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Geospatial Indicators and Metrics for Threats to Fish Habitat in the Fraser River Basin with Thompson-Nicola as a Case Study

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Foreword

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

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ACRONYMS

AIS	Aquatic Invasive Species
BC	British Columbia
COSEWIC	Committee on the Status of Endangered Wildlife in Canada
CSAS	Canadian Science Advisory Secretariat
CU	Conservation Unit
DO	Dissolved oxygen
DU	Designatable Unit
EDU	Ecological Drainage Unit
FFHPP	Fish and Fish Habitat Protection Program
FIDQ	Fisheries Inventory Data Queries
FRB	Fraser River Basin
FWA	Freshwater Atlas
GCM	General Circulation Model
IPSE	Integrated Planning for Salmon Ecosystems
KOC	organic carbon partition coefficient
LED	Light emitting diode
LiDAR	Light Detection and Ranging
logKOW	Octanol/water partition
MAD	Mean annual discharge
PAH	Polycyclic aromatic hydrocarbons
PAWPIT	Pollutants Affecting Whales and their Prey Inventory Tool
PCB	Polychlorinated biphenyls
PCIC	Pacific Climate Impacts Consortium
pH	Potential of hydrogen
PSE	Pacific Salmon Explorer
PSSI	Pacific Salmon Strategy Initiative
RCP	Representative Concentration Pathway
SAR	Species at Risk
SBOT	Stewardship Baseline Objectives Tool
TN	Total nitrogen
TP	Total phosphorus
US	United States
VIC-GL	Variable Infiltration Capacity - Glacier
WWF	World Wildlife Fund

ABSTRACT

Managing and reporting on fish and fish habitat requires spatially extensive information on how threats to fish and fish habitat vary across the landscape and which may pose the most risk for ecosystems and species of concern. Geospatial methods are best suited to providing such information at large scales through modeling and mapping of ongoing threats from human activities and landscape disturbances, as well as projecting climate change threats across a region. We conducted a cumulative threat assessment for the Fraser River Basin stream network to estimate threats (applied here as exposure) important to managing Pacific salmon and Species at Risk in freshwater, and to characterize spatial patterns in threat levels across streams and habitat extents of focal species. We presented a methodology that builds on existing geospatial assessments in British Columbia for estimating human-mediated threats of Aquatic Invasive Species, flow alteration, in-stream habitat destruction, latitudinal fragmentation, longitudinal fragmentation, riparian disturbance, nutrients, pollution, and sedimentation, as well as climate change-based threats of flood risk, low stream flow, high stream flow, and high stream temperatures. We provided estimates and summaries of threats across streams, watersheds, and Pacific salmon and Species at Risk habitat extents. The ability to reassess threats over time for reporting on the status of threats to the state of fish and fish habitat was also evaluated based on the data inputs required. We then showcased examples of how information from threat scores, associated inputs, and salmon values (i.e., Conservation Units, modeled favourable spawning habitat) can be used collectively to help inform planning and prioritization for management and restoration. This was done for the Thompson-Nicola Ecological Drainage Unit and provided spatial information related to riparian restoration, water withdrawal allowance, and barrier mitigation. Uncertainties and limitations, as well as steps for future evaluation of the cumulative threat assessment were detailed.

1. INTRODUCTION

1.1. CONTEXT

On August 28, 2019, a new *Fisheries Act* came into force with restored protections and modernizations to help safeguard fish and fish habitat. To implement the modernized *Fisheries Act*, modern tools and approaches to track and assess the health or state of fish and fish habitat are needed to support responsive and integrated regulatory, planning, partnership and monitoring activities by the Fish and Fish Habitat Protection Program (FFHPP) and to demonstrate improved outcomes for sustainability of fish and fish habitat.

In July 2022, initial science advice was provided on geospatial mapping tools, indicators, and metrics for fish habitat in the Pacific Region (DFO 2022). Public facing geospatial tools that provided indicators of human activities and threats to fish habitat and watersheds in the Pacific Region were reviewed to determine whether, and how, they estimated elements of key habitat threats of Fisheries and Oceans Canada (DFO)-managed freshwater and anadromous species as identified by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC). Habitat threats included those listed in the Fish and Fish Habitat Protection Policy Statement (DFO 2019a), the Interim Risk Management Guide for the Protection of Fish and Fish Habitat[1], and relevant COSEWIC documents. The threats listed in the policy (DFO 2019a) and reviewed in DFO (2022) were Aquatic Invasive Species (AIS), habitat degradation, habitat modification, pollution, and climate change. Threats addressed from the associated guide were: deleterious substances, sedimentation, and change or loss of aquatic habitat and vegetation, dissolved oxygen (DO), fish passage, nutrients, and riparian zone. The resulting report recommendations included further work to develop a geospatial approach to report on the state of fish habitat and incorporate a temporal component to reflect changes over time (DFO 2022). This Canadian Science Advisory Secretariat (CSAS) process is intended to address the further work identified.

FFHPP has requested that Science Branch develop a geospatial approach to report on the state of fish habitat and evaluate which elements can be assessed temporally. Outcomes of this assessment will be used to report on the status of threats to the state of fish habitat, including but not limited to those listed in the Fish and Fish Habitat Protection Policy Statement (DFO 2019a). FFHPP also requested a spatial analysis of intersecting climate change impacts to stream flow and temperature and human activity based threats on Pacific salmon ecosystems in the Thompson-Nicola Ecological Drainage Unit (EDU).

The Thompson-Shuswap and Nicola River watersheds have been identified as pilot areas to deliver Integrated Planning for Salmon Ecosystems (IPSE) under the Pacific salmon Strategy Initiative (PSSI), in partnership with Indigenous organizations and the Province of British Columbia (BC). These collaborative planning processes intend to identify and prioritize actions that benefit salmon ecosystems within these watersheds, while considering impacts from climate change and human uses. The results of the Thompson-Nicola spatial analysis undertaken as part of this CSAS regional peer review will be used to inform these processes.

As these two requests use related methods, they have been combined for a consistent and thorough review. Threats assessed in this process (estimated here as exposure; see 'Background' for details on terminology) were selected to align with the key threats included in DFO (2022) and based on feasibility and foundational methods determined in Boyd et al.

[1] DFO. 2019. (Interim) risk management guide for the protection of fish and fish habitat. Fisheries and Oceans Canada – Fish and Fish Habitat Protection Program. Internal document.

(2022). The evaluated anthropogenic based threats are AIS, flow alteration (i.e., habitat modification), in-stream habitat destruction (i.e., habitat degradation), latitudinal and longitudinal fragmentation (i.e., fish passage), riparian disturbance, and human-mediated changes in nutrients, pollution, and sedimentation. These threats are provided as individual and additive cumulative threat scores applied to the Fraser River Basin (FRB). Climate change related threats are addressed separately and include projected flood risk, low stream flow, high stream flow, and high stream temperatures. Threats listed in the policy and guide that are currently outside of scope for geospatial analysis at broad spatial scales based on existing data are overexploitation of fish and provincially managed species, and change or loss of: aquatic habitat and vegetation, DO, electromagnetic field, food supply, light, and noise.

The assessment and advice arising from this Canadian Science Advisory Secretariat (CSAS) Regional Peer Review process will be used to inform FFHPP Pacific Region activities related to the implementation of the modernized *Fisheries Act*, including being able to articulate how FFHPP Pacific is working to develop habitat status or health indicators. The Thompson-Nicola spatial analysis will be used to inform IPSE collaborative planning processes in the Thompson-Nicola watersheds.

1.2. BACKGROUND

Where and how fish and fish habitat is impacted by human activities and climate change is critical information needed to focus resources on the most effective management actions to help preserve populations. However, the scale of landscape disturbance and climate change effects is intractable for addressing these questions with sole reliance on traditional field-based assessments. Advancements in spatial analysis programming, satellite data, and publicly accessible databases have enabled estimations of threats to fish and fish habitat across large spatial scales using geospatial tools (e.g., Vörösmarty et al. 2010; Halpern et al. 2015). In particular, the recognition that species are facing many simultaneous threats has led to a field of study on cumulative effects (Orr et al. 2020) that in application uses geospatial tools to produce estimations of these effects and resultant maps (Halpern et al. 2008a; Halpern and Fujita 2013). Cumulative effect assessments typically map estimated stressor intensities as a first step, then apply vulnerability weightings or stressor-response curve weightings specific to a species or habitat type, and finally create an additive or multiplicative summation of the stressors into a cumulative effects score (Halpern and Fujita 2013; MacPherson et al. 2023). Each of these steps requires estimations and assumptions, and the approach taken for this varies greatly among applications (Halpern and Fujita 2013; DFO 2022). The development and improvement of methods for estimating individual threats and cumulative effects provides valuable information on where resources are most needed to better manage and conserve fish and fish habitat.

The composition of a cumulative effect assessment is determined by whether the focus is on a particular human activity or stressor, or on an ecosystem component (i.e., species or habitat type). The former requires identifying the potential impacts of a focal human activity or stressor on all relevant ecosystem components (i.e., top-down), and the latter seeks to identify all stressors and impacts to a focal ecosystem component (i.e., bottom-up; Murray et al. 2020). In the assessment presented here, a bottom-up approach has been taken for the purpose of providing information for managing and reporting on the state of fish and fish habitat. The focal ecosystem components are freshwater habitat, anadromous Pacific salmon, and fish Species at Risk (SAR). The threats to these ecosystem components have been identified in the FFHPP Policy Statement (DFO 2019a), the Interim Risk Management Guide for the Protection of Fish and Fish Habitat[1], and relevant COSEWIC documents (Boyd et al. 2022; DFO 2022). The overarching framework for the assessment is area-based in that it identifies threats from activities occurring in a specific area (i.e., the Pacific Region) and across multiple ecological components (Murray et al. 2020). An additive summation of individual threats into a cumulative threat score can be applied broadly across the region as a first step towards a cumulative effects assessment. Further refinement of a cumulative effect assessment involves identifying weightings or stressor-responses specific to particular species or freshwater habitat types within the region.

Given the pervasiveness of different terminology and definitions used in cumulative effects research (Orr et al. 2020), it is necessary to identify the terms and definitions, and subsequently the scope of measures, used in an assessment. Stressors in some cases have been defined as any biotic or abiotic variable that generate a positive or negative biological response (Orr et al. 2020; Rosenfeld et al. 2022), and in other cases has focused on human-related drivers that produce negative effects on an ecosystem (Murray et al. 2020). The term 'effect' may also be used to identify a positive or negative deviation from the expected value (Murray et al. 2020). For instance, an increase of nutrients from human activities (i.e., stressor) may lead to lower DO in a system (i.e., effect). Note, this use of the term 'effect' is different than in 'cumulative effects'—the former refers to deviation from a value characterizing habitat conditions, and the latter refers to the estimated impact that deviation may have on a focal ecosystem component. We use the term 'threat' hereafter to create a framework that is broadly inclusive and to match the language and scope of threats listed in the FFHPP Policy Statement and associated guide[1] (DFO 2019a, 2022). Specifically, our use of the term 'threat' is to represent an estimate of exposure. When referring to nutrients, pollution, and sedimentation estimates, we use the term 'loading' to emphasize that these scores are estimates of human-derived inputs into the system and do not represent the relative importance or various effects on fish (i.e., some pollutants are more detrimental than others); this is also true of the other threat estimates as these scores did not have bins or thresholds applied at this stage to identify values that are more impactful to fish. Threat measures in this assessment focused on human related drivers and could be biotic (e.g., AIS) or abiotic (e.g., sedimentation from roads, but not including natural processes). Threats may create a positive biological response depending on the context and intensity; for instance, nutrients in an oligotrophic system can increase biotic production. However, the threats in this assessment were generally considered to produce an undesired effect given that the focus was solely on human-derived inputs that create a deviation from the natural state.

The first step of quantifying cumulative effects—estimating threat intensities—is primary information needed for managing and reporting on the state of fish and fish habitat across a region. Methods used to estimate threats range from direct application of human activity metrics as threat indicators (e.g., road density) to developing models relating human activities to the consequent stressor or effect on the system (e.g., sediment loading from multiple human activities) (DFO 2022). The former is more readily accessible and achievable, and as such, has been produced as a part of the Pacific Salmon Explorer (PSE) for most of BC (Pacific Salmon Foundation [PSF] 2021). This information identifies where human activities are highest, and can be used to create risk scores across a landscape (PSF 2021). However, estimating threats using mechanistic models or metrics that closely relate them to potential impacts to fish and fish habitat creates indicators that are more directly linked to the state of fish and fish habitat—e.g., sediment loading versus road density—and are more meaningful for application in further cumulative effect analyses (e.g., stressor-response curves; Rosenfeld et al. 2022; MacPherson et al. 2023). This level of analysis requires working to identify all human activities and landscape disturbances that influence a threat and the context-dependency of that influence. For instance, sedimentation risk has been estimated by BC provincial tools using a variety of road and environmental attributes, with different decisions made around the context of influence; in particular, the Stewardship Baseline Objectives Tool (SBOT) applies metrics of road density within 100 m of a stream and length of roads on slopes >60%, whereas the Southern Interior Watershed Assessment Protocol (SIWAP; van Rensen et al. 2020) uses a 50 m distance and

>50% slopes (DFO 2022). This highlights some of the analytical challenges and layers of decisions that can go into more detailed estimation of threats. An improved ability to quantify the mechanisms and context-dependency that relates human activities to threats and ultimately the state of fish and fish habitat requires broad scale field studies. However, simplified and generalized mechanistic relationships of inputs to derive threats can be used to produce first order estimates of threat levels across large spatial extents that provide useful information for planning, prioritization, and management.

