DEFINING AN HISTORICAL BASELINE AND CHARTING A PATH TO RESTORING HABITAT CONNECTIVITY FOR SALMONIDS IN A HIGHLY URBANIZED LANDSCAPE

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Riley Finn

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The following individuals certify that they have read, and recommend to the Faculty of Graduate and Postdoctoral Studies for acceptance, a thesis entitled:

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in Forestry

Examining Committee:

Dr. Tara Martin, Forestry, UBC
Supervisor

Dr. Scott Hinch, Forestry, UBC
Supervisory Committee Member

Dr. Brett Eaton, Geography, UBC
Additional Examiner

Additional Supervisory Committee Members:

Dr. Sarah Gergel, Forestry, UBC
Supervisory Committee Member

Abstract

Loss of connectivity caused by anthropogenic barriers is a key threat for migratory freshwater species, barriers on streams can decrease the amount of habitat available for spawning and rearing. To set appropriate targets for restoration it is important to know how different populations have been impacted in terms of the location and extent of historically available habitat that has been lost or has become inaccessible. I mapped and predicted barriers to fish passage in streams and diking infrastructure to estimate the amount of floodplain and stream habitat that remains for 14 populations of salmon in the Lower Fraser River, British Columbia, Canada's most productive salmon river. To place these estimates within a historical context, the floodplain area was estimated using vegetation records from the 1850's, and lost streams were estimated. Accessibility to floodplain was poor across the entire region with only 15% of the historical floodplain remaining accessible. Linear stream habitat ranged in accessibility from 28-99% across populations. I used conservation planning software to maximize the amount and quality of stream habitat that can be restored across a range of budgets. An estimated 75% of habitat blocked by barriers could have access restored with an investment of 200 million dollars. With small budgets it was more efficient to remove a high number of culverts, but when budgets were larger, restoration included restoring passage past dams and flood infrastructure. The amount of habitat restored for each species varied depending on whether habitat quality was also prioritized, highlighting where restoration of freshwater habitat requires more than the removal of barriers.

Lay Summary

The freshwater habitat that salmon rely on for reproducing has experienced widespread impacts from human settlement. The processes that degrade freshwater habitat happen over time and can result in altered perceptions of how much habitat existed historically for salmon, changing potential targets for restoration of this habitat. The pervasiveness of habitat impacts can also make it difficult to decide where to spend scarce resources on restoration. The Lower Fraser River in British Columbia, Canada is one of the most productive salmon regions in the world. With salmon in this region in decline, I use historical datasets and conservation planning to quantify the amount of habitat that has been lost and chart a path to efficiently restoring access to this habitat. Across the region, an estimated 15% of floodplain and 46% of stream habitat remains accessible but this varies by species. By restoring passage past dams, culverts, and flood infrastructure I estimate 75% of inaccessible stream habitat can be restored for 200 million dollars.

Preface

This research project was originally conceived by Riley Finn, Dr. Tara Martin, and partners at Raincoast Conservation Foundation. It evolved out of work done by Riley Finn with Raincoast Conservation Foundation to collate existing information and datasets that characterize salmon habitat in the Lower Fraser. The amount of data illustrating barriers that limit habitat connectivity in the Lower Fraser and Dr. Tara Martin's expertise of decision science and spatial optimization was the initiation point for the systematic conservation planning approach used in Chapter 3. Common approaches to systematic conservation planning involve setting targets for protecting a certain proportion of a species range, since this project focused on spatially optimizing restoration of alienated habitat, a more detailed analysis of the historical habitat was needed to inform the spatial optimization, this was the motivation for Chapter 2. All data was comprised of public datasets collated by Riley Finn, except for information on the locations of pump stations and floodgates which was collected and shared by Watershed Watch Salmon Society. A version of Chapter 2 has been accepted for publication and will be published in 2021 [Finn RJR, Chalifour L, Gergel SE, Hinch SG, Scott DC, Martin TG. 2021. Quantifying lost and inaccessible habitat for Pacific salmon in Canada's Lower Fraser River. Ecosphere]. For this paper Riley Finn was responsible for all analyses and writing of the initial draft. Dr. Tara Martin provided valuable edits, supervision, and guidance throughout the project, while Dr. Sarah Gergel, Dr. Scott Hinch, Dave Scott, and Lia Chalifour all provided further edits. Chapter 3 is largely based on the same publicly available data as Chapter 2. Riley Finn carried out all analysis and wrote the first draft, edits, adjustments, and suggestions were provided throughout the work by the supervisory committee – Dr. Tara Martin, Dr. Sarah Gergel, and Dr. Scott Hinch.

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Chapter 1: Introduction

1.1 Habitat connectivity and historical baselines

Habitat loss directly impacts the ability for species to persist (Sih et al. 2000; Brooks et al. 2002) and is recognized globally as a key driver in the decline in biodiversity (Fahrig 1997). Intimately coupled with direct loss of habitat is the impact of connectivity among remaining pieces of viable habitat patches where species can persist – often referred to as habitat fragmentation (Fahrig 2003). For freshwater ecosystems the threat of habitat loss and loss of connectivity is particularly acute. Due to elevated levels of biodiversity compared to many terrestrial systems, and the number of ecosystem services that they provide to humans, freshwater ecosystems are among the most impacted and harbor the highest number of endangered species in the world (Dudgeon et al. 2006), and many of these threats are accelerating (Reid et al. 2019).

Anthropogenic barriers in freshwaters habitats consist of structures that limit the movement of species, populations, nutrients, and sediment throughout the linear stream system or laterally with the adjacent floodplain (Coleman et al. 2018). Barriers that prevent connectivity are common throughout the world and have been growing in number in response to flood control, and the ongoing exploitation of hydro energy (Reid et al. 2019). Given pervasive impacts of habitat loss and fragmentation, there is a clear need to both restore freshwater habitat that has been lost altogether and restore or facilitate access to habitats that remain, but go unused due to anthropogenic barriers. To curb the extinction crisis, ambitious landscape scale restoration actions must be identified and prioritized (Díaz et al. 2019; Albert et al. 2020).

A challenge that comes with habitat restoration involves defining a baseline with which to target and work towards (Lee et al. 2014). In human dominated landscapes, collective perceptions of what the historical state of the ecosystem was can shift due to the loss of knowledge at both generational and individual levels (Papworth et al. 2009). The altered perceptions of baseline ecosystem condition influences actions that are taken and the goals or benchmarks we use to manage ecosystems – termed shifting baseline syndrome (Pauly 1995; Jackson 1997). To abate the effects of shifting perceptions of ecosystem condition and to inform restoration or management targets, historical data can be employed to address gaps in knowledge. Historical data might include direct field measurements prior widespread ecosystem change occurred (e.g., Bjorkman & Vellend 2010; Gayeski et al. 2011; Tomscha & Gergel 2015), or more indirect sources such as oral history (e.g., Eckert et al. 2018; Abu et al. 2020), archeological data (e.g., Boyd et al. 2006), or other sources (e.g., Price et al. 2019). In most cases, the historical context of an ecosystem can only be understood to a limited resolution, but this information is important for the design of tangible management or restoration objectives that are grounded in knowledge of the historical landscape, vegetation, and disturbance regime (Dey & Schweitzer 2014; Higgs et al. 2014).

1.2 Limited resources for restoration

While it is important to understand the socio-ecological backdrop of the landscape, deciding where to implement action and restore habitat is a problem that comes with additional challenges. Widespread degradation of habitat for multiple species, in a world where resources to spend on restoration are scarce, means decisions must be made about what actions to take and where to achieve the greatest benefit. Put simply, the challenge for restoring freshwater habitat connectivity is to maximize the amount of connected habitat for minimal cost. This decision requires the consideration of multiple factors including species presence and status, cost of removing different types of barriers, the quality of the habitat being restored, complementarity of multiple barrier removals, and migration patterns of target species.

For the case of prioritizing barrier removal in freshwater systems there have been numerous studies examining prioritization approaches for deciding which barriers to remove (McKay et al. 2017). Common approaches for prioritizing barrier removal include using local expert judgment or scoring and ranking of barriers based on measured attributes such as cost, amount of habitat, or quality of habitat. Importantly, these approaches do not consider the potential connectivity of multiple barrier removals that could offer improved cost effectiveness (O'Hanley & Tomberlin 2005). The application of mathematical optimization has been used to address connectivity and thereby identify an "optimal set" of barriers that are complimentary (i.e. work together to increase connectivity), and is the most sophisticated approach to identifying priority barriers (McKay et al. 2020). Optimization algorithms can be used to maximize the amount of habitat that is restored while minimizing cost by identifying the set of barriers that should be removed to achieve the defined objective function (O'Hanley et al. 2013). Due to the heavy reliance on data, and the need to act on a set of barriers in order to achieve the efficiencies of complementarity, mathematical optimization as a way of prioritizing barriers has been criticized for being difficult to carry out and implement in practice but offers a transparent framework for understanding spatial priorities for restoration (McKay et al. 2020).

1.3 Salmon and the Lower Fraser River

Pacific Salmon (*Oncorhynchus* spp.) are keystone species, who's anadromous life histories provide vital marine derived nutrient subsidies to freshwater and surrounding ecosystems as adults return to their natal streams (Naiman et al. 2002). Salmon also play important role in providing food security and cultural values (Nesbitt & Moore 2016). Patterns of salmon abundance vary by population and species however broad trends indicate that Chinook salmon (*Oncorhynchus tshawytscha*) are in decline throughout British Columbia, sockeye (*Oncorhynchus nerka*) and coho (*Oncorhynchus kisutch*) are experiencing declines particularly in southern portions of their range, while chum salmon (*Oncorhynchus keta*) and pink salmon (*Oncorhynchus gorbuscha*) are faring comparatively better exempting certain populations (Grant et al. 2019). There is no individual factor that explains these trends, variations in the marine environment (Lawson 1993), fisheries (Price et al. 2019), climate change (Battin et al. 2007), hatcheries (Hilborn 1992), disease (Mordecai et al. 2019), and freshwater habitat degradation (Beechie et al. 1994; Honea et al. 2009) have all been identified as contributing threats to wild salmon.

The Lower Fraser River and its associated tributaries have a disproportionate importance for wild salmon as a migratory corridor and for the number of populations that rely on the area (Nesbitt & Moore 2016). For salmon in the Lower Fraser River, the degradation of freshwater habitat has been widespread and ongoing related to colonialism agricultural, urban and industrial expansion and resulting landcover change (Boyle 1997). An understanding of the historical extent of salmonid habitat has been forgotten due to the incremental nature of these processes. The Lower Fraser boasts some of Canada’s most valuable agricultural land, and largest port. The tidal characteristics and low-lying nature of the Fraser Valley have precipitated the construction of floodgates along many of the tributaries (Thomson & Confluence Environmental Consulting 1999). The operation of floodgates in the Lower Fraser have been shown to create hotspots for invasive species, reduced native fish diversity, and cause hypoxic conditions up to 100 meters upstream (Gordon et al. 2015; Scott et al. 2016; Seifert & Moore 2018). In addition to floodgates, the ever expanding road network has created additional barriers, with over 170,000 closed bottom culverts impeding fish passage across British Columbia (Fish Passage Technical Working Group 2014).

The thrust of this thesis was to address two key questions related to salmon habitat in the Lower Fraser such that restoring connectivity for these populations could be contextualized and understood. Chapter 2 addresses the problem of understanding the historical context of the ecosystem for salmonids and how current infrastructure impacts accessibility to stream and floodplain habitat for 14 populations of Pacific salmon. The included populations encompass 4 species of Pacific salmon including Chinook, sockeye, chum, and coho salmon. Each of these species include populations who freshwater habitats were contained completely within the Lower Fraser.

Specifically, this chapter asks (1) what was the historical extent of salmon habitat in the Lower Fraser River?; (2) How much of the historical habitat has been lost entirely?; (3) How much of the historical habitat is now inaccessible as a result of anthropogenic barriers?; and (4) How does habitat accessibility and the presence of barriers compare against the assessed status of Pacific Salmon populations that rely on the Lower Fraser River for spawning and rearing?

Chapter 3 addresses the second challenge of prioritizing where to invest in restoring access to alienated stream habitat for salmonids in the Lower Fraser. Given that there is a large number of barriers that have been mapped in the region, and that these barriers vary widely in their cost to restore, the amount and quality of habitat that exists upstream, and the context of their watersheds, I use an optimization approach typically used in systematic conservation planning to demonstrate how we can identify which barriers to restore in priority to maximize habitat accessibility to previously alienated habitat for multiple salmon populations.

Finally, Chapter 4, interprets the results of Chapter 2 & 3 in light of the results on the historical loss, alienation, and degradation of freshwater habitat in the Lower Fraser. I outline how the outputs of the optimization can be improved, the complexities of implementing barrier restoration with guidance from the optimization, and opportunities to use the insights gained in this thesis to improve the cost effectiveness of restoration. I place these insights into a broader adaptive framework that relies on the understandings from the history of the landscape and outputs of the optimization to implement restoration of instream habitat connectivity for the same 14 populations of salmon in a time and place where urgent restoration is needed, and expand on the how this approach can implemented to similar contexts elsewhere.

Chapter 2: Quantifying lost and inaccessible habitat for Pacific salmon in Canada's Lower Fraser River

2.1 Synopsis

Loss of connectivity caused by anthropogenic barriers is a key threat for migratory freshwater species. The anadromous life-history of salmonids means that barriers on streams can decrease the amount of habitat available for spawning and rearing. To set appropriate targets for restoration it is important to know how different populations have been impacted in terms of the location and extent of historically available habitat that has been lost or has become inaccessible. Using mapped and predicted barriers to fish passage in streams and diking infrastructure, the amount of both floodplain and linear stream habitat that remains accessible today was estimated for 14 populations of salmon in the Lower Fraser River, British Columbia, Canada's most productive salmon river. To place these estimates within a historical context, the floodplain area was estimated using vegetation records from the 1850's, and lost streams were estimated using a digital elevation model derived stream network. To bolster areas where little mapping has been done, current barrier data were used to predict locations likely to have barriers. Accessibility to floodplain was poor across the entire region with only 15% of the historical floodplain remaining accessible. Linear stream habitat ranged in accessibility from 28-99% across populations based on mapped barriers. Inclusion of predicted barriers revealed an additional 33 km of potentially inaccessible stream habitat and the modelled stream network located approximately 1,700 km of stream length that has been completely lost. Comparing habitat accessibility and barrier density against the assessed status of populations, revealed insights useful for understanding the impact of barriers on spawning and rearing and guiding the allocation of restoration effort. Applying

methods for addressing missing data, such as lost streams and unmapped barriers, was essential for estimating the accessibility of habitat within a historical context. While much emphasis has been placed on the role of marine conditions in wild Pacific salmon recovery, the magnitude of habitat loss in the Fraser cannot be ignored and suggests it is a major driver of observed salmon declines.

2.2 Introduction

Loss of connectivity of freshwater habitat is widespread and recognized as one of the key threats to aquatic systems (Dudgeon et al. 2006; Fuller et al. 2015). Barriers that create connectivity issues are often anthropogenic structures that restrict the longitudinal movement of freshwater species throughout a stream network or lateral movement between stream and adjacent floodplain habitats (Coleman et al. 2018). While barriers in freshwater systems almost always have impacts on the quality of habitat itself, they can completely alienate stretches of otherwise usable habitat for anadromous species (Zhong & Power 1996; Gardner et al. 2012), which require connectivity between freshwater and marine environments. The impacts of habitat loss are broad and include both demographic and ecological impacts, from increased extinction risk (Seabloom et al. 2002), and decreased species richness (Helm et al. 2006), to altered evolutionary trajectories and resilience (McClure et al. 2008).

Pacific Salmon, like many anadromous species, are impacted by the alienation of habitat from barriers, with numerous studies demonstrating the impact of anthropogenic barriers (Gibson et al. 2005; Sheer & Steel 2006; van Puijenbroek et al. 2019). These barriers include dams, flood control structures, road culverts and other structures. In addition to an increase in the number of barriers, the last century has seen other anthropogenic pressures including land use change (Bilby & Mollot 2008), climate change (McDaniels et al. 2010; Beechie et al. 2013), disease (Mordecai et al. 2019) and over-exploitation (Price et al. 2019) resulting in freshwater habitat degradation and declining marine conditions, which impact salmon at every stage of their lifecycle (Grant et al. 2019). As a result, many salmon populations are at record low numbers compared to historical levels (Peterman & Dorner 2012; Malick & Cox 2016; Grant et al. 2019; Price et al. 2019). Recently, much of the emphasis for regional declines has been focused on the change in productivity of the marine environment (Beamish et al. 2010; Peterman & Dorner 2012; Malick & Cox 2016). However, the relative resilience of pink and chum salmon has been noted as a possible indicator that the freshwater environment may be playing a bigger role in declines than previously thought, as these species are less dependent on freshwater habitats (Grant et al. 2019). sockeye, Chinook, and coho salmon are all faring comparatively worse in the southern portions of their range where both increases in water temperature, and the degree of anthropogenic disturbance on freshwater habitat have been most severe (Grant et al. 2019).

In addressing these threats to salmon, the removal of barriers and restoring access to freshwater habitat is among the most successful restoration strategies that can be undertaken due to its comparatively nominal cost, quick biological response, long lasting effect, and relatively high likelihood of success (Roni et al. 2002). Understanding the extent of habitat connectivity loss and how it impacts different populations depending on their position in the landscape is important for informing management priorities and setting restoration baselines.

The establishment of appropriate baselines requires the consideration of the historical context of the habitat and is important for avoiding changing human perceptions of biological systems, also known as shifting baselines, which can lead to a managed decline of the ecosystem (Pauly 1995; Papworth et al. 2009). To do this, estimation of habitat that still exists, but has become inaccessible to salmonids, needs to be assessed in tandem with habitat that has been completely lost from the landscape. Particularly in urban locations, streams can be replaced with sub-surface infrastructure with no value as habitat (Napieralski & Carvalhaes 2016), which may contribute to significant habitat loss for species and populations that used them historically.

The purpose of this study was to quantify the amount of stream and floodplain salmon habitat that has been alienated by anthropogenic barriers in the Lower Fraser River. The Lower Fraser River and its associated tributaries have a disproportionate importance for wild salmon as a migratory corridor and for the number of populations that rely on the area (Nesbitt & Moore 2016). Over the last century resource extraction, urbanization, and land conversion to agriculture have eliminated, severely degraded, and alienated much of the freshwater stream systems in the area (Boyle 1997). Specifically, the motivating questions were (1) what was the historical extent of salmon habitat in the Lower Fraser River?; (2) How much of the historical habitat has been lost entirely?; (3) How much of the historical habitat is now inaccessible as a result of anthropogenic barriers?; and (4) How does habitat accessibility and the presence of barriers compare against the assessed status of Pacific Salmon Conservation Units (CUs) that rely on the Lower Fraser River for spawning and rearing? By assessing salmon habitat availability within a historical context, a better understanding of the baseline conditions can be used to help guide restoration of habitat for these culturally, economically, and ecologically important species.

2.3 Methods

2.3.1 Study area

The Fraser River is the largest river in British Columbia with a total watershed area of 233,000 km^2, it has an average annual discharge of about 3,700 m^{3}s^{-1} and a bimodal hydrograph characterized by spring snow melt run-off and increased autumn precipitation (Northcote & Larkin 1989). The Lower Fraser region is generally delineated as the portion of river between the community of Hope, BC, where it begins flowing in a predominately western direction, and the Pacific Ocean. In this study, it has been delineated hydrographically using the watershed groups defined in the provincial Freshwater Atlas that contain at least a portion of this stretch of river. These watershed groups include Fraser Canyon, Chilliwack, Harrison, Lillooet and Lower Fraser and drain an area of 20,203 km^2 (Figure 2.1). The Fraser River as a whole is Canada's largest producer of wild salmon, yet despite representing a relatively small portion of the entire basin, the Lower Fraser has disproportionate importance for salmonids. The region supports a diversity of populations (Nesbitt & Moore 2016), as well as acting as a migration corridor for all other populations in the Fraser Basin.

