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Effects of rail infrastructure on Pacific salmon and steelhead habitat connectivity in British Columbia

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Summary

The effects of rail infrastructure on the connectivity of habitat for Chinook (*Oncorhynchus tshawytscha*), Coho (*O. kisutch*), Sockeye (*O. nerka*), Chum (*O. keta*), and Pink salmon (*O. gorbuscha*) and anadromous Rainbow Trout (*O. mykiss*) in British Columbia were estimated. Habitats upstream of major hydro dams lacking fishways were not considered. Natural habitat accessibility was modelled for each species based on swimming ability and stream gradient, excluding habitats upstream of steep gradients, large waterfalls, or areas with subsurface flows. Within these naturally accessible habitats, areas that may support spawning and rearing were identified using intrinsic potential models. Anthropogenic structures that may be barriers to fish movement were then overlaid to identify habitat that may be blocked. Similar estimates of lateral habitat fragmentation were made by modelling lateral habitat along the floodplain, overlaying rail-stream crossings and lines, and identifying areas that may be disconnected by them.

Up to 882 kilometres of longitudinal spawning or rearing habitat may be blocked by 343 rail-stream crossings that were identified as potential barriers. An additional 1,101 road- or trail-stream crossings or dams may also fragment habitat in conjunction with rail barriers. An estimated 126 km of spawning or rearing habitat may be blocked by rail barriers alone (either with no other barriers upstream or counting only habitat to the next non-rail barrier), with 52 km blocked by the top 10 rail barriers. On the regional scale, the Fraser Basin was estimated to have the most spawning or rearing habitat blocked by rail barriers, followed by the Skeena Basin, then coastal watersheds. No longitudinal spawning or rearing habitat was estimated to be blocked in the Columbia – Okanagan region. Approximately 4.5% of total potential lateral habitat in the study area may be disconnected by rail infrastructure, covering 62,381 hectares. Just under half (48%) of the disconnected lateral habitat occurred in seven watershed groups in the Fraser and Skeena basins.

Several uncertainties were inherent in the models, which may have led to overestimation of the amount of spawning or rearing habitat blocked by rail infrastructure. Lateral habitat fragmentation models and estimates should be considered preliminary. Model results could be used to prioritize field assessment of potentially important barriers, which could validate results and confirm rail barriers blocking large amounts of habitat.

Introduction

Linear infrastructure such as roads and rails cross streams and rivers, often using structures that can impede fish passage and fragment freshwater systems. Rail infrastructure designed for transporting freight involves specific requirements for maintaining suitable grades for heavy train cars (McGonigal 2006), generally resulting in railways located in valley bottoms along wider, flatter terrain and often following major river and lake shorelines. These same valley bottoms naturally form productive floodplains that provide valuable habitats for migratory fishes such as Pacific salmon (*Oncorhynchus* spp.) and anadromous Rainbow Trout (*O. mykiss*; henceforth steelhead), among others, in the form of side channels and sloughs, ponds and oxbows, lakes, and tributaries (Brown 2002). Although some railway construction continues in British Columbia (B.C.), most B.C. railways were built in the late 19th century to mid-20th century (Flanigan 1907, Pooley 2013, Regehr 2013, Regehr 2014, ICF 2021, Madison 2021, CSCE 2022, PDMAS 2022, SRY 2022). During most of this construction period, fish passage was not a primary design consideration. Bridges installed at larger stream crossings do not typically block fish passage; however, most rail-stream crossings involve culverts or other closed-bottom structures (E. Cheung, personal communication November 2020; K. Graf, personal communication May 17, 2021), which often act as partial or complete barriers to fish movement (Belford and Gould 1989, Forest Practices Board 2009, Mount 2017, Rebellato and Lapointe 2023).

The first studies in the United States of America to examine how culverts affect fish passage were published in 1956 (McKinley and Webb 1956, Shoemaker 1956, Hoffman et al. 2012), though culvert studies and design guidelines became more prominent in North America in the 1970s (Anderson and Bryant 1980, Copstead et al. 1998, Moore et al. 1999, Hoffman et al 2012). Despite this research, it was not until the mid-1990s and early 2000s that governments in the Pacific Northwest, including B.C., began to develop strategies, guidelines, and legislation related to fish passage (Hoffman et al. 2012, MFLNRO et al. 2012).

In B.C., the *Forests Practices Code of British Columbia Act* was enacted in 1995 and included requirements for proponents of forestry activities to provide fish passage where roads cross fish-bearing streams. This requirement was maintained when the Act was superseded by the *Forest and Range Practices Act* in 2004. Additionally, the *B.C. Water Sustainability Act* contains provisions that allow for the management of connectivity and stream flows, including the issuance of fish population protection orders. Federally, the *Fisheries Act* prohibits the harmful alteration, disruption, or destruction of fish habitat. The Minister of Fisheries, Oceans and the Canadian Coast Guard can also require that an obstruction to fish passage be removed under Section 34.3(2) of the *Fisheries Act*, and section 34.3(4) requires that structures be designed to allow fish passage, including partial obstructions, be properly maintained. This legislation applies to railways but is not specific to them. Major rail operators tend to have environmental departments that work to address fish passage and other environmental issues.

Even rail-stream crossings that have been designed and installed with fish passage in mind can become degraded over time, leading to perched outlets, collapsed culverts, infilling with debris, and other issues that create barriers to fish passage. This is particularly true of closed-bottom structures, which are commonly used for rail-stream crossings in B.C., due to the challenges with installing and maintaining open-bottom structures such as arches and bridges (E. Cheung, personal communication November 2020; K. Graf, personal communication May 17, 2021). Replacing rail-stream crossings can be relatively costly compared to replacing road-stream crossings because of the need to maintain the structural integrity of the rail line and a safe, gentle curvature of the line. These requirements can also limit options for constructing detours during construction (McGonigal 2006, E. Cheung, personal communication August 4, 2020). Limited infrastructure and restoration resources should be directed to replacing rail barriers that block the most significant habitats when planning and implementing fish-passage rehabilitation projects on railway corridors.

Most rail-stream crossings occur near the confluence of tributaries with larger rivers, because they are typically located in valley bottoms. This potentially blocks access to entire tributaries for migratory fishes. The rail-stream crossings and rail lines themselves (if located on dykes or rail berms acting as dykes) may also prevent access to lateral habitats along the floodplain. Floodplains and associated lateral habitats provide important rearing and overwintering habitat for juvenile salmonids. Seasonally flooded habitats can play an important role in the growth and survival of salmonids. Such habitats provide juveniles access to thermal refugia and a higher proportion of terrestrial invertebrates as food sources (Brown 2002). Jeffres et al. (2008) found that juvenile Chinook Salmon (*O. tshawytscha*) rearing in floodplain habitats had higher growth rates than those rearing in riverine habitats and that ephemeral floodplain habitats provided higher growth rates than perennial floodplain habitats. Off-channel ponds with sufficient upwelling, flows, and substrates may also be used for spawning by salmonids (Hall and Wissmar 2004). For salmonids to use any of these habitats, adequate hydraulic connection is needed to maintain water quality and channel-forming processes and provide safe access and egress (Brown 2002).

Given the number of stream crossings in B.C., methods are needed to prioritize field assessments and fish-passage restoration projects. Mount et al. (2011) used GIS models of fish habitat and road-stream crossings to estimate how many crossings block fish passage in British Columbia. Intrinsic potential (IP) models have been widely used in North America to examine where aquatic species are most likely to occur, with several models developed for Coho (*O. kisutch*) and Chinook salmon and steelhead (Agrawal et al. 2005; Burnett et al. 2007; Busch et al. 2013; Bidlack et al. 2014). Models based on stream gradient and mean annual discharge (PCIC 2020, Foundry Spatial 2021) or channel width (Thorley et al 2021) can be used to identify streams that have the potential to support spawning or rearing for fish species of interest in the absence of barriers. Though IP models are not accurate predictors of a species' distribution, they can be useful in excluding areas that species are unlikely to use aside from as movement corridors (Sheer et al. 2009). A combination of habitat accessibility models based on natural features, IP models, and data on rail-stream crossings can then be used to estimate how much useable spawning or rearing habitat may be blocked by rail-stream crossings. Similar estimates of lateral habitat fragmentation can be made by modelling lateral habitat, overlaying rail infrastructure (i.e., rail lines and rail-stream crossings), and identifying areas that may be disconnected from other habitat by these linear features.

This study focuses on steelhead, and Chinook, Coho, Sockeye (*O. nerka*), Chum (*O. keta*), and Pink (*O. gorbuscha*) salmon in B.C. and aims to answer the following questions:

1) How much longitudinal (i.e., linear stream network) spawning and rearing habitat may be blocked by rail-stream crossings, regardless of effects of non-rail barriers?
2) To what extent do other potential non-rail barriers (e.g., road-stream crossings, trail-stream crossings, and non-hydro dams) exacerbate longitudinal salmon habitat fragmentation in streams with rail-stream crossings?
3) Which rail-stream crossings potentially block the most spawning or rearing habitat in combination with other potential barriers, and individually?
4) What extent of lateral (i.e., floodplain) habitat may be disconnected by rail infrastructure?