A fundamental consideration of estimating threats to fish and fish habitat in freshwater is the direction of flow that can transport and accumulate upstream inputs into downstream habitats, and the contribution of surface runoff in carrying terrestrial inputs into freshwater. For relevant geospatial tools that span BC, these aspects have either not been addressed or have been handled with differing degrees of complexity (DFO 2022). One method for addressing terrestrial inputs identified the area of land that drains into a system when delineating the spatial extent of human activities that may have an effect (PSF 2021), and another for identifying effects of flow created estimates at the pour points of catchments to encompass activities upstream (Linke et al. 2019). A more complex approach to account for downstream accumulation across a stream network identified human activities within a catchment and accumulated their contributions in the direction of flow (Vörösmarty et al. 2010; Boyd et al. 2022); dilution of inputs was then estimated using river discharge estimates (Vörösmarty et al. 2010) or catchment area as a proxy for discharge (Boyd et al. 2022). Contributions from surface runoff have been most directly quantified to-date by Pollutants Affecting Whales and their Prey Inventory Tool (PAWPIT), using literature-based coefficients for land use and land class inputs and modeled runoff rates (Environment and Climate Change Canada [ECCC] 2022). Further development of methods that explicitly incorporate aspects of flow accumulation, dilution, and surface runoff is important for refining estimation of threats that are not solely localized in nature (e.g., pollution flows downstream, whereas riparian disturbance is specific to the location).

The science advice that was previously provided on geospatial mapping tools and indicators of fish habitat was based on 13 public facing tools that spanned the Pacific Region (DFO 2022). These tools had various strengths and weaknesses in their spatial scope, resolution, threats addressed, and methods used to estimate threats. The World Wildlife Fund (WWF)-Canada Watershed Reports ranked the highest among tools based on the suite of criteria evaluated to determine its applicability for reporting on the state of fish and fish habitat (DFO 2022). However, this tool used sub-drainage areas for reporting, which are large in extent (e.g., the Fraser River Basin has four sub-drainages), and focused on five threats; one of the threats measured was climate change, using air temperature and precipitation as proxies for water conditions. A need was ultimately identified for an improved tool built for the purpose of reporting on the state of fish and fish habitat and evaluating cumulative effects on fish habitat, as well as for considering changes over time (DFO 2022). Incorporation of the strengths of the existing tools, as well as recent developments in spatial data within the Pacific Region, have enabled advancement of this requirement. The development of an initial cumulative threat analysis for the Fraser Valley, BC (Boyd et al. 2022) provided the starting point for this new tool, which is presented here in an enhanced and expanded version applied to the extent of the Fraser River Basin (FRB). Most of the datasets used to develop the threats estimated in this tool are available across the majority of BC, so that the tool can be expanded further in future iterations. Specific applications of the tool are also showcased for the Thompson-Nicola EDU to begin addressing information needs for prioritization and planning of riparian restoration, water withdrawal allowances, and barrier mitigation in the context of climate change and salmon values (i.e., Conservation Units [CUs] and modeled favourable spawning habitat).

1.3. OBJECTIVES

The specific objectives of this paper are to:

Part I: Geospatial Mapping Indicators and Metrics for Fish Habitat in the Fraser River Basin

1. Develop methods to estimate nine anthropogenic-based threats (AIS, flow alteration (i.e., habitat modification), in-stream habitat destruction (i.e., habitat degradation), latitudinal and longitudinal fragmentation (i.e., fish passage), riparian disturbance, and human-mediated changes in nutrients, pollution, and sedimentation) and apply individual and cumulative threat estimates to stream reaches across the FRB as a template for extending threat assessments across the Region.
2. Develop and compile the four estimates of climate change related threats (low and high stream flow, summer stream temperatures, and flood risk) and apply to stream reaches across the FRB.
3. Determine overlap of anthropogenic-based threats and climate change threats with critical habitat of *Species at Risk Act* (SARA)-listed aquatic species, salmon Designatable Units (DUs) assessed by COSEWIC as Threatened and Endangered, and other salmon CUs within the basin. Identify the relative contribution of each threat to each habitat.
4. Evaluate, and demonstrate where possible, the ability to reassess threats temporally based on the current data available.
5. Examine and identify uncertainties and limitations in the data and methods, including those threats not covered herein. Identify ability and limitations to apply methodology to the rest of the Pacific Region.

Part II: Thompson-Nicola Case Study

1. For the Thompson-Nicola EDU, apply the anthropogenic and climate change threats developed in objectives 1–2 to identify associated threat levels to salmon populations (i.e., CUs) and salmon ecosystems (i.e., stream reaches). Highlight those that are most at-risk based on the estimated threats.
2. Provide initial examples of applications of the threat scores that can be used to help inform restoration prioritization activities in the EDU. Combine with scores of environmentally favourable spawning habitat (Iacarella and Weller 2023) and delineated CUs, as relevant, to indicate where high levels of estimated threats correspond with potentially important habitat for salmon. Focus on threats and human activities that may be mitigated through restoration and management actions:
    a. riparian disturbance where nutrient, pollution, and sedimentation inputs from human activities and landscape disturbance are estimated to be high;
    b. water withdrawal licence allowances where flow is low under projected current and future conditions; and
    c. barriers to upstream passage that block potentially important habitat for salmon spawning.

2. METHODS

2.1. STUDY AREA

The FRB (240,000 km^2) is the largest basin in BC, comprising one quarter of the province (Fig. 1). The Fraser River runs 1,375 km across a large elevation gradient from 3,950 m to sea level (Déry et al. 2012). It encompasses a range of climate conditions with mean annual air temperatures from 0.5°C in the north to 7.5°C in the southern interior, and precipitation averaging 400–800 mm/yr in the interior plateau to exceeding 3,000 mm/yr in coastal and mountainous areas (Déry et al. 2012). The FRB supports 3 million people, almost two-thirds of British Columbians[2]. Land uses include mining, forestry, agriculture, ranching, and urbanization. The FRB is critical habitat for many SAR[3], and has historically been the world's largest Sockeye Salmon (*Oncorhynchus nerka*) producer and a major producer of Chinook (*O. tshawytscha*), Chum (*O. keta*), Coho (*O. kisutch*), Pink (*O. gorbuscha*), and Steelhead Salmon (*O. mykiss irideus*; DFO 1998).

The Thompson-Nicola EDU (56,000 km^2) makes up a quarter of the FRB as one of four sub-drainages in the basin (Fig. 1). It spans portions of the Cariboo and Thompson-Okanagan Natural Resource Regions. These regions have experienced major environmental disturbances in the last several years including wildfires, floods, and forest pest infestations. Increasing the regions' resilience to climate change is a key concern. These regions have experienced major environmental disturbances in the last several years including wildfires, floods, and forest pest infestations. Increasing the regions' resilience to climate change is a key concern.

[2] Fraser Basin Council. About the Basin.

[3] DFO. Fraser and Columbia Watersheds Priority Place (BC).

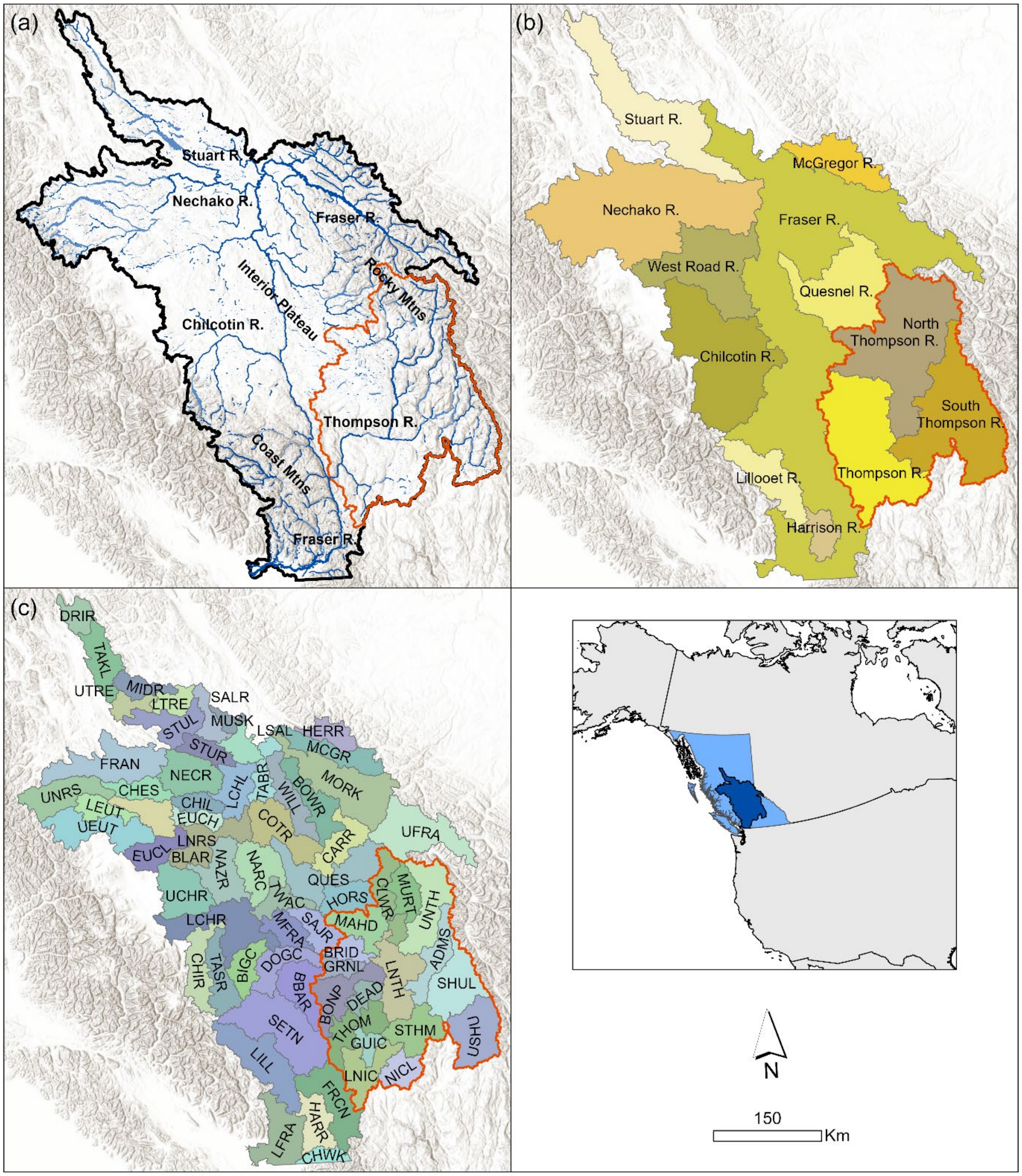

Figure 1. Extent of the Fraser River Basin (a; black outline) and the Thompson-Nicola Ecological Drainage Unit (a; orange outline) in British Columbia, Canada. (light blue polygon in North America map). Major rivers and topographic features are depicted in (a), major watersheds in (b), and watershed groups in (c). Watershed group abbreviations ('codes') are in Appendix A, Table A1.

2.2. FOCAL ECOSYSTEM COMPONENTS

The base ecosystem component assessed was all stream reaches (mean length = 422 m, range = 0.1–9,208 m) delineated by the 1:20,000 scale BC Freshwater Atlas (FWA; GeoBC 2011) within the FRB. Focal species included those listed under the *Species at Risk Act* and the five Pacific salmon species (i.e., Chinook, Chum, Coho, Pink, Sockeye). We identified 8 fish SAR that used habitat in the FRB. Salmon CUs were categorized by at risk status (i.e., Special Concern, Threatened, or Endangered) as assessed by COSEWIC as of February, 2024 (Appendix B, Table B1). Steelhead were not presently included as they were not identified as a SAR or one of the five Pacific salmon species; however, it would be of interest to include them in future assessments as populations within the FRB have been assessed by COSEWIC as Endangered. We also excluded coastal species with limited information on freshwater habitat use such as Eulachon (*Thaleichthys pacificus*). The included species were: Bull Trout (*Salvelinus confluentus*), Chinook Salmon (18 CUs total, 15 at risk), Chum Salmon (1 CU), Coastrange Sculpin (*Cottus aleuticus*), Coho Salmon (7 CUs total, 5 at risk), Green Sturgeon (*Acipenser medirostris*), Mountain Sucker (*Catostomus platyrhynchus*), Nooksack Dace (*Rhinichthys cataractae* ssp.), Pink Salmon (2 CUs total), Salish Sucker (*Catostomus* sp. cf. *catastomus*), Sockeye Salmon (25 CUs total, 16 at risk), Westslope Cutthroat Trout (*O. clarkii lewisi*), and White Sturgeon (*Acipenser transmontanus*, 2 DUs).