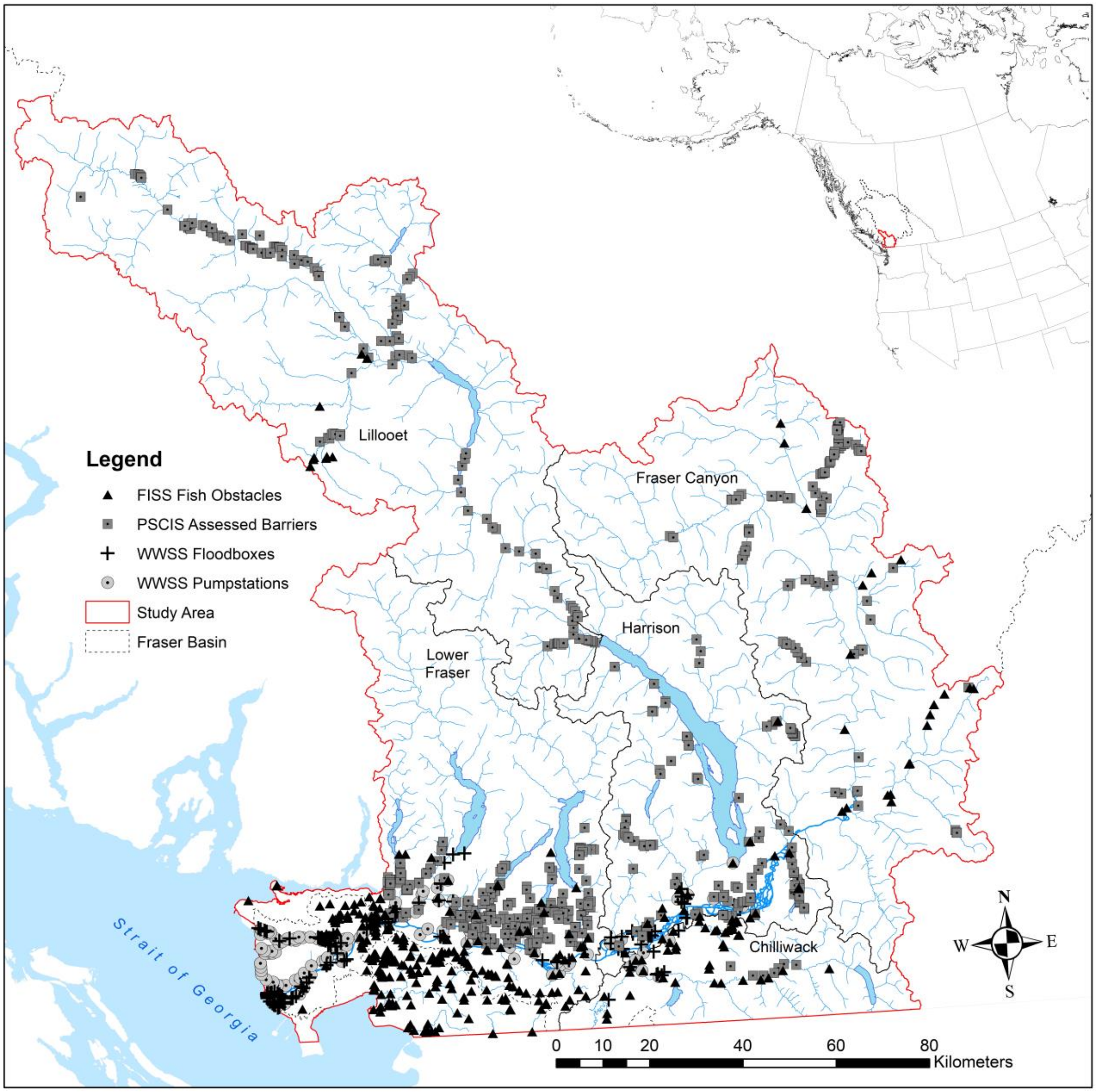

Figure 2.1 Map of study area comprised of the Lillooet, Fraser Canyon, Chilliwack, Harrison, and Lower Fraser watershed groups showing location of mapped barriers. Sources of barrier data include the Fish Information Summary System (FISS), Provincial Stream Crossing Inventory System (PSCIS), and Watershed Watch Salmon Society (WWSS). Inset shows context of study in the broader Pacific Northwest Region.

Pacific Salmon in Canada are federally managed under the Wild Salmon Policy at the level of the Conservation Unit (CU). The CU is defined as a group of wild salmon that is sufficiently isolated from other groups that if it were to go extinct it would not recolonize within an acceptable time frame such as a human lifetime or specified number of salmon generations (Fisheries and Oceans Canada 2005). Spatial boundary polygons that delineate the freshwater habitats of all CUs were overlaid with the watershed group polygons to identify a total of 14 CUs whose habitats fell completely within the study area (Table 2.1, Appendix A.1). Lake-type sockeye were excluded from this study as their CUs are delineated only by the lakes in which they rear, leaving no stream length for the assessment of accessibility – if the lake were not accessible then the CU would not exist. For the purpose of status assessments, CUs act as the designatable units for the Committee On the Status of Endangered Wildlife in Canada (COSEWIC). Information on the status of each CU as assessed by COSEWIC was collected from the species registry for comparison with habitat accessibility. Among the primary roles of COSEWIC are the identification of species for assessment, and to carry out those assessments determining whether species are classified as extinct, extirpated, endangered, threatened, of special concern, or not at risk (SARA 2002).

Table 2.1 Conservation units (CUs) of salmon within the Lower Fraser River included in this study, and the assessed status of the CU according to the Committee On the Status of Endangered Wildlife In Canada (COSEWIC). Numbers in the Chinook CU names indicate the mean number of years spent in freshwater (before decimal) and marine environment (after decimal). Half of the CU's have not been assessed.

Species	Conservation Unit	COSEWIC Status
Chinook (*Oncorhynchus tshawytscha*)	Fraser Canyon Spring 1.3	Endangered
	Lower Fraser River – Upper Pitt Summer 1.3	Endangered
	Lower Fraser River Fall 0.3	Threatened

	Lower Fraser River Summer 1.3	Threatened
	Lower Fraser River Spring 1.3	Special Concern
	Boundary Bay Fall 0.3	Not Assessed
	Maria Slough Summer 0.3	Not Assessed
Chum (*Oncorhynchus keta*)	Lower Fraser	Not Assessed
Coho (*Oncorhynchus kisutch*)	Boundary Bay	Not Assessed
	Fraser Canyon	Not Assessed
	Lillooet	Not Assessed
	Lower Fraser	Not Assessed
Sockeye (*Oncorhynchus nerka*)	Widgeon (river-type)	Threatened
	Harrison River (river-type)	Not at Risk

2.3.2 Quantifying the extent of historical floodplain

Floodplain habitat downstream of each CU boundary was assumed to have been utilized or available to out-migrating juveniles or as part of their rearing habitat (Brown & Hartman 1988; Sommer et al. 2001). This was identified using a map of the historical vegetation of the Lower Fraser Floodplain created through the translation of surveyor's notebooks into spatial information on vegetation communities that existed between the years 1859 to 1890 (North & Teversham 1984). From this dataset, 26 distinct vegetation communities were identified, and those with flood tolerant species compositions, or were likely to have high hydrological connectivity to the Fraser Mainstem or coast were assumed to be floodplain fish habitat with at least seasonal regularity. This assessment was informed by Kistritz *et al.* (1996) and habitats were generally characterized as marshes, grasslands, cottonwood, spruce or other coniferous forest. A table of all communities outlined by North and Teversham (1984) and those selected as floodplain fish habitat is provided in supplemental material (Appendix A.2). A large gap exists in the floodplain assessment due to the historical presence of Sumas Lake in the eastern portion of the Fraser Valley. Sumas Lake was drained in 1924 and is currently kept dry through a series of canals and pumps for farming in the eastern portion of the Lower Fraser Valley (Murton 2008). For this study, the lake was included as floodplain habitat as there are historical accounts of wide variation in lake levels throughout the year, ranging from a low of nine feet deep in winter to 36 feet deep during the spring freshet (Murton 2008). Due to these variations it is likely that a precise measurement of the lake's area would not capture the dynamic nature of the system. The original mapping of the Lower Fraser vegetation communities done by North and Teversham (1984) omitted the lake. For this study, a polygon was created to fill this gap representing a point estimate for the size of the lake-floodplain habitat.

Accessibility to floodplain fish habitat was assessed using currently mapped dikes. Diking data were downloaded from the provincial data repository (Table 2.2, https://catalogue.data.gov.bc.ca/dataset?download_audience=Public). Floodplain isolated by diking infrastructure from either the coast or the Fraser River mainstem was marked as inaccessible. The area of lost and accessible floodplain was then calculated for each CU by selecting all floodplain polygons both within and downstream of each CU polygon.

Table 2.2 Description and source of all datasets used in the spatial analysis of salmonid habitat accessibility in the Lower Fraser River.

Layer Name	Description	Source	Date Downloaded
Freshwater Atlas Stream Network	Stream hydrography mapped at 1:20,000 scale	Province of BC	Jan. 10, 2019
Freshwater Atlas Lake Polygons	Lakes mapped at 1:20,000 scale	Province of BC	Feb. 1, 2019
Pacific Salmon Conservation Unit Boundaries	Polygons of the freshwater habitat range for each CU	Government of Canada	Mar. 20, 2019
BC Digital Roads Atlas	Roads in BC including resource roads	Province of BC	Jul. 29, 2019
Linear Diking Infrastructure	Linear flood infrastructure collated from multiple sources	Province of BC	Jun. 15, 2018

Provincial Stream Crossing Inventory System – Assessments	Assessments of culverts that follow the provincial protocol for Fish barrier assessment	Province of BC	Sep. 26, 2019
Fish Information Summary System – Fish Obstacles	Collation of various reported potential obstacles fish passage	Province of BC	Apr. 14, 2019
Floodgates and Pump stations	Point locations of floodgates and pumps that may represent barriers to fish movement	Watershed Watch Salmon Society	-
Digital Elevation Model	DEM at 0.75 arc-second resolution	Government of Canada	Jul. 20, 2019
Historical Vegetation of the Lower Fraser Floodplain	Vegetation communities of the Lower Fraser Floodplain estimated from surveyors' notebooks between 1859-1890	North and Teversham (1984)	-

2.3.3 Identifying naturally inaccessible stream habitat

To identify naturally inaccessible linear stream habitat, natural barriers were delineated and the accessible lengths of stream were measured by breaking the Freshwater Atlas stream network into 300-meter segments and assessing their average gradient using a 0.75 arc second Digital Elevation Model (DEM) in ArcGIS (ESRI 2018). A reach length of 300 meters was used as this corresponds to the maximum reach length used in a similar study looking at watershed accessibility by Sheer and Steel (2006). The gradient thresholds for each species were also determined following the methods of Sheer and Steel (2006), where a threshold of 16% was used for Chinook, coho, and sockeye, while a gradient of 5% was used for chum. These gradient thresholds are derived from recommendations by Washington State Fish and Wildlife Department (Washington Department of Fish and Wildlife 2019). The gradient barriers were combined with other known natural barriers not identified by the slope analysis, most notably Stave Canyon, which blocks access to Stave Lake, and the upper Stave system, which acted as a historical fish barrier but is now a hydro dam (Stockner & Bos 2002). For the purposes of this study all stream length below these natural barriers was assumed to be salmonid stream habitat and was measured linearly along the stream length.

Streams that have been classified as ditches in the Freshwater Atlas have been straightened or simplified into drainage channels. For the purposes of assessing habitat accessibility, these channelized streams often form loops in the network and were unreliably identified as accessible or inaccessible using the network topology. It is also likely that streams which have been channelized for drainage harbor only degraded habitat (Rosenvald et al. 2014), for these reasons, the length of channelized streams was quantified separately to the naturally accessible habitat.

2.3.4 Mapped anthropogenic barriers to fish passage

To identify inaccessible habitat, information on barriers in the Lower Fraser were collated from three sources (Figure 2.1, Table 2.2). Two of the sources were provided through the province of BC: the Provincial Stream Crossing Inventory System (PSCIS), which follows a standardized fish passage assessment (Fish Passage Technical Working Group 2014), and the Fish Information Summary System (FISS), which is a collation of potential 'obstacles' to fish passage that potentially cause fish habitat fragmentation but have not necessarily been assessed for their impact on connectivity. The third source is comprised of barriers specifically related to flood infrastructure along the Fraser River and was collected by a local non-governmental organization, Watershed Watch Salmon Society. Due to the potential unreliability of the FISS database, records from all three datasets were evaluated for redundancy and, where overlap of the FISS data was observed with either of the other two datasets, the FISS data was removed. All anthropogenic barriers were assumed to be a complete barrier to salmonids.

The combined barrier data were spatially joined and linear referenced to the Freshwater Atlas stream network using a 30m snapping distance to account for spatial error in barrier coordinates. When a barrier was outside of this snapping distance, but assessment information identified the stream that the barrier was supposed to be located on, the point location was moved to the appropriate stream to be included in the analysis. Using a set of queries, the first barriers that cut off access upstream from either the mainstem of the Fraser River, the coast, or the southern border were identified. All streams upstream of these first barriers were labelled as “inaccessible”, while streams downstream of these barriers were assumed to be accessible. Proportions of accessible and inaccessible habitat were calculated for the region using the estimated naturally accessible length, and for each of the 14 CUs using the CU boundary as the population extent.

2.3.5 Identifying lost streams

The extent of streams that have been lost to urbanization or development was estimated by creating a digital elevation model (DEM) derived stream network from the Canadian Digital Elevation Model at 0.75 arc second resolution and comparing it with the Freshwater Atlas stream hydrography. First the DEM was filled, and the Freshwater Atlas stream hydrography was “burned in” using a rasterized version of the mapped hydrography. The burn in was done to ensure the DEM derived network matched the Freshwater Atlas hydrography and to identify only large areas where streams are expected but have not been mapped within the Freshwater Atlas. Both the Freshwater Atlas stream network (1:20,000) and the DEM were at similar scales, which minimizes the negative impacts of burn in on the final DEM stream network (Lindsay 2016). The burned in DEM was then converted to a flow direction raster, and finally a flow accumulation raster using the D8 method (O'Callaghan & Mark 1984). To identify an appropriate threshold for channel initiation on the flow accumulation raster, points were created at the initiation of currently mapped streams not identified as ditches in the Fraser Valley below 100m of elevation. The average flow accumulation at these points was approximately 0.25 km^2, which was used as the threshold value for channel initiation of the DEM derived stream network. This estimate is a uniform critical support area for streams on the valley bottom, so it does not consider the variation in potential erosional forces such as slope and soil types (Montgomery & Foufoula-Georgiou 1993). Using streams initiated under 100m of elevation is likely a conservative estimate for channel initiation and, subsequently, channel length. Streams within 50m of currently mapped Freshwater Atlas streams were assumed to be the same as those already mapped and removed from the DEM-derived stream network, leaving only streams potentially lost due to filling and urbanization. The remaining DEM derived streams were measured for their along-stream length, average slopes and elevations. Natural barriers were delineated following the methodology already described, and lost streams were labelled as naturally inaccessible where appropriate. The polygon representing Sumas Lake derived from North and Teversham (1984) was used to remove any lost streams estimated in this area.

2.3.6 Predicting unmapped barriers

Whereas mapping of barriers has occurred in the Lower Fraser River, these maps are incomplete, particularly for road culverts. In order to account for unmapped potential barriers, all stream road intersections were mapped, and a model was developed to predict whether these intersections represented potential barriers to fish passage in R (R Core Team 2019). The Freshwater Atlas was overlaid with the BC Roads Atlas Layer and a point was created at each intersection except where the road was labelled as a bridge, ferry or overpass, or where streams were estimated to be naturally inaccessible to anadromous salmonids. Boosted Regression Trees (BRTs) from the "gbm" package (Greenwell et al. 2019) were used to develop a model that can predict the probability that each road crossing poses a barrier to fish passage. BRTs differ from traditional regression methods as they adaptively combine a large number of relatively simple models to optimize predictive performance, rather than producing a singular 'best' model (Elith et al. 2008). Following the methodology of Januchowski-Hartley *et al.* (2014) the site, reach, and segment slope of the stream, as well as the catchment area of the intersection were used as predictors. In addition to these stream characteristics, the number of lanes of the road and the surface type of the road were also used as predictors (Table 2.3). Fish passage assessments in the PSCIS that were labelled as either a barrier or passable (n = 567) were used to develop the predictive model. Code from Elith (2008) was used to determine the optimal learning rate, tree complexity and number of trees. Due to the smaller sample size, only tree complexities of 2 and 3 were tested across learning rates of 0.01, 0.005, and 0.001. The learning rate determines the contribution of each tree to the growing model while the tree complexity controls the fit of interactions or number of branches (Elith et al. 2008). The bag fraction was kept at 0.5 while multiple learning rates and tree complexities were tested. The bag fraction controls the level of stochasticity, as each iteration of the model uses the specified proportion of randomly selected data as the training data for the model. Final model parameters were selected based on the model with smallest deviance and at least 1000 trees using the "gbm.step" function (Elith et al. 2008). Model performance, as measured by the Area Under the Receiver Operator Characteristic Curve (AUC), was estimated using 10-fold cross-validation along with standard errors. Variable importance was calculated based on the contribution to model fit attributable to a given predictor averaged across all trees, in order to understand the characteristics of stream-road intersections that are more likely to be barriers to fish passage.

Table 2.3 Predictors used to estimate the probability a given stream-road intersection would be assessed as a barrier to fish passage.

Predictor	Description	Relevance
Stream Segment Slope	Slope of confluence bound stream line (%)	Hydrological regime
Stream Reach Slope	Slope of 300m stream reach (%)	Reach scale stream energy
Stream Site Slope	Slope of stream at site of barrier assessment (%)	Site scale topography
Catchment Area	Area contributing flow to the site of the potential barrier (m^2)	Stream size
Number of Lanes	Number of lanes on the road indicated by the BC roads Atlas	The number of lanes indicates the length of the culvert
Road Surface Type	The surface of the road as indicated in the BC roads Atlas categories include paved, loose, and rough	Difference in jurisdiction and landscape context between resource and municipal roads

The final model was then used to predict the probability of whether each road-stream intersection was a barrier. The optimal threshold for categorization of a barrier was determined using the “optimal.thresholds” function which identifies the threshold that correctly classifies the most sites in the PresenceAbsence R package (Freeman & Moisen 2008). These model predicted barriers were combined with mapped barriers and where overlaps were identified, predicted barriers were removed. This created a set of road-stream intersections that were not mapped as barriers but were estimated to have a high probability of being a barrier, combined with the mapped barriers. The assessment of accessibility was re-run with this combined barrier dataset to see how model predicted barriers influenced the amount of accessible habitat.

2.4 Results

2.4.1 Floodplain habitat

An estimated 659 km^2 of floodplain fish habitat existed historically in the Lower Fraser. Of this, approximately 102 km^2 remains accessible according to currently mapped dikes, representing only 15% of the historical habitat (Figure 2.2). The amount of accessible historical floodplain habitat varies widely by CU depending on its context in the landscape and what lies downstream. An estimated 4-5% of the historical floodplain habitat for the Boundary Bay populations of both coho and Chinook remain accessible, whereas the Fraser Canyon Chinook and coho and the Lower Fraser coho are comparatively better off with an estimated 16-17% of their floodplain habitat remaining accessible (Table 2.4). A few remaining regions with accessible floodplain appear to be in the islands of the eastern portion of the Fraser River mainstem, and in the Pitt River System.

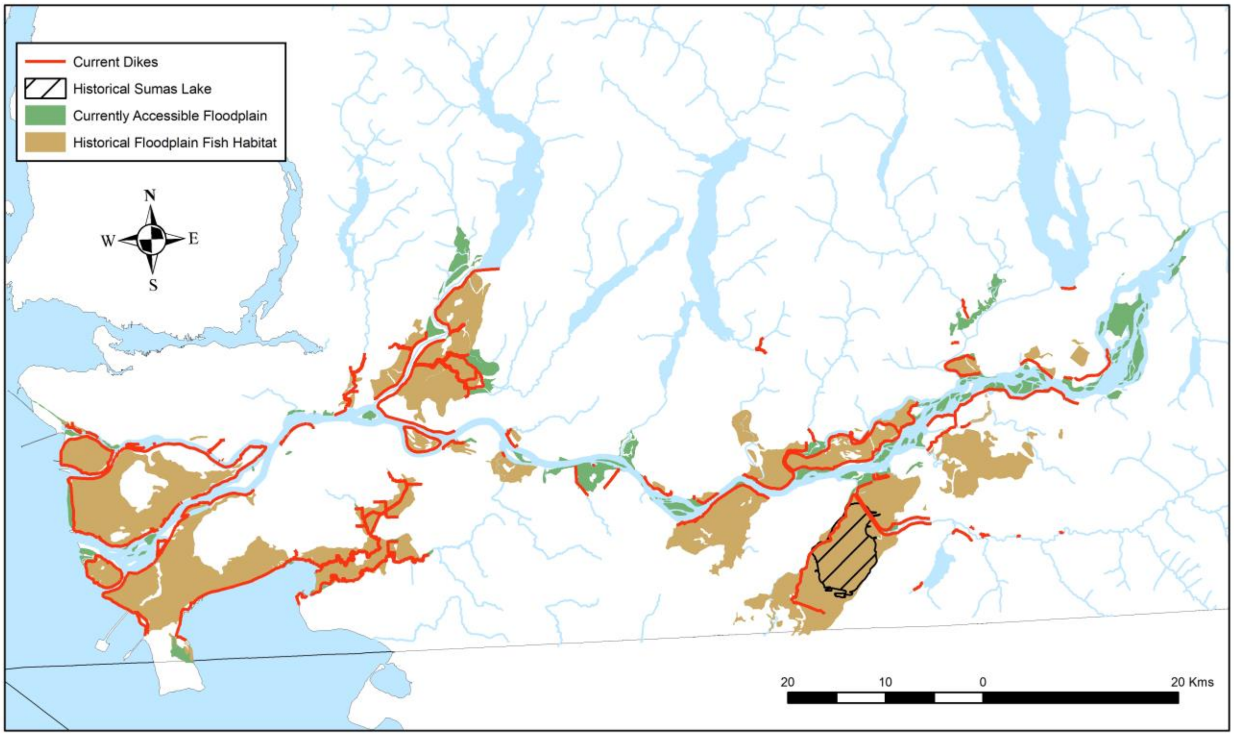

Figure 2.2 Map showing the estimated historical extent of floodplain fish habitat (brown), current diking infrastructure and estimated accessible flood plain fish habitat (green). Historical habitat was estimated using North and Teversham (1984) historical vegetation maps. Area with diagonal lines represents historical extent of Sumas Lake that is no longer in existence, derived from North and Teversham (1984) data.