Methods

Project Scope

The study area included all B.C. Freshwater Atlas (FWA) 1:20,000 watershed groups in B.C. that contain both railways and salmon, and was divided into the following regions: Fraser Basin, Skeena Basin, coastal watersheds (including the Vancouver Island, Squamish, and Work Channel FWA watershed groups), and Columbia – Okanagan Basin. Of the Canadian portion of the Columbia Basin, Pacific salmon are only present in the Okanagan River watershed. Only watershed groups with rail tracks and Pacific salmon or steelhead (hereafter referred to as "salmon") populations were included (Figure 1; Table A1). The National Railway Network dataset (taken from the Railway Track Line layer in the BC Geographic Warehouse) was used to define the railway network in B.C. Any additional historic and abandoned rail lines not included in the National Railway Network were not considered. Watershed groups containing salmon were identified in a review of salmon distributions in B.C. (Mazany-Wright et al. 2023). Areas upstream of hydroelectric dams known to be barriers to salmon were excluded because most of these areas are likely to be unavailable to salmon for the foreseeable future. Information on dams was extracted from the Canadian Aquatic Barriers Database hosted by the Canadian Wildlife Federation (https://aquaticbarriers.ca/).

Longitudinal Fragmentation Models

To estimate how rail-stream crossings affect connectivity of streams within the study area, connectivity was modelled using "bcfishpass" (Norris 2022a), which contains spatial models based on the B.C. Fish Passage Technical Working Group fish passage modelling framework (Mount et al. 2011). The models in bcfishpass are open source, linked to externally-managed data layers, and apply the most recent data along with user-defined edits to the layers each time they are run. Links to all source datasets and licensing information are available within the bcfishpass documentation (Norris 2022a). All datasets for this study were accessed in February 2023.

A model of naturally accessible habitat was developed to identify habitat that would likely be accessible to anadromous salmonids in the absence of anthropogenic (e.g., dams and stream crossings) or transient natural barriers (e.g., debris flows and log jams), with an assumption that all mapped streams have sufficient flow for migration. To generate the accessibility model, a dataset of known natural barriers to fish passage was developed, and additional natural barriers were identified based on stream slope. Known natural barriers included waterfalls (>5 m), areas of subsurface flow, and miscellaneous natural barriers identified by local knowledge holders. Areas upstream of these locations were considered naturally inaccessible. Waterfalls >5 m were identified based on the "Provincial Obstacles to Fish Passage" layer, the B.C. Freshwater Atlas Obstructions layer, stakeholder/expert input, and CWF internal review. Areas of subsurface flow were obtained from the FWA Stream Network layer. Natural barriers identified by stakeholders included waterfalls or cascades not identified in provincial inventories, steep gradients not captured by modelling, channels known to be dry year-round, and other similar features.

Additional natural barriers were identified by local knowledge holders in two areas where CWF has undertaken additional connectivity planning (Bulkley River and Lower Nicola watershed groups). Some waterfalls were excluded in these areas based on CWF internal review. Natural barriers to

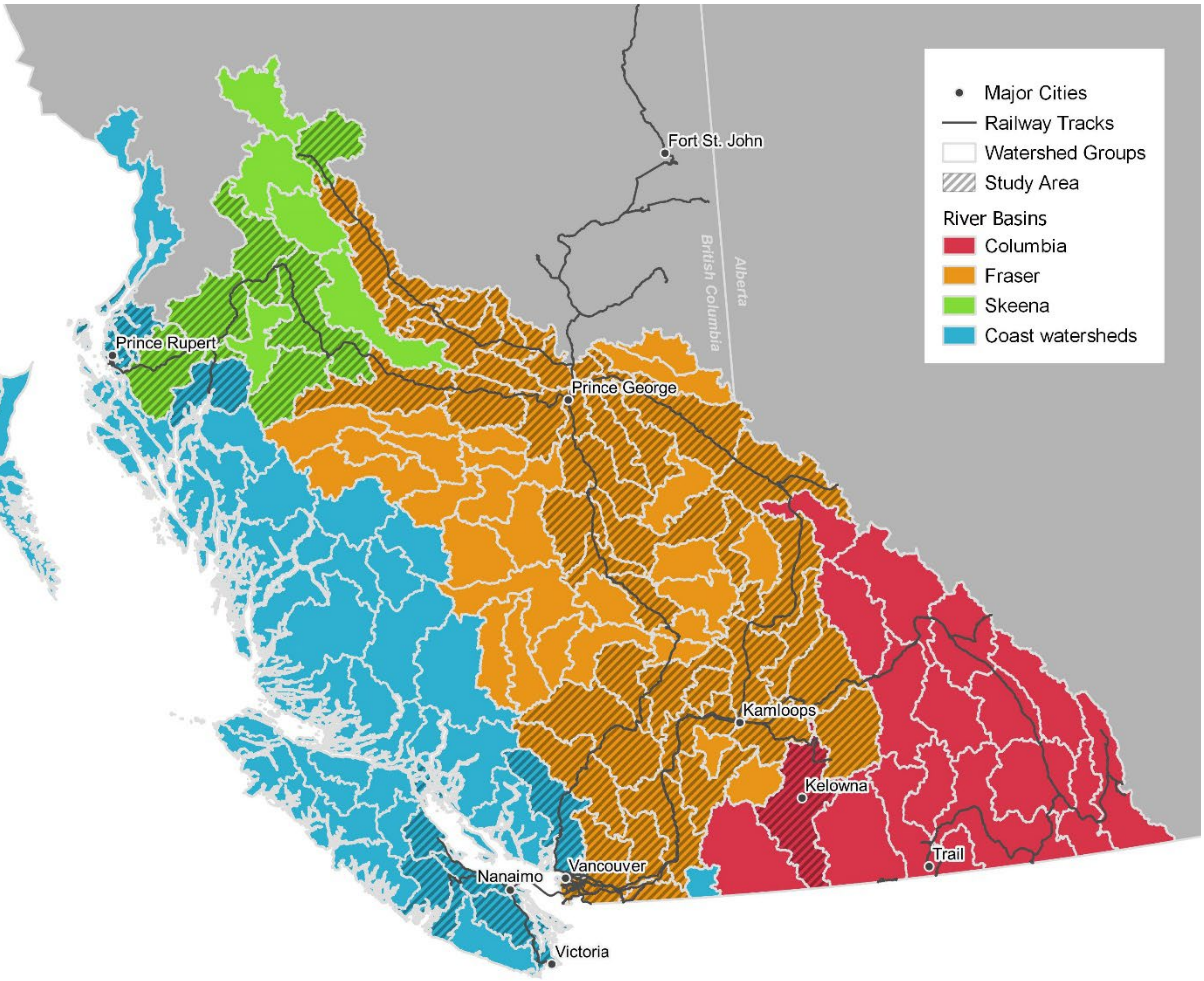

Figure 1. Study area for estimating the effects of railways on salmon habitat connectivity in British Columbia. The study area consists of Freshwater Atlas 1:20,000 watershed groups that contain both railways and salmon. Watershed group names and codes within the study area are listed in Appendix A, Table A1.

migration due to stream slope ("gradient barriers") were identified based on known abilities of salmon to navigate steep sections of river.

Chinook, Sockeye and Coho salmon pass gradients up to 16% (WDFW 2009), whereas steelhead pass gradients up to 20% (Sheer and Steel 2006, WDFW 2009). No evidence of passable gradients for Chum or Pink salmon was available in the scientific literature. Instead, observations of these species (n=4,511 Chum Salmon and n=3,695 Pink Salmon) from the Known Fish Observations layer in the BC Geographic Warehouse were linked to the FWA Stream Network layer stream features by "bcfishobs" (an open-source script to generate the most current information on fish presence in B.C.; Norris 2022b), and the maximum gradient of all downstream locations was identified for each observation. For Pink Salmon, 96% of observations had downstream locations with maximum gradients of 15% or less, and results for Chum Salmon were similar (97%). To confirm whether literature-derived gradient thresholds for Chinook and Coho salmon reflected observed thresholds in B.C., the same analysis was undertaken for these species. Results were similar in that 98% of Chinook (n=8,323) and 94% of Coho salmon observations (n= 20,653) had a maximum downstream gradient of 15%. Based on these results, gradients ≥15% were considered barriers for all Pacific salmon (Coho, Sockeye, Chinook, Pink, and Chum salmon), and gradients ≥20% were considered barriers for steelhead. Stream gradient was estimated using stream network and elevation data. Each vertex of a stream flow line in the FWA Stream Network layer includes a standardized Z value representing elevation, derived from the B.C. Digital Elevation Model with further processing to ensure that all streams flow downhill.

To identify locations where stream slope exceeded a given gradient threshold, upstream gradient was calculated for each vertex to a point 100 m upstream, starting at the mouth of each stream (identified by the blue_line_key in the FWA). Each vertex with a calculated slope that exceeded the species-specific threshold was considered a gradient barrier for the relevant species (Norris 2022a). Natural barriers where >4 salmon observations (of any of the six species combined) were recorded upstream since 1990 were excluded from the natural barriers dataset unless they were confirmed as barriers by expert input or through data quality assurance and quality control (QA/QC; see Appendix B). All habitat located downstream of remaining natural barriers was considered accessible, with one naturally accessible habitat model produced for steelhead and a second for all Pacific salmon species.

