulnerable periods that salmon spend in nearshore marine waters. Therefore, human drivers on the local and regional scale, in this case in a watershed, are considered as potentially influencing salmon survival and development during both freshwater and marine life cycle phases. Scenarios were applied to both freshwater and marine life stages.

It was recognized that there may be hundreds of different drivers and factors, both human and environmental, that affect salmon. For simplicity and practicality, only the factors deemed most influential were considered in this assessment. Finally, decisions and human drivers that influence salmon populations directly, such as fishing and fisheries management and conservation measures (fishing restrictions or habitat restoration) were not considered in this assessment; although they could be included in the future in addition to the physical parameters assessed in this example.

4.3.1 Scoping

The Cowichan River watershed occupies an area of 930 km^2 in the southeastern part of Vancouver Island and includes Cowichan Lake, Cowichan River and their tributaries. The lake is located in the mountainous region at an elevation of 162-165 m above the sea level and discharges into the river that runs for 45 km before emptying into the Strait of Georgia between Vancouver Island and the mainland of British Columbia (Figure 10). Discharge into the river from the lake is regulated through the weir at Cowichan Lake by holding enough water in the lake during wintertime to maintain a minimum flow of 7.08 m^3/s in summer, while allowing water in excess of lake's storage capacity to overflow the weir freely in winter.

The Strait of Georgia is connected to the open ocean through Juan de Fuca Strait in the south and Johnstone Strait in the north. The circulation in the strait is primarily influenced by discharge of Fraser River across the strait from Cowichan River that reaches a maximum in June as the winter snowpack melts (Thomson, 1981).



WA State Parks GIS, Esri Canada, Esri, HERE, Garmin, FAO, NOAA, USGS, Bureau of Land Management, EPA, NPS, NRCan, Parks Canada
Cowichan Valley Regional District. (2020). CVRD Watershed Atlas - Watershed Planning Area [Data file]. Retrieved from https://maps.cvrd.ca/Html5Viewer/index.html?viewer=WatershedAtlas

Figure 10. Study Area.

The two anadromous salmonid populations used as VCs in our study, fall Chinook and Coho, spawn in autumn and early winter in the upper reaches of Cowichan river below Cowichan Lake (Bert & Robert, 2002; Lill et al., 1975; Lister et al. 1979; Nagtegaal & Riddell, 1998; Neave, 1943; Pellet, 2017; Tompkins et al., 2005). Early life stages of both species, such as egg incubation and juvenile rearing occur in the freshwater environment. Egg incubation for both species occurs during winter, and juvenile fish (fry) emerge mainly in the spring of the following year.

Juvenile Chinook (fry) emerge in March-April and spend less than 90 days in the river, migrating to the estuary from April through June (Candy et al., 1995; Craig, 2015; Healey, 1991; Nagtegaal et al., 2004). Adaptation to marine life (smoltification) occurs in the estuary where juvenile Chinook spend from two to four months (Pearcy, 1992) before migrating to nearshore marine areas of the Gulf Islands in the Strait of Georgia in June to September (Atkinson & Pellett, 2018; Thakur et al., 2018). It is believed that the majority of Cowichan River Chinook population remains in the Strait of Georgia at least for the first several months of their marine life (Beamish et al., 2011; Neville et al., 2015), even though some Cowichan Chinook have been found to migrate as far north as Queen Charlotte Strait, to the west coast of Vancouver Island and as far south as Washington and Oregon (W. Luedke pers. com., as in V. Kommori & Assc., 2010).

Cowichan Chinook spend from 1.5 to 4.5 years in the marine environment and return for spawning as sexually mature fish primarily at ages of 3 or 4 years with a considerable contribution of age-2 males (jacks) (Tompkins et al., 2005). The proportion of age-5 adults is considerably smaller and is usually less than 2%.

After emergence, which occurs almost at the same time as Chinook’s, Coho juveniles spend a full year in the freshwater, until April - May of the following year (Atkinson & Pellet, 2018; Craig, 2018; Pearce et al., 2020). Coho smolts spend only a brief period in the estuary (Pearcy 1992) and enter the Strait of Georgia in May. Until the last few decades Coho were thought to remain in the Strait of Georgia for the entire duration of their marine residence (Beamish et al., 1999; Chittenden et al., 2009). However, migration of Coho out of the Strait of Georgia in October to December of the first year in the marine environment has been observed increasingly over the last few decades and is thought to be related to changes in physical conditions in the strait due to climate change (Beamish et al., 1999). Coho spend a maximum of a year and a half in the marine environment (Pearcy, 1992) and return to the native stream as jacks or 3-year-old mature adults (Sandercock, 1991; Pearce et al., 2020).

Therefore, in our assessment we consider both freshwater and marine stages of Chinook and Coho life cycles independently. The geographic limits of the freshwater part of the assessment are the boundary of the Cowichan River watershed; the spatial area of the marine part are zones of the Northwest Pacific where marine growth and maturity of these two populations occurs, mainly the Strait of Georgia and Juan de Fuca Strait.

The temporal boundaries of the assessment are from the present time to 2050, or approximately 30 years from now. These temporal boundaries are within the scope of present climate models and are practically foreseeable for decision makers at a local scale.

The effect indicator used for both VC populations is survival rate expressed as percentage of a cohort surviving to the end of each life stage. Effects on salmon survival rates were assessed for both freshwater and marine environments and then combined to produce overall survival rates for each of four future scenarios developed and assessed as described hereafter.

While anadromous Pacific salmon life cycles transition between freshwater and marine habitats, there are also transitional periods between the freshwater and marine environments that take place in estuaries, with durations varying from species to species (from days to months). However, habitat conditions in the estuaries critical for salmon survival are largely dependent on riverine runoff and marine physical conditions, and there are no data on estuarine survival that could be used in this study. Therefore, estuarine life stages are not considered separately in this assessment but are integrated in the marine assessment.

4.3.2 Key Drivers and Pathways

Effect pathways were determined through extensive literature review of physical factors affecting the two species in the freshwater and marine environments and statistical analysis examining linkages between available data on survival for each phase of the life-cycle and environmental variables in each habitat.

4.3.2.1 Freshwater Habitat

Water temperature and streamflow are considered the most important physical factors influencing survival and production of salmon in freshwater habitats (Beacham & Murray, 1985; Bell, 1986; Brett, 1952; Brett et al., 1982; Burck 1993; Carter 2005; Flett et al., 1996; Hicks, 2000; Lill et al., 1975; Mantua et al., 2010; McCullough et al., 2001; Murray & McPhail, 1988; Raleigh et al., 1986; Richter & Kolmes, 2005; Spence et al., 1996; Sullivan et al., 2000). Therefore, temperature tolerance and streamflow requirements were selected as our VCs’ main sensitivities, while changes in stream temperature and discharge are determined to be the main stressors.

Streamflow and temperature are mainly dependent on meteorological conditions, such as air temperature and precipitation, but are also influenced by many other factors, including overland runoff/groundwater partitioning, soil type and thickness, soil moisture conditions, and land cover type (SCS, 1974; Mather, 1978), all of which are factors affected by land use (Feddema et al., 2013). Therefore, we selected two main drivers of effects on our VCs: land use and climate change. These two drivers represent two major forces: local and global (Figure 11).