2.4.2 Stream habitat

In total, 1264 barriers to fish passage have been previously mapped in the study area. Of these, 985 were within 30m of a mapped stream and were included in the analysis of accessibility. These barriers are responsible for alienating approximately 2224 km of stream length, representing 64% of the estimated 6118 km of naturally accessible salmonid stream habitat in the Lower Fraser Region. An additional 1727 km of stream length is estimated to be completely lost from the landscape, and 516 km, concentrated primarily in the developed valley bottom, have been channelized (Figure 2.3). Marked differences in accessibility of stream habitat was observed among CUs' (Table 2.4). As with floodplain habitat, the Boundary Bay populations of Chinook and coho had the highest amount of alienated habitat, with mapped barriers preventing fish passage to approximately 70% of the naturally accessible stream length in those CUs. However, there are also some CUs with much smaller alienated habitat than the region as whole (Table 2.4). For instance, mapped barriers did not appear to have much impact on the amount of habitat that is inaccessible to the Fraser Canyon CUs. According to currently mapped barriers, the more remote Fraser Canyon Chinook and coho, and the Lillooet coho have 87-99% of their linear stream habitat remaining accessible.

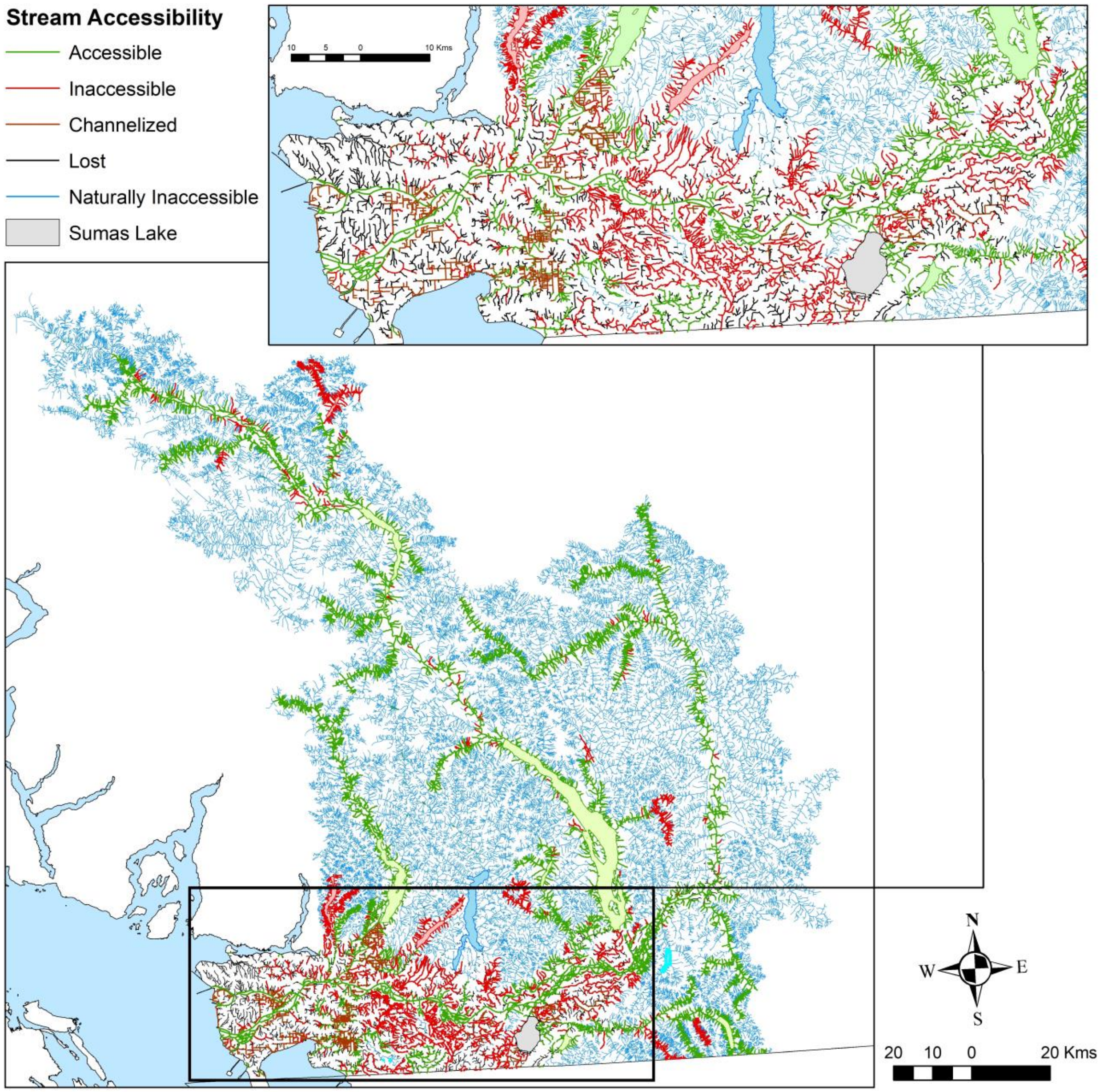

Figure 2.3 Map of stream connectivity in the Lower Fraser according to currently mapped barriers to fish passage. Also included are lost streams identified from a digital elevation model derived stream network, and a map of historic Sumas Lake derived from North and Teversham (1984). This map depicts the 16% gradient threshold for natural accessibility, for the 5% threshold used to assess chum salmon habitat accessibility see Appendix A.3.

2.4.3 Model estimated barriers and updated accessibility estimates

The final model used 2550 trees, with a learning rate of 0.001 and a tree complexity of 2, and an estimated AUC of 0.742 (SE +/- 0.028) based on 10-fold cross-validation. The most important predictors for whether a given stream-road intersection was a barrier were catchment area and segment slope (Appendix A.4). The two road attributes, the number of lanes and the surface type, were the least important, however all predictors had enough influence to remain in the model.

There were 819 stream-road intersections mapped and the final model was used to estimate the probability that every stream-road intersection was a barrier. The resulting probability distribution was bimodal, with a minimum probability of being a barrier of 17%, a maximum of 81% and a mean probability of 56%. The optimal threshold used to identify potential unmapped barriers was determined to be 55%, this value was chosen as it minimizes the distance between the Receiver operator curve (ROC) and the upper left corner of the unit square (Freeman & Moisen 2008). If a stream-road intersection had a probability higher than 55% of being a barrier it was added to the existing mapped barriers data set, resulting in an additional 286 unmapped potential barriers in the study area. After re-running the accessibility assessment with the combined mapped and predicted barriers, the amount of additional alienated habitat was generally small and varied by CU. Generally, those CUs with the greatest amount of remaining habitat were most impacted by predicted barriers. In particular, the estimated accessible habitat for the Fraser Canyon Chinook and coho CUs decreased by approximately 2% (Figure 2.4) after accounting for modelled predicted barriers. In total, the predicted barriers highlighted up to 33 km of stream length that has a high probability of being inaccessible, but where no barriers have been mapped.

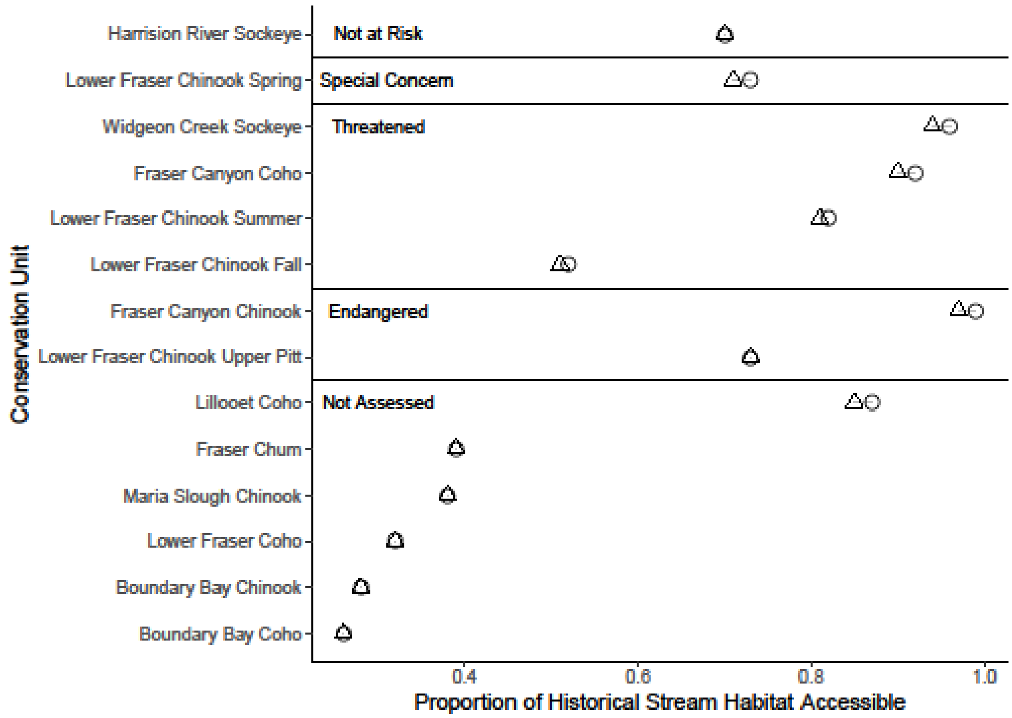

Figure 2.4 Proportions of stream length accessible by Conservation Unit of salmon in the Lower Fraser Region ordered by the Committee On the Status of Endangered Wildlife In Canada assessed status. Circles indicate estimates based only on mapped barriers while triangles are accessibility estimates with both mapped and model estimated barriers.

When predicted barriers were added to mapped barriers, the density of barriers per km of stream habitat increased slightly for most CUs except for Harrison River sockeye and the two Boundary Bay CU's (Figure 2.5). When estimated proportion of accessible habitat was plotted against the mapped barrier density the relationship was slightly negative and became somewhat more pronounced when predicted barrier density was also included (Figure 2.6). After modelled barriers are considered, the only CU that was assessed as not at risk (Harrison River sockeye) had the lowest barrier density *and* access to most of its habitat (Figure 2.6).

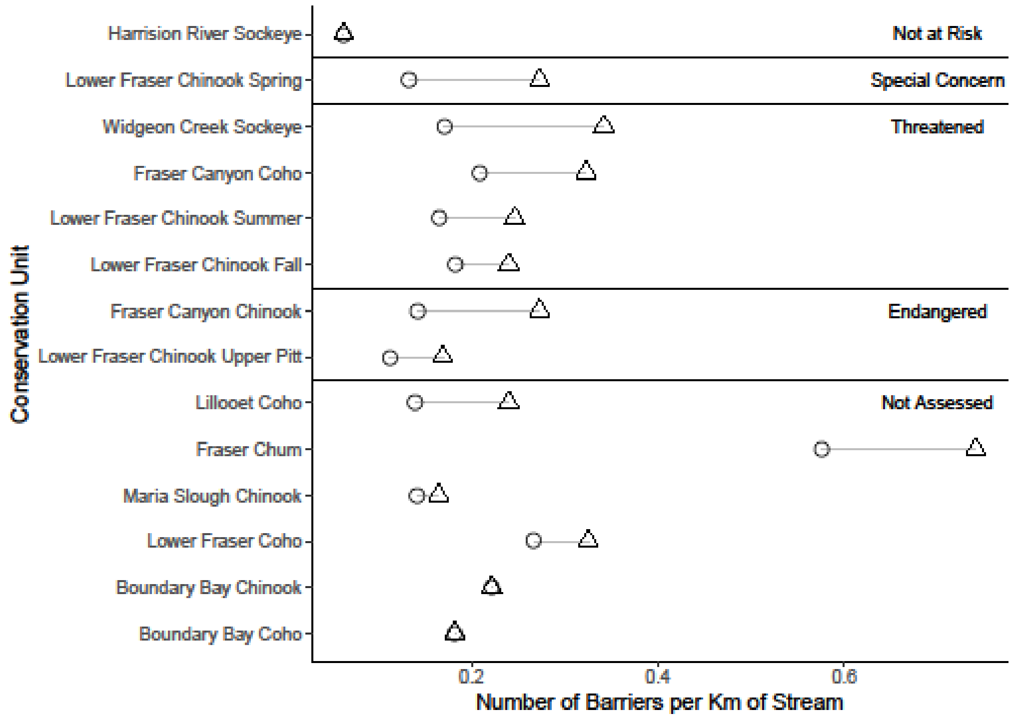

Figure 2.5 Number of barriers per kilometer of stream habitat by conservation units of salmon in the Lower Fraser Region ordered by the Committee On the Status of Endangered Wildlife In Canada assessed status. Circles indicate mapped barrier densities; triangles indicate combined mapped and predicted barrier densities.

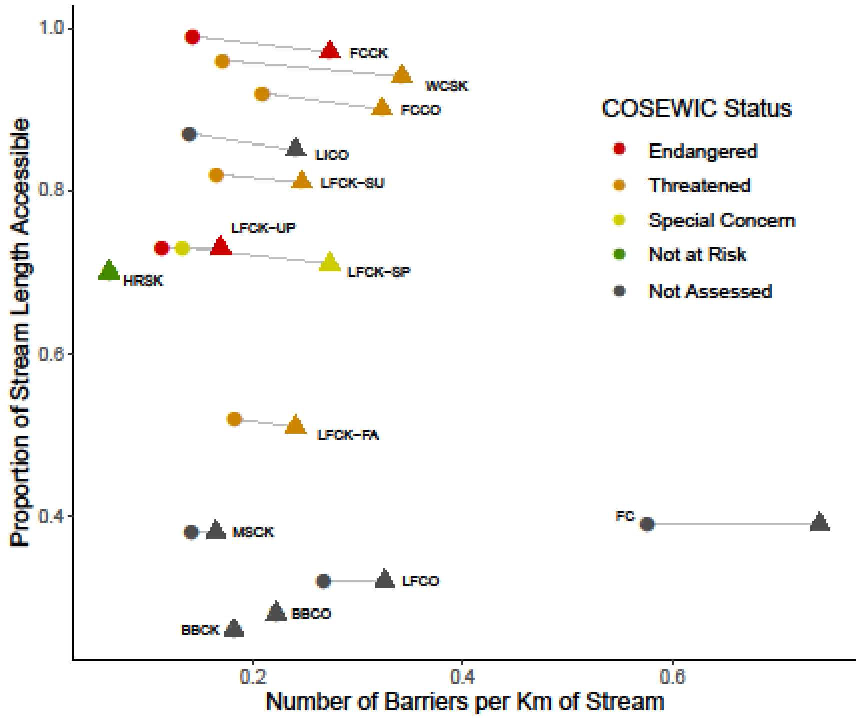

Figure 2.6 Number of barriers for mapped (circles) and mapped and predicted (triangles) and the corresponding proportion of stream habitat that is accessible for 14 conservation units of salmon in the Lower Fraser River. Colors indicate the assessed status by Committee On the Status of Endangered Wildlife In Canada. (WCSK = Widgeon Creek Sockeye, LFCK-SP = Lower Fraser Chinook Spring, FCCK = Fraser Canyon Chinook, HRSK = Harrison River Sockeye, LICO = Lillooet Coho, LFCK-SU = Lower Fraser Chinook Summer, FCCO = Fraser Canyon Coho, LFCK-UP = Lower Fraser Chinook Upper Pitt, LFCK-FA = Lower Fraser Chinook Fall, FC = Fraser Chum, MSCK = Maria Slough Chinook, LFCO = Lower Fraser Coho, BBCO = Boundary Bay Coho, BBCK = Boundary Bay Chinook).

While most CUs are impacted by the loss of floodplain, some seem to be particularly worse off when it comes to the remaining accessible stream habitat. These CUs include the Chinook and coho of Boundary Bay and Lower Fraser Coho. Figure 2.7 shows the proportions of both floodplain and stream habitat that remain accessible and inaccessible as well as the proportions of streams that have been lost and converted to drainage channels. Many of the most highly impacted CUs remain unassessed by COSEWIC and are impacted by not only the alienation of habitat, but also the loss of streams from the landscape.

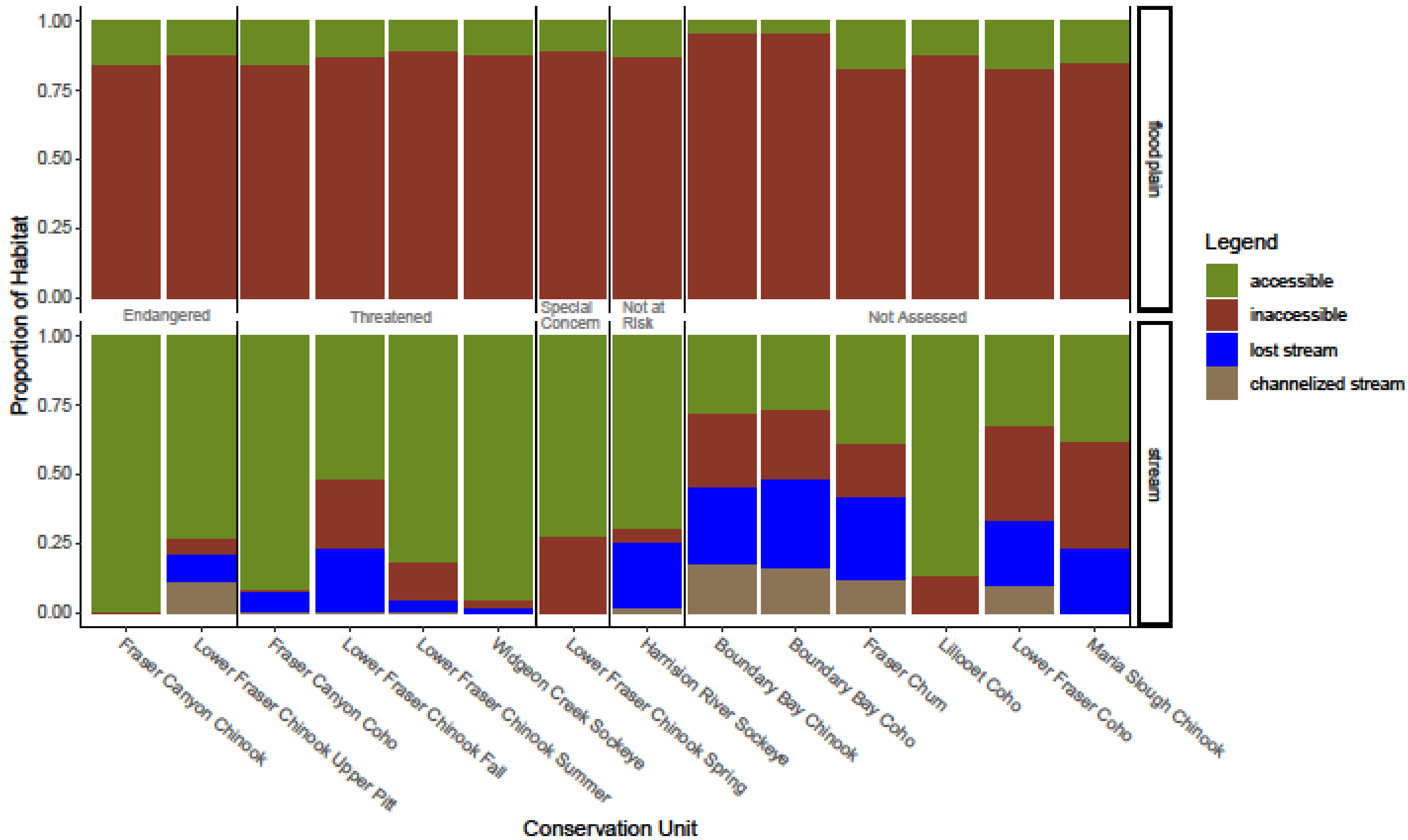

Figure 2.7 Combined proportion of accessible and inaccessible stream and floodplain habitat for 14 conservation units of salmon in the Lower Fraser River. Proportion of stream habitat that has been completely lost and stream habitat that has been converted to drainage channels are also shown. Conservation Units are organized by their assessed status according to the Committee On the Status of Endangered Wildlife In Canada.

Table 2.4 Stream length and floodplain area accessibility estimates for 14 conservation units (CUs) of salmon in the Lower Fraser River; Where Access=Accessible; Chan=Channelized; Inacc=Inaccessible; % Access=Proportion Accessible.