We mapped important streams for SAR using distribution or spawning information depending on the species and available data (Boyd et al. 2022) (Fig. 2). We used spatial layers of species distribution polygons provided by the DFO SAR Program for Coastrange Sculpin, Green Sturgeon, Mountain Sucker, Nooksack Dace, Salish Sucker, and Westslope Cutthroat Trout. For White Sturgeon, we used three sources of data to capture important habitat use for Threatened (Lower Fraser) and Endangered DUs (Upper Fraser), including: spawning polygons for the Lower Fraser DU from SBOT; a polygon delineated from a cluster of observations for the Middle Fraser population (Upper Fraser DU) using data from the BC Fisheries Inventory Data Queries (FIDQ); and DFO distribution polygons for the remainder of the Upper Fraser DU. Only FIDQ data were available for Bull Trout; we used observations specific to population locations identified in COSEWIC documents (Ryan River, Ure Creek, Lillooet River, Pitt River, Chilliwack Lake, Birkenhead Lake, Birkenhead River, and Chehalis Lake). Salmon species habitat extent was delineated based on their CU extents. All of these habitat delineations were then associated with stream reaches of the network.

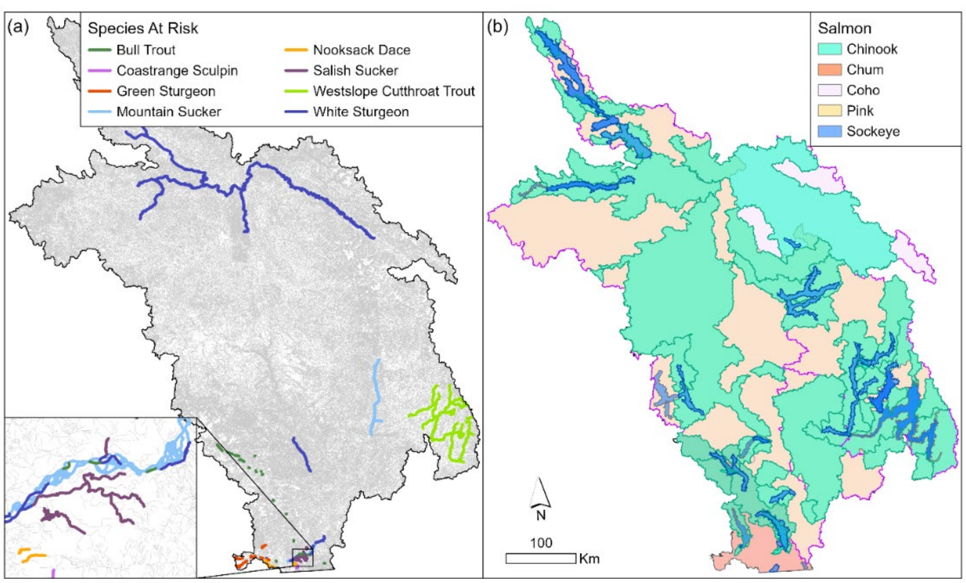

Figure 2. Focal ecosystem components of the cumulative threat analysis. Includes (a) the full stream network for the Fraser River Basin (left panel, grey lines), delineated stream habitat for fish Species at Risk, and (b) Pacific salmon Conservation Units (CUs) and those identified as Special Concern, Threatened, or Endangered ('at risk') by COSEWIC (colour-coded outlines; note, Coho CUs cover the full FRB).

2.3. THREAT ESTIMATION

The threats included for estimation were compiled from:

1. the FFHPP policy document (DFO 2019a) and associated guide[1],
2. the original tool development in the Fraser Valley (Boyd et al. 2022), and
3. a review of COSEWIC assessment and status reports for each newly added species (Appendix B, Table B1).

We excluded threats for which there was no or limited geospatial information (i.e., overexploitation of fish and provincially managed species, and change or loss in: aquatic habitat and vegetation, DO, electromagnetic field, food supply, light, and noise). The nine evaluated human activity and disturbance based threats were AIS, flow alteration, in-stream habitat destruction, latitudinal fragmentation, longitudinal fragmentation, riparian disturbance, human-derived nutrients, pollution, and human-derived sedimentation (Fig. 3). Climate change related threats were treated separately in the cumulative threat scoring and included projected changes in flood risk, low stream flow, high stream flow, and high stream temperatures. We focused this assessment on human-derived threats and associated inputs to help identify potential needs for management actions (note, forest fires and forest pest defoliation were considered human-derived as they are both influenced by human activities including through climate change); therefore, the assessment does not fully encompass all of the pressures that species of concern may be facing (e.g., predation by native species, sedimentation from natural processes, etc.).

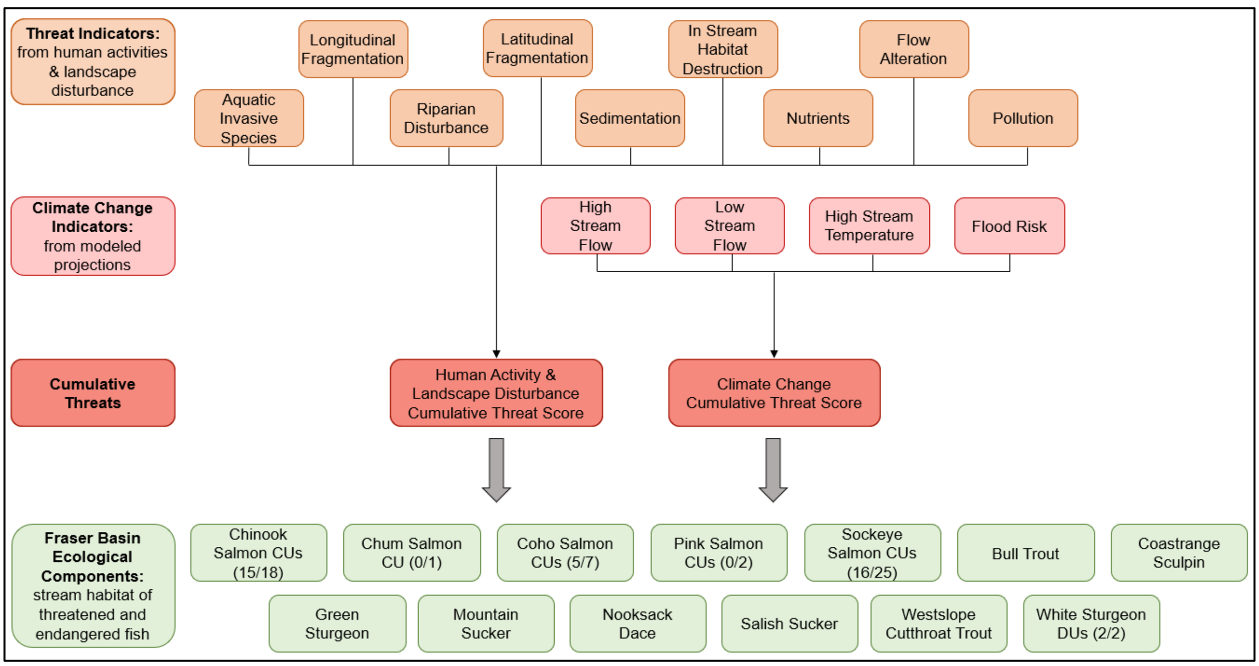

Figure 3. Assessment framework for cumulative threats to fish and fish habitat in the Fraser River Basin, BC. Parentheses for focal species indicate the number of Designatable Units (DUs) identified for Species at Risk or salmon Conservation Units (CUs) that are Special Concern, Threatened, or Endangered out of the total within the basin.

Threats were evaluated for each stream reach within the FWA (a 'reach' was defined as a continuous section of stream between two junctions, or a junction and a stream origin/outlet). Land cover and land use attributes were summarized and assigned to stream reaches using the

FWA fundamental watersheds, which represent the local watershed of a stream reach (Appendix A, Fig. A1). The flow accumulated threats (nutrients, pollution, and sedimentation) used an expanded dataset to capture parts of the FRB outside of BC and account for upstream inputs from the entire catchment (GeoBC 2011; Weller et al. 2023). Modified FWA fundamental watersheds were used for riparian disturbance and habitat destruction to capture the water surface and riparian zones of individual stream reaches in large rivers. The full FWA stream network was used for all threats except stream temperatures, which were modeled for catchments with a minimum size of 1 km^2 (Weller et al. 2023). We considered lake shorelines for calculating in-stream habitat destruction and riparian disturbance threats, but did not include lakes in final threat scoring owing to their different hydrological characteristics. Requirements for data and model inclusion to estimate threats were:

1. Spatial coverage for the entire FRB,
2. Standardized information across the FRB,
3. Resolution applicable to stream reaches, and
4. Publicly accessible.

Extensive spatial coverage and standardized information were particularly important so that threat scores were not unevenly weighted across the FRB based on available information. All spatial analysis and mapping was completed using ArcGIS Pro (ESRI Inc., version 2.9.8) and coding was done in Python (Python Software Foundation 2023) and R (R Development Core Team 2022).

2.3.1. Human activity and landscape disturbance threats

Threats were calculated from a series of spatial data on human activities and landscape disturbances. The human activities and landscape disturbances used for each threat were selected based on:

1. other existing geospatial tools for BC (DFO 2022),
2. a literature search on human contributions to the threats (Boyd et al. 2022), and
3. data availability.

Pathways of effects diagrams are provided for each of these threats, as in DFO (2022). All threat values were transformed either using $\log_{10}(x+1)$ or cube root transformation ($x^{1/3}$) based on which transformation provided a lower Fisher's moment coefficient of skewness. Transforming the scores before normalizing creates more equivalent weighting between scores that are based on different ranges of values (Halpern et al. 2008b). Scores were then scaled from 0–1 using the formula $z_i = (x_i - \min(x))/\max(x) - \min(x)$, where z_i is the normalized value, x_i is the i^{th} value in the dataset, min(x) is the minimum value in the dataset, and max(x) is the maximum value in the dataset. Individual and cumulative threat scores were generated for each stream reach of the FWA network for the FRB.

2.3.1.1. General data details

Human activity and landscape disturbance layers that were represented as grid cells (i.e., urban, agriculture, and rangeland) were at a 10 m resolution (Appendix C, Table C1). Other data layers were represented as vector inputs (points, polygons, and polylines), which were either rasterized at a matching 10 m resolution and summarized by the fundamental watershed unit (i.e., for in-stream habitat destruction, riparian disturbance, nutrients, pollution, and sedimentation), or applied to the FWA network as vectors and summarized by stream reach (i.e., for AIS, flow alteration, latitudinal fragmentation, and longitudinal fragmentation)

(Appendix C, Table C1). Rasters were applied as presence-absence. The forestry cut blocks layer combines forest harvest data from multiple sources, and does not include forest reserves (e.g., riparian buffers and wildlife trees) or uncut areas within the footprint of a cut block. For forest pest defoliation, we included forest insects and pathogens, and excluded animal damage (e.g., bears) and abiotic factors (e.g., fire). Only 'severe' and 'very severe' levels of forest pest defoliation were used to identify presence for input into the nutrients threat as increased nutrient export into streams from pest infestations tends to occur when there is limited vegetation and dominant decomposition of dead trees (Hélie et al. 2005). All severity levels were included for riparian disturbance as this threat is not specific to riparian function, and pest defoliation levels likely influence riparian functions differently (e.g., loss of shading vs. loss of filtering function). For identifying presence of rangeland, only grid cells from the land cover and land use dataset that overlapped designated pasture areas were used in the threat calculations (the land cover and land use dataset has a broader definition of rangeland that includes fires and other disturbances).

2.3.1.2. Aquatic invasive species

A common definition of AIS is a species that has been introduced outside of its natural habitat and can harm the environment, economy, or society (Commissioner of the Environment and Sustainable Development 2019). AIS can impact fish and fish habitat through a variety of mechanisms including predation, resource competition, disease transfer, and habitat alteration depending in part on their trophic position (Gallardo et al. 2016). Non-native species is a broader term for species that are not native to the region, irrespective of impact. Many non-native species may not have a detectable impact, or their impact may not be observed until some time after the invasion (Crooks 2005). However, the presence of multiple non-native species has frequently been found to facilitate their likelihood of survival and/or ecological impact (Braga et al. 2018), referred to as an 'invasion meltdown' (Simberloff and Von Holle 1999). Native species can also have predatory or competitive effects that may be detrimental to species of conservation concern; this was considered outside the scope of human-derived threats, but may be an additional limitation to recovery of at risk populations.