For each species, IP models were developed and applied to the study area to identify the subset of naturally accessible habitats that may be used for spawning or rearing, rather than simply as movement corridors to reach these habitats. Species-specific IP models were generated for every watershed group containing that species (Mazany-Wright et al. 2023), within the subset of accessible habitat modelled for that species. Modelled discharge was available for watersheds in the Fraser Basin (aside from two streams near Surrey, which were omitted; PCIC 2020, Foundry Spatial 2021) and the Bulkley River watershed group in the Skeena Basin (Foundry Spatial 2021). Modelled channel width was used for the remainder of the study area as a surrogate for discharge. Stream segments were used as the basic unit of analysis for IP models and were created by splitting source FWA stream features at all point features considered in this study. These included natural barriers, modelled stream crossings, dams, and the edges of known spawning locations.

All fish observation locations from "bcfishobs" for Pacific salmon, steelhead, Westslope Cutthroat Trout (*O. clarkii lewisi*), and Bull Trout (*Salvelinus confluentus*) were additionally used to split streams into segments, so that species associated with each stream segment could be identified. Trout species were included because models for those species were being run simultaneously in bcfishpass.

Stream segment length was derived from the FWA Stream Network layer, and gradient (rise over run) was calculated. Stream segment discharge or channel width were derived from values calculated for source streams. Stream segments ranged in length from 0.2 to 7,337 m, with a median length of 255 m. All lotic features in the FWA were included in spawning habitat models for all species and in rearing habitat models for Chinook and Coho salmon and steelhead, including river and stream polygon and line features, and canal line features. Canal polygon features were included with reservoirs as "manmade waterbodies," and both were considered equivalent to lakes for this study. Lakes were generally excluded from spawning IP models because only a subset of lakes are likely used for spawning by certain species (see next paragraph for exceptions).

Discharge and channel-width thresholds for Chinook, Sockeye, and Coho salmon spawning and rearing IP models were derived from primary literature sources (Table 1). Similar thresholds were not available in the literature for Chum or Pink salmon, so these were estimated based on known spawning locations in B.C. obtained from the Pacific Salmon Explorer (PSE; https://salmonexplorer.ca). A dataset of gradient, mean annual discharge, and channel width for each known spawning site was derived from the FWA Stream Network layer and previously noted sources. Maximum gradient and minimum discharge/channel width thresholds for spawning habitat IP models were selected based on the range of values associated with observed spawning locations for Chum and Pink salmon.

Additional refinements were made to IP models for each species and life stage. For Chum and Pink salmon, some spawning in large lakes was documented in the PSE. All additional spawning locations documented in the PSE, including these lakes, were manually added to the modelled spawning habitat layer. Rearing habitat IP models were not developed for Chum or Pink salmon because these species typically out-migrate immediately after hatching rather than rearing in fresh water (Salo 1991; Gallagher et al. 2013). For Sockeye Salmon, lakes ≥200 ha were considered rearing habitat (Woll et al. 2017). These were converted to linear features, and their lengths were multiplied by 1.5 to account for the larger area relative to lotic habitats. Suitable upstream segments were modelled as spawning habitat if they were directly connected to such lakes or to modelled Sockeye Salmon spawning segments (i.e., directly upstream of another spawning segment). An exception was made for suitable spawning segments that were separated from a ≥200 ha lake by a ≤2-m-long unsuitable segment. These short segments occasionally had higher gradient values that more likely represented errors in the FWA or gradient model, rather than barriers to adult Sockeye Salmon. Sockeye Salmon spawning habitat was also identified within 3 km downstream of ≥200 ha lakes if there were no segments with gradients of 5% or greater between the spawning segment and the lake. Segments in downstream tributaries to the channel connected to the lake were not considered as potential spawning habitat for Sockeye Salmon. For Chinook and Coho salmon and steelhead, rearing habitat models included suitable segments that were either: 1) also modelled spawning habitat for that species;

Table 1. Gradient and discharge thresholds for intrinsic potential spawning and rearing habitat models for salmon in British Columbia. Where indicated, habitat-association data were obtained from the primary literature. Gradient and channel-width parameters were selected for Chum and Pink salmon based on geomorphic characteristics of spawning sites identified in the Pacific Salmon Explorer.

	Spawning habitat			**Rearing habitat**		
Species	**Channel gradient (%)**	**Mean annual discharge (m3/s)**	**Minimum channel width (m)**	**Channel gradient (%)**	**Mean annual discharge (m3/s)**	**Minimum channel width (m)**
Chum Salmon	0-6	>0.023	2.1	NA	NA	NA
Chinook Salmon	0-3 (Busch et al. 2013, Cooney and Holzer 2006)	0.46-322.5 (Bjornn and Reiser 1991, Neuman and Newcombe 1977, Woll et al. 2017, Roberge et al. 2002, Raleigh and Miller 1986)	4	0-5 (Woll et al. 2017, Porter et al. 2008)	0.28-100 (Agrawal et al. 2005)	1.5
Coho Salmon	0-5 (Roberge et al. 2002, Sloat et al. 2017)	0.164-59.15 (Bjornn and Reiser 1991, Sloat et al. 2017, Neuman and Newcombe 1977, Woll et al. 2017, McMahon 1983)	2	0-5 (Porter et al. 2008, Rosenfeld et al. 2000)	0.03-40 (Agrawal et al. 2005, Burnett et al. 2007)	1.5
Pink Salmon	0-6	>0.411	2.1	NA	NA	NA
Sockeye Salmon	0-2 (Lake 1999, Hoopes 1972)	0.175-65 (Bjornn and Reiser 1991, Woll et al. 2017, Neuman and Newcombe 1977, Roberge et al. 2002)	2	NA	NA	NA
Steelhead	0-4 (Sheer and Steel 2006, Cooney and Holzer 2006)	0.447-75 (Bjornn and Reiser 1991, Neuman and Newcombe 1977, Roberge et al. 2002)	4	0-7.4 (Porter et al. 2008)	0.02-60 (Agrawal et al. 2005, Burnett et al. 2007)	1.5

2) downstream of and in the same stream as modelled spawning habitat for that species; 3) in a tributary downstream of modelled spawning habitat for that species, provided the tributary segment was directly connected to the stream or immediately upstream of another spawning segment for that species (similar to Sockeye Salmon spawning models, exceptions were made for downstream tributary segments that were separated from the spawning stream by a ≤10-m long unsuitable segment); or 4) within 10 km upstream (including in upstream tributaries) if there were no segments with gradients of 5% or greater between the segment and the associated downstream spawning habitat. Additional rearing habitat was modelled for Coho Salmon for all wetlands. All wetland flow lines in the FWA that met one of the four criteria for connectivity to Coho Salmon spawning habitat were considered Coho Salmon rearing habitat. Wetland rearing suitability for Coho Salmon was not restricted by gradient and discharge or channel width, and the length of wetland flow lines was multiplied by 1.5 to account for the larger area relative to lotic habitats. All stream segments identified as potential spawning or rearing habitat by IP models are henceforth described as spawning or rearing habitat.

Potential barriers on accessible habitat downstream of spawning and rearing habitat were identified. The bcfishpass potential-barriers dataset identifies potential anthropogenic barriers to fish passage by mapping intersections of FWA stream features and linear infrastructure (roads, rail lines, major trails) as mapped in the B.C. Digital Road Atlas, the Railway Track Line, the B.C. Forest Tenure Road Segment Lines, and two oil and gas road layers. The Ministry of Transportation Road Structures and National Railway Network Structure datasets were used to remove locations of known bridge structures from the mapped intersections. Locations where linear infrastructure intersects FWA river polygons (‘double line streams’) or streams of 6th order or higher were presumed to be open-bottom structures, such as bridges, that are not typically barriers and were therefore removed from the potential-barriers dataset. Non-hydroelectric dams classified as barriers (i.e., lacking fishways) in the Canadian Aquatic Barriers Database were added to the potential-barriers dataset. One weir was added based on feedback from local knowledge holders in the Lower Nicola watershed group.

The potential-barriers dataset was reduced based on field-assessment data and QA/QC. Field-assessment records in the Provincial Stream Crossing Inventory System (PSCIS; Province of B.C. 2017) classify stream-crossing structures as either open-bottom (bridges, open-bottom arch culverts, open-bottom wood box culverts), closed-bottom, or fords. In each record, structures are classified as passable, potential barriers, or barriers based on a scoring matrix of their attributes in relation to the associated stream attributes (B.C. Ministry of Environment 2011). Open-bottom structures are automatically classified as passable in PSCIS, and fords are classified as “unknown.” Both open-bottom and ford structure types were removed from the potential-barriers dataset, along with assessed closed-bottom structures that were classified as passable. Assessed closed-bottom structures that were classified as potential barriers or barriers were retained or added if the road was not mapped. Satellite imagery was reviewed for stream crossings without field assessment data, and crossings that were identified as bridges or non-existent were excluded (Appendix B). Potential barriers on side channels were excluded based on an assumption that there were no barriers on the associated main channel, so upstream habitats were not considered blocked. All remaining potential barriers are henceforth referred to as barriers, recognizing that field validation is required for the majority to evaluate whether they block passage.