		Stream									Floodplain			
		Mapped Barriers			Mapped+Predicted Barriers									
Species	CU	Access (km)	Inacc (km)	Access(%)	Access (km)	Inacc (km)	Access(%)	Chan (km)	Lost (km)	Total (km)	Access (km^2)	Inacc (km^2)	Total (km^2)	Access(%)
Chinook	Boundary Bay	184.3	176.7	28	184.3	176.7	28	116.3	182.4	659.7	4.3	87.6	91.9	5
	Fraser Canyon	167.4	1.1	99	164.3	4.2	97	0.0	0.0	168.5	73.4	396.6	470.0	16
	Lower Fraser Fall	70.0	34.1	52	69.6	34.6	51	0.8	30.3	135.2	53.2	350.6	403.8	13
	Lower Fraser Spring	207.6	78.0	73	201.8	83.8	71	0.0	0.0	285.7	39.6	336.8	376.4	11
	Lower Fraser Summer	595.3	99.2	82	588.5	106.0	81	0.8	32.1	727.4	39.6	336.8	376.4	11
	Lower Fraser Upper-Pitt	214.9	15.6	73	213.0	17.6	73	32.0	30.8	293.4	28.0	207.5	235.5	12
	Maria Slough	21.2	21.3	38	21.0	21.5	38	0.0	12.7	55.2	71.4	396.0	467.4	15
Chum	Lower Fraser	921.0	446.5	39	918.9	448.6	39	282.0	712.4	2361.9	97.2	469.8	567.0	17
Coho	Boundary Bay	252.8	241.3	26	252.8	241.3	26	156.4	310.0	960.4	4.4	102.5	106.9	4
	Fraser Canyon	503.2	4.7	92	494.2	13.6	90	1.1	38.9	547.8	73.4	396.6	470.0	16
	Lower Fraser	1241.8	1315.2	32	1230.0	1327.0	32	382.1	904.9	3844.1	54.9	387.8	442.7	12
	Lillooet	653.3	100.8	87	641.7	112.5	85	0.0	0.0	754.1	97.2	469.8	567.0	17
Sockeye	Harrison River	30.0	1.9	70	30.0	1.9	70	0.8	10.3	43.0	53.2	350.6	403.8	13
	Widgeon Creek	17.1	0.4	96	16.8	0.8	94	0.0	0.4	17.9	28	207.5	235.5	12

2.5 Discussion

The Lower Fraser River is an important location for salmon spawning, rearing, and migration. It is also a location with intense development and environmental degradation; restoring salmon habitat in this location requires an understanding of the historical habitat of the area. In this study, I collated a dataset of over 1200 instream barriers which indicate the alienation of approximately 64% of otherwise accessible stream length in the region and use historical vegetation maps to demonstrate the disconnection of 85% of historically accessible floodplain by diking infrastructure. Importantly I try to address key pieces of missing data throughout the region and include these in my assessments. Estimating lost streams using a DEM derived stream network revealed an additional 1727 km of habitat that may have been accessible historically, but no longer exist. I also modelled potential barriers based on where barriers have already been observed to compensate for watersheds where little mapping has been done, which highlighted 33 km of habitat with a high probability of being inaccessible.

2.5.1 Pervasive loss of habitat

According to historical floodplain vegetation communities and current diking infrastructure approximately 85% of the historical floodplain fish habitat has been alienated in the Lower Fraser River, and this number ranges from 96% to 83% depending on the salmon CU. A similar analysis that looked at all wetland fish habitat in the same region (Kistritz et al. 1996) found that 90% of wetlands that could have been used as fish habitat in the Lower Fraser were lost. Kistritz *et al.* (1996) used the same historical vegetation dataset used here, in combination with historical aerial photos to identify wetlands outside of the floodplain and by comparing this to the Canadian Wildlife Service wetlands inventory to determine differences between the contemporary and historical wetlands. However, they did not have diking information and were unable to consider floodplain forests and Sumas lake within their estimates. The loss of floodplain habitat may have important implications for salmon productivity in the Lower Fraser system, particularly for coho and Chinook, which rely on these habitats for increased growth rates relative to other areas (Brown & Hartman 1988; Sommer et al. 2001, 2005). In California, Chinook salmon have been observed to benefit from the use of seasonally flooded farmlands (Katz et al. 2017) and ephemeral floodplain habitats (Jeffres et al. 2008) in the form of increased growth rates and improved body condition. Given the importance of this habitat, the loss of access to 85% of historical floodplain habitat in the region likely has large impacts on the carrying capacity and condition for many of the Fraser Chinook and coho populations.

My prediction of lost streams revealed an estimated 1727 km of linear stream habitat that may have been completely eliminated from the landscape. Descriptions from Indigenous Communities of the Lower Fraser indicate that these streams likely functioned as salmon habitat. For example, the ubiquity of salmon is captured by stories of the *Stó:lō*, who possess 147 words for the catching and processing of fish, fished salmon for most of the year, and describe salmon as the essence of *Stó:lō* identity and life (Smith 2001). Additionally, oral histories collected by Proctor (1978) from Vancouver pioneers, describe nearly all of the streams found within Vancouver's boundary as having spawning habitat for salmon with many swamps and wetlands at the headwaters acting as ideal rearing habitat. While the original assessment done by Proctor (1978) identified approximately 120 km of lost streams within Vancouver's boundary, Canada's Department of Fisheries and Oceans (DFO) built upon this work and raised this number from 120 to 157 km of lost streams in Vancouver City (Fraser River Action Plan (Canada) & Precision Identification Biological Consultants 1998). The estimates from the DEM derived stream network are consistent with a total of 165 km of lost streams for the same area. Some of the differences between the DFO estimates and those of the DEM derived stream network may be explained by the difference in shoreline estimation, where this study estimated stream length up to the current shoreline, the DFO estimations use the historical shoreline which has been reclaimed over time. Although the estimation of extent is important for understanding the amount of habitat that may have existed historically, it is likely that the horizontal accuracy of the DEM derived stream network is reduced in particularly flat areas such as the mouth of the Fraser River. However the results from the DEM may be combined with, or used to narrow the scope of more exhaustive analyses using historical maps or sewer systems in the future (Broadhead et al. 2015). Moving forward, it will be important to develop multiple lines of evidence for confirming the locations and extents of lost streams and to identify cost-effective opportunities for the restoration of habitat connectivity.

2.5.2 Habitat accessibility varies by conservation unit

Some CUs appear to be much less impacted by in-stream barriers in terms of the amount of linear stream length that has been alienated. Even after estimating for potentially unmapped barriers, only 3% of the stream habitat was upstream of barriers in the watersheds relevant for Fraser Canyon Chinook. This may be explained by the steep topography and the nature of the road system in the Fraser Canyon. A majority of the road network in these areas is comprised of resource roads that run parallel to the larger rivers and intersect the smaller tributaries that begin in the steep mountains. It is likely that many of these intersections are potential barriers, but according to the gradient model for accessibility, even if a barrier does exist it does not alienate a large length of habitat. In addition, the type of habitat being lost in these regions is unknown. Certain habitats are disproportionately important, such as spawning and overwintering areas, therefore even modest losses in the estimated accessible stream length, could lead to large implications for the population. For example, coho are known to rely on small streams and side channels for winter rearing (Beechie et al. 1994). For Fraser Canyon coho 90% of their estimated habitat remains accessible but much of what is alienated may be habitat that is important for overwintering as small streams become cut off by the road network in the system. The alienation of small streams is also of broader concern beyond this region. When predicting the likelihood of a stream-road intersection, the size of the stream was an important determinant (Appendix A.4), with smaller streams being more likely to have a barrier on them, consistent with the findings of Januchowski-Hartley *et al.*, (2014). Generally, smaller streams are more likely to be inaccessible, yet they remain important for the production of salmonids (Brown & Hartman 1988).

While barriers in regions with high remaining habitat accessibility may not be disconnecting a substantial proportion of stream length, they may act as an indicator for more indirect impacts happening in the watershed. Some of the CUs with the most remaining habitat had higher barrier density after including model predicted barriers. This could reflect the steep topography and road network in these watersheds, where streams with steeper gradients generally exhibited stream-road intersections with higher probability of being a barrier to fish passage. Unpaved forest roads have been demonstrated to alter flow regimes of streams and provide a source of excess sediment that can impact salmon rearing and spawning habitat downstream (Al-Chokhachy et al. 2016). Development of road networks is ubiquitous with human developed landscapes and have the potential to influence flow regimes, connectivity, sediments and geomorphology (Wellman et al. 2000) as well as facilitate the accelerated exploitation of previously undisturbed systems (Johnson et al. 2019).

2.5.3 Implications of barriers on the status of Conservation Units

Based on the analysis of barrier density and habitat accessibility, loss and alienation of habitat appears to contribute to the observed salmon declines for some populations. Less than half (40%) of the Lower Fraser coho stream habitat and only 17% of the historical floodplain habitat remains accessible. Additionally, it is likely that a sizeable portion of what habitat remains accessible has experienced some form of degradation with impacts on productivity. While it is important to acknowledge the role of marine conditions in stock recovery, it is difficult to ignore a loss of habitat on this scale, especially when the condition of juvenile coho salmon leaving the freshwater environment has been observed to enhance survival when marine conditions are poor (Holtby et al. 1990).

The association of barrier density and habitat accessibility within the context of the population status is informative. When these values were plotted against each other after including predicted barriers, the Harrison river-type sockeye were the only CU identified to have both high habitat accessibility and relatively low barrier density. The Harrison river-type sockeye is also the only population to have been assessed as not at risk by COSEWIC. It is also important to note that many of the CUs that have not been assessed by COSEWIC (Table 2.1) appear to be the ones most impacted by loss of habitat connectivity and based on this, I suspect that when assessed by COSEWIC, they will be designated as 'threatened' or 'endangered'. These CUs include the Lower Fraser coho, and both Boundary Bay Chinook and coho. As of 2019, Lower Fraser coho are considered a "stock of concern" within the integrated fisheries management plan for salmon in southern BC, however the cause of concern is attributed purely to marine conditions (DFO 2019).

These measures of barrier density and habitat accessibility may also guide prioritization of watersheds for systematic assessment and implementation of connectivity restoration. The number of barriers mapped in a system may be used to identify candidates (e.g., Maitland *et al.*, 2016), however, simply looking at the number of barriers can be misleading as many barriers may be alienating small amounts of habitat. By considering both habitat accessibility and barrier density, on a spatial scale that is relevant to individual or multiple populations of concern, the identification of broad locations where restoring connectivity may be achieved. For example, the Maria Slough Chinook CU appears to have both low habitat accessibility and low barrier density (Figure 2.6). The watersheds for this CU may represent a location where the removal of relatively few barriers could have large benefits in terms of the amount of habitat that would become accessible. However, the distribution of barriers in the watershed will determine the efficiency with which habitat will be gained from barrier removal. Indicators such as the Dendritic Connectivity Index may be used to shed light on the orientation of barriers (Cote et al. 2009), and optimization can be used to understand the potential complementarity of multiple barrier removals (O'Hanley & Tomberlin 2005; McKay et al. 2020).

This study demonstrates a historical view of salmon habitat loss in the Lower Fraser and attempts to understand how different salmon CUs are impacted by loss of connectivity. It is important to note that salmon conservation units were only recently developed as part of the Wild Salmon Policy (DFO 2005) and COSEWIC's assessments of these CUs are based on recent estimates of abundance. In other words, the baselines on which I make these assessments have already shifted. For example, the loss of Sumas Lake occurred in 1924 and represents 7% of the entire floodplain habitat loss in the Lower Fraser, long before any written record keeping of salmon populations and their abundances. Another example of shifting baselines in the Lower

Fraser are the Alouette and Coquitlam reservoirs, two lakes which historically had runs of sockeye salmon in them, but due to dam construction in the 1910s and late 1920s these runs have been extirpated and are not considered to be modern CUs. Land locked sockeye, called kokanee currently populate the lake (Godbout et al. 2011). These examples illustrate the importance of considering historical landscape legacies and how the shifted baselines which guide current day management priorities hide historical declines in salmon productivity.

2.5.4 Broader implications

This chapter attempts to identify a baseline for restoration and management for salmonid habitat in the Lower Fraser River through combining multiple measures of habitat loss and alienation. In order to be a useful tool for guiding restoration and management of freshwater systems the assessment of habitat fragmentation needs to consider not only current barriers and streams but the historical conditions of the landscape. It is possible that the deceptive nature of the shifting baseline syndrome has skewed the perceptions of what appropriate targets for the restoration of freshwater habitat should look like (Humphries & Winemiller 2009). Further, the restoration of ecosystem function will require the consideration of more than just physical habitat but also important biotic components that may have also been lost (Byers et al. 2006).

Although I have demonstrated a high degree of habitat isolation in the Lower Fraser, I also provide examples of how my analysis can be used to identify cost-effective opportunities for restoration, such as restoring habitat connectivity through the remediation of a small number of barriers which prevent access to large areas of potentially intact habitat. It will also be important to pair species specific estimates of barrier density and habitat accessibility with methods for prioritizing specific barriers (McKay et al. 2017). A more detailed understanding of historical conditions provides a lens through which to understand the potential outcomes of barrier removal, and where the daylighting of streams may be used to restore habitat (Wild et al. 2011).

In conclusion, the consideration of lost streams, and the use of historical vegetation records were able to supplement an analysis of barriers on stream and floodplain habitat and reveals a high degree of lost and alienated habitat for multiple CUs of in the Lower Fraser River. I believe this demonstrates that freshwater habitat loss and connectivity is a factor which must not be ignored in the discussion of recovery actions for Pacific salmon.

Chapter 3: Using systematic conservation planning to prioritize freshwater barrier removal for salmon passage

3.1 Synopsis

Instream barriers are among the most common threats to freshwater habitats and the species that rely on these habitats. Deciding which barriers to remove to maximize habitat area and connectivity for freshwater fish is challenging due to the large number of barriers to assess, uncertainty regarding species presence and abundance, uncertain habitat quality, high cost of removal or remediation, and limited budgets. Here, I apply systematic conservation planning to express in-stream barrier removal as an optimization problem with the objective of maximizing the amount of restored habitat for 14 populations of Pacific wild salmon in the Lower Fraser River, Canada's largest producer of salmon. I examined scenarios that maximized habitat extent for the 14 populations of salmon and contrasted these with scenarios that also included 4 indicators of habitat quality to understand how priorities changed when stream quality was also optimized. Region wide, approximately 75% of the alienated habitat could have full access restored with an investment of $200 million, whereas 60% of the habitat could be restored for half this amount. When quality was emphasized within the optimization, priority barriers shifted away from the urbanized valley bottom and toward less developed areas of the study region. The spatial shift in priorities meant that species like chum salmon (*O. keta*), which rely more heavily on the valley bottom, saw less habitat restored when quality was included in the optimization. To inform on-ground decisions about barrier removal using these model predictions, an iterative and adaptive approach will be required that includes stakeholders and decision makers providing input on which values should be prioritized along with continuous improvement of data quality, accuracy and feedback from monitoring as barriers are restored.

3.2 Introduction

Freshwater ecosystems have disproportionate species richness and face a variety of threats that vary in both temporal and spatial scales (Dudgeon et al. 2006; Reid et al. 2019). Globally, freshwater ecosystems are vital sources of ecosystem services and support billions of livelihoods (Maltby & Acreman 2011). The convergence of anthropogenic pressures and diversity of species supported by freshwater ecosystems have resulted in a crises of biodiversity decline that requires urgent action at regional scales. Actions must consider the distribution of multiple species and in the case of pacific salmon, multiple populations of species along with an understanding of the potential benefit and cost of alternative actions (Magurran 2016; Albert et al. 2020).

Restoration and rehabilitation efforts are commonly taken at the scale of a single reach or multiple reaches throughout a watershed and have had mixed success due to the challenge of considering the watershed scale processes of ecosystem threats, and historical conditions (Roni et al. 2008). Failure to identify watershed stressors can lead to wasted resources and poor return on investment in the form of ecological recovery (Palmer et al. 2010). Instead of approaches that focus on repairing specific habitat conditions, actions are needed that address the restoration of landscape processes which shape and sustain thriving habitats (Roni et al. 2008; Beechie et al. 2010). Integrated approaches that assess the threats acting on an entire watershed are needed in order to implement holistic actions that address the primary causes of ecosystem degradation (Beechie et al. 2010). Recognition of the importance of the spatial connectedness and influence of watershed scale processes on the quality of aquatic habitat lend themselves to systematic approaches to planning restoration efforts since the potential number of solution options is vast and becomes intractable quickly (Hermoso et al. 2011; Langhans et al. 2016; Salgado-Rojas et al. 2020).

Instream anthropogenic barriers are among the most ubiquitous threats to freshwater systems consist of structures that restrict longitudinal movement of organisms throughout a stream network or laterally with the floodplain (Coleman et al. 2018) and have multiple impacts including limiting movement of nutrients (Tockner et al. 1999), changing flow regimes (Tonkin et al. 2018), changing sediment deposition patterns (Fryirs et al. 2007) and thermal characteristics (Gordon et al. 2015). Barriers also block access to habitats required for different life stages of migratory species (Gibson et al. 2005) and can fragment resident fish populations (Jager et al. 2001; Esguícero & Arcifa 2010). Restoring connectivity of habitat isolated by instream anthropogenic barriers is a priority in watershed restoration due to its often quick biological response and relatively high success rate when suitable upstream habitat exists (Roni et al. 2002). However, deciding which barriers to remove in priority to achieve the greatest benefit for multiple freshwater species remains a challenging question. The removal of barriers to potentially productive habitat is complicated by a variety of factors including the spatial connectedness of barrier removal actions and therefore potential complementarity of multiple barrier removal projects, uncertainty regarding species benefit, limited financial resources, and the goals or values of the entity carrying out restoration. Depending on the species of concern, migration and movement patterns may pose further constraints on the potential benefit of a barrier removal (McManamay et al. 2015).

The identification of priority barriers for removal has been approached using a variety of methods (McKay et al. 2017). Broadly these approaches include mathematical optimization, scoring and ranking techniques, and approaches that rely on local knowledge, unexpected failures or reactive responses (McKay et al. 2020). Each of these approaches have their strengths and drawbacks. Scoring and ranking methods can be intuitive, and flexible but commonly do not consider spatial relationships of barriers and the complementarity of multiple barrier restoration projects (O'Hanley & Tomberlin 2005; McKay et al. 2020). Mathematical optimization on the other hand is useful for identifying the complementarity of multiple potential projects while maximizing quantitative criteria, however may be limited by data constraints, and has been criticized for being overly prescriptive, requiring action on a set of barriers in order to achieve benefits (McKay et al. 2020).

To address some of the inflexibility of previous optimization methods I use a systematic conservation planning approach to explore the potential benefits of barrier removal and identify locations that may require additional management action for freshwater restoration to succeed. The systematic conservation planning framework is commonly applied to area based conservation problems to optimize the spatial representation of conservation action, most commonly the designation of protected area networks (Possingham et al. 2000). Many of the challenges that come with protected area optimization problems are shared with the issue of prioritizing freshwater barrier removal. Often a large number of land parcels may be candidates for protection, each land parcel has a variable cost of acquisition or protection, and they all have varying benefits when it comes to the types and amount of habitat or species that are contained within (Church et al. 1996; Ball et al. 2009). The same can be said when it comes to anthropogenic barriers in freshwater systems, in many cases databases of observed instream barriers are recorded and can be candidates for removal, they may have varying costs for removal depending on the type of barrier and its location, and each barrier delivers varying amount of habitat upstream depending on the species of concern and other barriers in the system.

The connectivity of potential restoration sites can also be considered using tools that are applied for protected area optimization. The connectedness of potential protected areas is important, and optimization algorithms can be constrained to penalize solutions with sparsely connected land parcels (Ball et al. 2009) or even require complete connectivity (Önal & Briers 2006). In fact, specific constraints that stress the importance of upstream connectivity in freshwater systems have been incorporated into area-based prioritizations (Hermoso et al. 2011). For freshwater barriers the connectivity of projects can be defined through a mapped river network topology and complementarity of multiple connected projects can be considered in the solution.

In this Chapter, I use a systematic conservation planning framework to understand opportunity for restoring connectivity for salmonids in the Lower Fraser River, Canada, through the removal of anthropogenic barriers. To ensure priority sites consider threats at the watershed scale and fit into an integrated watershed planning approach, several scenarios are developed to understand the potential benefits and cost trade-offs of different sets of barriers. These scenarios include the consideration of the amount of habitat upstream of each barrier, the species that may be present, and indicators of the quality of that upstream habitat. The Lower Fraser presents an important case in terms of barrier removal as it has some of the highest diversity of salmon populations in the world (Northcote & Larkin 1989), while at the same time high levels of economic development and dense human population growth have caused the isolation of an estimated 64% of linear stream habitat (Finn et al. 2021, *Chapter 2*).

By estimating the cost of restoration and quantifying the amount of habitat upstream of each barrier for 14 populations of salmon, and the assessment of 4 indicators of habitat quality at the watershed scale, I investigate how barrier removal priorities change across scenarios that emphasize quantity and quality of habitat differently. I also examine how the representation of the populations within the solutions change across scenarios to gather insights on potential restoration needs. My results are then placed into a broader adaptive management context intended to address how model outputs might be implemented in a time and place where decisive action for salmonids is urgently needed.

3.3 Methods

3.3.1 Study area

The Fraser River Watershed covers a quarter of the Province of British Columbia with an area of 233,000 km^2 (Northcote & Larkin 1989). The Lower Fraser is commonly defined as the final 150 km stretch of river downstream of Hope, BC, where the flow diverts westward toward the estuary that empties into the Strait of Georgia. For this study, the Lower Fraser was delineated hydrographically using the watershed groups that have been created through BC Freshwater Atlas. All Watershed groups that contribute to this final 150 km of river were used to delineate the Lower Fraser Watershed, these included the Fraser Canyon, Chilliwack, Harrison, Lillooet, and Lower Fraser watershed groups (Figure 3.1). The Lower Fraser defined hydrologically covers an area 20,203 km^2, although only representing a modest portion of the entire basin, the Lower Fraser contains considerable geographic diversity. The valley that surrounds the Fraser Mainstem is largely populated by the Vancouver metropolitan area, which is home to 2.5 million people, approximately half the population of BC.