We used non-native species richness as a general metric of AIS threat as native species may be differentially affected, and detailed knowledge of the impacts of non-native species in Canada is lacking (Commissioner of the Environment and Sustainable Development 2019) (Fig. 4). We used observations of aquatic non-native species post-1980 from a compiled database that included 130 species of plants (n = 89), algae (n = 1), fish (n = 29), amphibians (n = 3), invertebrates (n = 6), and reptiles (n = 2) (Appendix C, Table C1). Point locations of aquatic non-native species are unlikely to capture their full extent within BC, so we created distribution polygons around point locations using a distance-based clustering method with a 10 km search radius (Fig. 5). We then counted the number of unique species in each fundamental watershed from the presence of a distribution polygons or outlying point location to obtain aquatic non-native species richness. These values were then rescaled from 0 to 1 and applied to each stream reach, where 0 indicates no estimated presence of non-native species and 1 indicates the highest number of non-native species.

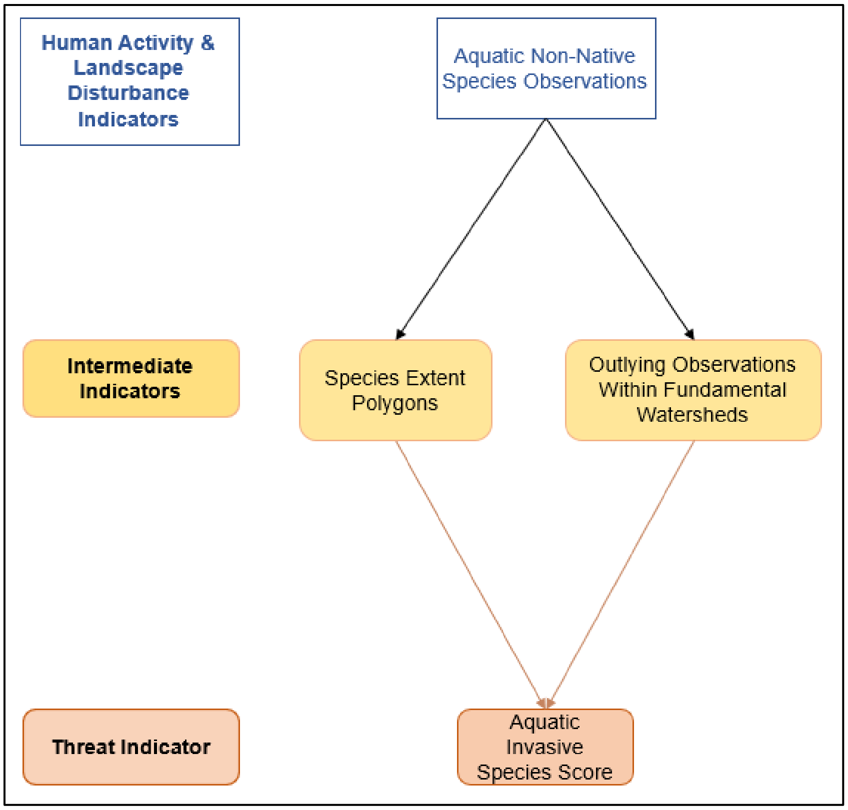

Figure 4. Aquatic Invasive Species threat Pathways of Effects diagram.

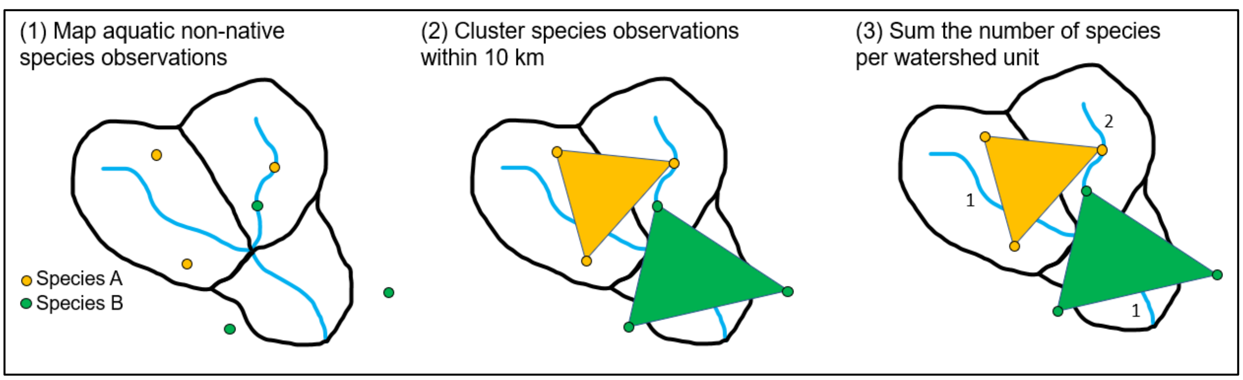

Figure 5. Method to calculate the Aquatic Invasive Species threat score from aquatic non-native species richness.

2.3.1.3. Flow alteration

Flow alteration is a form of habitat modification that is receiving increased attention owing to concerns of deleteriously low flows for fish under climate change conditions (Brice et al. 2021). This score focused on three primary sources of flow alteration: water extraction and dams owing to their potential to alter water quantity, and culverts from their potential to change flow velocities through restricted passageways (Merrill 2005; Graf 2006) (Fig. 6).

We included active water extraction licences, active dams (all regardless of barrier status), and culverts within each fundamental watershed for this threat. Scores were calculated for each of these human activities separately based on scaled values across the FRB and then were summed for a final score. Water extraction licences were scaled based on the maximum allowed water extraction; dams were scaled based on their height; and culverts were scaled based on culvert density within each fundamental watershed unit. Therefore, each activity was given similar weighting to each other, but based on their own relative values across the FRB. The flow alteration scores for each fundamental watershed unit were then applied to their corresponding stream reach. A score of 0 indicated no estimated flow alteration based on water extraction, dams, and culverts, and a score of 1 indicated the highest estimated amount of flow alteration from these activities. Maps of separate scores for flow alteration from change to water quantity and change to flow velocity are in Appendix D (Fig. D1).

Future iterations may consider additional approaches and inputs to this threat. For instance, water extraction licences generally correspond with higher flow streams (see Fig. 60a for example), and may be scaled based on stream discharge. The current non-scaled approach gives a higher score to licences with greater withdrawal allowances, but these may not have a greater effect on water if they correspond with larger streams. Water licences also currently included those for conservation purposes and may be excluded in future iterations as they can have a positive intended effect on fish habitat; however, details on the purpose of the conservation licence were not provided in the dataset. Another consideration is the upstream and downstream effect of dams and water extraction on flow. For instance, hydroelectric dams can alter downstream flow conditions over 100 km away (Ferencz et al. 2019). We did not have a generalized relationship for decay rates with distance from dams, but this warrants further development. In addition, forest disturbances including logging, pest defoliation, and fires also alter stream flow. Stand-replacing events (i.e., clearcutting or severe wildfire) often increase stream flow in the short term from a net decrease in canopy evapotranspiration, but seasonal low flows tend to decline over longer time periods (15–25 years post-harvest) as overstory canopy grows and evapotranspiration increases (Coble et al. 2020; Goeking and Tarboton 2020). Many of the reviewed studies on this topic are from historic forestry practices that do not retain riparian buffers; studies on flow responses to forest practices with buffer retention have found variable results and require more research to determine general mechanisms (Coble et al. 2020). Similarly, non-stand-replacing disturbances have had highly variable effects on flow depending on evapotranspiration from remaining understory (Goeking and Tarboton 2020). Forest disturbances can be included in future calculation of the flow alteration threat, though the currently used datasets for forest harvest and fires do not have information on the intensity of disturbance (pest defoliation does include intensity ratings).

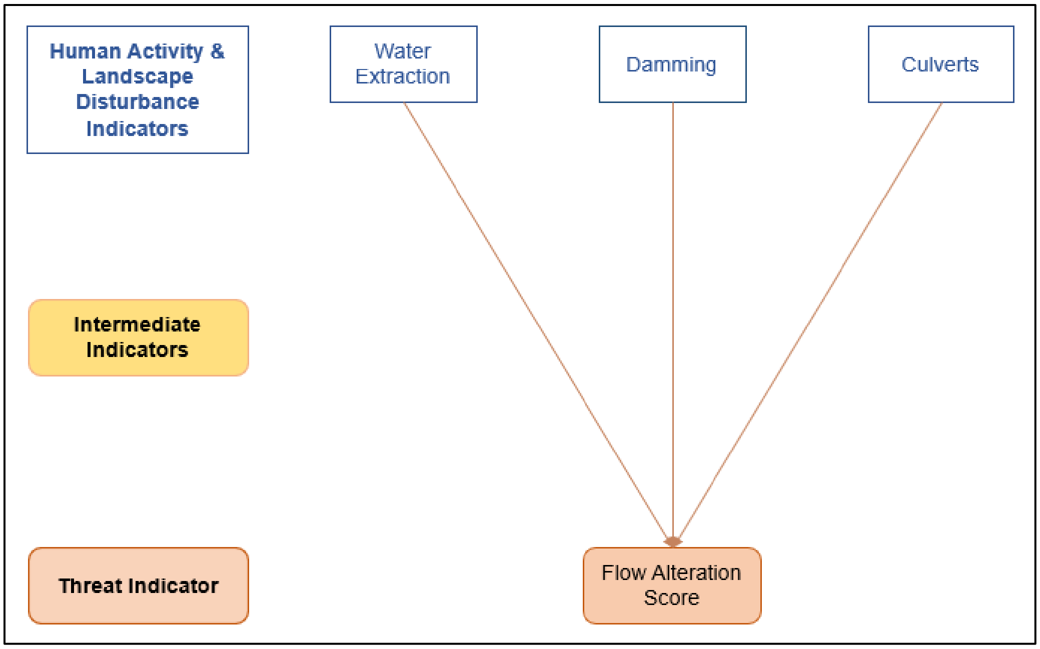

Figure 6. Flow alteration threat Pathways of Effects diagram.

2.3.1.4. In stream habitat destruction

In stream habitat destruction is a measure of habitat degradation that is specific to the water course. We accounted for human activities that overlapped with a raster of the stream network and/or a raster of the lake's surface area as potential for direct degradation of freshwater habitat (Fig. 7). We also included mining activities within 30 m of freshwater as mines can harm in-stream habitat from built infrastructure, as well as from direct mining operations within a stream (Nener and Wernick 1997). For instance, aggregate (sand, gravel, and rock) excavated from stream beds, particularly along the Fraser River, has been a primary mining commodity in BC (Rosenau and Angelo 2000). Sand dredging for channel navigation and construction uses has also been prevalent, especially along the lower Fraser River (Rosenau and Angelo 2000); however, geospatial information on dredging was not available. Culverts have direct in-stream effects, and road and railway crossings without culverts largely represented bridges which can have in-stream impacts from pillars and retaining walls, and from traffic or trains above. The inclusion of culverts captured many stream crossings, so all culvert grid cells were removed from the road and railway rasters when there was overlap. Private land was not included as a distinct human activity and landscape disturbance layer for the in-stream habitat destruction threat calculation. Disturbance within private land was captured by several other layers (e.g., urban land use, forest harvest). Private land was not considered beyond these layers as more specific spatial data on the human activities and disturbances within private land was not available.

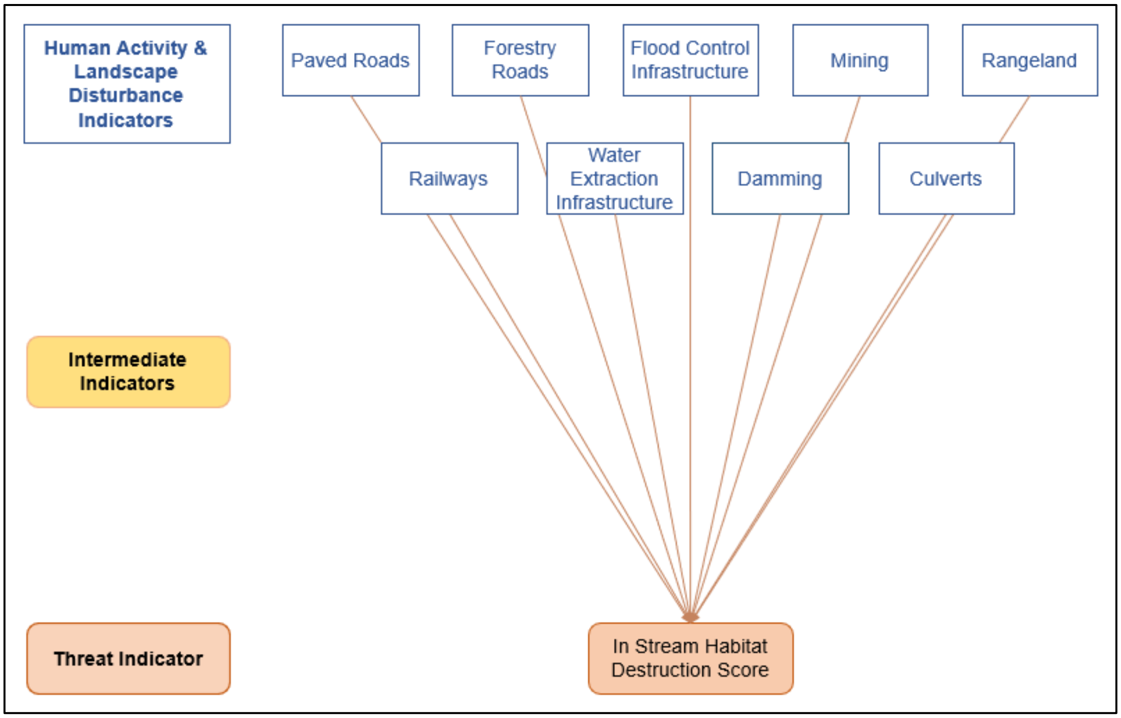

Figure 7. In-stream habitat destruction threat Pathways of Effects diagram.