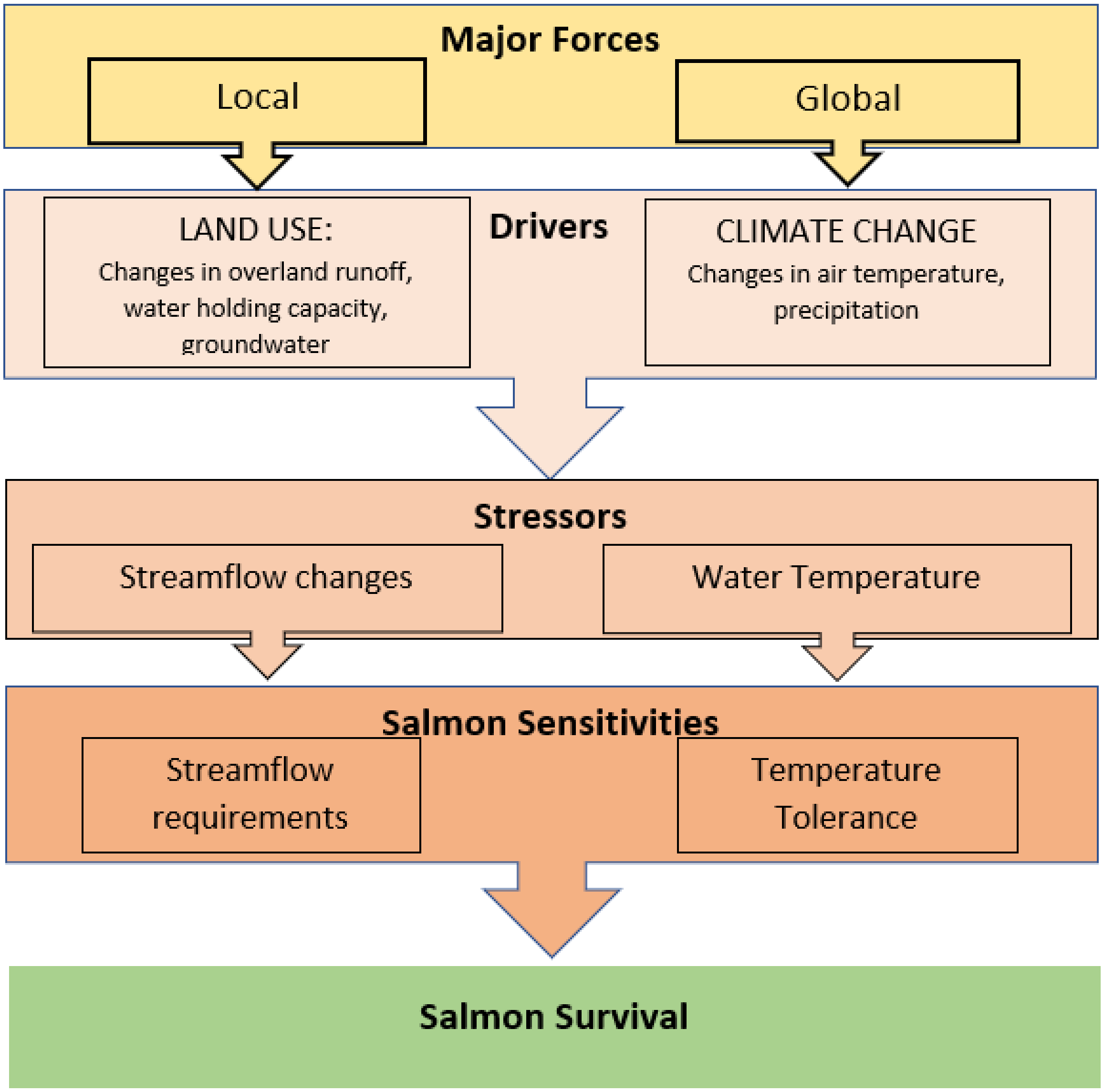


Figure 11 Freshwater Effect Pathways for Cowichan Salmon

A series of models were developed to simulate top-down effect pathways for freshwater phase of Cowichan River fall Chinook and Coho (Ospan et al. unpublished, Chapter 2 in this dissertation). They included physical models to simulate effects of the land use, the local driver, and climate change, the global driver, on discharge and stream temperature, and physico-biological models to project effects of the two stressors, discharge and stream temperature, on salmon survival, the effect indicator.

To predict streamflow for future scenarios, a daily time-step hydrologic model that uses basic water balance methodologies was built using Microsoft Excel software (Feddema et al., 2013, Savage et al., 1996; Mather, 1978; Ospan et al., unpublished, Chapter 2; Thornthwaite, 1948;). The model used meteorological input data (air temperature and precipitation) and land use data to predict stream flow by partitioning overland runoff from precipitation (SCS, 1974; Mather, 1978), estimating potential evapotranspiration (PET; Thorntwaite, 1948), snow accumulation, snowmelt (Willmott et al. 1985), soil moisture conditions, actual evapotranspiration (AET), moisture surplus and deficit conditions. Details of the models used, it’s assumptions, calibration and results can be found in Ospan et al. (unpublished, Chapter 2). Model validation showed it to be very effective at simulating conditions at three Water Survey Canada (WSC) hydrometric stations measuring Cowichan Lake level, discharge from Cowichan Lake to Cowichan River and Cowichan River streamflow at the lower river near Duncan. Validation with all three data points based on Legates and McCabe (1999) and Willmott et al. (1985, 2012) model validation metrics showed that the model had high explanatory power (e.g., d_r[17] and R^2[18] for river discharge at Duncan were 0.87 and 0.85 respectively [Ospan et al. unpublished, Chapter 2]).

Factors influencing stream temperature were examined through Pearson correlation and stepwise regression analyses using Cowichan River daily water temperature data from August

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[17] d_r – index of agreement.

[18] R^2 – coefficient of determination.

2000 to July 2012 from a monitoring station near Duncan. The analysis resulted in regression equations with high explanatory power (e.g., $R^2 = 0.94$) showing that mean and maximum daily stream temperatures were highly dependent ($p < 0.05$) on 20-day average air temperature (direct correlation) and average daily discharge (inverse correlation) (Ospan et al., Chapter 2).

Cowichan fall Chinook egg-to-fry survival data for a period from 1990 to 2001 (ratio of out-migrating fry abundance to an estimated number of eggs produced; Nagtegaal et al., 2004) was used to derive relationships between Chinook freshwater survival and physical variables such as discharge and stream temperature. These linkages between the effect indicator (survival) and stressors (physical variables) were evaluated using correlation analysis and a reverse stepwise regression (Ospan et al. unpublished, Chapter 2).

The stepwise regression analysis selected two variables that affected Chinook freshwater survival most significantly ($p < 0.05$): maximum water temperature in December (direct correlation) and mean annual monthly maximum water temperature of the brood year (inverse correlation). The regression has high explanatory power ($R^2 = 0.74$).

A second model of salmon survival used the concept of environmental thresholds, similar to climate envelope modeling (Pearson & Dawson, 2003; Hijmans & Graham, 2006; Feddema et al., 2013). Literature-based temperature and discharge thresholds were applied to two main phases of Chinook development in Cowichan River since egg fertilization, incubation, occurring during winter (December to February) and fry rearing, occurring mainly in March and April (Table 17). In this study we used evidence-based inference that exceedance of the discharge or temperature survival thresholds negatively affects salmon survival. The 31-year long model simulation of daily discharge and water temperature was used to estimate a survival probability. The probability of exceedance of the threshold at any stage was estimated as a ratio of the number of days when thresholds were exceeded to the total number of days of this stage in the simulation. The term *survival* was used as a probability of simulated favourable environmental conditions (conditions within the thresholds) for each stage, estimated as follows:

$$Survival = \frac{Days\ within\ thresholds}{Total\ days},$$

$$\text{or } Survival = \frac{Total\ days - Exceedance\ days}{Total\ days}$$

The product of threshold-based survivals of all freshwater stages was used as an overall threshold-based freshwater survival.

Chinook survival rates predicted by the regression were multiplied by the survival based on the thresholds to produce the “final” freshwater survival. This was based on an assumption that the observed independent variables used in the regression analysis of Chinook freshwater survival were mostly within the normal survival thresholds and, therefore, the regression did not account for potential future threshold exceedances.

No long-term data was available on Cowichan River Coho freshwater survival. An average survival rate of 3.4% was estimated from the literature (Bradford et al., 2000) and used as an “intrinsic” Coho freshwater survival on which the estimated threshold-based survival rates were applied. For Coho we determined six life history phases in freshwater residence from the first winter (egg incubation) to the second spring (smoltification) (Table 17). So, to derive an overall freshwater threshold-based Coho survival rate, the product of six threshold-based survivals was multiplied by 3.4% to produce the “final” Coho freshwater survival rate.