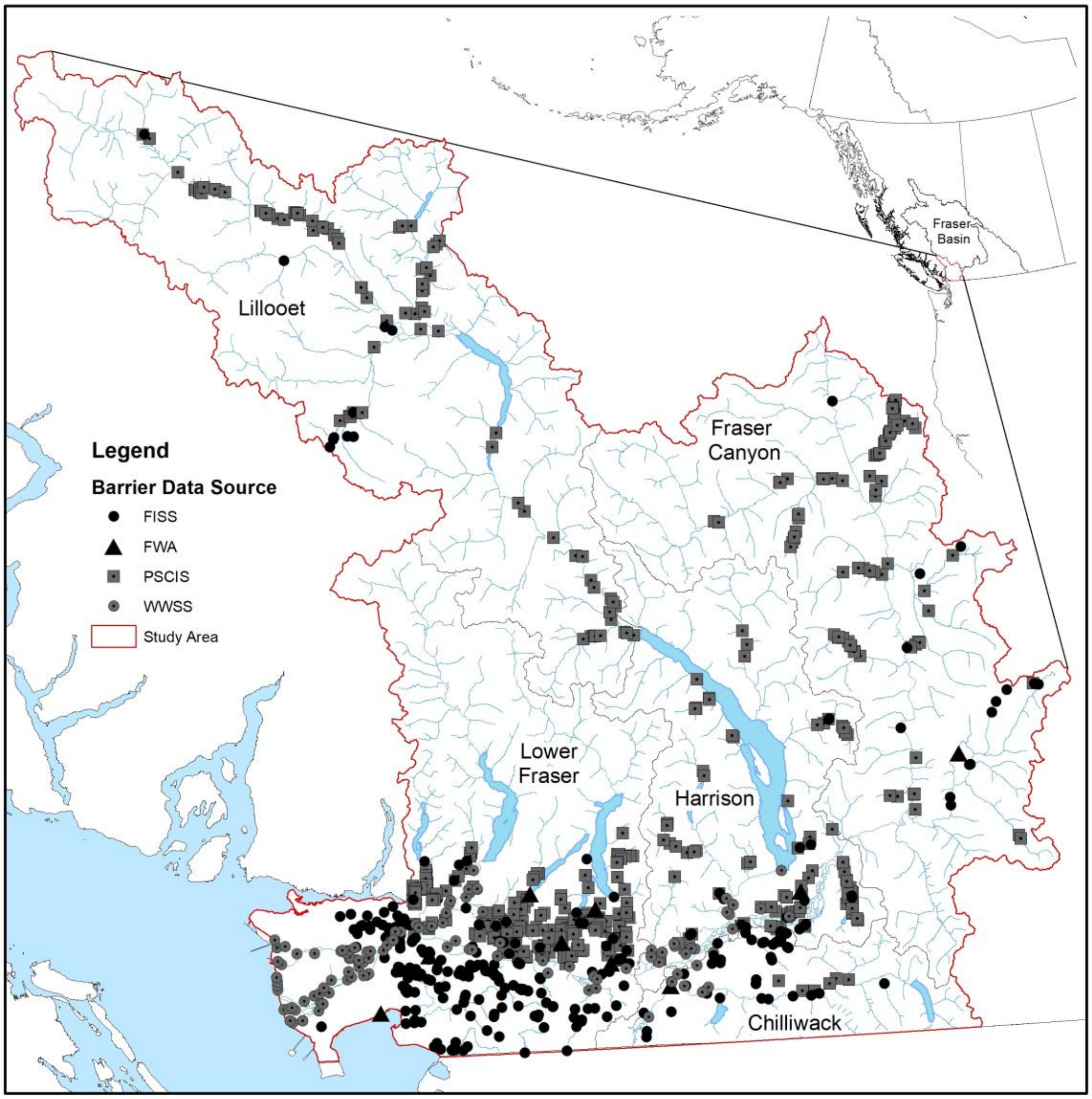

Figure 3.1 Map of Lower Fraser River and barriers included in this study. Barriers data comes from the Fish Information Summary System (FISS), Freshwater Atlas (FWA), Provincial Stream Crossing Summary System (PSCIS), and Watershed Watch Salmon Society (WWSS).

For salmonids, the Lower Fraser is disproportionately important, it supports the highest diversity of populations in the entire basin (Nesbitt & Moore 2016), and acts a migration route for all others. Pacific salmon in Canada are managed at the level of CU (Holtby & Cirunia 2007), they are defined as the a group of salmon that are isolated enough such that if they were to be isolated, re-colonization would not happen within an acceptable timeframe (Fisheries and Oceans Canada 2005). The watersheds used by each CU have been mapped and these boundary files were overlaid with the study area, CUs were included if their CU boundary was completely contained within the study area. Lake-type sockeye salmon were excluded from consideration as their CU boundary is defined as their natal lakes, rather than watersheds. Since the lake must be accessible for the CU to exist, this gives no barriers to assign to the CU. In total 14 CUs were included (Table 3.1); maps of CU boundaries can be found in the supplementary information (Appendix A.1). Many of these CUs are currently at record low abundances, with 5 CU's designated as threatened or endangered by the Committee On the Status of Endangered Wildlife In Canada (COSEWIC), and a further 7 remain unassessed or data deficient (Grant et al. 2019).

Table 3.1 Species and Conservation Units (CU) included in the study area. Chinook CUs include season that adults return to spawn where FA = fall, SP = spring, and SU = summer. The numbers in the Chinook CU name indicate the usual number of years spent in freshwater as a juvenile (first number) and the usual number of years spent in the marine environment (second number).

Species	Conservation Unit
Chinook (*Oncorhynchus tshawytscha*)	Boundary Bay FA 0.3
	Lower Fraser FA 0.3
	Lower Fraser SP 1.3
	Lower Fraser SU 0.3
	Lower Fraser – Upper Pitt SU 1.3
	Maria Slough SU 0.3
	Middle Fraser – Fraser Canyon SP 1.3
Chum (*Oncorhynchus keta*)	Lower Fraser
Coho (*Oncorhynchus kisutch*)	Boundary Bay
	Fraser Canyon
	Lillooet
	Lower Fraser
Sockeye (*Oncorhynchus nerka*)	Harrison River – River Type
	Widgeon – River Type

3.3.2 Define anthropogenic barriers

Anthropogenic barriers to fish passage used in the prioritization were collated in the same way as Chapter 2. The three primary sources include Provincial Stream Crossing Inventory System (PSCIS), Fish Information Summary System and Watershed Watch Salmon Society Flood Infrastructure Mapping. Freshwater Atlas obstructions data was also included from an updated version of the Freshwater Atlas. The PSCIS, FWA, and WWSS datasets were compared against the FISS dataset for any redundancy and any overlapping entries within the FISS dataset were removed. The barriers were then combined to a single dataset, in total 1281 anthropogenic barriers were identified within the study area and they included hydro dams, road culverts, and flood infrastructure (floodgates and pump stations), small dams, and weirs. Barriers were removed from the analysis if they were upstream of a natural barrier to salmonids (defined below) or if spatial error meant that the barrier could not be placed on a stream. This left 638 barriers to be included in the optimization.

3.3.3 Defining benefit

Several metrics were used to characterize the potential benefit of removing each of the barriers that have been mapped in terms of both the amount and quality of habitat that would be restored. The amount of habitat that would be gained by the removal of a barrier was measured for those streams that are naturally accessible to salmonids using the linear stream length from the 1:20,000 stream layer from the BC Freshwater Atlas. To only measure streams accessible to salmonids, the locations of natural barriers to fish passage were estimated by following a similar methodology to Sheer & Steel (2006). First, the stream layer was broken into 300m segments, these segments were then measured for their slope using a 0.75 arc second DEM. Segments with an average slope of 5% or greater for chum, and 16% or greater for all other species had a point placed on the downstream end of the segment and were assumed to be natural gradient barriers (Washington Department of Fish and Wildlife 2019). The estimated natural gradient barriers were then combined with other known natural fish barriers, most notably Stave Canyon, which is now a Hydro Dam but historically blocked access to the upper Stave system and Stave Lake (Stockner & Bos 2002). The combined natural barrier data was then linear referenced to the original stream network and used to adjust the amount of salmon accessible habitat upstream of each barrier. Any anthropogenic barriers that were determined to be upstream of a natural barrier were removed from the analysis. The quantity of habitat was then standardized to a proportion of the total alienated habitat length to improve model performance. Maps of salmon CUs were then used to define whether the habitat upstream of a barrier would benefit that CU.

Metrics of habitat quality corresponding to additional potential management actions were also quantified so that barriers downstream of poor habitat could be avoided or selectively prioritized. For each stream segment, the watershed was determined using the corresponding 1:20,000 watershed layer in the BC Freshwater Atlas. The spatial extent of riparian zones are difficult to determine precisely, due to the heterogeneity of stream processes and community functional attributes (Naiman and & Décamps 1997). The primary role of this assessment is to understand the spatial orientation of watershed disturbance as degradation in the riparian zone may have more direct impacts on bank stability and sediment inputs, while broader watershed disturbance can result in hydrological changes and nutrient loading (Allan 2004). A 30m buffer distance was chosen to characterize the status of the riparian habitat as it corresponds to the most common measurement used by regulation in North America for waterbodies of all sizes (Lee et al. 2004). A landcover raster was developed by integrating data from a time series analysis of logging in Canada (White et al. 2017) with landcover data from Hermosilla et al., (2016).

Because landcover data did not include information on forest loss, areas that had been identified as being logged within the last 20 years (from 2000 onward) were selected and integrated into the landcover raster. The integrated layer was then used to summarize impervious surface (indicated by urban landcover), and watershed disturbance (indicated by the amount of logged, urban, and cultivated landcover within the watershed and upstream riparian area of all stream segments) (Table 3.2). In addition to landcover indicators of quality, the proportion of upstream habitat that was described as "ditch" in the Freshwater atlas was also quantified (Table 3.2). For each indicator of disturbance, a threshold was used to determine whether the threat was present for the stream where the barrier occurred. Thresholds for disturbance levels were adapted from the assessment of wild, threatened, and endangered streams of the Lower Fraser Valley (Fraser River Action Plan (Canada) & Precision Identification Biological Consultants 1998) and included > 10% impervious surface cover in the watershed, > 50% disturbance of the riparian area, > 50% disturbance of the Watershed, and > 50% channelization upstream. If a stream was below these thresholds, the barrier sitting on the stream was given the value of its estimated length benefit for that quality indicator, whereas if it was above these thresholds the barrier received a zero for that feature. By assigning the value of the habitat quantity to barriers that sit on streams that indicate good quality habitat, I give weight to barriers that sit on both high quality habitat and have a large potential amount of habitat to restore. Assigning the upstream amount value for a barrier on a stream is necessary to avoid the prioritization of a high number of small projects with *instances* of high-quality habitat, for the preferred outcome of prioritizing projects that contain large amounts of high-quality habitat.

Table 3.2 List of features quantified for each barrier and a description of how they were measured.

Quality Indicator	Measurement description	Function

Species-specific length	The stream length measurement calculated only for barriers that fall within the CU boundary for 14 CUs of Salmon	Barriers that block passage for multiple species will confer greater benefit of removal; this also allows for species specific priority weighting
Watershed riparian cover	Proportion of forest or wetland landcover within 30m of all streams upstream of the segment the barrier sits on	Provides an indicator of condition of riparian habitat that is contributing to that point in the watershed
Watershed impervious surface	Proportion of the watershed that has impervious (urban) landcover	Indicates level of hydrological disturbance and contaminant input
Watershed disturbance	Proportion of watershed that is of a disturbed landcover type	Indicates human activity in the watershed that impacts habitat quality including urbanization, agriculture, and forestry
Upstream channelization	Length of streams upstream of barrier that has been converted to ditch	Provides indicator of the destruction of channel complexity and potential degradation habitat

3.3.4 Estimating cost

Cost estimates were used to differentiate the primary types of barriers that inhibit salmon passage in the Lower Fraser River. These barriers are predominantly made up of Hydro dams, flood infrastructure such as floodgates and pump stations, as well as road culverts. Both the Coquitlam and Alouette dams have had detailed feasibility studies done within the last 20 years that contain cost estimates for the installation of fish passage infrastructure (Gaboury & Bocking 2004; R2 Resource Consultants, Inc. 2018). These estimates were converted to 2020 Canadian Dollars and applied to their respective dams, the average of the two was applied to the Ruskin Dam which sits on the Lower Stave River. It should be noted that restoration costs for the two dams do not include ongoing costs of water management to assist fish movement (Gaboury &

Bocking 2004; R2 Resource Consultants, Inc. 2018 p. 2). Estimates for both culvert restoration and restoration of flood infrastructure were derived from a structured expert elicitation and collated information on past projects. For detailed methods on expert elicitation process see Chalifour et al. (*in prep*). Other barrier types that were less common, such as small dams and weirs were assigned the same cost as culverts which was estimated as $300,000. Cost estimates for flood infrastructure was set at $3,000,000 per site (Table 3.3).

Table 3.3 Estimated costs for the restoration of barrier types and a description of the action that is assumed to be implemented.

Barrier Type	Site	Estimated Cost (CAD $)	Description of action	Source
Culvert	All sites	300,000	Complete replacement of road culvert with passable structure	Expert elicitation
Flood Infrastructure	All sites	3,000,000	Replacement of existing infrastructure with fish friendly design	Expert elicitation
Hydro Dam	Alouette Dam	5,613,320	Installation of fishway	Gaboury & Bocking 2004
	Coquitlam Dam	22,750,450	Floating surface connector to bypass pipe	R2 Resource Consultants, Inc. 2018
	Ruskin Dam	14,181,885	Assumed installation of fishway or other fish passage mechanism	Average calculated from other dams in the study area

3.3.5 Optimization

I used the r package “prioritizr” (Hanson et al. 2019) with Gurobi Optimization solver (Gurobi Optimization LLC 2020) to optimize the selection of priority barriers for removal (R

Core Team 2019). The package uses integer linear programing and provides a wide range of potential objective functions, constraints, and penalties to express conservation problems as mathematical optimization problems. To maximize the amount of the features achieved within a given budget, I used the maximum utility objective function. This objective function does not use targets, but rather the representation of features in the output is controlled by feature weights and is expressed as:

$$Objective = Max \sum_{i=1}^{I} -sc_i x_i + \sum_{i=j}^{J} a_j w_j$$

$$subject\ to$$

$$a_j = \sum_{i=1}^{I} x_i r_{ij} \ \forall\ j \ \in J$$

$$\sum_{i=1}^{I} x_i c_i \leq B$$

Where x_i is the decision variable for whether barrier i is included in the solution, and c_i is the cost of barrier i. a_j is the total amount of each feature upstream of selected barriers where r_{ij} represents the amount of feature j upstream of barrier i calculated for all (∀) features within the set (∈) of features. w_j is the user given weight of feature j. The cost is minimized using the scaling factor s, and is constrained to be less than or equal to the budget B (Hanson et al. 2019).

To accommodate the anadromous life history of salmonids the “add contiguity constraints” function was used to ensure that barriers were selected from the base of the watershed upwards. This means that barriers downstream must be selected within the optimal solution before the secondary barrier can be selected, if the secondary barrier is selected, it then allows the selection of the next barrier immediately upstream. The connectivity of the barriers was defined using a mixture of symmetric and asymmetric connectivity (Figure 3.2). For the optimization to consider all potential barriers in the system the first barriers in a tributary to the Fraser River or the marine environment were defined as symmetrically connected meaning they are connected with barriers both downstream and immediately upstream in the system. This characterizes how the marine environment or Fraser River mainstem allows free movement of fish up to any of these barriers, and if the barrier were to be removed up to the next barrier in the system. The barriers that exist upstream of other barriers were characterized as having asymmetric connectivity, where they were not connected to barriers downstream, but are connected to the next barrier or barriers immediately upstream. The result of this constraint is a set of barriers that, if removed would form a continuous unit with the marine environment.

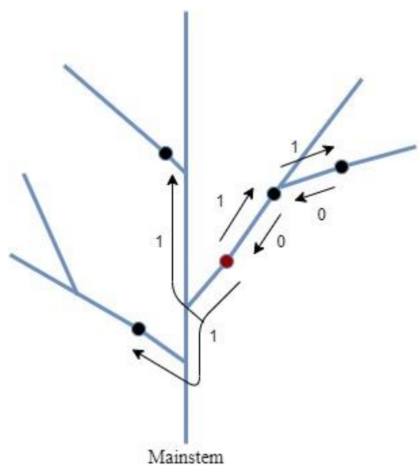

Figure 3.2 Simplified diagram for connectivity among mapped barriers. Arrows indicate direction of connectivity with next barrier, with a 1 indicating connectivity and a 0 indicating lack of connectivity. The red barrier displays symmetric connectivity with the barrier immediately upstream, as well as the first barriers in other tributaries to the mainstem. Barriers upstream of the red barrier display asymmetric connectivity, only connecting with those immediately upstream.

Individual barrier priority was assessed using two metrics. First was the selection frequency, which represents the number of times the barriers were selected to be part of the optimal solution at a given budget level and scenario. All budget levels and scenarios calculated 10 solutions that were closest to optimality to build a sample size of potential solutions and portray a higher resolution of potential priority. The second metric for understanding the importance of specific barriers was the calculation of the irreplaceability score using the replacement cost method (Cabeza & Moilanen 2006). Replacement cost calculates the change in the objective value that is achieved when each barrier is locked out of the solution, this indicates the change in the quality of the solution when the barrier is not available. The irreplaceability score ranges from 0 to 1 with higher scores signifying a higher priority barrier, while a replacement score of 0 means that the barrier can be swapped out of the solution without impacting the quality. An infinite replacement score indicates a barrier in the solution that is required for a solution to be feasible (e.g. The barrier blocks habitat for a species appears found nowhere else) (Hanson et al. 2019). Figure 3.3 shows a conceptual model for how datasets feed into each other to calculate the planning unit attributes that are then entered into the optimization model.

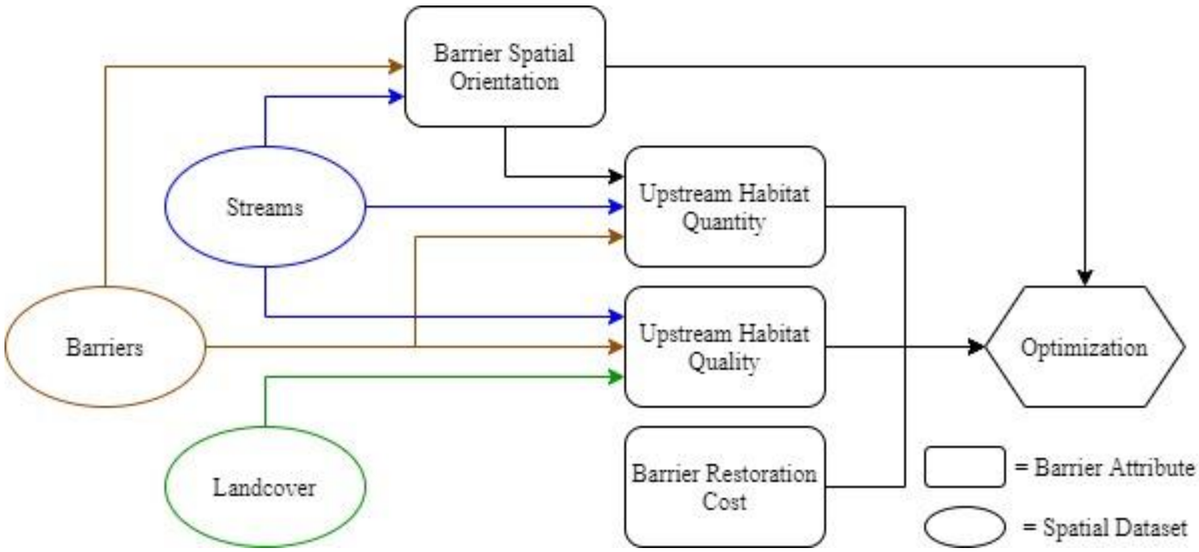

Figure 3.3 Conceptual model for the optimization. Spatial datasets include the barriers that are being prioritized, the streams are used to orient the barriers and determine habitat quantity, and landcover data are used to inform habitat quality indicators. Barrier cost was estimated using structured expert elicitation, and all barrier attributes are then used to spatial optimize barrier removal for a given budget.

3.3.6 Scenarios: habitat quality vs. quantity

Potential trade-offs among priorities were examined through the development of several scenarios that emphasized different characteristics of habitat upstream of barriers that might motivate restoration (Table 3.4). The first scenario only maximized the amount of habitat across the 14 CU's of salmon that would have access restored. This was then contrasted against a scenario that considered the quality of the habitat along with the amount of habitat that is being restored. Within prioritizr, weights can be assigned to different features to emphasize their representation in the final solution. These weights are often numeric values that are raised or lowered to achieve this change in representation. To understand how the quality of habitat might impact the spatial distribution of priority barriers, the final scenario assigned a weight of 10 to each indicator of habitat quality. A feature weight of 10 was used for each indicator after some sensitivity testing, results remained similar for weights of 10 to 500.