To assess habitat destruction, a binary disturbance raster was produced by combining all the relevant activity rasters. The footprint of the stream network and lakes were then rasterized and used as a mask to only include the disturbed cells within the stream surface. The threat score was calculated as the proportion of the in-stream footprint that was disturbed (Fig. 8). A score of 0 indicated none of the stream footprint was estimated to be disturbed, and a score of 1 indicated the entire stream footprint was identified as disturbed.

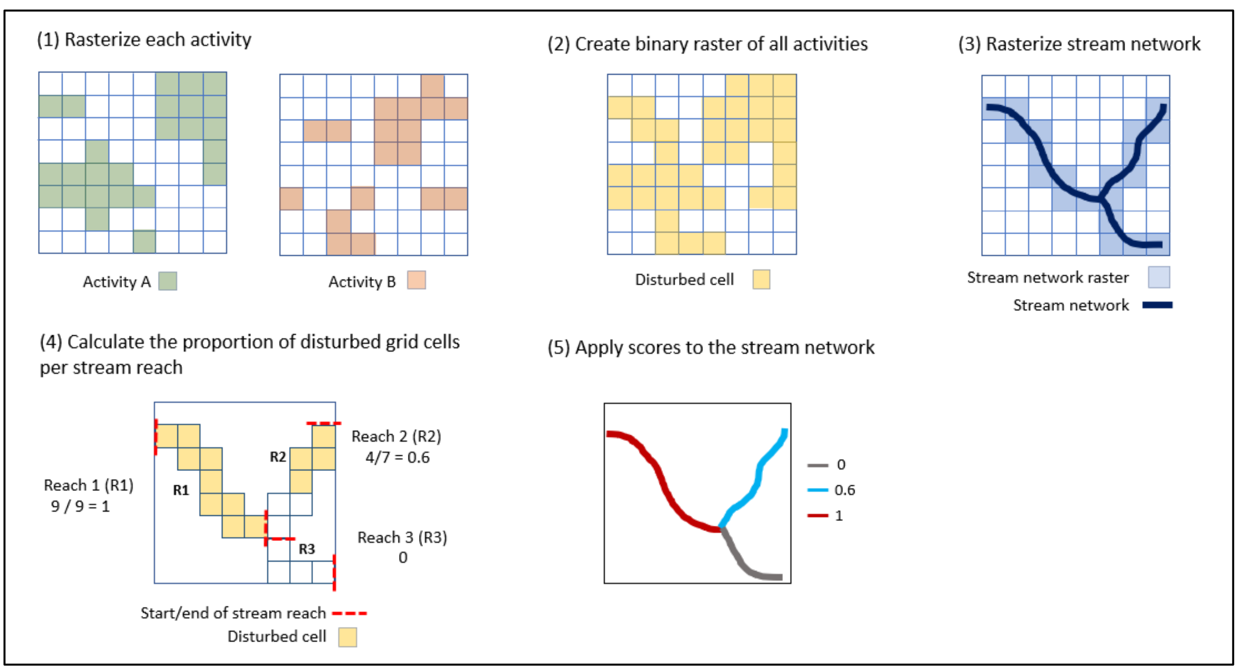

Figure 8. In-stream habitat destruction threat calculation.

2.3.1.5. Latitudinal fragmentation

The latitudinal fragmentation threat score accounted for the presence of flood control infrastructure (i.e., dykes and bank protection) that may cut off fish passage to floodplain habitat (Fig. 9). Floodplain habitat is important for rearing and overwintering juvenile salmonids (Brown 2002). To determine fragmentation for each stream reach, we created perpendicular transects spaced 150 m apart and extending 500 m on either side of streams along the network (Fig. 10). Flood control infrastructure within 500 m of the stream network was detected from intersections between the transects and the infrastructure polylines. We chose 500 m as a search distance from streams to flood control infrastructure based on visual inspection of the distance required to capture associated structure while not overextending to infrastructure associated with nearby streams. Extending this method to other basins may require different transect lengths; one approach could be to scale transect lengths based on stream order (i.e., stream size) with smaller transects applied to lower stream orders. When a transect intersected flood control infrastructure on both sides of a stream, we applied a score of 1, when it intersected on one side, we applied a score of 0.5, and no intersection received a score of 0. If there were multiple transects for a stream reach and they had different scores, the maximum score was assigned. Stream reaches that overlapped urban areas also were assigned a score of 1 to indicate complete lack of connection to floodplain habitat.

This score would be improved by accounting for the extent of floodplain habitat that has been made inaccessible. However, floodplains are generally continuous along the stream network, and delineating how much floodplain is associated with a given stream reach is a challenge. This is more computationally achievable when focusing on the floodplain habitat itself, delineated as spatial polygons (i.e., distinct units), and determining blockage to that habitat as a focal unit (Rebellato et al. 2022).

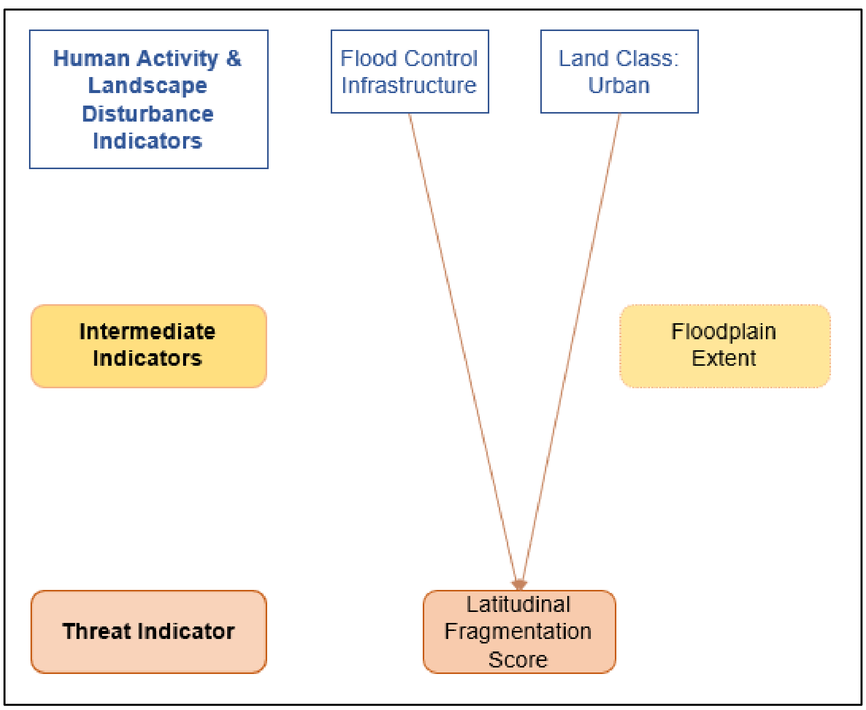

Figure 9. Latitudinal fragmentation threat Pathways of Effects diagram. Floodplain extent was not included in the scoring, but is indicated as important context for the score.

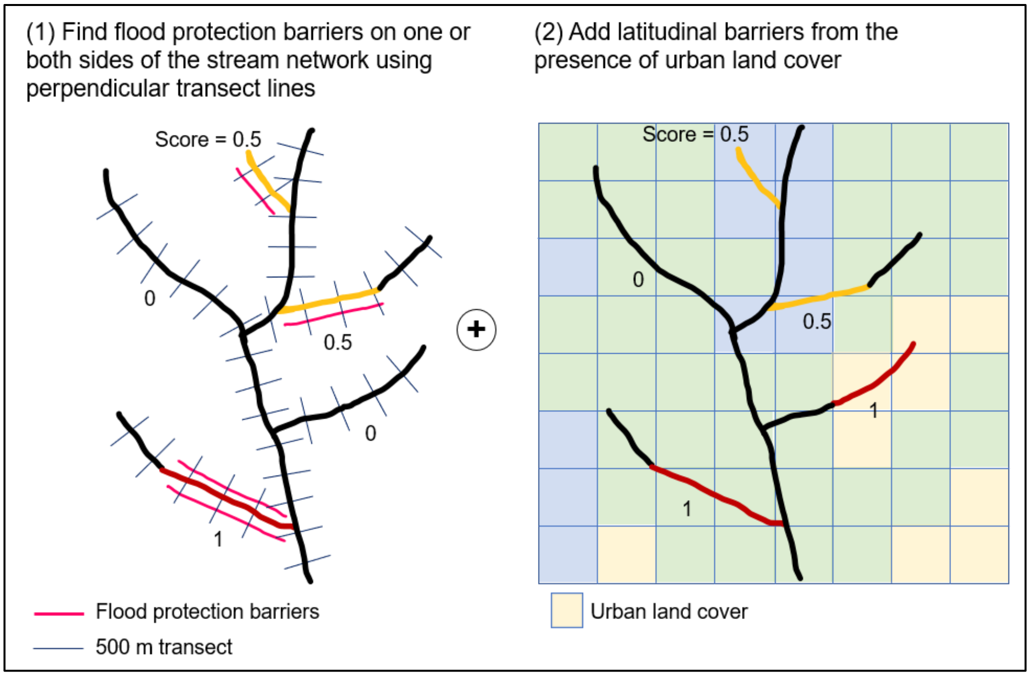

Figure 10. Method used to determine the association of barriers to floodplain habitat.

2.3.1.6. Longitudinal fragmentation

Longitudinal fragmentation represents barriers to fish passage upstream and downstream. We delineated longitudinal fragmentation separately for resident and anadromous species, as resident species can access habitat above barriers provided they were already there, whereas anadromous species need clear passage to and from the ocean. We included dams identified as full barriers as a human-made source of longitudinal fragmentation; these were defined as structures that impede the ability of fish to travel upstream[4]. We also accounted for natural barriers which included waterfalls ≥5 m in height, subsurface flows, other major barriers such as canyons, and stream reaches with gradients >15% (gradient included only for anadromous fragmentation) (Rebellato et al. 2022) (Fig. 11).

Culverts from rail, road, and trail stream crossings also create many barriers for fish throughout the FRB (Rebellato et al. 2022). For instance, 282 rail crossings in the FRB have been estimated to block 1,015 km of potential spawning and rearing habitat of anadromous salmonids (Rebellato et al. 2022). However, not all crossings create barriers; 81% of 18,000 closed-bottom road crossings have been found to be barriers to fish passage in BC (Mount 2017). Assessments of which culverts create full, partial, or no barriers are in progress (Rebellato et al. 2022). Dams identified as partial barriers (e.g., from the presence of fish ladders) may also present full blocks to passage depending on factors such as flow levels and species. Furthermore, low stream flows and seasonal stream disconnections can be important barriers that were not yet considered. We chose to only include barriers that were known to be full blocks as a first step towards representing their contribution to threats to fish and fish habitat across the FRB. Therefore, the longitudinal fragmentation scores are not a full representation of barriers to passage for resident and anadromous species. We recommend including dams identified as partial barriers and culverts either assessed as barriers or not yet assessed for evaluations focused on guiding field survey efforts to assess potentially important blocks to

[4] Canadian Wildlife Federation. Data Catalogue.

passage for mitigation or removal efforts. In particular, the Canadian Wildlife Federation is leading geospatial assessments and field surveys in BC focused on identifying important barriers to fish passage for mitigation and removal efforts. They have also developed other methods for assessing both longitudinal and latitudinal fragmentation (Rebellato et al. 2022)—for instance, identifying the benefits of removing series of barriers (N. Mazany-Wright, Canadian Wildlife Federation, pers. comm.)—that would be beneficial to explore for detailed evaluation of these threats.