Table 17. Cowichan River Coho and Chinook freshwater normal development and survival thresholds (From Ospan et al. unpublished).

Stage	**Timing**	**Temperature range (° C)**		**Discharge range (m^3/s)**	
		Lower limit	**Upper limit**	**Lower limit**	**Upper limit**
Chinook					
Incubation	December - February	2.0	12.0	4.5	212.0
Fry rearing	March - April	5.0	16.0	4.5	212.0
Coho					
Incubation	December-February	2.0	12.0	4.5	212.0
Emergence/ fry	March - May	4.4	16.0	4.5	212.0
Summer parr	June - September	4.4	24.0	4.5	212.0
Fall parr	October - November	4.4	24.0	4.5	212.0
Second winter parr	December - February	4.4	24.0	4.5	212.0
Second spring/ smolt	March - April	4.4	24.0	4.5	212.0

4.3.2.2 Marine Habitat

Effect pathways in the marine environment were examined by assessing linkages between salmon marine survival rates and various environmental physical factors using correlation and reverse stepwise regression analyses. Marine survival rates were estimated using coded-wire tags (CWTs) inserted into hatchery-raised smolts when released. The number of 2-year-old fish with CWTs, estimated from fishing reports and counts of fish returned to Cowichan River, was divided by the total number of CWTs released (Tompkins et al., 2005). Data for hatchery raised Cowichan Chinook for smolt years 1986 to 2013 (brood years 1985 to 2012) was obtained from DFO (May 10, 2019; Figure 12).

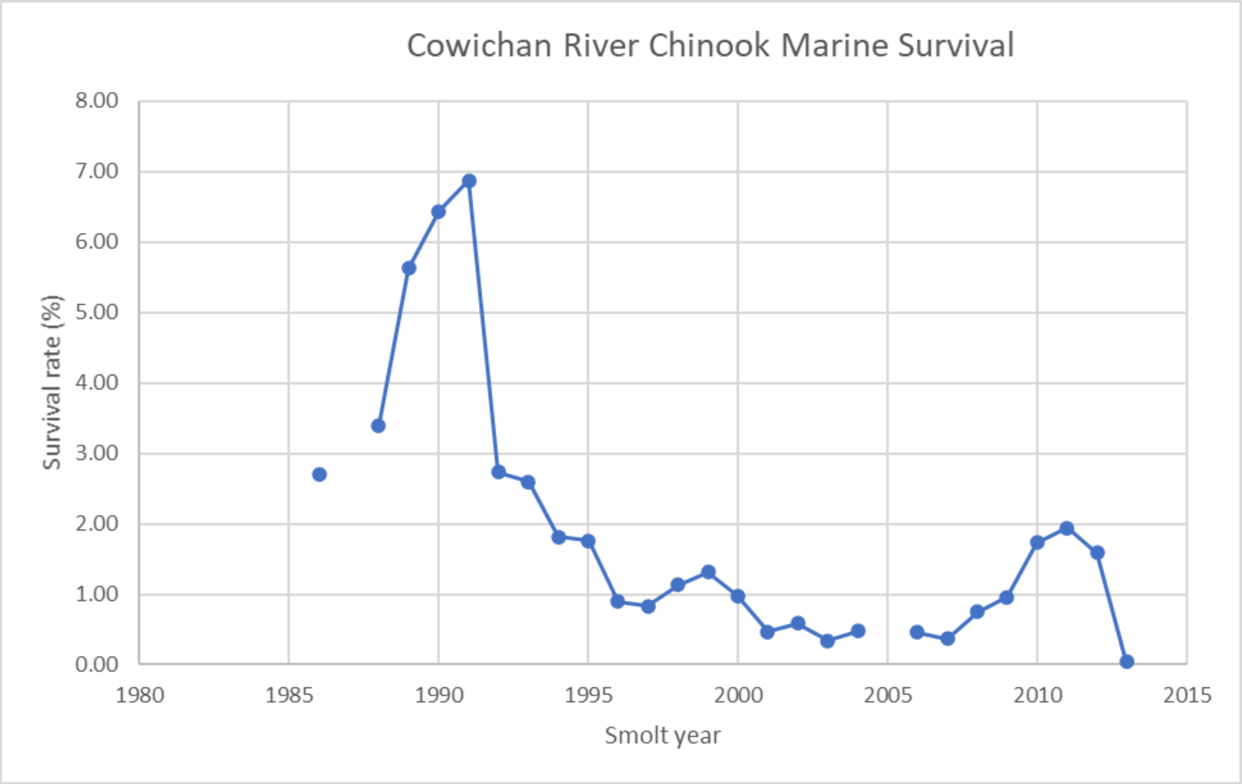

Figure 12. Cowichan River Chinook Marine Survival (DFO, pers. com., May 2019).

No long-term data on Cowichan River Coho marine survival were available. Instead, overall Strait of Georgia hatchery and wild Coho survival rates based on CWT programs were used in the analysis; hatchery data consisted of combined CWT-based estimates for Inch, Big Qualicum, Chilliwack, and Quinsam hatcheries; wild Coho survival estimates were based on CWT-based studies run on Black and Myrtle creeks and Salmon River wild Coho stocks (Irvine et al., 2013). Survival data for both hatchery and wild Coho was provided by DFO for 1985 to 2016 smolt years (Figure 13).

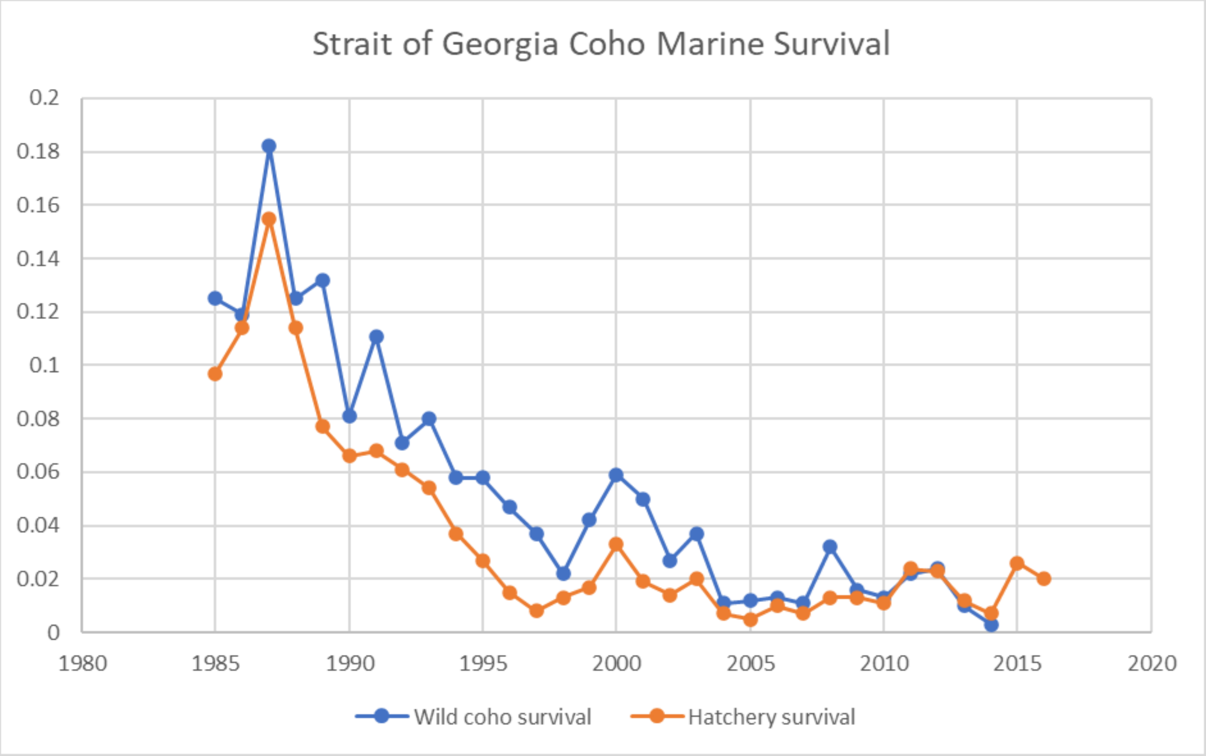

Figure 13. Strait of Georgia Coho Marine Survival (%; DFO pers. com.)