Table 3.4 Scenario examined for identifying priority barriers. Features describe the measured characteristic of habitat that are being prioritized for.

Scenario Name	Description	Features included
Length Only	Maximize the amount of habitat that would become available for all CUs	Upstream length
Length+Quality	Maximize both the amount and the quality of that habitat without weights	Upstream length, upstream riparian cover, watershed disturbance, watershed impervious cover, upstream channelization
Length+Quality Weighted	Maximize the amount of habitat and while giving weighted importance to the quality of that habitat	Upstream length, upstream riparian cover, watershed disturbance, watershed impervious cover, upstream channelization

Each scenario was run across a range of budgets to understand trade-offs in the types of barriers that can be removed across the scenarios. The budget range covered funding levels between 1 and 200 million dollars with 5 million-dollar increments. A ceiling of 200 million dollars was selected as it extends the ceiling of recent investments focused on aquatic habitat restoration and fisheries made by the Federal and Provincial governments including the BC Salmon Restoration and Innovation Fund at 143 million dollars (Government of Canada & Fisheries and Oceans Canada 2019a), and the Coastal Restoration Fund at 75 million dollars (Government of Canada & Fisheries and Oceans Canada 2019b). It is important to consider that these investments were made for a variety of types of aquatic habitat restoration over areas larger than the Lower Fraser. For example, the BC Salmon Restoration and Innovation Fund funds projects who's focus ranges from aquaculture, to hatchery upgrades. In the first round of project funding only 19% of funds were assigned to the entire Fraser Basin (Government of Canada & Fisheries and Oceans Canada 2019a). An investment of 200 million dollars that exclusively funds aquatic habitat connectivity in the Lower Fraser represents a large increase in funding for addressing this threat in this region. The ceiling can be extended to explore what is possible at higher levels of investment but diminishing returns as remaining un-restored sites become less cost effective mean further investment may not be warranted.

3.4 Results

3.4.1 Regional connectivity restoration

The optimization identified the “optimal set” of barriers to restore at each budget level. The proportion of alienated habitat that could be restored by removing these barriers was plotted against a range of budgets from 1 to 200 million dollars for all three scenarios and used to observe a diminishing marginal returns curve for each scenario (Figure 3.4). The length only scenario indicates that approximately 75% of the alienated habitat is the maximum amount of habitat that can be restored with a budget of $200 million. Importantly, the first 60% of this habitat can be opened for approximately $100 million, with dramatically reduced marginal gains past this level of investment. When quality of the habitat was included in the optimization, the amount of habitat being restored did not change by a large margin, however, as quality was given more weight the amount of habitat that was being restored decreased across budgets by about 10% (Figure 3.4).

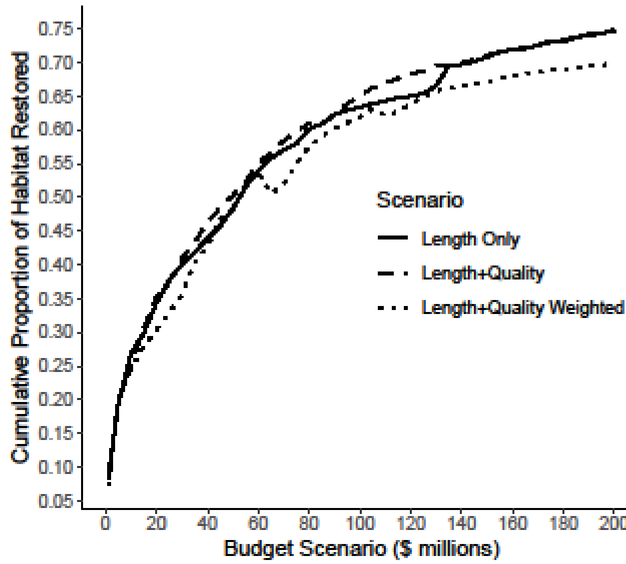

Figure 3.4 Marginal habitat restoration across a range of budgets in millions for three scenarios.

3.4.2 Species representation

Although optimal removal of barriers showed similarities across scenarios in terms of the amount of habitat that was being opened, the species that benefit from the optimal solutions varied. Perhaps the clearest example of this was in the case of sockeye salmon, where both CU's of sockeye salmon did not have priority barriers selected until the budget for barrier removal exceeded approximately $160 million (Figure 3.5). Similarly, Fraser River Canyon CUs of Chinook and coho salmon also received little attention when it came to identifying priority barriers, however, this changed for those CU's as the quality of the habitat became more important. When the quality of habitat was given weight in the prioritization, barriers impacting the Fraser River Canyon CUs became priorities at a budget of $40 million rather than $100 million. The opposite trend was observed for chum salmon, as the quality of the habitat being restored increased in importance, fewer barriers that would benefit chum salmon and restore access to habitat were included in optimal solutions. The quality weighted scenario resulted in about 20% less habitat being restored for chum salmon across budget scenarios (Figure 3.5).

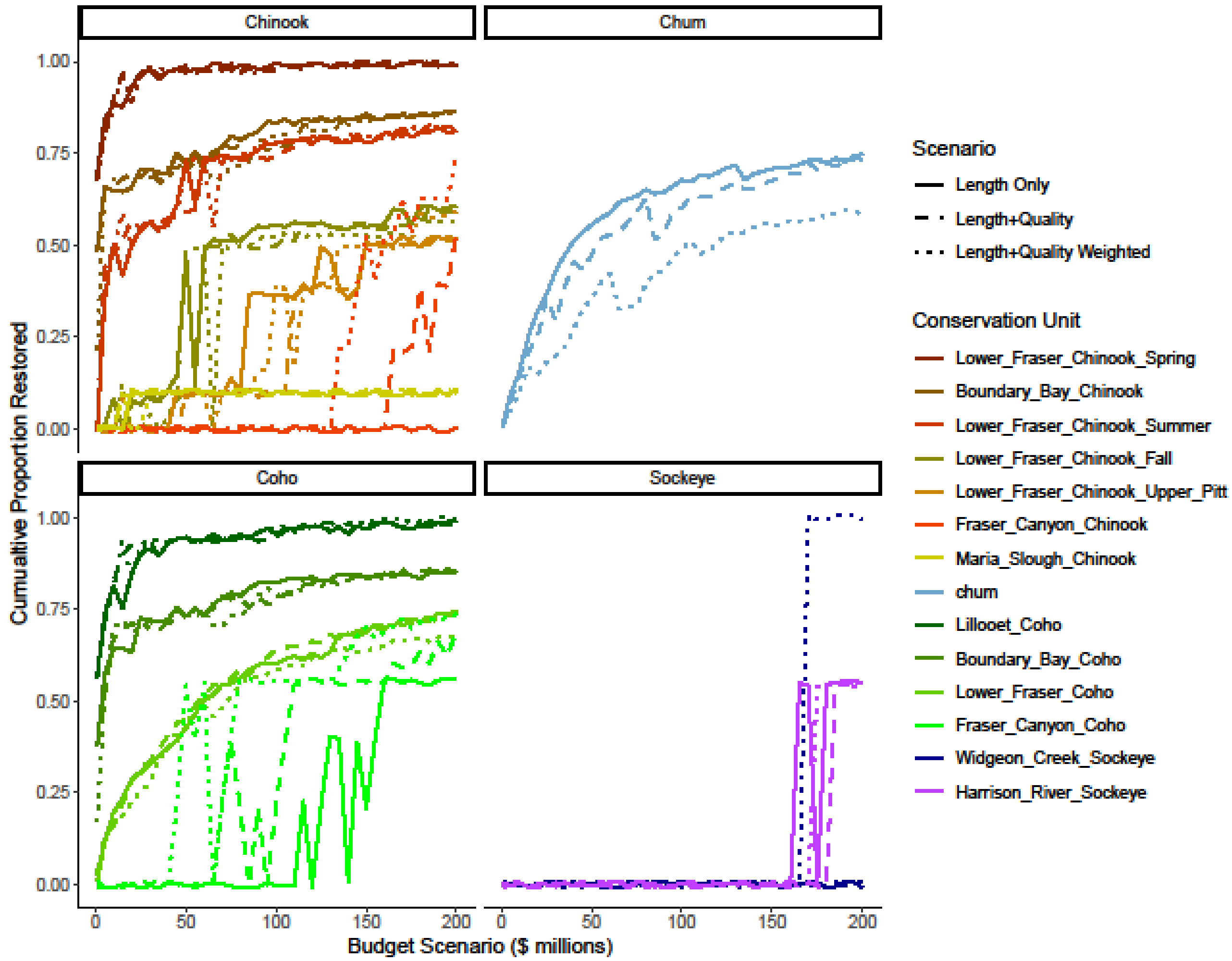

Figure 3.5 Cumulative proportion of habitat that is restored for 14 conservation units of salmon across three scenarios for barrier removal prioritization. Minor random variation has been applied to visualize overlapping lines.

3.4.3 Barrier types and priority locations

Priority barriers appear to be somewhat evenly distributed throughout the study area across all scenarios (Figure 3.6). There appears to be a subtle shift in selection frequency towards projects in the Lillooet, Fraser Canyon, and upper Chilliwack systems in scenarios where habitat quality was given more weight, this was also reflected in species representation (Figure 3.5). Certain barriers remained priorities across all scenarios and budget ranges. For example, this was observed at the Sumas River and Hatzic Slough floodgates where there appears to be an abundance of potential habitat upstream. Several culverts were also consistently selected ranging from key sites on the Nicomekl and Campbell Rivers in the south to multiple tributaries of the Birkenhead river in the north. Contrasting selection frequencies among scenarios can give insight into what might be driving the importance of specific barriers and if there were additional considerations that needed to be made. Differences in selection frequency between the length only and quality weighted scenarios indicated a general decline in the number of floodgates being selected in favor of culverts, but also indicated investment in restoring passage past the larger hydro dams when quality was given more weight (Appendix B.1).

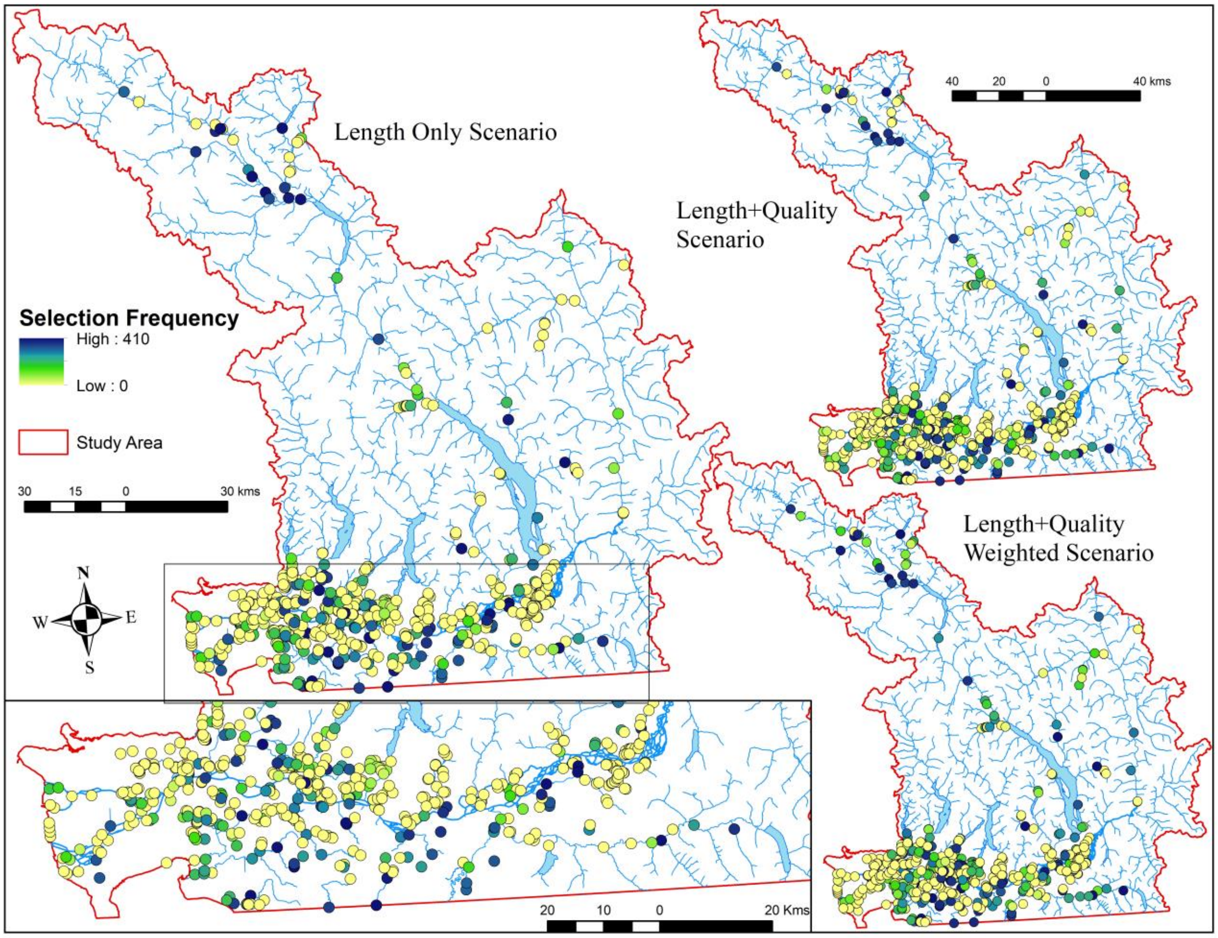

Figure 3.6 Spatial distribution of mapped barriers to fish passage and cumulative selection frequency for all scenarios examined. The cumulative selection frequency indicates how many times a barrier was selected in the optimal solution across all budget levels.

The calculation of replacement cost for barriers indicates how important they are to the optimal solution for a given scenario at a given budget level. For Hydro Dams, both the Alouette and Coquitlam dams were consistently selected in optimal solutions. The importance was amplified for both dams in scenarios that also considered habitat quality, with the replacement cost of Alouette Dam increasing to 0.75 at or above investments of $25 million dollars and the Coquitlam Dam at investments levels of at or above $60 million. The Ruskin Dam on the Lower Stave River was also selected at investment levels larger than $110 million (Appendix B.1). The relative representation of the barrier types considered here also illustrated the shift from floodgate priority towards hydro dam restoration. Figure 3.7 shows the relative representation of each of the barrier type across budgets and scenarios. The relative representation is the number of each type of barrier normalized to the proportion of that barrier type in the set of all barriers (i.e. if barriers were selected randomly the value should approach 1). The representation of floodgates steadily increased towards their expected representation before leveling out at approximately $60 million of investment however this number drops when quality of the habitat is added to the equation. At the same time a greater number of hydro dams were included in optimal solutions above $80 million in investment for length only and $30 million when habitat quality was included (Figure 3.7).

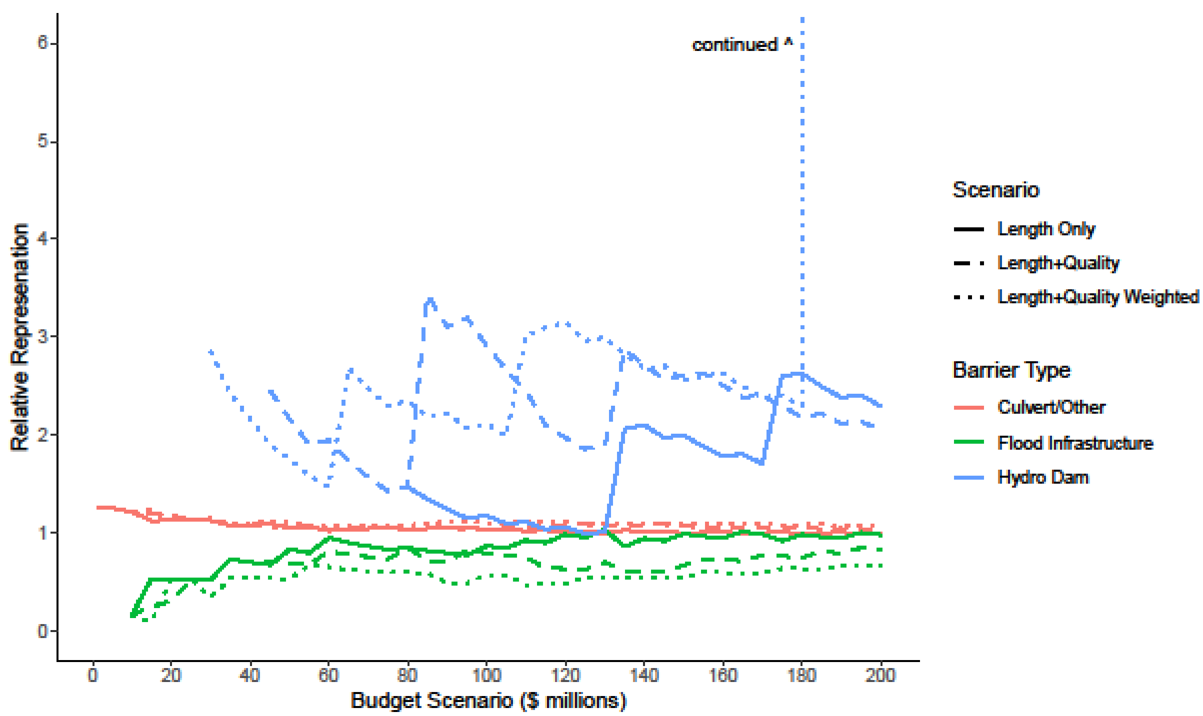

Figure 3.7 Relative representation of barrier types in optimal solutions for each scenario. The relative representation is calculated as the difference between the number of each barrier type in the optimal solution and the expected number based on the proportion of each barriers type in the set of all barriers.

3.5 Discussion

Systematic conservation planning software commonly applied to plan protected area networks was used to prioritize the removal of over 600 in-stream anthropogenic barriers to restore salmon habitat connectivity. Expressing barrier removal as a conservation problem in this way provides a flexible framework for the optimization of different habitat values, across a range of budgetary constraints. In the Lower Fraser, a $200 million investment in restoring connectivity for salmonids could restore approximately 75% of the stream length that is currently inaccessible, half this investment could restore 60%. Multiple scenarios of optimal restoration were explored to identify where, and for which species, additional restoration or management actions may need to be taken. Generally, as the quality of habitat was given more weight in the prioritization, the amount of habitat that was being restored decreased, and projects shifted out of the Lower Fraser Valley and into the surrounding mountainous areas. The resultant shift in priorities across space impacted certain species more than others, suggesting CUs that may require more than just barrier removal in order to restore productive freshwater habitat. Restoring passage past two of the large hydro dams was a consistent priority at high levels of investment. Floodgates were important for restoration, often due to their position in the catchment, but they became less of a priority as habitat quality was given importance in the prioritization, suggesting the quality of some habitats upstream of floodgates may need to be addressed.

3.5.1 Species considerations

The regional trade-off of between the total amount of habitat that is restored, and the quality of habitat did not hold when specific CUs were examined. For chum salmon in the Lower Fraser the regional trend was exaggerated, there was less habitat restored as habitat quality was given more weight in the prioritization. There are many opportunities for barrier removal that would help chum salmon, however the habitat that was being restored was also being impacted by other threats that could be degrading the habitat. These threats include agricultural development and urbanization. The Fraser River Canyon CUs of Chinook and coho salmon on the other hand, saw a reversal of the regional pattern, with more habitat being restored with increasing emphasis put on indicators of habitat quality.

The relative representation of CUs in the optimal solutions of each scenario did not consider the total amount of their historical habitat that was restored, but rather showed the proportion of habitat upstream of barriers that had access restored. Each CU is impacted by barriers to differing extents, in Chapter 2, I report that while the Fraser River Canyon CUs likely still have access to approximately 98% of their habitat, the CU's in Boundary Bay only have access to about 26-28% of their habitat. This means that complete restoration of alienated habitat could be achieved for CUs in the Fraser Canyon by the removal of only a few barriers, while many more barriers might need to be addressed to restore a high proportion of habitat in Boundary Bay. Additionally, CUs vary in the extent to which they are impacted by stream loss – not just alienation. For a species like chum salmon, over 700 kms of stream habitat was estimated in the Lower Fraser that cannot be returned by restoring passage past an instream barrier. The representation of species in the optimal solutions can be controlled by weighting CUs in the same way that habitat quality indicators were weighted in the scenarios examined in this study. By giving chum salmon a higher weight in the prioritization, barrier removals that restore chum habitat will increase in priority, however this might obscure the observations related to habitat quality. By running multiple scenarios and putting emphasis on different components of the prioritization, barriers that remain priorities across multiple scenarios can be identified as candidates while changes across scenarios can be used to inform decisions about additional restorative actions that are needed.