Fragmentation (the amount and proportion of habitat blocked) was estimated by overlaying barriers on accessible habitat and identifying how much spawning or rearing habitat was located upstream. The bcfishpass connectivity model was used to estimate the length of longitudinal spawning or rearing habitat blocked by rail barriers. The subset of rail barriers with no other rail barriers downstream was identified to avoid double-counting when two or more rail barriers occurred on the same stream. The amount of habitat upstream was calculated from the downstream-most rail barrier in that set. The length of spawning and rearing habitat upstream was estimated for each species individually and pooled. The number of other rail and non-rail barriers downstream and upstream of each rail barrier was also calculated.

To address question 1 (how much longitudinal habitat is blocked by rail), the amount and proportion of salmon spawning and rearing habitat upstream of rail barriers was estimated for each species and pooled across species. For question 2 (additional effects of non-rail barriers), the number of non-rail barriers located upstream and downstream of rail barriers was counted. The amount of habitat blocked by rail barriers alone was calculated by identifying rail barriers with no non-rail barriers downstream and counting upstream habitat to the next non-rail barriers (plural if there are barriers on multiple tributaries), if any. The amount of habitat blocked by rail barriers alone was contrasted with the amount of habitat blocked by rail and non-rail barriers combined. To address question 3 (which rail-stream crossings potentially block the most habitat), rail barriers were ranked by the amount of habitat upstream, and the subset of rail barriers with no non-rail barriers downstream was ranked by the amount of habitat upstream to the next non-rail barrier, if any.

Lateral Fragmentation Models

Within the lateral habitat study area, three general sources of potential floodplain/off-channel habitat data were combined. First, unconfined valleys were identified using a valley confinement algorithm (Nagel et al. 2014). An open-source valley confinement algorithm adaptation (Cairns 2021) was integrated into the bcfishpass model. The valley confinement algorithm extracted unconfined valleys from an analysis of the digital elevation model and stream channels within a given area (see https://github.com/smnorris/bcfishpass/blob/main/model/03_habitat_lateral/valley_confinement.md for more info). Second, all FWA waterbodies (lake, wetland, river, and reservoir layers) were merged into a single layer. This layer included all mapped, inundated features such as side channels and oxbows. Third, the "Mapped Floodplains in BC" layer was downloaded from the BC Data Catalogue. Finally, all three inputs were combined into an initial floodplain raster layer.

The floodplain raster was refined to exclude regions with no connectivity to stream segments modelled as spawning or rearing habitat (i.e., a region of floodplain must touch or be connected to spawning or rearing habitat to be included). Areas mapped as urban in the European Space Agency Land Cover map were excluded because they are unlikely to provide suitable habitat regardless of connectivity. All of the Fraser Valley downstream of Agassiz was also excluded because drainage and land use in this area was too modified for these methods to produce reasonable results. The resulting area is henceforth described as lateral habitat.

To identify lateral habitat that may be blocked by rail, the lateral habitat layer was overlaid with rail lines buffered by 25 m. All lateral habitat located on the river or stream side of the rail line was considered connected, whereas all lateral habitat polygons on the opposite side of the rail line from a river were considered disconnected. Exceptions were made for polygons opposite rail-stream crossings with open-bottom structures, which may provide access to lateral habitats (see https://github.com/smnorris/bcfishpass/blob/main/model/03_habitat_lateral/README.md for more details). Exemptions were not made for lateral habitats opposite rail-stream crossings with closed-bottom structures. Though some closed-bottom structures under rail lines have been assessed and scored as passable to fish in PSCIS, these structures may hold back sediments, have major effects on floodplain functionality, or be impassible under high-flow conditions when floodplain access typically occurs.

To address question 4 (extent of disconnected lateral habitat), the total area of lateral habitat in the study area was estimated along with the proportion disconnected by rail infrastructure and the number of disconnected polygons. This was also estimated for each of the 1:20,000 FWA watershed groups in the study area.

Results

Along 7,153 km of rail in the study area, 4,155 rail-stream crossings were identified. Of these, 3,583 (86%) were modelled as closed-bottom structures, with approximately half (1,782) on habitat that was considered naturally accessible to salmon. Of these, 343 had spawning or rearing habitat upstream, though many were co-located on the same stream; there were 298 streams with one or more rail barriers.

Rail barriers were estimated to block 548 km of longitudinal salmon spawning habitat, along with 840 km of Chinook, Coho, and Sockeye salmon and steelhead rearing habitat. Some segments were considered both spawning and rearing habitat for a species or were considered habitat for more than one species; therefore, the sum of values presented in Table 2 surpasses the total habitat upstream of rail barriers reported in Table 3. The amount of spawning habitat blocked was highest for Chum Salmon (405 km; 3.6% of Chum Salmon spawning habitat the study area), and the amount of rearing habitat blocked was highest for Coho Salmon (669 km; 3.2% of Coho Salmon spawning habitat the study area).

Rail barriers were estimated to block 882 km of spawning and rearing habitat combined without accounting for the effects of other barrier types (Table 3). Another 1,101 non-

Table 2. Amount and proportion of salmon spawning and rearing habitat estimated to be blocked by rail barriers in B.C.

Species	Total spawning habitat upstream of rail barriers (km)	Proportion of total spawning habitat in study area (%) blocked by rail barriers	Total rearing habitat upstream of rail barriers (km)	Proportion of total rearing habitat in study area (%)
Chinook Salmon	128.57	0.9	205.70	1.3
Chum Salmon	405.27	3.6	n/a	n/a
Coho Salmon	264.99	1.6	668.52	3.2
Pink Salmon	188.73	1.5	n/a	n/a
Sockeye Salmon	4.78	0.5	30.14	0.2
Steelhead	99.31	1.0	449.64	3.0

rail barriers contributed to this fragmentation, with an average of <1 non-rail barrier downstream and 2.8 upstream of the lowermost rail barriers in a stream. Of the 298 streams with one or more rail barriers, a rail barrier was the most downstream barrier on 54% (n=160). These had a combined 126 km of spawning and rearing habitat upstream to the next non-rail barriers, if any, representing habitat blocked by rail barriers alone (Table 3).

Table 3. Summary of the amount of salmon spawning and rearing habitat estimated to be blocked by rail barriers in B.C. and the number and effects of associated non-rail barriers. Summary statistics are based on rail barriers that are downstream of salmon spawning or rearing habitat and have either no rail barriers downstream (n=298) or no barriers of any kind downstream (n=160). The amount of habitat blocked by rail barriers alone was calculated by identifying rail barriers with no non-rail barriers downstream and estimating upstream habitat to the next non-rail barriers, if any.

Summary statistic	**Number of non-rail barriers**		**Total spawning or rearing habitat (km)**	
	Downstream of rail barriers (n=298)	**Upstream of rail barriers (n=298)**	**Upstream of rail barriers (n=298)**	**Blocked only by rail barriers (n=160)**
Average	0.93	2.76	2.96	0.73
Max	9	48	54.97	8.04
Min	0	0	0.01	0
Sum	277	823	882.42	126

Of the 126 km of spawning or rearing habitat estimated to be blocked by rail barriers alone, 42% was in the top 10 streams with one or more rail barriers (Table 4). Five of these streams were located within the Fraser Basin, four within the Skeena Basin, and one within coastal watersheds. Half of this habitat was in the top 14 streams with one or more rail barriers, and 75% was in the top 36 streams. The remaining 32 km was blocked in 124 streams with one or more rail barriers, 45 of which had <100 m of spawning or rearing habitat upstream of the lowermost rail barrier to the next non-rail barrier. No spawning or rearing habitat was blocked in the Columbia – Okanagan region. Region-specific summaries of the amount of spawning or rearing habitat estimated to be blocked by rail barriers alone are provided in Appendix C, Table C1.

Of the 882 km of spawning or rearing habitat estimated to be blocked by rail barriers in combination with non-rail barriers, 29% was in the top 10 streams with one or more rail barriers (Table 5). Half of this habitat was in the top 26 streams with one or more rail barriers, and 75% was in the top 64 streams. The remaining 222 km was blocked in 235 additional streams with one or more rail barriers, 33 of which had <100 m of spawning or rearing habitat upstream of the lowermost rail barrier. There were 135 streams with one or more rail barriers where >1 km of spawning or rearing habitat was blocked by rail and non-rail barriers.

Of the total estimated 1,398,682 ha of lateral habitat in the study area, 62,381 ha (4.5%) was estimated to be disconnected by rail infrastructure (Table 6). A total of 1,977 lateral habitat polygons were disconnected by rail infrastructure, with an average polygon size of 32 ha. These included areas directly adjacent to rail lines along larger rivers and areas adjacent to tributaries blocked by rail barriers (Figure 2). Half of the disconnected lateral habitat occurred in seven watershed groups (Tabor River, Stuart Lake, Takla Lake, Bulkley River, San Jose River, Francois Lake and Morkill River). Watershed groups with the highest proportion of disconnected lateral habitat included Tabor River (40%), Parksville (23%), and Takla Lake (17%; Table 6).