Physical data examined included Cowichan and Fraser river flows, Strait of Georgia and Juan de Fuca Strait surface temperature (SST) and sea surface salinity (SSS), air temperature, precipitation, monthly extreme gust speed, and open ocean SST. Criteria for data selection included geographical closeness to assumed Chinook and Coho habitats and migration pathways, and availability of continuous data for the period between 1985 and 2016 (Figure 10Figure 12).

Stepwise regression analyses resulted in regression models with high explanatory power for Chinook and both hatchery-raised and wild Coho marine survival rates. Index of agreement d_r (Willmott et al., 1985, 2012) values were 0.8, 0.78 and 0.81 for Cowichan Chinook, and Strait of Georgia hatchery-raised and wild Coho respectively, and equivalent coefficient of determination R^2 values are 0.75, 0.7, and 0.77 respectively (Ospan et al. unpublished; Chapter 3).

The stepwise regression showed significant ($p < 0.05$) dependence of Cowichan River Chinook marine survival on three physical variables. Chinook marine survival was inversely correlated to July SST at Entrance Island and mean October Cowichan River discharge and was directly correlated to October mean minimum daily air temperature at Salt Spring Island.

Regression analysis of Strait of Georgia hatchery-raised and wild Coho regression analyses showed dependence of Coho survival on salinity in Juan de Fuca strait, summer air temperature and gust speed at Gulf Islands. Both hatchery-raised and wild Coho marine survival showed positive correlation to SSS at Race Rocks (two-year mean for hatchery-raised and mean summer for wild), and negative correlations to June to September air temperature (mean minimum monthly for hatchery-raised and mean for wild) at Salt Spring Island and to mean annual extreme monthly gust speed observed at the Victoria International Airport.

Therefore, the pathway analyses shows that marine survival of Cowichan River Chinook may potentially be affected by changes in land use through changes in discharge of the Cowichan River that affects salinity and water temperature in October, as well as by climate change through changes in SST and air temperature. At the same time, Coho marine survival shows no dependence on variables associated with either Cowichan or Fraser River discharges but only on variables directly affected by climate change (Figure 14).

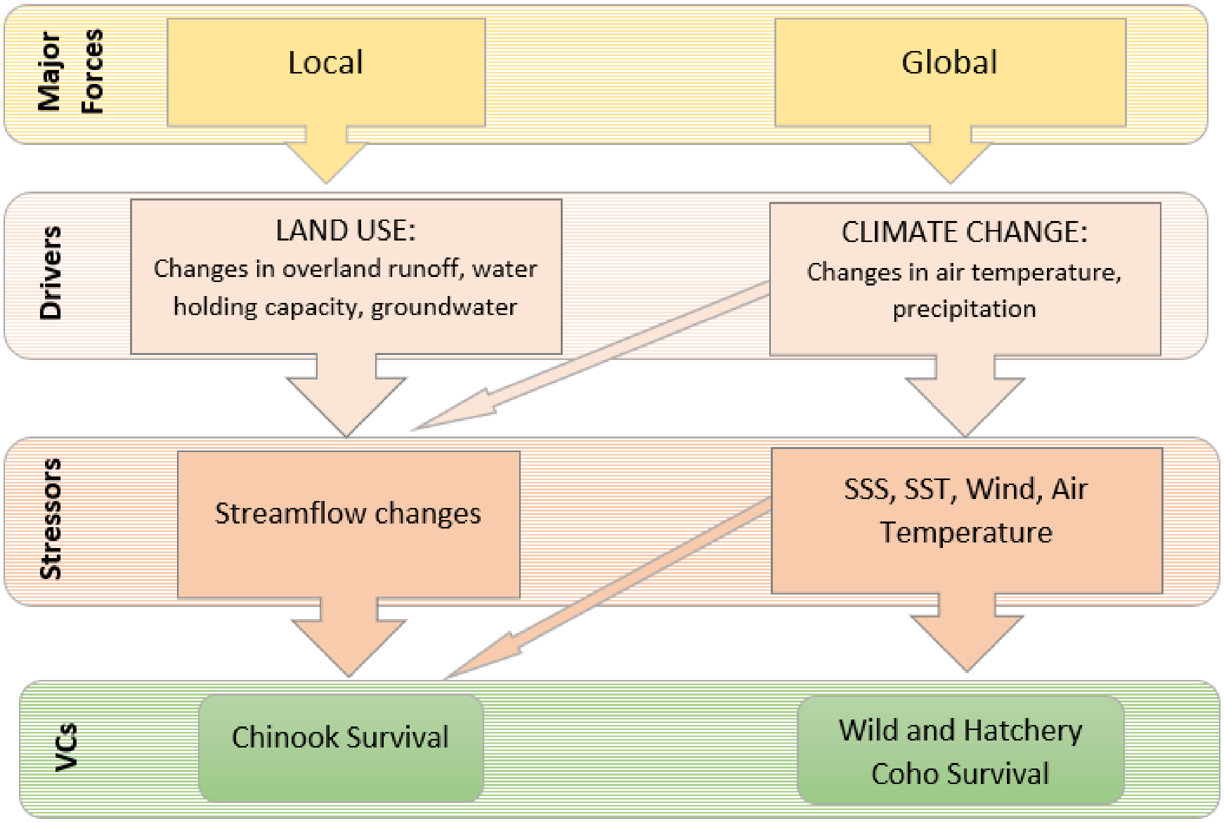

Figure 14. Salmon Marine Effect Pathways

4.3.3 Scenario Development

The approach to scenario development was similar to that in Duinker (2008), Creed and Laurent (2015) and Laurent et al (2015). Four scenarios of divergent futures were created using two orthogonal axes that represented major forces of impacts as shown in Figure 15 (Ospan et al. unpublished, Chapter 2). Since it was established that the key pathways at the local level affecting salmon survival were through changes in hydrology, temperature and precipitation; land use and climate change were used as the major drivers that determined the scenarios logic. From these two drivers the scenarios were built using the conceptual model shown on Figure 15. The Y axis (Global, climate changes) represents two significantly different scenarios of climate change, more extreme and moderate, while the X axis (Local, land use) represented two significantly different watershed land cover scenarios, one directed towards forest conservation and restoration, and the other towards increasing land development to logging, urbanization and agricultural use.