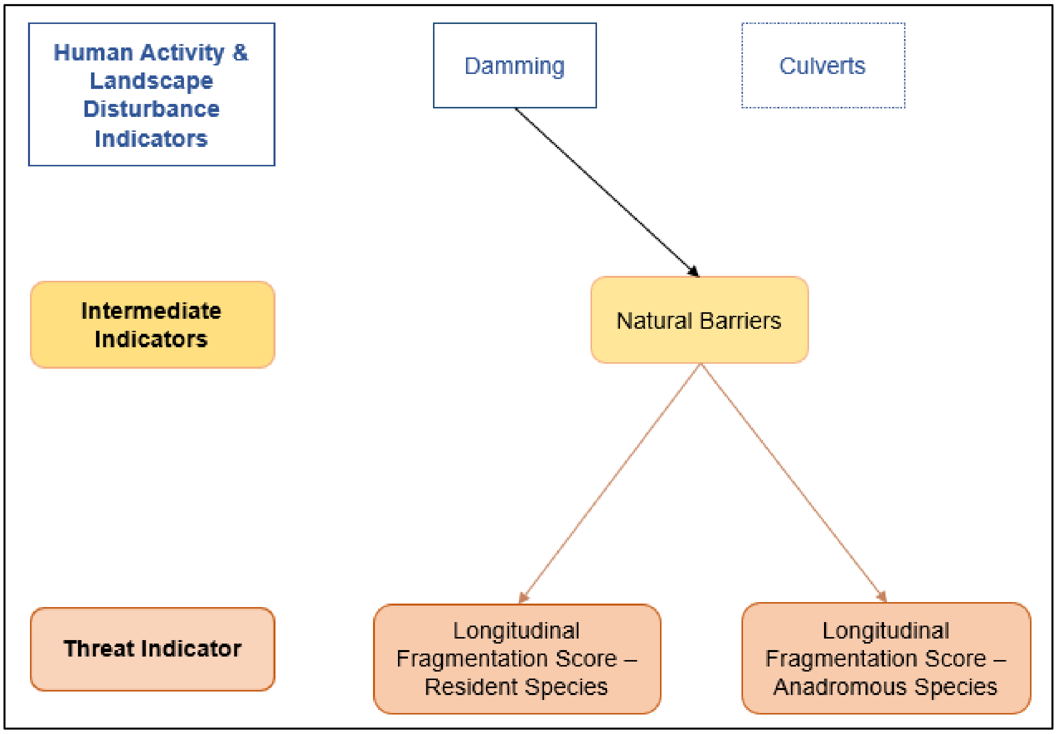

Figure 11. Longitudinal fragmentation threat Pathways of Effects diagram. Only dams identified as full barriers were included in this evaluation, though partial barriers may also present full blocks to passage. Culverts were not yet included for the FRB as they have not been fully assessed for blockages, but are known to create thousands of barriers in BC and are an important consideration for future threat estimation.

The focus of longitudinal fragmentation for resident species was from the perspective of habitat extent between barriers, with smaller habitat extents being more deleterious for a population. Longitudinal fragmentation for resident species was therefore calculated as the length of stream network that is accessible from each stream reach (i.e., the 'swimmable area'; Vörösmarty et al. 2010). We split the stream network at barrier locations (full barrier dams and natural barriers) within 50 m of the reaches (to account for positional error between the barrier and stream coordinates), then grouped all reaches that were connected in between barriers (Fig. 12). We next measured the total length of the connected reaches within each stream network patch. We calculated scores so that streams that were blocked only by natural barriers and had no association with dams were given a score of 0 as our focus was on human contributions to threats. To do this, we first assigned stream patches with no associated dams a connected length of the maximum patch length + 1. We then transformed and scaled the patch lengths (x) and took 1 - x. The final score was closer to 1 for stream reaches with less accessible length (i.e., smaller patches) owing at least in part to the presence of dams, closer to 0 for stream reaches with more accessible length, and 0 for streams blocked only by natural barriers. Dams associated with high stream reach scores (i.e., smaller patches) may be a priority for mitigation focused on resident species.

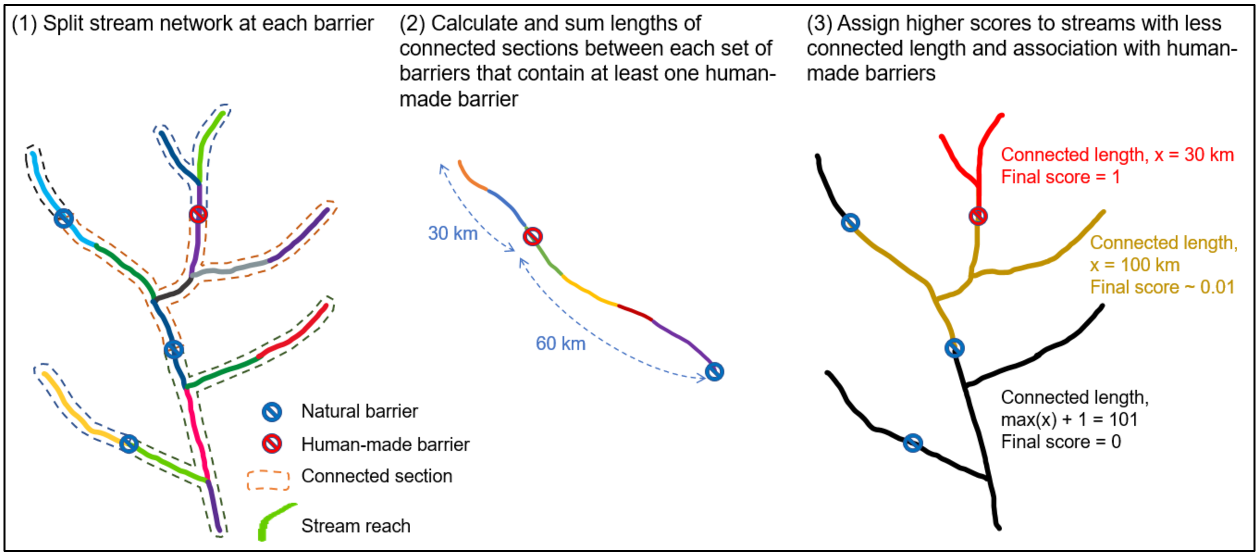

Figure 12. Longitudinal fragmentation for resident species based on accessible stream length between dams and natural barriers.

Longitudinal fragmentation for anadromous species had a different focus than resident species based on the directionality of migratory movement. This score focused on the first presence of a dam ('initial dam') that blocked passage from the ocean, with dams that blocked larger habitat extents being more impactful to anadromous species. The stream network was first split at dams and natural barriers within 50 m, as for resident species fragmentation (Fig. 12). All stream sections that were upstream of a natural barrier were given a score of 0, regardless of patch size or the presence of subsequent dams or natural barriers. These streams would naturally be inaccessible to anadromous species, whereas the score was focused on human-derived fragmentation. The fragmentation score was calculated as the total length of stream network (i.e., the patch size) that was blocked by an initial dam, up to the point of the next upstream dam, natural barrier, or headwater. This score was then applied to all upstream portions of the stream network. Patches created by dams upstream of initial dams (i.e., 2nd dam or more) were not scored separately as the initial dam is the one currently impacting anadromous migration and would first need to be mitigated before actions targeting the next set of dams would have any benefit for anadromous species. Future iterations can remove these initial dams if passage is restored, and then run the evaluation with a new set of initial dams. The final score was rescaled from 0 to 1 so that a stream reach with a score of 0 was below an initial dam or above an initial natural barrier; stream sections that had more length that had been blocked by an initial dam had scores closer to 1. This scoring system highlights initial dams that block anadromous passage to the greatest amount of upstream habitat (which may be limited further upstream by more dams or natural barriers).

An alternative approach is to calculate the full length of stream network blocked by successive dams (but downstream of natural barriers) for a total amount of stream network that is no longer accessible to anadromous species. This approach would place the focus on the full scope of the threat to fish habitat, which is in line with the overall cumulative threat assessment, but may reduce the ability to guide potential management responses based on the feasibility of addressing several dams at once. Therefore, for this iteration, we chose to apply a score that combined a focus on the threat to fish habitat with more feasible management implications.

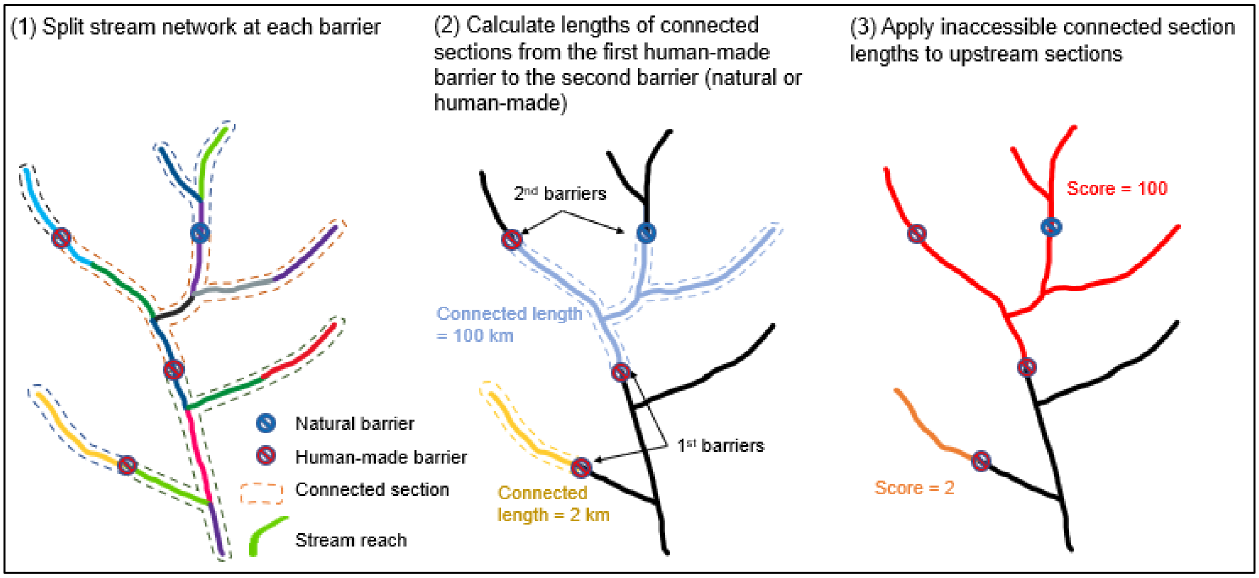

Figure 13. Longitudinal fragmentation for anadromous species based on blocked stream lengths above initial dams.

2.3.1.7. Riparian disturbance

Riparian areas are transitional areas between terrestrial and aquatic ecosystems with important ecosystem functions (Quinn et al. 2020). Riparian areas influence stream morphology, wood recruitment, and stream temperatures, as well as filter excess nutrients, pollution, and sedimentation (Quinn et al. 2020). We used 30 m from the water's edge to delineate the riparian buffer zone following current regulatory standards in BC (Riparian Areas Protection Regulation 2019, BC Reg 178/2019 s. 8; DFO 2020). Four of the primary data layers used to estimate riparian disturbance had timeseries (land use and land cover, forest fires, forestry cut blocks, and forest pest defoliation) (Fig. 14). We used the most recent year available for land use and land cover (2022) and the last 10–11 years available for the forest related datasets (fires: 2012–2023; cut blocks: 2012–2022; pest defoliation: 2012–2022) (Boyd et al. 2022); we chose to include the most recent year available for forest fires, but kept the same starting year (2012) to match the other forestry datasets. We selected a conservative 10 to 11-year inclusion cut-off for forest related inputs based on relevant literature suggesting returns to previous levels of nutrients and sedimentation within 6 years of forest disturbance (Jewett et al. 1995; Hélie et al. 2005; Silins et al. 2014; Palviainen et al. 2015; Nasirzadehdizaji and Akyuz 2022). This was directly relevant for our calculation of nutrient, pollution, and sediment loading (see 'Nutrients, Pollution, and Sedimentation: Flow Accumulation Calculations'). However, disturbed riparian buffers are not expected to return to full functionality within a decade. In particular, the riparian function of contributing large woody debris to streams has been modeled to peak after 70 years of regrowth for hardwoods and increases for at least 100 years after regrowth of conifers (Beechie et al. 2000). A fully comprehensive assessment for riparian disturbance would include multiple timeframes for evaluation to capture other important functions (Quinn et al. 2020).

We used 30 m from the water's edge to delineate the riparian buffer zone following current regulatory standards in BC (Riparian Areas Protection Regulation 2019, BC Reg 178/2019 s. 8; DFO 2020). Data inputs included all publicly available spatial footprints for human activities along riparian buffer zones within the FRB. Urban land cover captured multiple types of disturbances within buffer zones, including various processing facilities (e.g., pulp and paper mills). Urban land cover and forestry footprints also included many disturbances that may occur on private land. Parts of southern BC and Vancouver Island are subject to the provincial Riparian Areas Protection Regulation for residential, commercial, and industrial activities within 30 m of freshwater, which requires setbacks from riparian areas for development unless an environmental assessment deems the development will not harm riparian fish habitat (Ministry of Forests, Lands and Natural Resource Operations 2016). Private land not subject to this Regulation (e.g., northern watersheds in the FRB) may have activities within riparian zones that could not be captured.

We used a similar process for the riparian disturbance threat calculation as for in-stream habitat destruction. A binary disturbance raster was produced by combining all relevant human activity and landscape disturbance rasters (Fig. 14). The riparian buffer zones of the stream network and lakes were then rasterized and used as a mask to only include the disturbed cells located within 30 m. The threat score was calculated as the proportion of the riparian buffer zone footprint that was disturbed, where a score of 0 indicates no disturbance and a score of 1 indicates 100% disturbance (Fig. 15).