3.5.2 Regional insights

The two dams that were included in optimal solutions have received attention for fish passage remediation in the past. The Alouette Dam was installed in 1928 and has since blocked access to all anadromous species to upstream habitat (Gaboury & Bocking 2004), while the Coquitlam Dam has blocked anadromous salmonids since 1914 (R2 Resource Consultants, Inc. 2018 p. 2). Although the dams are included in optimal solutions, they are only included at higher levels of investment for scenarios that are prioritizing the maximum length of habitat. No dams were selected in optimal solutions until a budget of $80 million. This indicates that at lower levels of investment, more habitat can be restored by addressing a large number of culverts and some floodgates before any hydro dams become priorities. However, the budget at which dams become a priority declines dramatically to $30 million when the quality of the habitat is given weighted priority. The inclusion of these dams in optimal solutions, despite their elevated costs for restoration, supports the findings of previous work that has demonstrated how aligning dam restoration with the restoration of other barriers increases the cost-effectiveness of action (Fitzpatrick & Neeson 2018). Importantly, this analysis reveals the levels of investment at which those return-on-investment gains can be realized, however, the point at which this happens depends on the goals of who is doing the restoration and what they wish to restore. Further, considerations need to be made when it comes to these dams in particular as the cost estimates that were available for achieving dam passage at both Alouette and Coquitlam sites only included physical structures for the passage of fish and do include cost related to lost energy potential from reservoir releases that will be incurred on annual basis for the facilitation of that movement (Gaboury & Bocking 2004; R2 Resource Consultants, Inc. 2018). These details in funding needs highlight the importance of funding regimes and how resources are invested in restoration actions. The elevated costs of the dams require large upfront investments that may not be available through regular funding channels that deliver lower, yearly installments (Neeson et al. 2015) but also rely on maintained funding sources to facilitate passage and speaks to the need for coordinated governance and funding to achieve regional scale restoration for salmonids (Kehoe et al. 2020).

The increased emphasis on dam restoration that was observed as habitat quality was given more value seems to be facilitated by a slight shift away from the restoration of flood infrastructure. While the number of individual floodgates included in optimal solutions decreased when the quality of habitat increased its importance, there still remained several sites that gradually grew in their replacement cost, and eventually became required for the feasibility of the solution. This indicates that the habitat upstream of floodgates is being impacted by the habitat quality indicators included here, and additional management actions may be needed to address these threats. Recent work has established how floodgates create local upstream environments that may be hotspots for invasive species due to increased water temperatures, and lower dissolved oxygen (Scott et al. 2016). It is important to note however, that improved flow regimes through floodgates can abate these threats, and the very act of restoring fish passage could improve habitat quality (Gordon et al. 2015; Seifert & Moore 2018).

3.5.3 Limitations and potential future directions

Like any modelling approach the outputs need to be verified in the field, and the degree of accuracy will depend on the quality of the data used in the model. In this analysis I integrated 4 public datasets on barriers to fish passage, these datasets varied in their reliability and it is likely that there are both false positive and false negative barriers throughout the region. McKay et al. 2020 pointed out that a potential weakness of optimization as a barrier prioritization approach is that priorities can change as the data changes, however this can also be said for ranking methods. With mixed reliability of information these outputs could most effectively be used to guide the systematic confirmation of habitat in an iterative process of modelling, ground-truthing, data improvement, and implementation.

The removal of barriers does not stand alone in the effort to restore the processes of freshwater ecosystems (Roni et al. 2002; Beechie et al. 2010). Other optimization models have incorporated additional actions directly into the spatial optimization, including river protection, monitoring, and invasive species (Erős et al. 2018; Salgado-Rojas et al. 2020), however these models are often much more complex to define and often rely on the prioritization of river segments or sub-catchments rather than the specific site of restoration (Wilson et al. 2007). Importantly, I have not included all potential values or habitat features that could be included and used to inform priorities. Site characteristics that could indicate the feasibility of projects including infrastructure upgrades (Neeson et al. 2018), social license (Christensen et al. 2009), or ecosystem service improvement (Adame et al. 2015) are project attributes that could be quantified for inclusion in the prioritization and spatial optimization process. Many barrier characteristics often included in spatial optimization describe positive aspects to barrier removal, however, in some locations the removal of barriers can facilitate the spread of invasive species and this threat must be balanced with habitat connectivity restoration (Pratt et al. 2009; Milt et al. 2018). Even where data are rigorous, model outputs from optimizations are meant to be coupled with ground-truthing and expert judgement to help inform on-ground actions.

3.5.4 Implementing action

From an anadromous species recovery perspective, each species or population will benefit differently from a mix of management actions ranging from high level fisheries policy reform to different restoration actions in the freshwater, marine and terrestrial realm (Walsh et al. 2020). For these reasons it is important that a process like barrier removal optimization be situated into a broader adaptive management framework focused on ecosystem process restoration (Linke et al. 2019). An iterative approach will rely on involvement of decision makers and stakeholders to determine the priorities that will influence the site characteristics (e.g. species presence, habitat values) that are included in the prioritization (Grizzetti et al. 2016; Erős et al. 2018). As priority barriers are identified, they will need to be ground-truthed to confirm the existence of potential habitat upstream and the existence of additional barriers that change potential complementarity of projects. As mentioned above, as data are collected and sites restored, the analysis can be re-run with improved information on barrier locations. As locations for restoration action are confirmed site specific plans for how to restore connectivity can be developed with a monitoring program to continually guide our understanding of the effectiveness of barrier restoration techniques.

Ideally, perfect information on the amount of habitat that can restored, and the precise locations of a barriers would be mapped before preforming an optimization. However, in a context where habitat restoration is urgently needed to aid in the recovery of species and populations, the use of imperfect information can be used as a road map for guiding where to invest in the further understanding of habitat connectivity. This model provides an approach that integrates a high level understanding of potential benefits from barrier removal, with cost information and potential complementarity of multiple restoration sites to highlight priorities for restoring connectivity wherever the data describing river networks and barriers within those networks is available.

Chapter 4: Conclusion

4.1 Salmon and barrier restoration

Pacific salmon in the Lower Fraser River have experienced over a century of dramatic landscape change resulting in degradation and loss of freshwater habitat. Understanding the extent to which access to historically available habitat has been altered is a critical first step toward restoring connectivity. By using several methods to account for gaps in our knowledge of the historical availability of stream and floodplain habitat for 14 CU's of salmon in the Lower Fraser River I was able to demonstrate a dramatic loss of access to freshwater habitat needed for rearing and spawning. Across the board, Pacific salmon in the Lower Fraser River have little access to historical floodplain habitat, with only 15% remaining in the entire region. Stream habitat accessibility varied widely depending on the CU ranging from 26 to 99%, with approximately 1700 kms of streams that has been lost entirely.

Perhaps the most startling result of this work was the demonstration of the loss of floodplain habitat that can support migratory juvenile salmon on their way to the ocean. The reliance on transitory habitat may vary by species, but Chinook salmon are known to benefit from floodplain and non-natal habitats throughout their freshwater juvenile stage (Phillis et al. 2018). Tidal habitats are also important for Chinook salmon growth - a recent estimate in the Fraser River estuary notes the average residence time at approximately 42 days (Chalifour et al. 2020). Much of the floodplain would have been tidally influenced (North & Teversham 1984), this combined with seasonal variability in river levels could have produced an abundance of rearing habitat that is no longer available for CUs throughout the entire Fraser River Basin.

The extent to which barriers currently alienate habitat was variable across the species and CUs I examined. However, the variation in species life-history strategies also means the impact of barriers will depend on the species. In Chapter 2, I emphasized the importance of small streams for coho salmon as potential rearing habitat, and in Chapter 3 I reference the reliance on low gradient valley bottom streams for chum salmon. Species that do not rely on freshwater habitat for rearing such as chum salmon and pink salmon (Quinn 2005) will benefit by gaining access to spawning habitat, while species like chinook and coho that spend more time rearing in freshwater water may benefit from both spawning and rearing habitat being restored (Bradford 1995; Sommer et al. 2001; Phillis et al. 2018). The sockeye CUs examined in this thesis were minimally impacted by barriers, however current efforts at re-andromization of kokanee at the Alouette Dam show the potential of recovering extinct populations ("Improving Fish Passage at Alouette Dam" 2017). Historically, urbanization and large infrastructure projects were a leading cause of salmon population extinctions, including those in the Coquitlam and Alouette lakes (Slaney et al. 1996). Removing barriers to productive habitat can help raise the capacity of freshwater ecosystems to produce salmon, but threats throughout their life cycle including climate change (Crozier et al. 2021), and the marine conditions (Ruggerone & Irvine 2018; Oke et al. 2020) all play a role in determining how population trends of each species will be impacted by the restoration of freshwater habitat connectivity.

The contribution of the historical context to the interpretation and power of the optimization approach is important for shedding some light on the implications of barrier removal. Chapter 2 highlights how chum salmon were estimated to have lost over 700 km of habitat which represents nearly a third of the historically available stream length, approximately 450 km of streams lie upstream of barriers currently. This means a third of the stream length in the Lower Fraser River previously accessible to chum salmon cannot be restored even if we remove all barriers. This insight helps to guard against a shifting baseline and guide more appropriate targets for connectivity restoration. With an understanding of how much habitat is lost and no longer represented on contemporary maps, a target of restoring 30% of chum salmon alienated habitat changes from ~133 km to ~350 km when considering lost streams. These two goals are quite different and could have measurable differences in the change in population trends.

A future direction of this work could be to gain a more mechanistic understanding of how the removal of these barriers contributes to improving the quality of these aquatic ecosystems, raises the capacity for spawning and rearing, and how this contributes to the prevention of further extinctions, or to the elevation of stocks that are already at depressed levels. This research should also work to form a causal connection with barrier remediation and conservation outcomes of the salmon populations it intends to benefit. Understanding the causal impact of habitat restoration can be exceedingly difficult especially for techniques that require decades to effect habitat change such as riparian planting or complete road removal (Tear et al. 2005; Roni et al. 2010). However, estimates for the response of coho salmon have been made for some restoration techniques including barrier remediation (Roni et al. 2010), that show restoration actions can produce substantial increases in fish production. Variation in fish populations and site characteristics requires broad monitoring in a consistent manner to establish this understanding locally. Additionally, it is important to integrate the spatial optimization of specific freshwater habitat restoration with the broader identification of key actions that will recover thriving wild Pacific salmon populations (Walsh et al. 2020).

4.2 Site specific complexity and improved restoration efficiency

While some structures undeniably create complete barriers to movement for all species, variation in swimming and jumping abilities, combined with seasonal variation in water levels mean that some barriers impact some species or life stages more than others. This variation was handled to some extent by assuming different gradient thresholds when estimating natural gradient barriers for each species, however, the incorporation of this level of detail is made difficult by the breadth of the problem. The realities of understanding the seasonal dynamics of fish passage across each species for all sites, can be an impractical burden to establish before acting. This is realized in the current BC provincial protocol for assessing whether culverts are barriers to fish, where requirements are set to the minimum standard of passage for all species and life-stages (Mount & Thompson 2011). This low threshold is precautionary and can guide toward the remediation of in-stream barriers in a way that does not limit certain species or life-stages, however, may highlight sites that do not represent barriers for some species. There is a balance to be made between investing in reducing critical uncertainty that may change spatial priorities and investing in taking action (Buxton et al. 2020). Putting off a decision to act, in favor of continued monitoring and information gathering, can result in missed opportunity from funding agencies or result in population impacts that could have been avoided (Martin et al. 2017).

A future approach to try to accommodate more of this complexity within the optimization model could be through integrating estimates of barrier permeability as has been incorporated into some spatial optimization models (O'Hanley et al. 2013). There have also been recent efforts to combine spatial optimization with value of information analyses to optimize when and where to take action or collect more data (Raymond et al. 2020).

On a related note, the optimization only considered a single technique for barrier restoration at each site. For culverts and flood infrastructure I assumed the complete replacement of structures to make it passable for salmonids, while hydro dams used recommended actions from previous feasibility studies. The complete replacement of infrastructure is not always needed, improved operation of floodgates (Gordon et al. 2015) and the installation of small baffles can facilitate passage through existing infrastructure (Cabonce et al. 2019) among other techniques. These actions are often much less expensive than complete replacement of structures meaning that the total cost estimates for restoring habitat are likely on the high end of what is needed to restore habitat in the Lower Fraser River. The outputs of my prioritization allow for the proactive identification of sites for restoration that can be addressed in a timely manner. Outputs from the optimization can help facilitate partnerships between stewardship groups or government agencies interested restoring habitat with those who have jurisdiction over the structures that create the barriers. In the Lower Fraser, municipalities most often hold responsibility for flood infrastructure and road maintenance, by coupling scheduled infrastructure upgrades and restoration action, cost effectiveness can be further improved (Neeson et al. 2018). Estimating site specific cost for restoration was beyond the scope of this project. However, variation in *how* a given barrier may be restored can be implemented within this framework quite simply by assigning more site-specific cost estimates.

4.3 Broader applications

Moving forward the results of the optimization model can be adapted and used to support decision making about where to take action to restore access to habitats that have been alienated from salmonids in the Lower Fraser. It can be used by managers to identify key areas for field verification and to identify strategic partnerships with jurisdictional responsibility for maintaining infrastructure. A key achievement has been the use of existing optimization software commonly used for systematic conservation planning. This is a step towards improving the applied value of mathematical optimization for prioritizing barrier removal. There have been multiple optimization tools designed specifically for the prioritization of barriers (Lin et al. 2019). Yet, systematic conservation planning tools such as Marxan are among the most widely used conservation prioritization software in the world (Watts et al. 2009). Prioritizr is an improvement on these programs due to the employment of exact solving algorithms and integration into existing, widely used, and free r statistical software (Schuster et al. 2020).

Although mathematical optimization has been criticized for being overly reliant on data, the only information beyond what would be required in a standard scoring and ranking approach was the definition of symmetric and asymmetric connectivity among barriers. Information on the estimates of habitat amount, species benefit, and cost are all standard calculations when scoring and ranking barriers for prioritization (McKay et al. 2020). Spatial data on barrier location, and the river network is all that is required to define the spatial connectivity need for the optimization. With the use of this framework an analysis of this type could be carried out anywhere in the world that the data exist. With freshwater barriers being a global issue (Reid et al. 2019), this approach is only limited in where it can be applied by the availability of spatial data on streams and barriers.

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Appendices

Appendix A

A.1 Salmon Conservation Unit Maps

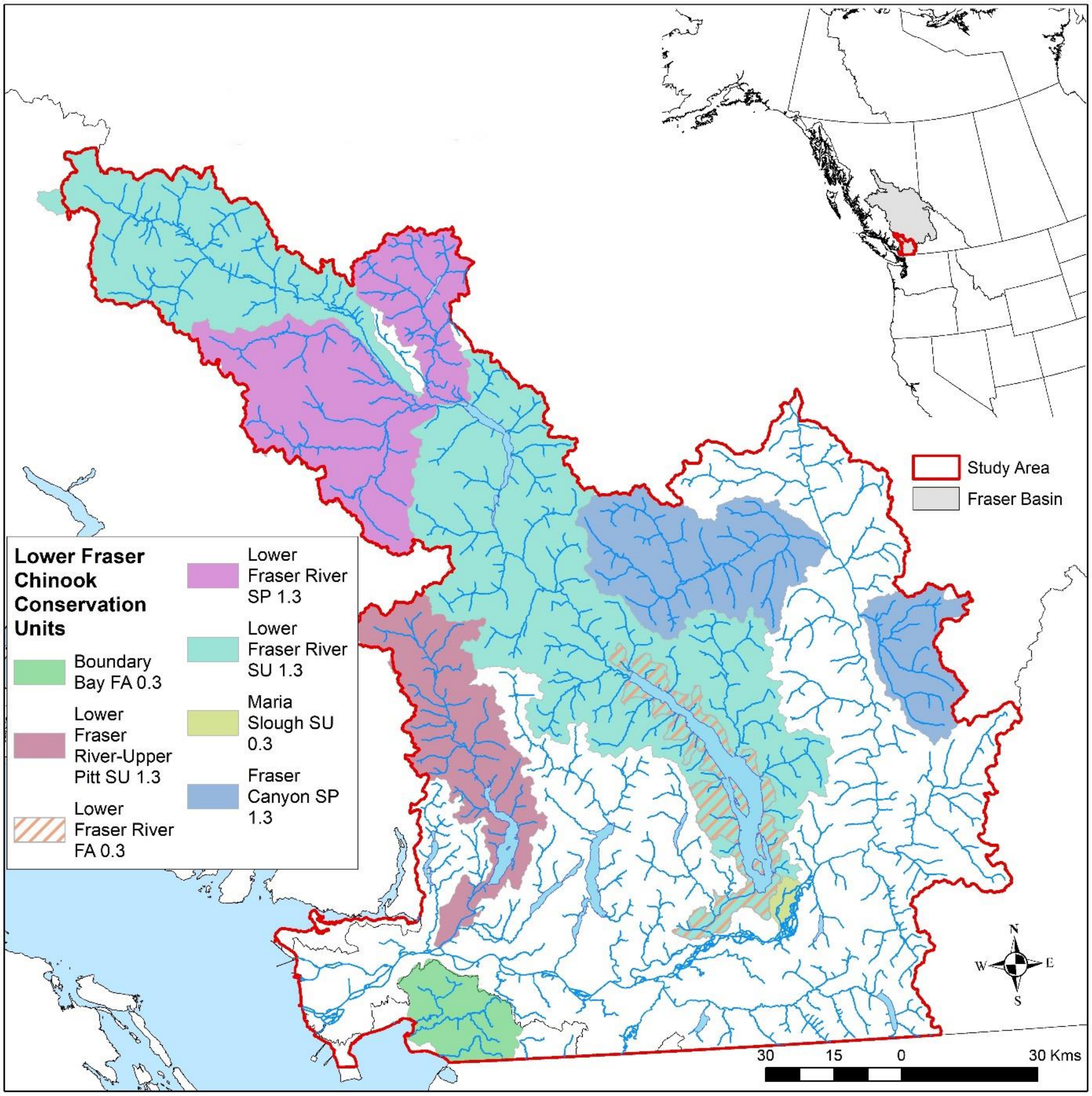

Figure A1.1 Map of Chinook Conservation Units in the Lower Fraser River. Inset shows study area and Fraser Basin in context of Pacific Northwest.

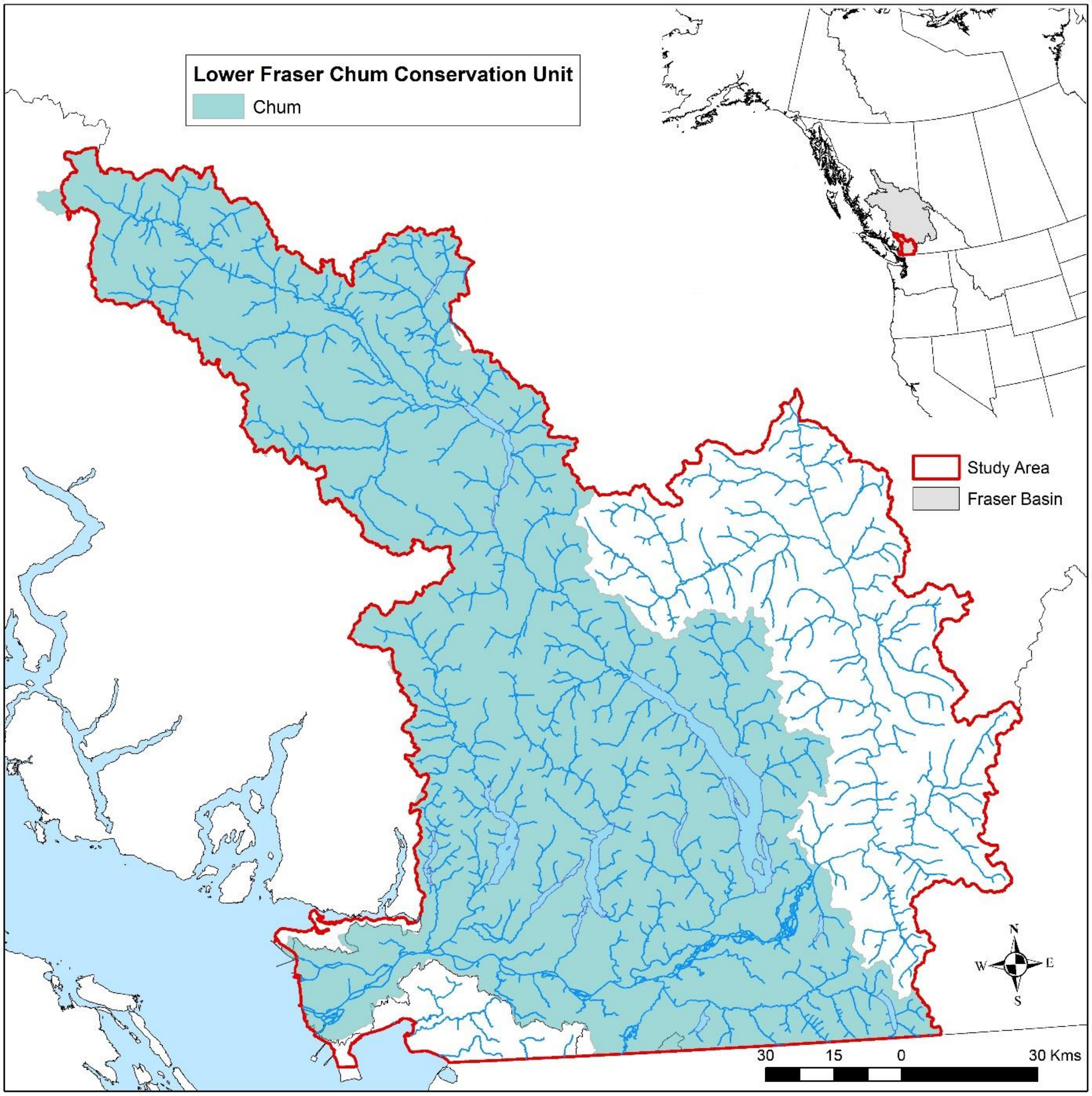

Figure A1.2 Map of Chum Conservation Unit in the Lower Fraser River. Inset shows study area and Fraser Basin in context of Pacific Northwest.