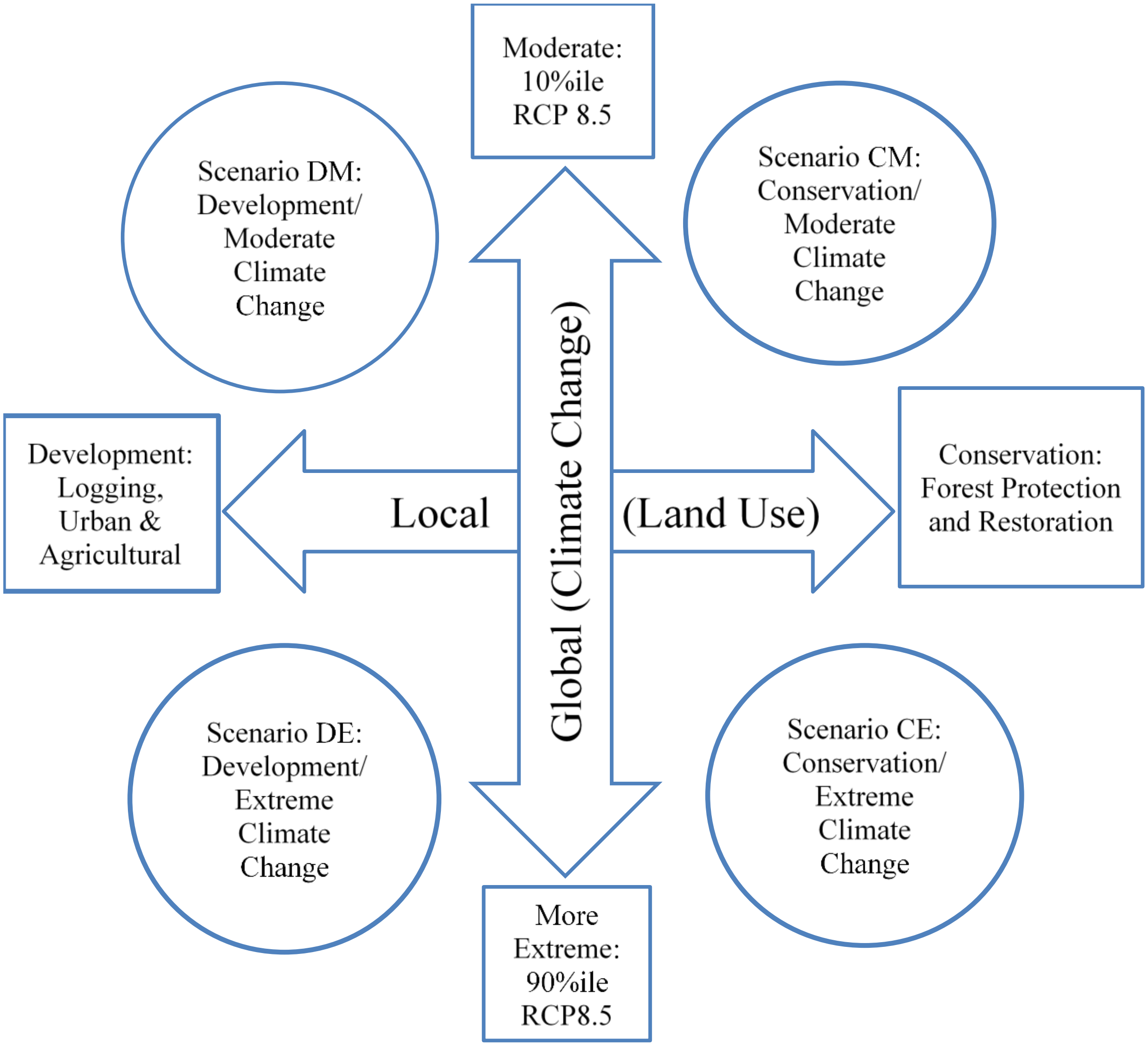

Figure 15. Future Watershed Development Scenarios (from Ospan et al. unpublished, Chapter 2)

The four selected scenarios represented each of the quadrants in Figure 15: CM (forest conservation and moderate climate change), CE (forest conservation in combination with more extreme climate change), DE (land development and more extreme climate change), and DM (land development and moderate climate change; Ospan et al. unpublished, Chapter 2). All four of these scenarios were applied to the models simulating stressors in the freshwater phases of both salmon species life cycles, while for the marine phase, all four scenarios were applied to Chinook future only. Since marine Coho survival does not show any dependence on Cowichan River hydrology, only the two climate change scenarios, moderate and extreme, were applied to future marine survival of Coho.

Climate change scenarios were based on Global Climate Models (GCM) high-emission climate change scenario RCP 8.5 projections (Collins et al. 2013). The 10-percentile values RCP 8.5 climate projections for 2050 are used for the *moderate* climate change scenario (the upper end of Y axis in Figure 15), while the 90-percentile projections of the same RCP scenario were used for the more *extreme* scenario (the lower end of the Y axis) (Ospan et al., unpublished; Chapter 2 and 3). Two extremes of the same RCP scenario projections were used in the analysis because differences between the projections for two different RCPs (e.g., between RCP 8.5 and RCP 4.5 or RCP 2.6) were less than the differences projected from the different models for the same scenario (e.g., Loder & van der Baaren, 2013; Ishizaki et al., 2012).

Future projections of air temperature, precipitation, SSS and SST for the assessment region for 2050 were taken from open sources available online (e.g., https://pacificclimate.org; Lodder & van der Baaren 2013). For example, projected summer and winter temperature increases for the Cowichan River valley were 1.8 and 2.0° C respectively for the moderate climate change scenario, and 3.3° and 4.2° C respectively for the extreme climate scenario (Ospan et al. unpublished). Projected changes in precipitation in the Cowichan River Valley were -0.7% in winter and +2.8% in summer for the moderate scenario and +8.1% in winter and -42% in summer for the extreme scenario. Mean SST in the Strait of Georgia was projected to increase from the baseline (1986-2013) 18.1° C in July to 19.6° C for the *moderate* climate change scenario, and to 22.2° C for the *extreme* scenario. Mean annual salinity was projected to slightly increase from the baseline of 31.1 PSU to 31.3 for the *moderate* climate scenario and decrease to 30.0 PSU for the extreme scenario.

There were no conclusive future projections of wind speed for the Vancouver Island area with literature reviews finding increasing trends (Young et al., 2011), decreasing trends (McVicar et al 2012) or no significant trends at all (Merryfield et al., 2009; Morrison et al., 2014; Wang et al., 2016). Therefore, gust speeds for the scenarios were based on 54-year (from 1964 to 2017) mean annual extreme monthly gust speed observations from the Victoria International Airport meteorological station. The 10th percentile extreme monthly gust speed was used for the *moderate* scenario and the 90th percentile values was used for the extreme scenario (Ospan et al., unpublished; Chapter 3).

The two hypothetical scenarios of local management, *Conservation* and *Development*, represented two different attitudes to land use, the former focused on forest restoration and an increase in forested land cover, and the latter associated with increases in logging, urban and agricultural land cover (Ospan et al., unpublished, Chapter 2). The *Conservation* scenario envisioned an increase in the forest cover from the current 66% of the entire watershed area to 88%, at the same time decreasing clear-cuts, roads, urban and agricultural land cover from the current 27% to 5% of the entire watershed area. The *Development* scenario envisaged a decrease in the forest cover to 32% of the total watershed area, while increasing urban/residential, agricultural and clear-cut areas to 61% of the watershed.

4.3.4 Scenario Assessment

For each scenario, the entire 31-year long hydrological and temperature models were run using the scenario climate change projections for 2050 and the selected land use scenarios. The resulting mean discharge and stream temperature projections were then applied to the two species freshwater survival models (Ospan et al., unpublished, Chapter 2 and 3).

Similarly, mean future marine survival rates of each three salmon populations (Chinook, hatchery-raised and wild Coho) for each scenario are simulated by running the regression models using each scenario's input variables (Ospan et al., unpublished, Chapters 2 and 3).

Finally, freshwater and marine survival rates for Cowichan Chinook and Strait of Georgia wild Coho were combined (*Equation 2*) to estimate the overall survival for each scenario. We only estimated marine survival for hatchery-raised Coho since freshwater survival scenarios did not apply to them.

4.3.5 Result

Projections for Chinook showed decreases in future survival from the estimated baseline for all four scenarios in both freshwater and marine environments (Table 18). As a result, overall survival was low for all scenarios. Even for the most optimistic future scenario (CM, *conservation and moderate climate change*) the overall projected survival rate fell below the sustainable productivity level that we assume to be at least of one adult progeny per parent.

The best outcome for Chinook was projected for scenario CM with 4.4% and 0.63% survival rates for freshwater and marine phases respectively. Scenario CM was followed by DM (*Development* and *Moderate Climate Change*) with 4.1% and 0.56% survival rates for freshwater and marine phases respectively. Scenario DE showed the lowest freshwater (1.64%) and marine (-0.16 [resulting overall is 0.00%]) survivals of all scenarios. Negative survival rates essentially meant that there would be no survival for these scenarios, but the negative values were used to indicate the severity of impacts relative to baseline conditions.

Future projections showed that, in all scenarios, decreases in marine survival indicated reductions in overall survival for all three VCs (tables 18 through 20). None of the three studied populations of salmon were likely to survive in the marine environment in the scenarios with extreme climate change, while scenarios with moderate climate change showed positive survival rates albeit lower than base levels.