Discussion

Given the distribution of salmon and extent of railways in B.C., potential habitat fragmentation is a major concern. Understanding the extent and restoring connectivity seems daunting but can be facilitated by analyzing available data to estimate these effects and identify locations where fragmentation may be highest. This study provides an initial estimate of the degree to which railways contribute to salmon habitat fragmentation in British Columbia.

Similar model outputs have been used by CWF to estimate current longitudinal connectivity status and prioritize barriers for assessment and fish-passage restoration in locations such as the Lower Nicola (Mazany-Wright et al. 2021*a*) and Bulkley River (Mazany-Wright et al. 2021*b*) watershed groups. Reviews of modelled salmon spawning and rearing habitat by local knowledge holders typically affirmed that all or nearly all known spawning and rearing habitat was identified by the models. In contrast, field assessments of prioritized barriers and associated habitats often revealed that modelled structures did not exist or were passable, or that upstream habitats were unsuitable for target species despite modelled predictions. Given that this modelling framework identified sites where barriers may block access to the largest amount of upstream habitat, focusing field assessments on these sites quickly reduced uncertainty by confirming or rejecting barriers that had the greatest influence on connectivity status estimates. Sites where both barriers and upstream habitat suitability were confirmed became priorities for restoration (Mazany-Wright et al. 2021*a*,*b*). The same pattern can be expected of the results of this study; fragmentation effects are likely overestimated, but prioritized field assessments could quickly reduce uncertainty and confirm the most important barriers.

Table 4. Rail barriers estimated to block the top 10%, 50%, 75%, and 100% of salmon spawning or rearing habitat in B.C. that is unaffected by non-rail barriers. Only rail barriers with no other barrier downstream were included (n=160). The amount of spawning and rearing habitat to the next upstream non-rail barrier (if any) was estimated.

Rail barrier crossing ID	Region	1:20,000 watershed group	Stream	Amount of spawning or rearing habitat between rail barrier and next non-rail barrier upstream (km)	Cumulative total spawning or rearing habitat blocked		Rank
					km	%	
1009904765	Fraser Basin	LCHL	Hutchison Creek	8.04	8.04	6	1
1019500445	Skeena Basin	SUST	Minaret Creek	7.07	15.11	12	2
1008302857	Skeena Basin	KISP	Andi Creek	6.44	21.55	17	3
1009904804	Fraser Basin	LCHL	Unnamed	6.07	27.62	22	4
1003506134	Fraser Basin	COTR	Meadowbank Creek	5.37	32.99	26	5
1012401343	Skeena Basin	LSKE	MacMillan Creek	5.13	38.12	30	6
1023204207	Fraser Basin	UNTH	Lyon Creek	4.19	42.31	33	7
1008802634	Skeena Basin	KLUM	Steinhoe Creek	3.80	46.11	36	8
1024742020	Fraser Basin	LFRA	Hyland Creek	3.25	49.36	39	9
1003607014	Coastal watersheds	COWN	Holland Creek	3.18	52.54	42	10
1024718503	Coastal watersheds	PARK	Chase River	2.90	64.67	50	14
1010305071	Fraser Basin	LFRA	Unnamed	0.95	94.49	75	36
1012401279	Skeena Basin	LSKE	Unnamed	0.01	126.00	100	160

Table 5. Rail barriers that may block the top 10%, 50%, 75%, and 100% salmon spawning or rearing habitat in B.C., ignoring the effects of other non-rail barriers. Only rail barriers with no other non-rail barrier downstream were included (n=298).

Rail barrier crossing ID	Region	1:20,000 watershed group	Stream	Number of non-rail barriers		Amount of spawning or rearing habitat upstream (km)	Cumulative spawning or rearing habitat blocked		Rank
				Down-stream	Up-stream		km	%	
1010305109	Fraser Basin	LFRA	Salmon River	3	43	54.97	54.97	6	1
1017104195	Fraser Basin	QUES	Barlow Creek	3	25	31.39	86.36	10	2
1016502645	Coastal watersheds	PARK	Millstone River	0	48	27.75	114.11	13	3
197938	Skeena Basin	BULK	Bulkley River	0	9	26.65	140.76	16	4
1024403842	Fraser Basin	WILL	Hay Creek	1	30	23.48	164.24	19	5
1024723694	Fraser Basin	TABR	Cale Creek	0	6	20.52	184.76	21	6
1015605314	Fraser Basin	NECR	Hulatt Creek	0	25	20.37	205.13	23	7
1024712996	Fraser Basin	LFRA	Benson Canal	1	14	18.93	224.06	25	8
1009904804	Fraser Basin	LCHL	Sweden Creek	0	16	17.75	241.81	27	9
1011508272	Fraser Basin	LNTH	Paul Creek	0	8	16.99	258.80	29	10
51686	Fraser Basin	HARR	Anderson Creek	0	20	8.47	442.78	50	26
1003403396	Coastal watersheds	COMX	Roy Creek	1	5	3.57	660.96	75	64
1010305125	Fraser Basin	LFRA	Unnamed	9	0	0.01	882.42	100	298

Table 6. Lateral salmon habitat that may be disconnected by rail infrastructure in B.C., by Freshwater Atlas 1:20,000 watershed group. The top 10 watershed groups are displayed in descending order based on the proportion of disconnected lateral habitat.

Region	1:20,000 watershed group	Total lateral habitat area (ha)	Disconnected lateral habitat area (ha)	Proportion of disconnected lateral habitat (%)	Rank
Fraser Basin	TABR	18,520	7,322	39.5	1
Coastal watersheds	PARK	11,145	2,509	22.5	2
Fraser Basin	TAKL	33,870	5,635	16.6	3
Fraser Basin	SAJR	25,320	4,118	16.3	4
Fraser Basin	STUL	64,135	5,209	8.1	5
Skeena Basin	BULK	57,869	4,541	7.8	6
Fraser Basin	LCHL	34,483	2,400	7.0	7
Fraser Basin	FRAN	73,831	3,179	4.3	8
Fraser Basin	MORK	62,565	2,709	4.3	9
Fraser Basin	NECR	72,447	2,036	2.8	10
Overall		**1,398,682**	**62,381**	**4.5**	

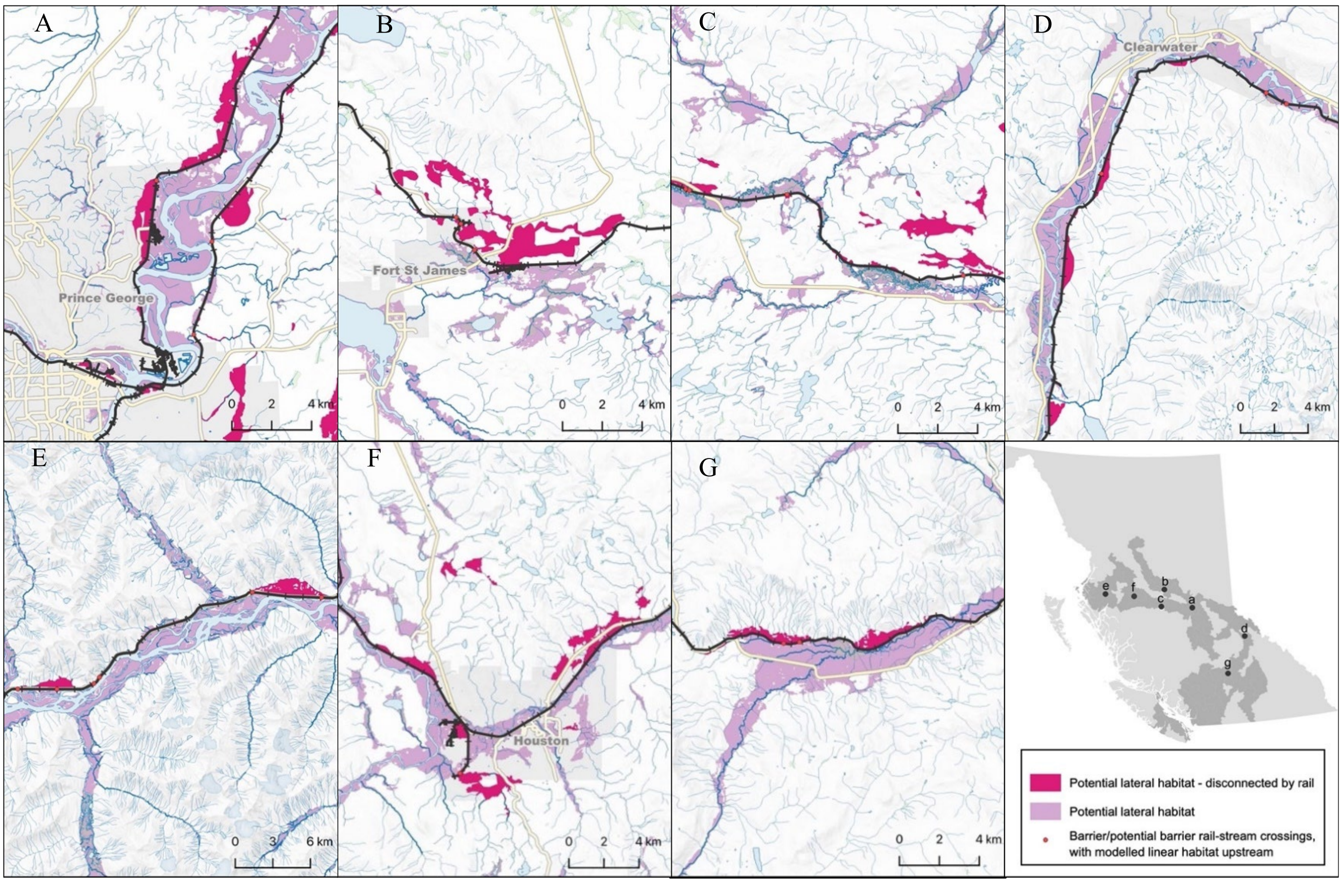

Figure 2. Examples of lateral habitat connectivity model results, including lateral habitat estimated to be disconnected by rail infrastructure in (A) Prince George, (B) Fort St. James, (C) Endako, (D) Clearwater, (E) Exstew, (F) Bulkley, and (G) Monte Lake, British Columbia.