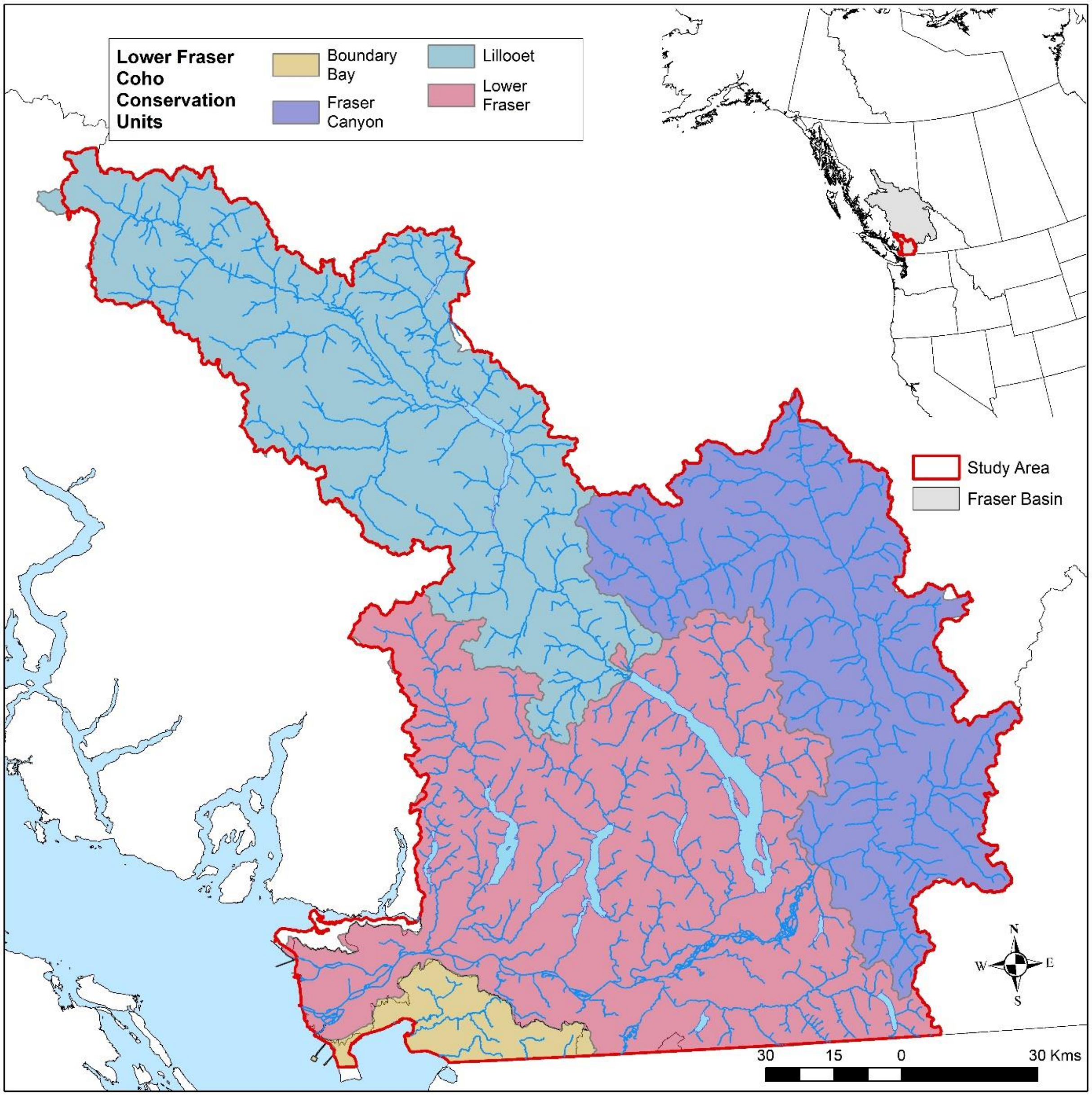

Figure A1.3 Map of Coho Conservation Units in the Lower Fraser River. Inset shows study area and Fraser Basin in context of Pacific Northwest.

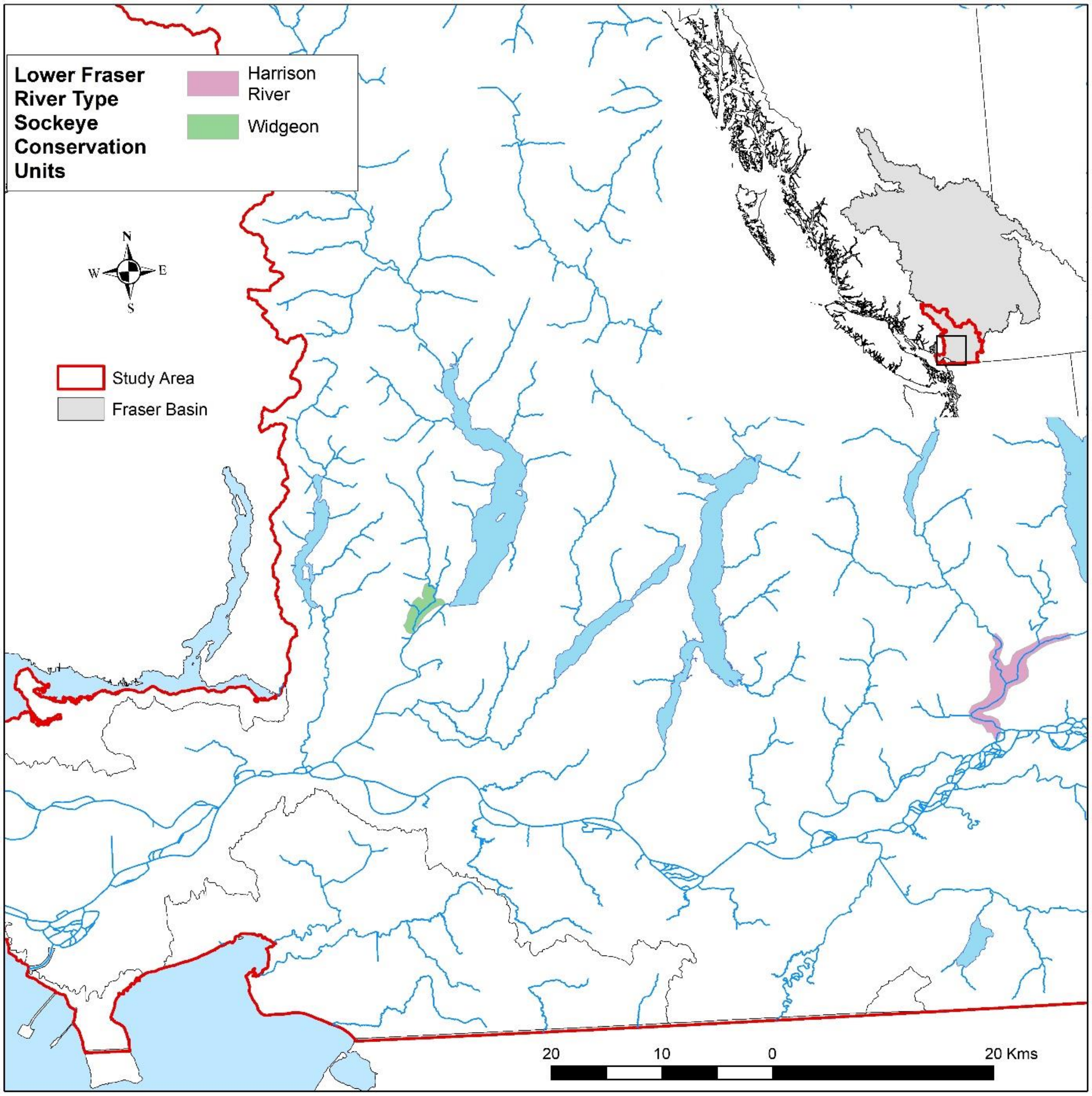

Figure A1.4 Map of River-Type Sockeye Conservation Units in the Lower Fraser River. Inset shows study area and Fraser Basin in context of British Columbia, Canada.

A.2 Historical vegetation communities

Table A2.1 Vegetation communities identified and evidence for flooding presented by (North & Teversham 1984). The evidence of flooding as a disturbance was used to determine inclusion as floodplain fish habitat.

Vegetation Community	Evidence of Flooding from North and Teversham (1984)	Extracted as floodplain fish habitat
Salt Marsh	Recognizable tidal nature made them unsuitable for agriculture.	Yes
Marsh	Always noted as being subject to tidal inundation in historical record.	Yes
Grassland	Single physiognomic group for a wide variety different types that were unable to be differentiated at the time due to early exploitation. Remaining sites were unable to be examined in 1980 due to flood waters.	Yes
Grass with Shrubs	Distributed throughout grasslands on slightly raised sites.	Yes
Mixed Scrub	Its position ensured an annual exposure to river flooding.	Yes
Willow Scrub	Willow scrub observed on the Harrison River in 1980 was partially flooded.	Yes
Crabapple Scrub	Sites varied by elevation and thus the amount of time they are flooded but require wet soils.	Yes
Alder Scrub	Locations suggest it would have been subject to flooding but not for frequent or prolonged times.	No
Regeneration Scrub (disturbed wet coniferous forest)	Was not likely to be subject to annual flooding.	No
Cranberry Swamp	More limited in the upriver parts of the floodplain to the back edge of the floodplain, may have been cultivated by indigenous groups.	No
Bog	Accumulation of organic matter indicates that the elevations of bogs sites were slightly above	No

	the floodplain and did not receive alluvial deposits.	
Moss with Trees	Little mention of flooding regime.	Yes
Open Pine Forest	No reference to disturbance of any kind.	No
Open Pine Swamp	Little mention of flooding regime but associated with cranberry bog.	No
Alder Bottomland	Noted as not being a true floodplain vegetation type, though would experience brief flash floods.	No
Cottonwood Forest	Sites were visited in 1980, and were still observable in the gravel reach of the river.	Yes
Mixed Woodland	Mixed woodland would have been less frequently inundated.	No
Cottonwood-Cedar forest	All sites would have been above normal floodplain level.	No
Disturbed Cottonwood-Cedar Forest	All sites are high above normal flood level.	No
Cedar Forest	Noted as being liable to flood.	Yes
Mixed Coniferous Forest	Occupied high banks and the foot of slopes generally was out of reach of flooding.	No
Wet Coniferous Forest	Sites were elevated above normal flooding level.	No
Spruce Forest	Sites are liable to flood when tidally backed up or when experiencing high run-off.	Yes
Cedar Swamp Forest	Sites were located at seeps at the foot of steep slopes and were not true floodplain vegetation types.	No
Bog Forest	Little reference to flooding regime, presence of *sphagnum* and bog hydrological regime assume little exposure to flooding.	No
Douglas Fir Forest	Not a true floodplain forest, sites were raised above storm waves and out of normal flooding.	No

A.3 Stream accessibility for chum salmon

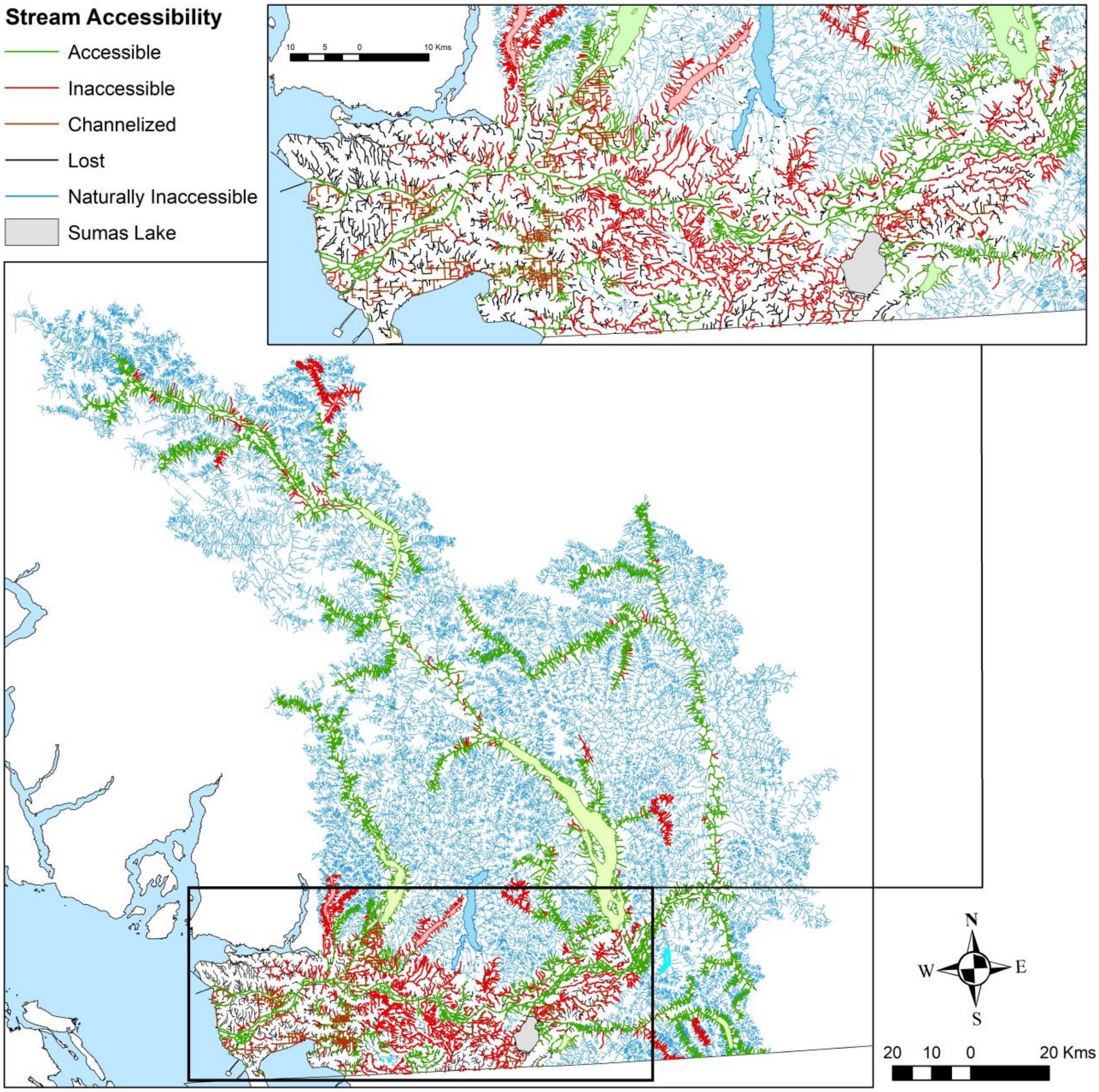

Figure A3.1 Map of stream connectivity in the Lower Fraser according to currently mapped barriers to fish passage. Also included are lost streams identified from a digital elevation model derived stream network, and a map of historic Sumas Lake derived from North and Teversham (1984). This map depicts the 5% gradient threshold for natural accessibility used to access habitat for chum salmon (*Oncorhynchus keta*).

A.4 Relative influence of barrier predictors

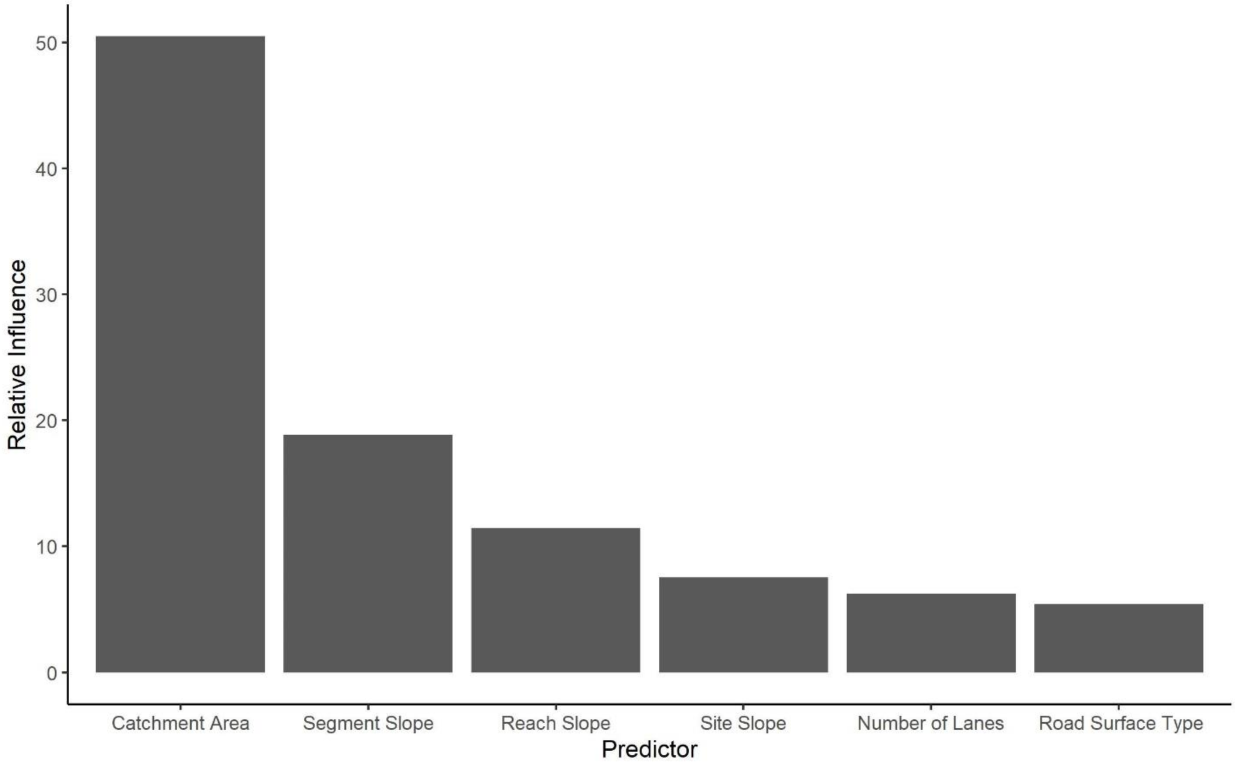

Figure A4.1 Relative influence of predictor variables in determining the probability of a stream road intersection being a barrier to fish passage. Relative influence is calculated as the number of times a variable is used to split the data, weighted by the squared improvement in the model and averaged over all trees, based on calculation from Friedman and Meulman (2003) and implemented in the gbm library (Elith et al. 2008).

Appendix B

B.1 Hydro dam replacement cost

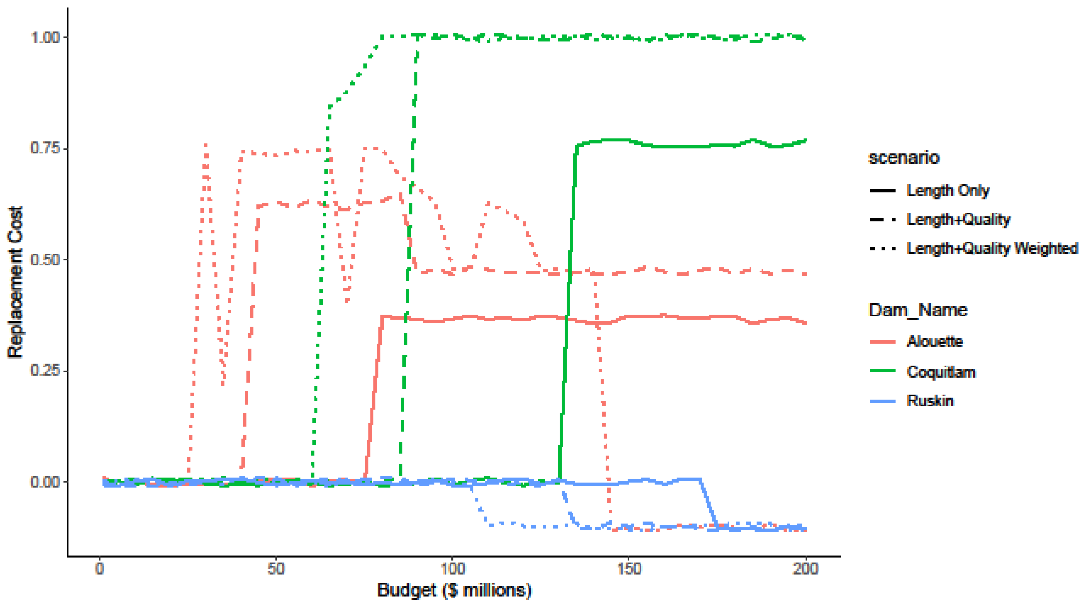

Figure B1.1 Replacement cost for the three dams that were selected in at least one optimal scenario across all budget levels. Replacement cost is calculated as the difference in the objective value when each potential barrier is locked out of the solution (Cabeza & Moilanen 2006). A negative replacement cost indicates that the inclusion of that barrier is required to achieve a feasible solution to the optimization problem.