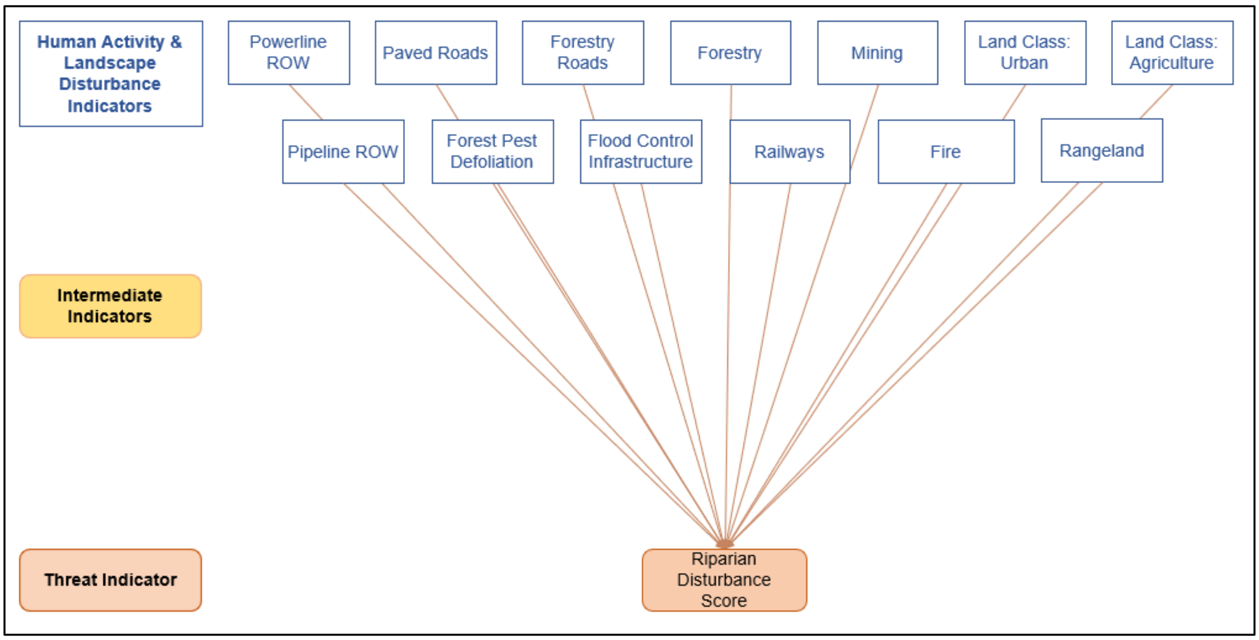

Figure 14. Riparian disturbance threat Pathways of Effects diagram. ROW is right of way.

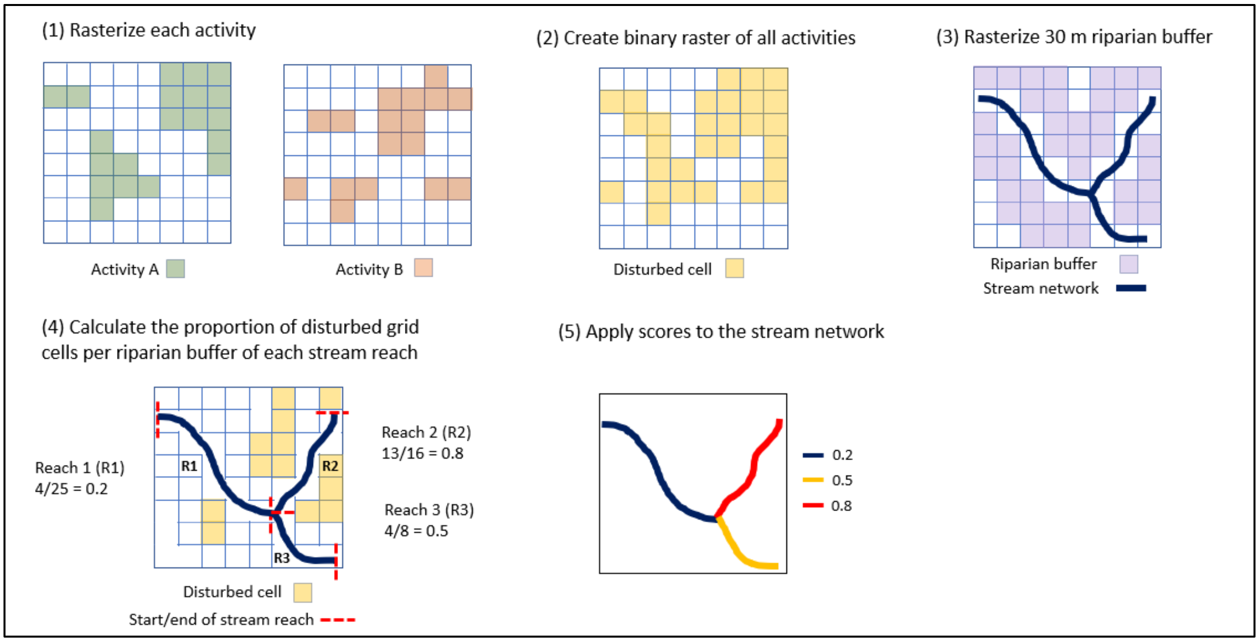

Figure 15. Riparian disturbance threat calculation.

2.3.1.8. Nutrients, pollution, and sedimentation: flow accumulation calculations

Input of nutrients, pollution, and sedimentation into streams from human activities and landscape disturbance can greatly harm fish and fish habitat. Excess nutrients can cause eutrophication and lead to algal blooms and die offs that deplete DO for aquatic organisms. For instance, 40% of Salish Sucker critical habitat has been estimated to experience hypoxia from interactions between low stream flow, high stream temperatures, and eutrophication (Rosenfeld et al. 2021). Pollution in freshwater can impair growth, immune system function, osmoregulation, and lead to increased stress and mortality of fish (Ross et al. 2013). Anadromous salmonids are considered especially vulnerable owing to diverse exposure to contaminants as they use different habitats across their life stages, and to their inherent sensitivity to toxins relative to other fish species (Ross et al. 2013). Excess sedimentation from human activities and landscape disturbance also reduces egg-to-fry survival of salmonids by suffocating and entrapping eggs laid in the gravel of stream beds (Jensen et al. 2009).

We calculated the loading scores using estimated concentrations of human-derived nutrients, pollution, and sedimentation based on best available information using a series of steps to account for key mechanisms: nonpoint source inputs based on land use classes and surface runoff rates, point source inputs, riparian filtering function, downstream accumulation, and dilution based on stream flow (see ‘Climate Change Threats: Stream Flow” for details on surface runoff and stream flow data) (Fig. 16). The approach applied here represents an estimation of the maximum load as it does not consider finer-scale processes that could reduce the in-stream load (e.g., settling, retention, uptake). In addition, the generalized relationships applied (e.g., riparian filtering function) likely better distinguish higher and lower values, whereas various sources of error may create more uncertainty for mid-range values.

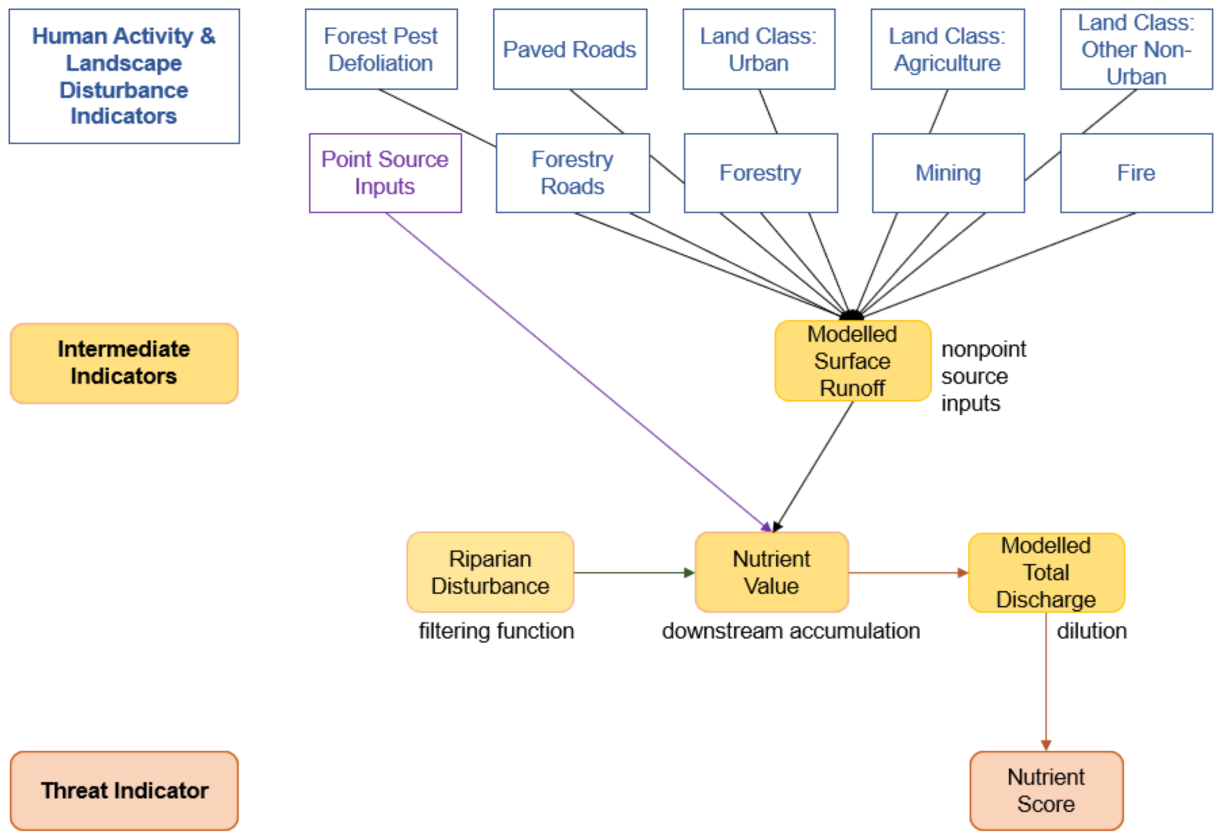

Figure 16a. Pathways of Effects diagram for nutrient loading. Point source inputs for nutrients contained values from human activities including mines, pulp and paper mills, PCB owners, seafood processing facilities, solid waste, spills, wastewater treatment plants, wood waste, and other commercial facilities as identified in a compiled database (ECCC 2022).

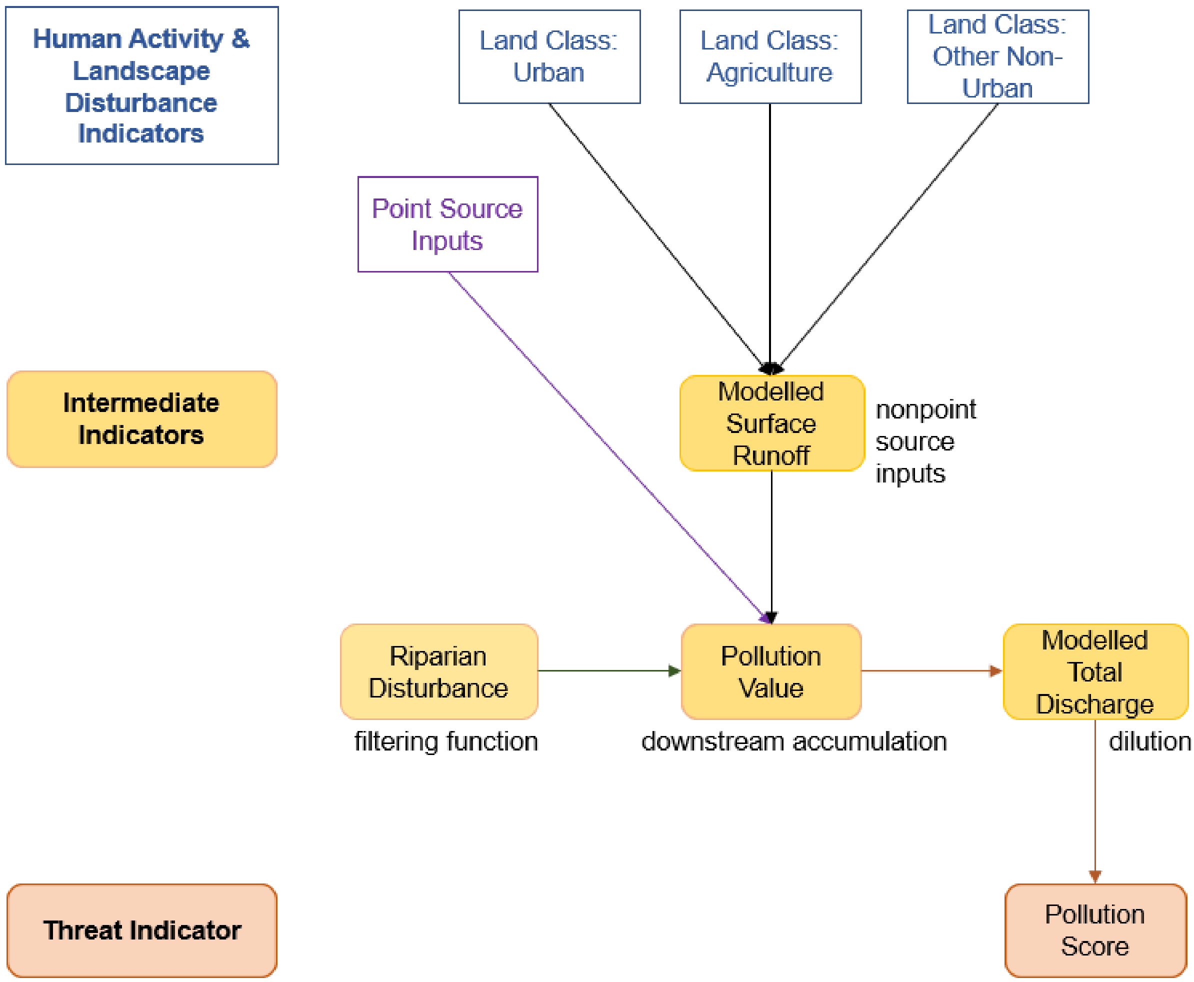

Figure 16b. Pathways of Effects diagram for pollution loading. Point source inputs for pollution contained values from human activities including mines, pulp and paper mills, PCB owners, seafood processing facilities, solid waste, spills, wastewater treatment plants, wood waste, and other commercial facilities as identified in a compiled database (ECCC 2022).