Longitudinal habitat fragmentation

Of the >4,000 rail-stream crossings in B.C. watershed groups with salmon, only ~8% potentially block access to spawning or rearing habitat. Rail and highway infrastructure often run in parallel along valley bottoms, and urban and rural resource roads are abundant on the B.C. landscape. For the habitat blocked by rail barriers alone, half occurs in 14 streams with one or more rail barriers. These could be priorities for fish-passage restoration should model results be confirmed by field validation.

The effects of rail barriers on longitudinal salmon habitat fragmentation may be overestimated due to the following factors:

1) Not all modelled spawning or rearing habitat is suitable for these purposes. IP models identify stream segments with geomorphic characteristics associated with habitat suitability for a particular species and life stage (Sheer et al. 2009). This is achieved by excluding the stream segments where suitable habitat is unlikely to occur, for which certainty is high because observations of fish-habitat use where model parameters are exceeded are rare. Conversely, certainty regarding suitability of modelled habitats is low because suitability is driven by local conditions (depth, temperature, velocity, substrate), and suitable habitat is only found in a subset of IP-modelled habitat. In some cases, modelled spawning or rearing habitat may occur on a watercourse that is dry during the times of the year when these activities occur. In other cases, there may be unsuitable spawning substrates or insufficient habitat complexity such as deep pools, overhead and instream cover. For example, some Sockeye Salmon rearing lakes were identified without co-located modelled spawning habitat. Although within Fraser Sockeye Salmon stocks several lakes have extensive shore spawning areas and may not require riverine habitats (R. Bailey, personal communication November 13, 2023), the models were not designed to identify shore-spawning habitat, and it is unlikely that the lakes identified by the model would support this alternative spawning method. Overall, comparison with existing datasets such as the PSE (Pacific Salmon Foundation 2020) demonstrated that the IP models used in this analysis successfully identified almost all known spawning and rearing habitat; however, field verification is required to confirm whether stream segments identified by the model are suitable for spawning or rearing. Field validation using similar model outputs has found some modelled spawning and rearing habitat to be unsuitable (B. Rebellato, personal observation, Mazany-Wright et. al. 2021*a*,*b*; Mazany-Wright et al. 2022). A review of PSCIS records indicated that between 30 to 47% of stream crossings on naturally accessible habitat were associated with low-quality habitat, which may be unsuitable for these species, though these habitat-quality ratings frequently represent an observation taken at a single point in time from the roadside (Rebellato and Lapointe 2023). Generally, IP models are more likely to overestimate habitat, and less suitable habitat is likely found upstream of rail-stream crossings than identified here.

2) The number of closed-bottom structures on railways was likely overestimated. After assuming that rail-stream crossings on river polygons were bridges and removing those classified as passable in PSCIS, 88% of rail-stream crossings were considered closed-bottom structures and assumed to be barriers. By comparison, the B.C. Forest Practices Board audited 1,110 road-stream crossings in 19 watersheds in 2009 and found that 66% were closed-bottom structures, though this increased to 91% on streams considered to have marginal habitat for fish (Forest Practices Board 2009). Assessments of 18,000 road-stream crossings on resource roads from 2008 to 2017 yielded similar results; 66% were closed-bottom structures (Mount 2017). In addition, not all modelled stream crossings exist. Of >200 modelled stream crossings assessed across four watershed groups in B.C., 46% did not exist (Rebellato and Lapointe 2023). Reasons included that the stream or road did not exist, or that the road had been decommissioned. Field assessments are required to validate estimates of structure type.

3) Not all closed-bottom structures are barriers to fish passage, yet all modelled closed-bottom structures were considered barriers in this study unless previous field assessment data confirmed otherwise. Factors such as the size of the structure relative to the natural stream width, and the structure's length, slope, perch height, and embeddedness influence which fish can pass at different flows (Belford and Gould 1989, Mueller et al. 2008, B.C. Ministry of Environment 2011, Johnson et al. 2012). Mount (2017) found that 81% of closed-bottom structures were barriers, and an additional 11% were potential or partial barriers. Rail-stream crossings tend to be located in valley bottoms with lower gradients, where some of the factors that affect passability (e.g., structure slope) are less likely to exceed thresholds. Few field assessments of rail-stream crossings have been completed, and additional assessments could allow estimation of the proportion that pass fish.

Conversely, other errors may have contributed to underestimating longitudinal fragmentation:

4) Fish sometimes pass reaches with higher gradients than the thresholds used in this study, possibly because of the arrangement of step-pools or other habitat features, particular flow conditions, or individual behaviour. For several species, ~5% of observations in B.C. occurred upstream of locations with selected gradient thresholds (i.e., rare occasions where salmon could pass steep slopes). Salmon could likely access some habitat upstream of modelled limits, contributing to underestimating fragmentation. Though salmon may not be able to reach some habitat modelled as naturally accessible (e.g., due to an unmapped waterfall), errors in the accessibility model seem more likely to underestimate than overestimate the amount of available habitat.

5) Despite the inherent generosity of IP models, some types of spawning and rearing habitat extent may be underestimated. Though Sockeye, Chum, and Pink salmon occasionally spawn in lakes (Kerns and Donaldson 1968, Zhivotovsky et al. 2012, Pacific Salmon Foundation 2020), lakes were excluded as spawning habitat because, although spawning locations in many lakes in B.C. are known and documented, habitat parameters associated with these locations can not be easily mapped and modelled within the broader B.C. lakes system. Likewise, stream segments with < 2 m channel width were excluded from IP spawning models to avoid overestimating spawning habitat extent. Pink, Chum, and Coho salmon have been observed spawning in smaller streams (< 2 m wide), if flows and substrates are suitable (McPhail 2007, J. Hwang, personal observation); however, these habitats are unlikely to be particularly valuable spawning habitats in most cases. Finally, the mean annual discharge thresholds used for spawning were lower than those used by all fish. For example, spawning and rearing areas for Chinook Salmon in the mainstem North Thompson River (DFO 1999) have mean annual discharge estimates of 425.9 m3/s (Perkins 2015). The extent of lakes, stream segments <2 m wide, and rivers with high mean annual discharge was high, and fish likely only use a small subset of these habitats for spawning; therefore, these habitats were excluded from IP models unless mapped in the PSE for Chum and Pink salmon, underestimating habitat extent.

6) Some rail-stream crossings modelled as passable may be barriers. The type of stream-crossing structures used in railway construction tend to differ from those used for resource roads, due to the load-bearing requirements of the tracks (AREMA 2003). Closed-bottom structures may be more common on railways as a result (E. Cheung, personal communication November 2020; K. Graf, personal communication May 17, 2021). Some open-bottom structures may also block fish if they contain pilings or in-stream concrete footings that constrict the stream channel. Rebellato and Lapointe (2023) found that approximately 6% of records classified as bridges in PSCIS may be barriers because they were undersized for the stream channel or had debris issues. These errors likely occur for a small proportion of stream crossings.

Other data errors affect estimates without inherently over- or underestimating fragmentation. Conditions may have changed since spatial layers were last updated. For example, the Railway Track Line was updated during this project, and some tracks were removed because they were transformed into trails or otherwise abandoned. There may also be instances where stream crossings have been decommissioned or replaced that are not captured in PSCIS. Differences in location between modelled stream crossings and PSCIS assessments were identified during data QA/QC (see Appendix B), and it was not always whether the stream crossing was mapped incorrectly, or the assessment was undertaken on an unmapped tributary. Combining these points when they represent different locations results in underestimating the number of barriers, whereas separating them when they represent the same location does the opposite.

Overall, the extent of errors associated with overestimating longitudinal fragmentation is likely greater than errors that result in underestimates. More modelled stream crossings considered barriers here are likely passable than those incorrectly classified as passable, and more of the modelled spawning and rearing habitat is likely to be unsuitable compared to the amount of suitable habitat that was omitted from the IP models (e.g., lakes, stream segments >2 m, and rivers with high discharge).