In an exception to all other survival simulations, only wild Coho showed an increase in freshwater survival from baseline for future scenarios involving moderate climate change (Table 19). This was because expected increases in winter air temperature and, consequently, water temperature will most likely be more favourable for winter survival of juvenile Coho. The projected threshold-based freshwater survival of Coho ranged from 1.98% for scenario DE to 3.01% for scenario CM. As a result, projected freshwater survival of wild Coho showed a slight increase in the scenarios with moderate climate change. However, these favorable freshwater survival rates were offset by decreasing survival in the marine environment when considering overall survival.

The baseline and projected marine survival of wild Coho was considerably higher than that of hatchery-reared Coho (tables 19 and 20). Wild Coho marine survival was 4.77% and -6.32% for scenarios with moderate and extreme climate change scenarios respectively, while projected hatchery-raised Coho survival was 0.88% and -8.73% in the moderate and extreme climate change scenarios, respectively.

For all three salmon populations, scenarios with moderate climate change resulted in higher projected survival in both freshwater and marine environments compared to conditions under extreme climate change. Similarly, for land use, forest conservation resulted in higher survival as compared to logging, urban and agricultural development. However, effects on salmon survival from changes in land use were weaker compared to effects from climate change. To illustrate this, scenario CE (*Conservation* and *extreme climate change)* resulted in lower projected survival rates compared to the DM scenario (*development* and *moderate climate change*) for the freshwater phase of both Chinook and Coho and the marine phase of Chinook (tables 18 through 20).

Table 18 Cowichan River Chinook mean historic and projected 2050 survival rates.

Scenario	**Freshwater survival based on regression (%)**	**Freshwater survival based on thresholds (%)**	**Overall freshwater survival estimate (%)**	**Marine survival (%)**	**Overall survival (%)**	**Production per spawner**
Base Scenario	5.79	96.35	5.58	1.30	0.07	1.46
Scenario DE	1.85	88.92	1.64	-0.16	0.00	0.00
Scenario CE	2.20	92.92	2.04	-0.08	0.00	0.00
Scenario DM	4.17	98.39	4.10	0.56	0.02	0.47
Scenario CM	4.42	98.98	4.38	0.63	0.03	0.56

Table 19. Strait of Georgia wild Coho mean historic and projected 2050 survival rates.

Scenario	**Freshwater survival based on literature (%)**	**Freshwater survival based on thresholds (%)**	**Overall freshwater survival (%)**	**Marine survival (%)**	**Overall survival (%)**	**Production per spawner**
Base Scenario	3.40	81.02	2.75	5.00	0.14	1.72
Scenario DE	3.40	58.36	1.98	-6.32	-0.13	0.00
Scenario CE	3.40	66.34	2.26	-6.32	-0.14	0.00
Scenario DM	3.40	86.40	2.94	4.77	0.14	1.75
Scenario CM	3.40	88.52	3.01	4.77	0.14	1.79

Table 20. Strait of Georgia hatchery-raised Coho mean historic and projected 2050 marine survival rates.

Scenario	**Marine survival (%)**
Base Scenario	3.32
Scenario DE	-8.73
Scenario CE	-8.73
Scenario DM	0.88
Scenario CM	0.88

4.4 Discussion

Our study showed that Cowichan River Chinook early life freshwater survival was affected by stream temperature and discharge, which, in turn, were dependent on climate factors such as air temperature, precipitation and local watershed management. In our model, maximum water temperature in December and mean monthly maximum water temperature in the brood year explained 75% of the variability in Chinook egg-to-fry survival (Ospan et al., unpublished, Chapter 2).

Because the model for Coho freshwater survival was based on literature-based thresholds only, not the stream-specific empirical data, it is less sensitive to future changes in streamflow and temperature compared to outcomes for Chinook. Coho freshwater residence is longer than that of Chinook and includes summer rearing and winter rearing when stream temperature and discharge levels maybe beyond both lower and upper limits of tolerance for normal development. Therefore, the effects of stream temperature and stream flow on Coho were most likely underestimated in our study and the real Coho early freshwater survival may be lower that what we have estimated.

For freshwater, climate change is a major driver for the survival of both Cowichan River Chinook and Coho within the assessment time horizon. Land use also influences salmon freshwater survival with measures towards forest conservation and restorations positively affecting survival. However, our scenario assessment showed that land use itself is insufficient to adequately mitigate the impacts from climate change. Therefore, other measures to mitigate climate change impacts on stream temperature and streamflow should be considered. These measures can include discharge management by increasing Cowichan Lake storage capacity, increase in groundwater exchange through increasing alluvial system complexity, increase in riparian shading, channel management including removal of stream impoundments and reduction of channel width during low flow period, reduction of water withdrawal, etc. (Beschta, 1997; Norton & Bradford, 2009; Poole & Berman, 2001a, b).

Our analysis shows that the marine survival of both Chinook and Coho is highly correlated with environmental conditions during the first year of marine residence, explaining 75%, 70% and 77% of survival variability for Chinook, hatchery-raised Coho and wild Coho respectively (Ospan et al., unpublished, Chapter 3). These findings support the critical period hypothesis by Beamish & Mahnken (2001) that the overall strength and survival of salmon cohort is largely determined by juvenile development within the first several months of marine residence, and are highly dependent on the environmental conditions within this period (Beamish & Mahnken, 2001; Beamish et al. 2010).

Our study also supports previous observation by Michel (2019) that riverine streamflow during early marine residence has an influence on Chinook marine survival. Cowichan River October discharge correlates highly with Cowichan Chinook marine survival, assumed to be explained by the influence of October river discharge on near shore marine environment conditions (e.g., salinity, surface temperature, turbidity, nutrient flows, water column structure, etc.), all of which are known critical salmon marine habitat attributes. Therefore, local watershed management in combination with climate change can potentially influence not only Chinook freshwater but also marine survival. Therefore, measures that mitigate climate change effects within the river watershed can potentially improve chances of Chinook survival in the marine environment.

Our study also suggests that Cowichan River stream conditions in the year following incubation are very important for both Chinook and Coho survival. In the case of Coho, who spend a whole year in the freshwater environment, stream temperature and discharge directly influence juvenile fish as main habitat attributes. In the case of Chinook, riverine discharge influences conditions in the near shore environment after they leave the river but are still within its influence during that period.

We also find that wild Coho show higher marine survival rates compared to hatchery-reared Coho both during baseline conditions and in future projections. This has been previously reported for Strait of Georgia Coho (Beamish et al. 2010), and similar trends are reported for other salmon species and other regions (Jonsson et al., 2003). This suggests that hatchery-raised Coho may be a poor substitute for wild populations, particularly in more dramatic climate change scenarios. Logically, hatchery enhancement is beneficial only if hatchery survival is high enough to offset for the difference in marine mortality (Locke, 1998), which we do not project to be the case. Strait of Georgia hatchery egg-to-smolt survival data is not available to derive any conclusion on overall survival of hatchery-raised Coho. Similarly, Beamish at al. (2012) report that wild Chinook also experiences better marine survival compared to hatchery Chinook, hence it is likely that wild Chinook populations will be more resilient in the future. However, there is presently no available data to demonstrate this.

In our study we projected scenarios of Chinook and Coho survival from parents spawning until progeny return to the native stream. We, however, do not assess survival during spawning migration and success of spawning. Even though there is information available on temperature thresholds during spawning and general trigger conditions for spawning (e.g., river discharge), we do not believe we have enough data to make reliable estimates of survival during spawning runs and success of spawning. This would be a logical next step of data gathering and analysis to close the loop on salmon life-cycle success as a population.

4.5 Conclusion

Using our methodology, we assess four potential scenarios of three Cowichan River salmon populations. As a result, we obtain a spectrum of potential fates ranging from no survival to more optimistic futures. With the exception of wild Coho, even the most optimistic scenarios lead to diminished survival of the VCs. In our most optimistic scenario, we selected a conservation-oriented land use management goal that may be difficult to achieve (given that a considerable portion of forested land in the Cowichan River watershed is privately owned by logging companies) and that the changes in the climate-related conditions that are in low probability range for the currently "business as usual" scenario. Intuitively considering that the truth is somewhere in the middle of the projected scenarios, the situation raises significant concerns for the viability of salmon survival in this region.