Error estimates could be developed and incorporated into the models. The proportion of closed-bottom structures that are barriers could be estimated by: a) incorporating modelled probabilities of stream crossings being barriers on watercourses in the lower Fraser River (17% to 81% with a mean probability of 56%; Finn 2021); b) using the proportion of PSCIS records of closed-bottom structures that scored as passable (8%; Mount 2017); c) examining a subset of PSCIS records on and in close proximity to rail lines, which may be more representative of the stream crossings considered here; or d) conducting field assessments of a random subset of rail-stream crossings. Randomized field assessments could also inform estimates of errors in the proportion of rail-stream crossings modelled as open-bottom structures, and of the proportion of open-bottom structures that are barriers.

These findings build on the first phase of this project (see Rebellato et al. 2022), and results differ slightly from what was reported there due to several changes in methods. The study area was expanded from the Fraser Basin to all of B.C.; two species were added (Chum and Pink salmon), and IP models were updated. For lateral habitat, the basic slope model was replaced with a floodplain-specific valley confinement model (Nagel et al. 2014). These changes resulted in some estimates of the amount or percent of habitat that may be blocked being lower than previously reported (Rebellato et al. 2022), despite the expanded spatial scope and additional species included in this study.

Lateral habitat fragmentation

Of the lateral habitat in the study area, 4.5% may be disconnected by rail infrastructure, with most of the disconnected habitat occurring in seven watershed groups. Estimates of lateral habitat fragmentation should be interpreted with greater caution compared to longitudinal fragmentation estimates. Approaches used to identify lateral habitat and its connectivity status were preliminary and have not been validated by field assessments. The alteration or removal of lateral habitats through draining, channelization, and diking for agricultural, urban, and industrial uses has rendered much of the lateral habitat unusable or of reduced quality even in the absence of railways, particularly in the lowest reaches of the Fraser River through the Lower Mainland, where only 15% of historic lateral habitat is estimated to remain connected for salmonids (Finn 2021). In this study, all lateral habitat in urban areas was excluded from consideration due to challenges in distinguishing rail impacts from other urban land-use effects. Lateral habitat was mapped based on the Provincial 1:20,000 25-m resolution Digital Elevation Model. Higher resolution (light detection and ranging) data are available for parts of the study area and could be used to improve the model. The degree to which other linear infrastructure (e.g., roads or dykes) may be exacerbating the effects of rail infrastructure on lateral habitat fragmentation was not considered.

Due to the dynamic nature of flows and channel formation, not all lateral habitat is usable at all times. Channel morphology changes as the active channel shifts through the floodplain over time. For example, oxbows may be cut off as the river channel shifts, then remain disconnected for years. Some lateral habitats may be connected during annual high-water events, whereas others may only be accessed during a one in 10-year (or greater) flood return period. Salmon may use lateral habitats that are only wetted for six to eight weeks of the year (R. Bailey, personal communication, March 2022), particularly in interior portions of the Fraser Basin where hydrographs are dominated by snow. At a given time, the amount of usable lateral habitat is likely only a portion of the lateral habitat modelled here.

Railways can affect lateral habitat availability by other mechanisms than fragmentation, including impeding channel-forming processes that adjust and maintain these habitats over time. Further investigation is required both in the field and through refinement of the lateral habitat model to help identify where and how rail infrastructure contributes to lateral habitat fragmentation.

Railways can affect salmon habitat connectivity via mechanisms that are not accounted for here. For example, a portion of the mainstem Eagle River in the Shuswap Lake watershed group was redirected near Mile 15.5 when the railway was constructed. Out-migrating juvenile salmonids now become entrained against the rail ballast when traveling through the diverted channel (R. Bailey, personal communication May 17, 2022; D. Pehl, personal communication May 19, 2022). The loss of access to lateral habitat in the Eagle River was accounted for in the lateral habitat analysis; however, the effects of this impingement were not. This is a connectivity issue analogous to turbine mortality during outmigration through hydro dams; in each instance, a portion of fish is unable to pass through these structures to complete their migration. Local knowledge is required to identify and address such additional rail-habitat issues.

Conclusions

This study provides an initial estimate of the scope of the effects of railways on salmon habitat connectivity, but given the errors discussed, individual sites may not be barriers or block suitable habitats. Field assessments are required to confirm whether modelled rail barriers are passable, and whether habitat is suitable at individual locations. Longitudinal barriers were ranked in terms of the amount of potential habitat gain, which can help focus field investigations on sites with the greatest potential benefits if restored. Field results combined with stakeholder and rightsholder input could then guide where to focus restoration efforts to realize the best gains in terms of both habitat quantity as well as quality. Future analyses could consider sets of rail and non-rail barriers to identify locations with broader connectivity restoration potential. For example, removing a rail barrier may only provide access to 100 m of spawning or rearing habitat but could result in several kilometres of habitat gain if one or more additional non-rail barriers upstream are also addressed (O’Hanley and Tomberlin 2005).

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Appendix A: 1:20,000 Freshwater Atlas Watershed Codes and Names

Table A1. 1:20,000 watershed group names and codes in the study area in B.C.

Watershed Group Code	Watershed Group Name
ALBN	Alberni Inlet
BBAR	Big Bar Creek
BONP	Bonaparte River
BULK	Bulkley River
CHWK	Chilliwack River
COMX	Comox
COTR	Cottonwood River
COWN	Cowichan
DEAD	Deadman River
DRIR	Driftwood River
FRAN	Francois Lake
FRCN	Fraser Canyon
HARR	Harrison River
KISP	Kispiox River
KITR	Kitimat River
KLUM	Kalum River
LCHL	Lower Chilako River
LFRA	Lower Fraser
LILL	Lillooet
LKEL	Lakelse
LNIC	Lower Nicola River
LNTH	Lower North Thompson River
LSAL	Lower Salmon River
LSKE	Lower Skeena River
LTRE	Lower Trembleur Lake
MIDR	Middle River
MORK	Morkill River
MORR	Morice River
NARC	Narcosli Creek
NECR	Nechako River
OKAN	Okanagan River
PARK	Parksville
QUES	Quesnel River
SAJR	San Jose River
SALR	Salmon River
SETN	Seton Lake
SHUL	Shuswap Lake
SQAM	Squamish
STHM	South Thompson River
STUL	Stuart Lake
SUST	Sustut River
TABR	Tabor River
TAKL	Takla Lake
THOM	Thompson River
TWAC	Twan Creek
UFRA	Upper Fraser River
UNTH	Upper North Thompson River
USHU	Upper Shuswap
UTRE	Upper Trembleur Lake
VICT	Victoria
WILL	Willow River
WORC	Work Channel

Appendix B: Summary of methods and results for QA/QC of dams, waterfalls, and stream crossing data

Methods

Quality assurance/quality control (QA/QC) was undertaken for a subset of waterfalls, gradient barriers, and stream crossings. Data for hydro and non-hydro dams were obtained from the Canadian Aquatic Barriers Database; see Mazany-Wright et. al. (2023) for details on associated QA/QC procedures.

Natural barriers

The validity of a subset of mapped waterfalls and areas with subsurface flows with salmon observations upstream or within the area of subsurface flows was assessed by reviewing the source of each upstream observation record and obtaining additional information if needed. Similar QA/QC was not undertaken for gradient barriers with salmon observations upstream. Only a selection of waterfalls and subsurface flows were reviewed, primarily in the Fraser basin. These were identified as follows:

1) Waterfalls in the Fraser and Skeena basins with at least one observation of Chinook, Sockeye, or Coho salmon or steelhead upstream (48 waterfalls; all reviewed).

2) Waterfalls and subsurface flows that represented the first potential natural barriers that salmon might encounter when migrating upstream from the ocean, anywhere in the study area, with at least one steelhead or Chinook, Sockeye, Coho, or Pink salmon observation and up to eight other observations of Chinook, Sockeye, Coho, or Pink salmon, steelhead, Rainbow Trout, Arctic Grayling (*Thymallus arcticus*), or Bull Trout combined upstream of the natural barrier or within the area of subsurface flows (111 features; 40 reviewed).

Evidence to confirm or reject each potential natural barrier was sought by reviewing the source information for each associated Pacific salmon observation, along with database and web searches for information on the associated stream when necessary. The Known BC Fish Observations and Fish Distributions layer identifies sources for each observation record. Sources included the B.C. Fisheries Information Summary System, Fisheries and Oceans Canada's (DFO) Fish Habitat Inventory and Information Program database, DFO's Canadian Data Report of Fisheries & Aquatic Sciences "Catalogue of Salmon Streams" report series, data-collection spreadsheets for observations made through provincial fish-collection permits, and occasionally more detailed reports describing fish sampling methods and results. Source data and reports were accessed through B.C.'s Cross-Linked Information Resources tool, the EcoCat Ecological Reports Catalogue, or the Fisheries and Oceans Canada Library. These databases, Google, and Google Scholar were searched when information from the previous sources was inconclusive or could not be found. The stream name associated with the feature and observation(s) in question was used as the search term, and up to three pages of results were reviewed.

The presence of a natural barrier was rejected, confirmed or considered inconclusive based on the information obtained. Evidence was considered inconclusive if source collection reports or literature were unavailable for the associated observation records, or if source collection reports or literature did not contain clear evidence, and no additional information was available. Rejected natural barriers were excluded from the natural barriers dataset, whereas those that were confirmed or considered inconclusive were retained.