One of the advantages of an effect-based and numeric pathway analysis is that it allows evaluators to focus on few important pathways to assess VC success. However, this reduces the focus on alternative pathways that may initially seem plausible. In our case, the pathways analysis allows us to exclude the premise that the local land use management within our watershed may affect Coho marine survival. This suggests that survival of Coho, particularly in the marine environment, may not be amenable to local or regional control.

Our simplistic models that determined effect pathways and were also used for projecting future scenario outcomes were focused on only a few variables as potential stressors with the objective of minimizing complexity. Despite the few selected stressors, these variables were still able to explain 75% and at least 70% of the variability in our effect indicators in the two assessment phases.

At the same time, assessing a range of future scenarios allow us not to focus on any one selected path forward which may not be representative of all possible future outcomes. Instead, we have a range of possibilities and, therefore, force consideration of a range of options for future outcomes, which in part depend on human or political actions. We should remember that it is not our intention or purpose to assign probabilities to our scenarios. We can, however, estimate the confidence or explanatory power of our projections since we can estimate goodness of fit or predictive accuracies to our models and, if all our scenarios were assessed using the same models, our confidence in all our scenarios results should be the same. Therefore, instead of focusing on one possibility that can be deemed the most probable, we can see a range of possible futures, all having a chance to occur but dependent on the path we choose. Therefore, scenario analysis allows us to focus on selecting plans for the future and provide the ability to formulate response and adaptation strategies.

Scenario analysis also allows us to see how sensitive our indicators are to changes in the input parameters. Our example assessment shows that there is a considerably stronger response to variations related to climate change than to land use options. We used estimates of the same “business-as-usual” RCP scenario for alternative climate change scenarios and it is telling that both caused a wide range of negative responses in salmon survival projections, with significantly poorer outcomes in the ‘extreme’ climate change scenarios compared to the ‘moderate’ climate change scenarios.

We also conclude that numerical modeling of effect pathways allows assessments to be applied to any number of scenarios developed, all with the same confidence of reliability in the outcomes. Even though the model may be focused on only a few pathways and stressors, scenario assessment allows practitioners to explore a wide variety of management decisions/measures and evaluate their effects on the final outcome.

Chapter 5. Conclusion

5.1 Synopsis

This dissertation aimed to develop a revised methodology for Cumulative Effects Assessment (CEA) with the purpose of improving the process by making it both more substantive and quantitative. It also conducted a practical implementation to demonstrate the use of the proposed methods. One of the objectives was to propose a simple assessment methodology/model that could be used by a practitioner without deep knowledge in specialized disciplines, such as animal physiology, hydrology, physical oceanography or modeling. The main framework of our method was scenario assessment, but the general procedure included the following:

- Effect pathways were determined using an effect-based (bottom-up) approach by examining linkages from VC sensitivities to potential stressors or combinations of stressors in turn influenced by effect drivers and forces behind those drivers.
- Quantitative models were developed based on statistical or historic trend analysis or literature review that predicted responses of the effect indicators (VCs) to changes in effect drivers.
- Scenarios of divergent futures were created that involved different developments of each effect driver or force, and the models were applied to each scenario to project the state of the studied VCs in each scenario.

For a practical implementation, the methodology assessed future population trends of two anadromous Pacific salmon species, Chinook and Coho native to Cowichan River, British Columbia in response to potential changes of major drivers. Since both species' life cycles include freshwater and marine environments the assessment was conducted for both freshwater and marine phases of their life. The focus of the assessment was on processes that could be controlled or mitigated through policy or development decisions within a certain geographic area, in our case the Cowichan River watershed. The timeframe for this assessment was through the year 2050.

The two main sensitivities and stressors determined for the early freshwater life stage of both species were water temperature and streamflow. The pathways analysis established two main drivers affecting these stressors, land use and climate change, and two main forces behind these stressors, *Local* and *Global* human development driven change, respectively. Two models were built to simulate effects of stream temperature and streamflow on salmon freshwater survival (the effect indicator). One was based on historic trends of Chinook freshwater survival correlations with stream temperature and it was developed only for Chinook; the other is based on literature-derived temperature and streamflow thresholds for each species. Connections between the stressors (stream temperature and streamflow) and drivers (land use and climate change) were established through a hydrologic model and stream temperature regression model.

Effect pathways in the marine environment were derived by linking marine survival of Cowichan hatchery-raised Chinook, and Strait of Georgia wild and hatchery-raised Coho, to various physical variables using Pearson’s correlation and stepwise regression analyses. It is established that Cowichan River Chinook marine survival depended on three physical variables: July sea surface temperature (SST) at Entrance Island and mean October Cowichan River discharge (reverse correlation) and October mean minimum daily air temperature at Salt Spring Island (direct correlation).

A regression analysis of Strait of Georgia hatchery-raised and wild Coho showed direct correlation of Coho survival with sea surface salinity (SSS) at Race Rocks (two-year mean for hatchery-raised and mean summer for wild), reverse correlation with June to September air temperature (mean minimum monthly for hatchery-raised and mean for wild) at Salt Spring Island and mean annual extreme monthly gust speed observed at the Victoria International Airport.

Therefore, the pathway analyses showed that marine survival of Cowichan River Chinook could be affected by changes in land use through Cowichan River discharge in October, as well as by climate change through changes in SST and air temperature. At the same time, Coho marine survival showed no dependence on Cowichan discharge but only on variables directly affected by climate change.

Future scenarios were developed from combinations of two opposite scenarios for each of the two drivers, land use and climate change. Two opposite scenarios of climate change were more extreme and moderate change. The two opposite watershed landcover land use scenarios, were forest conservation and restoration, and land development to for logging, urbanization and agricultural use.

As a result, four future scenarios were developed, namely CM (forest conservation and moderate climate change), CE (forest conservation in combination with more extreme climate change), DE (land development and more extreme climate change), and DM (land development and moderate climate change). All four of these scenarios were applied to the freshwater phases of both salmon species life cycles. For the marine phase, all four scenarios were applied to Chinook future only, while for marine Coho survival only the two climate change scenarios, moderate and extreme, were applied to future marine survival of Coho; this is because Coho survival to spawner return has not shown any dependence on Cowichan River hydrology.

The pathway models developed for the freshwater and marine survival of each of the assessed salmon populations were applied to each of the four scenarios. The resulting survival rates for freshwater and marine environments were combined (multiplied) to obtain the overall survival rate for each of the studied populations.

5.2 Practical Implementation

5.2.1 Results

Future projections showed a decrease in marine survival by 2050 for all three studied salmon populations in all scenarios. None of them were likely to survive in the marine environment in scenarios with extreme climate change, while scenarios with moderate climate change show positive survival rates albeit lower than present-day baseline levels.

In the freshwater environment, only two scenarios with moderate climate change for wild Coho projected a slight increase in early survival in comparison to the baseline, while the scenarios with extreme climate change for Coho and all four scenarios for Chinook resulted in decreases in freshwater survival.

For both assessed salmon species, scenarios with moderate climate change resulted in higher projected survival in both freshwater and marine environments as compared to the more extreme climate change scenarios. For land use, *Conservation* scenarios resulted in higher survival as compared to *Development* scenarios. As a result, the highest survival was projected for scenario CM (*Conservation* and *moderate climate change*), while the lowest survival was projected for scenario DE (*Development and extreme climate change*) for both phases and populations where the land use driver was applicable. However, the influence of changes in land use on salmon survival was weaker than the influence of climate change. So, scenario CE (*Conservation* and *extreme climate change)* resulted in lower projected survival rates compared to DM (*Development* and *moderate climate change*) for the freshwater phase of both Chinook and Coho and the marine phase of Chinook. Furthermore, none of the assessed populations are likely to survive in the scenarios with extreme climate change due to low freshwater survival and projected negative marine survival.

5.2.2 Major Findings and Key Points

Cowichan Chinook freshwater survival is affected by physical variables, such as water temperature and discharge, which, in turn, are dependent on climate factors such as air temperature and precipitation and local watershed management. Maximum water temperature in December and mean monthly maximum water temperature in the brood year can explain 75% variability in Chinook egg-to-fry survival.

Therefore, climate change is a major driver that will be affecting the fate of Chinook in the Cowichan River over the next three decades and beyond. Land use has been shown to influence salmon freshwater survival with measures towards forest conservation and restorations positively affecting survival. Land use scenarios considered in our assessment, however, are insufficient to adequately mitigate climate impacts. Therefore, other measures of stream temperature and streamflow management are important to consider. These measures may include, but not necessarily be limited to, increase in storage capacity of Cowichan Lake reservoir, increase in groundwater exchange through increasing alluvial system complexity, riparian shading, channel management including removal of stream impoundments and reduction of channel width during low flow period, reduction of water withdrawal, etc. (Beschta, 1997; Norton and Bradford, 2009; Poole and Berman, 2001a, b).

The model for Coho freshwater survival was less sensitive than that for Chinook. This was primarily because Coho freshwater survival was estimated using threshold-based survival model only. Therefore, effects of stream temperature and stream flow on Coho were most likely underestimated in our study. Even the threshold-based model showed that Coho has higher survival variability and, generally, lower survival rates based on temperature and discharge thresholds than Chinook. Cowichan River Coho freshwater residence includes summer rearing and winter rearing when stream temperature and discharge levels maybe beyond both lower and upper limits of tolerance for normal development. This makes Coho potentially more vulnerable than Chinook to future changes in temperature and stream flow. The Coho freshwater survival models used in this study however showed that future temperature increases may improve chances of second winter survival.

Analysis of marine survival of all three studied populations showed that the first few months in the marine environment were the most important in marine survival and that the environmental conditions during these few months determined their overall adult development and success. Thus, the study confirms the critical period hypothesis proposed by Beamish and Mahnken (2001).

The study showed that marine survival was mostly influenced by climatic and oceanographic conditions in the Strait of Georgia and partially in the Juan de Fuca Strait during the first-year residence in the marine environment. These conditions explained at least 70% of the variability in the marine survival of these three salmon populations. These findings confirmed conclusions of pervious authors (e.g., Beamish et al., 2004, 2010) that the decreases in salmon marine survival in the recent decades were related to climate change.

Our analysis suggested that ongoing decreases in salmon marine survival would continue in the future in all of our scenarios. Even in the best-case scenario for wild Coho, marine survival will continue to decline. In most cases salmon production in the Strait of Georgia in general and

Cowichan River, in particular, may stop by mid-century due to very poor marine survival and the decline may not be stopped unless climate change is impeded or slowed. Alternative coping strategies to mitigate the impacts of climate change may include reorientation of fisheries to new species that may occupy the historic salmon habitats and ranges (Cheung et al., 2011).

From this study there was evidence that wild Coho showed higher marine survival rates compared to hatchery-reared Coho both for baseline conditions and in future projections, a result supported by previously reported observations for Strait of Georgia Coho (Beamish et al. 2010). Similar trends have been reported for other salmon species and other regions (Jonsson et al., 2003). This suggests that hatchery-raised Coho will be a poor substitute for wild populations, particularly in more dramatic climate change scenarios. The proponents of hatchery enhancement argue that it increases overall survival because it bypasses detrimental effects from freshwater conditions that cause high mortality during early-life stages (Kennedy, 1988; White, 1994), even though hatcheries also experience issues causing high mortality (e.g., harmful algae [McCully, pers.com.]), hatchery survival is suggested to be considerably higher than wild early-life salmon survival (Gardner et al., 2004; McCully, pers. com.). However, hatchery enhancement is beneficial only if hatchery survival is high enough to offset for the difference in marine mortality (Locke, 1998). Data on Strait of Georgia hatchery egg-to-smolt output is not available to derive any conclusion on overall survival of hatchery-raised Coho. Furthermore, efficiency of hatchery enhancement is debated with some suggesting that inadequate timing of release may have contributed to poor marine survival of hatchery salmon (Gardner et al., 2004; Chittenden et al., 2018) and that better release timing and general management of hatchery-raised smolts may improve their marine survival. There are also indications that hatchery salmon affects survival and success of wild salmon (Gardner et al., 2004) and that removal of hatcheries may improve the success of wild populations (Jones et al., 2018). While important, this topic is outside of the scope of our study.

Another important finding of the analysis was that marine survival of Cowichan Chinook was influenced by Cowichan River October discharge and its effect on conditions of nearshore marine environmental (e.g., salinity, mixing, turbidity, nutrient flows, temperature stratification, etc.), a critical habitat for some salmon life cycle phases. Therefore, land use management and other stream management measures within the river watershed may influence Chinook marine survival.

Therefore, Cowichan River conditions in the year following incubation are very important for both Chinook and Coho. In the case of Coho who spend another year in the freshwater environment, stream temperature and discharge directly influence juvenile fish as main habitat attributes. For Chinook, after smolts leave the river, riverine discharge influences near shore environment conditions that are also critical for juvenile fish.

5.2.3 Sources of Uncertainty and Suggested Future Research

For Chinook, we used a model based on the wild population for freshwater survival and a model based on hatchery raised population for the marine environment. Based on the comparison between the wild and hatchery raised Coho marine survival and literature on Strait of Georgia Chinook (Beamish et al., 2012), it is very possible that wild Chinook marine survival is higher than that of hatchery-raised Chinook that we used in the study. Therefore, obtaining long-term information on wild Cowichan Chinook marine survival would be a logical next step. This would produce more accurate projections of Cowichan Chinook overall survival.

In our study of the Cowichan River salmon populations we use data for Strait of Georgia Coho populations for marine survival and literature-based information for the freshwater survival model. Therefore, studies on Cowichan Coho freshwater and marine survival are necessary for more accurate determination of effect pathways and modeling for both freshwater and marine environments.

Alternatively, a similar study on combined freshwater and marine salmon survival could be conducted on all Strait of Georgia stream watersheds. This will require data on salmon survival from the other streams of the Strait of Georgia and hydrologic modeling for all streams combined, including the Fraser River. This would be a very interesting study that would give a perspective on land management options for salmon conservation for the entire region.

This study assessed Chinook and Coho survival from the moment of parent spawning until progeny return to the native stream. What was not included in the study is assessment of success of upstream migration and spawning. There was not enough data to make estimates of survival during spawning runs and success of spawning. This should be the next step of assessment to close the loop on salmon life-cycle success as a population.

The scenario analysis showed that land use options considered in the assessment were not sufficient to offset the impact from climate change on salmon survival. Therefore, other measures of temperature and streamflow management should be included in the analysis to define the most suitable mitigation strategies to overcome the effects of climate change.

5.3 Evaluation of Methodology

In our assessment we used simplistic models that determined the main sensitivities of two salmon species and focused only on few variables as potential stressors. Viability of the stressor selection was verified through numerical models, which were also used for projecting future scenario outcomes. The objectives of focusing on only a few stressors were for simplicity in determining the pathways and making future projections. These few selected stressors, however, in our case explained 75% and at least 70% of variability in our effect indicators in the two of our assessment phases.

The proposed quantitative modeling helps to identify and focus on few, but the most significant, effect pathways and eliminates less significant pathways. The combination of scenario analysis and numeric modeling allows the user to test how vital and strong the selected stressors are for the VCs and to see how sensitive the effect indicators are to changes in the stressors. In our example, there was a considerably stronger response to variations related to climate change than to land use options indicating that land use management by itself cannot offset the climate change impacts.

The quantitative analysis that establishes few but significant pathways helps to overcome the main disadvantage of scenario assessment, which is the lack of certainty of each selected scenario. We can estimate the confidence or explanatory power of our predictions since we can estimate goodness of fit or predictive accuracies of our models. Furthermore, if all our scenarios were assessed using the same models, our confidence in results should be the same for all scenarios.

Even though our assessment is focused on few pathways and stressors, numeric models can be applied to any number of future scenarios. Therefore, a wide variety of development options, management tools and potential future directions can be evaluated for their effects on the selected VCs with the same confidence.

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