A feature was rejected as a natural barrier if evidence indicated that it did not exist, was passable (naturally or because of a fishway), or was plotted in the wrong location. It was also rejected if located on a braided channel with at least one passable channel, or if evidence indicated that channel access had been restored to a dewatered side channel. Other features were rejected as natural barriers if upstream observation records were considered valid because they were based on collection reports or source literature with specific location details, or there were multiple corroborating observations with supporting collection reports or literature. One area of subsurface flow was rejected because literature indicated that it held sufficient water for Coho Salmon to rear at certain times of the year. Another area of subsurface flow was rejected as a natural barrier because it was identified as a pump station.

A feature was confirmed as a natural barrier if evidence indicated that the barrier was impassable (e.g., a 15-m waterfall). It was also confirmed if observation records reflected fish release locations (e.g., hatchery releases, or trap and transport programs). In other cases, features were confirmed as natural barriers because the associated observation records were interpreted as likely to be invalid. Reasons for considering observation records to be invalid included likely data-entry errors, likely plotting errors, situations where there was only one observation record upstream of the natural barrier with evidence from other fish sampling in the stream indicating that salmon are only present downstream of it or in nearby streams.

Likely data-entry errors:

- The species was not mentioned in the source collection reports or literature for the observation record; the species was likely entered in error.
- One steelhead observation record was associated with a field survey that combined steelhead and Rainbow Trout.

Likely plotting errors:

- The source collection reports or literature provided an exact location that differed from the observation record; the location was likely plotted in error.
- The source collection reports or literature for the observation record did not provide an exact location; the location was likely plotted subjectively when the observation record was created.
- The observation was plotted just upstream of a waterfall or the downstream boundary of an area of subsurface flow, likely representing a minor positioning accuracy error.

Stream Crossings

Field assessment records in PSCIS for rail-stream crossings were matched to modelled rail-stream crossings using an automated script. A similar script was used to match field assessment records in PSCIS for road-stream crossings to modelled road-stream crossings. Assessed stream crossings with a large amount of habitat upstream were reviewed along with any identified as potentially incorrect to ensure that they were matched with the proper modelled stream crossing. This included confirming that PSCIS assessments matched to a modelled rail crossing and were not assessments from a nearby road or trail. In areas where CWF has undertaken additional connectivity planning, matches between all PSCIS-assessed crossings and modelled crossings were manually reviewed.

Manual QA/QC was undertaken for stream crossings without PSCIS records by reviewing commonly available satellite imagery (Google/Bing/ESRI). If imagery of a stream crossing clearly showed an open-bottom structure (primarily bridges) or ford, or that the stream crossing did not exist (infrastructure or stream not present), the stream crossing was excluded from the potential-barriers dataset. When imagery was not definitive and the stream crossing was in an area likely to have more data, air photo imagery was sought from regional district or municipality web maps. Google Street View was also reviewed when available. All rail-stream crossings were reviewed. All road-stream crossings downstream of remaining rail-stream crossings were then reviewed. Upstream of rail-stream crossings and in tributaries not affected by rail-stream crossings, road-stream crossings downstream of spawning or rearing habitat were reviewed from downstream to upstream until it seemed that no other bridges would be found. The review of modelled road-stream crossings is an ongoing process that resulted in fixes to 878 modelled crossings on naturally accessible streams in the study area prior to this study, including 25 rail-stream crossings. Those crossings were not reviewed again here.

Results

Natural Barriers

Of the 159 waterfalls and areas with subsurface flow identified for QA/QC, 88 were reviewed (Table B1). Evidence indicated that approximately 42% of those reviewed were passable or did not exist. Another 49% were confirmed to be barriers, and reviews for the remaining 17% were inconclusive. These were retained as barriers along with the 71 natural barriers that were identified for QA/QC but not reviewed. One waterfall (Goldstream Falls) was observed while reviewing satellite imagery for rail-stream crossings and was added to the natural barriers layer. A series of waterfalls on Slim Creek was excluded from the natural barriers layer based on a review of imagery and observations, which indicated that they were rapids rather than waterfalls.

Stream Crossings

Of the crossings matched with PSCIS assessment records, corrections were made to 54 erroneous matches including 9 of the 45 assessed rail-stream crossings. In areas where CWF has undertaken additional connectivity planning, 1,757 matches were adjusted manually. The number of adjustments was high because an earlier and more error-prone matching script had been used.

Satellite imagery was reviewed for 16,190 modelled stream crossings (road, trail, rail, dam/weir crossings) on naturally accessible streams in the study area, including 2,267 rail-stream crossings, 1,378 crossings downstream of rail lines, 11,337 crossings upstream of rail lines, and 1,468 crossings on streams not associated with railway infrastructure. Only five stream crossings modelled as bridges were reclassified as closed-bottom structures, whereas 556 crossings modelled as closed-bottom structures were reclassified as bridges (Table B2). Either no road or no stream was present for 1,263 modelled stream crossings.

Table B1. Summary of QA/QC results for waterfalls and areas of subsurface flow.

Barrier Type	Number considered for QA/QC	Number reviewed	Passable or did not exist	Confirmed barrier	Inconclusive results
Waterfall	105	54	17	31	6
Area of subsurface flow	54	34	20	5	9
Total	**159**	**88**	**37**	**36**	**15**

Table B2. Changes to modelled stream crossing types resulting from QA/QC of modelled crossings on naturally accessible streams within the project study area.

Criteria	Rail	Demographic road	Resource or other road	Trail	Total
Modelled as a closed-bottom structure, but a bridge or open-bottom structure was visible	44	201	294	17	556
Modelled as a closed-bottom structure, but a ford was visible	0	0	18	0	18
Modelled as an open-bottom structure or bridge, but a closed-bottom structure was visible	5	0	0	0	5
No road or stream was visible		257	1004	2	1263
Total	**49**	**458**	**1316**	**19**	**1842**

Appendix C – Region-specific Data Summaries

Table C1. Rail barriers that may block the most salmon spawning or rearing habitat not blocked by other barrier types in the Fraser Basin, Skeena Basin, and coastal watersheds. Only rail barriers with no barriers of any type downstream were included (n=160). The amount of spawning and rearing habitat to the next upstream non-rail barrier (if any) was estimated. The top 10 rail barriers are listed, followed by the rail barriers that block 75% and 100% of spawning and rearing habitat. There were only eight rail barriers in coastal watersheds with no other barrier types downstream. The Columbia – Okanagan region was not included because there were no rail barriers downstream of salmon spawning or rearing habitat.

Region	Rail barrier crossing ID	1:20,000 watershed group	Stream	Amount of spawning or rearing habitat between rail barrier and next non-rail barrier upstream (km)	Cumulative total spawning or rearing habitat blocked only by rail km	%	Rank
Fraser Basin	1009904765	LCHL	Hutchison Creek	8.04	8.04	13	1
	1009904822	LCHL	Unnamed	6.07	14.11	22	2
	1003506134	COTR	Meadowbank Creek	5.37	19.48	31	3
	1023204207	UNTH	Lyon Creek	4.19	23.67	37	4
	1024742020	LFRA	Hyland Creek	3.25	26.92	42	5
	1010305007	LFRA	Cougar Canyon Creek	3.07	29.99	47	6
	1024708246	HARR	Wades Creek	1.75	31.74	50	7
	1018303506	SHUL	Victor Creek	1.70	33.44	53	8
	1010305083	LFRA	Unnamed	1.53	34.97	55	9
	1024723695	TABR	Red Rock Creek	1.40	36.37	57	10
	1019106847	FRCN	Puckat Creek	0.94	47.38	75	24
	1012401276	UNTH	Unnamed	0.01	63.22	100	93
Skeena Basin	1005505883	SUST	Minaret Creek	7.07	7.07	13	1
	1008802631	KISP	Andi Creek	6.44	13.51	25	2
	1023204273	LSKE	MacMillan Creek	5.13	18.64	34	3
	1010304980	KLUM	Steinhoe Creek	3.80	22.44	41	4
	1008501818	KLUM	Newtown Creek	3.15	25.59	47	5
	1010305180	SUST	Unnamed	3.01	28.60	52	6
	1010305019	BULK	Unnamed	2.18	30.78	56	7
	1012401272	KLUM	Unnamed	2.01	32.79	60	8
	1009904822	BULK	Bulkley River	1.99	34.78	64	9
	1010305018	LSKE	Unnamed	1.75	36.53	67	10
	1006303996	SUST	Unnamed	1.03	40.78	75	14
	1012401333	LSKE	Unnamed	0.01	54.51	100	59
Coastal watersheds	1010305119	COWN	Holland Creek	3.18	3.18	38	1
	1018303471	PARK	Chase River	2.90	6.08	73	2
	1008302857	PARK	Millstone River	1.19	7.27	88	3
	1016502648	COWN	Bonsall Creek	0.34	7.61	92	4
	1010304996	SQAM	Unnamed	0.28	7.89	95	5
	1001805506	SQAM	Unnamed	0.26	8.15	98	6
	1006304000	SQAM	Mossom Creek	0.07	8.22	99	7
	1006303969	SQAM	Unnamed	0.05	8.27	100	8