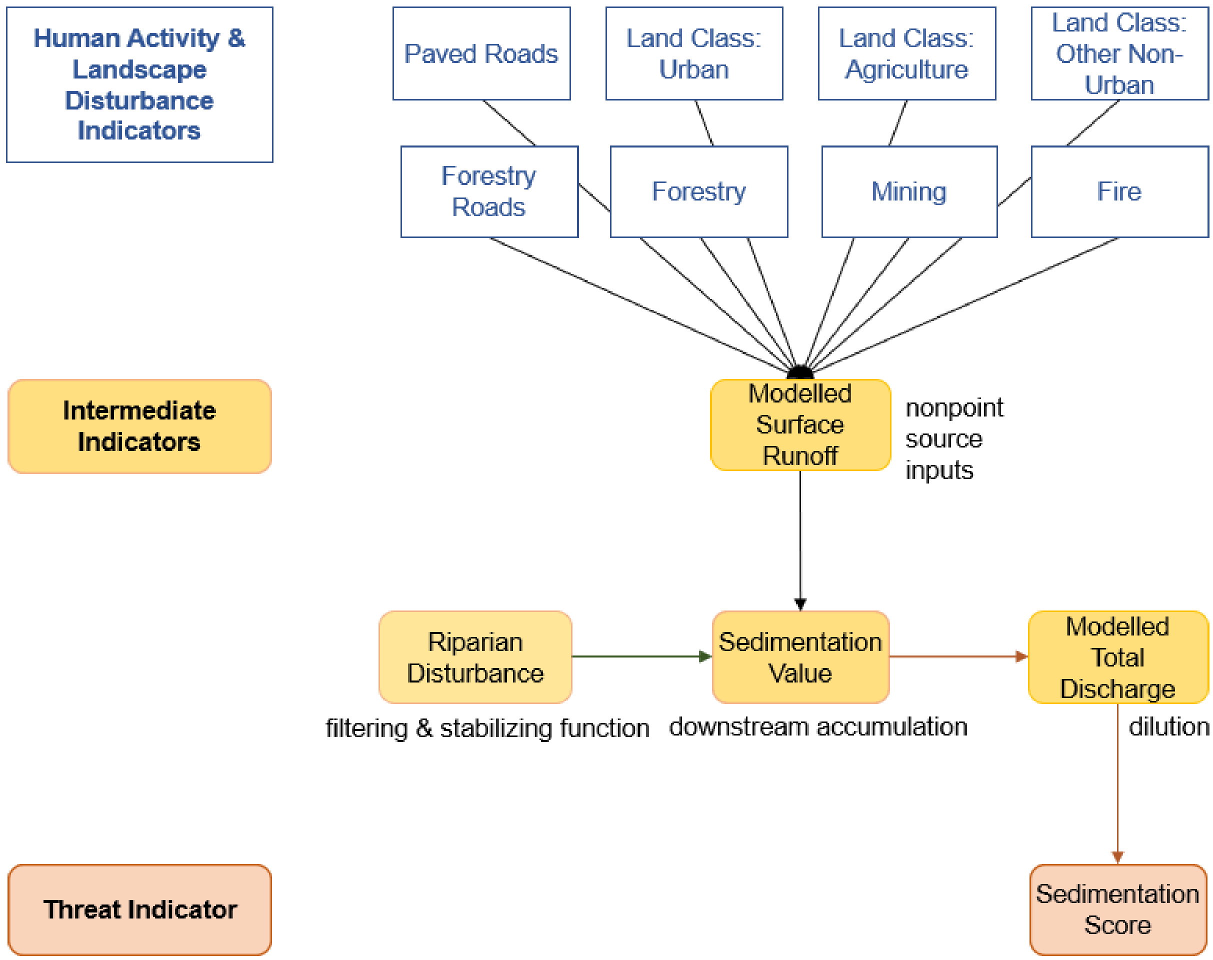

Figure 16c. Pathways of Effects diagram for sediment loading.

First, nonpoint source inputs were calculated using concentration coefficients applied to land use classes of agriculture, urban, and other non-urban provided by PAWPIT from their literature review; concentration coefficients were summed across relevant contaminant inputs for nutrients and pollution (ECCC 2022) (Fig. 17, step 1). We conducted an additional literature search to add nonpoint source concentration coefficients for nutrients and sedimentation, and for further human activity and disturbance classes (Table 1); we did not find additional nonpoint source coefficients for pollution. Forestry cut blocks, forest fires, and forest pest defoliation were all given an estimated coefficient for nutrients of double the PAWPIT coefficient for 'other non-urban' as each of these forest-related disturbances can have similar and relatively high impacts on nutrient runoff into streams (Hélie et al. 2005; Donahue 2013; Silins et al. 2014). The actual amount of nutrients that are exported into streams from forest disturbance depends on factors including the amount of remaining vegetation, regrowth, and nitrogen status of the forest (Hélie et al. 2005; Silins et al. 2014). For instance, a 7–9-fold increase in total phosphorus (TP) was found following a severe wildfire in Alberta (Silins et al. 2014), and a 1–2-fold increase in nitrogen resulted from intense fire loss in the Sierra Nevada Mountains, US (Johnson et al. 1997; Donahue 2013).

We created a single land cover dataset for the FRB using all of the relevant human activity and landscape disturbance layers for the nutrients threat; the suite of nutrient inputs included all of the inputs used for the sedimentation and pollution threats. Land cover types that were not included as an input for a threat (e.g., forestry was not an input for the pollution threat) were treated as ‘other non-urban’ for the calculation of that threat. Spatial overlaps in different rasterized land classifications within grid cells (e.g., mines and roads) were resolved through a prioritization sequence based on the scale of the features in the data layer (e.g., roads were finer scale features than agriculture, so roads were prioritized). Any overlap in the forest-related inputs—which included multiple years of data—were resolved as: forestry > pests > fire. This prioritized the inclusion of human activities over landscape disturbances (e.g., forestry would be included even if the location also experienced pest defoliation or fire). Since coefficients were the same across forest disturbance categories (except for no known coefficient for pest defoliation into sedimentation), this only affected our calculation of proportion contributions of each disturbance to these threats.

The proportion of each land cover type within a fundamental watershed was used to partition the mean total annual surface runoff rates (based on modeled climate averages from 1981–2010; see full details of stream flow models in ‘Climate Change Threats: Stream Flow’), which was then multiplied by the corresponding concentration coefficient (Fig. 17, step 2). We excluded water surface area (lakes and rivers) from the proportion calculation as area that does not contribute to nonpoint source runoff. This provided an initial estimate of the nonpoint source surface runoff contribution by land cover type.

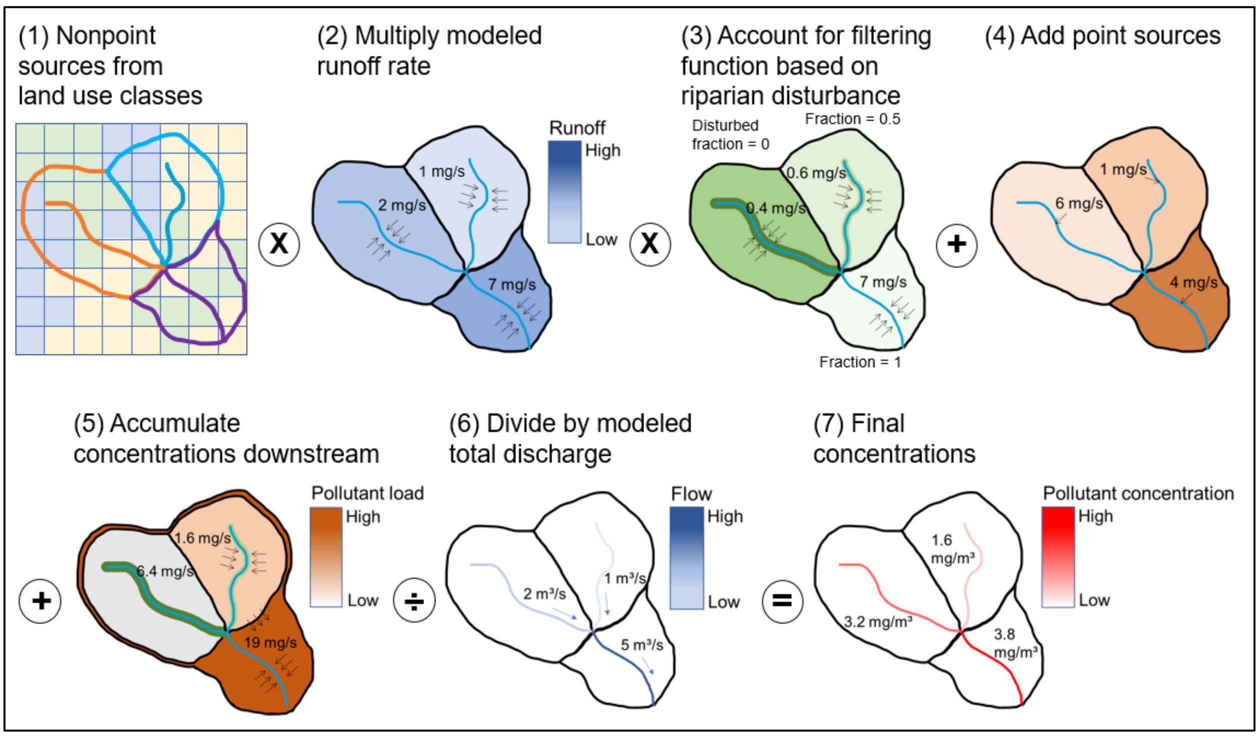

Figure 17. Flow accumulation steps used to estimate nutrient, pollution, and sediment inputs into streams from human activities and landscape disturbance.

Table 1. Concentration coefficients used to calculate contributions of nonpoint sources of nutrients, pollution, and sedimentation runoff into streams in BC.

Nonpoint Source	**Nutrients**	**Pollution**	**Sedimentation**	**References**
Land use class				
Agriculture	35.33	0.2834	86.2	ECCC (2022)
Urban	2.054	0.5292	31.2	ECCC (2022)
Other Non-Urban	0.64	0.032	13.6	Donahue (2013), Silins et al. (2014), ECCC (2022)
Human activities and landscape disturbance				
Forest Fires	1.28	NA	20.4	Hélie et al. (2005), Donahue (2013), Silins et al. (2014)
Forestry Cut Blocks	1.28	NA	20.4	Donahue (2013), Silins et al. (2014)
Mining	1.33	NA	93.94	Donahue (2013), ECCC (2022)
Forest Pest Defoliation	1.28	NA	NA	Hélie et al. (2005), Donahue (2013)
Roads	12.425	NA	50.65	Donahue (2013)

We then approximated the ability of riparian buffers to filter nonpoint source inputs using the fraction of disturbed riparian area from the riparian disturbance threat calculation (Fig. 17, step 3). Removal efficiency is determined largely by buffer width, but is also influenced by topographic slope and vegetation type (Quinn et al. 2020). A previously published nonlinear equation of removal efficiency based on buffer width ($E_R = a + b \ln(width)$) was found to have a descriptive power (R^2) of up to 0.37 for sediment, 0.44 for nitrogen, 0.39 for phosphorus, and 0.61 for pesticides (Zhang et al. 2010; Quinn et al. 2020). A 30 m riparian buffer corresponds with an estimated average removal efficiency of approximately 95% for sediment, 80% for nitrogen, 99% for phosphorus, and 99% for pesticides (Quinn et al. 2020). We did not account for topographic slope and vegetation type as these influences are complex and fine scale vegetation data would need to be acquired through sources such as Light Detection and Ranging (LiDAR), though this aspect could be incorporated in future, smaller-scale models. In this iteration, we only accounted for whether the riparian buffer had been disturbed by human activities based on the 30 m buffer width. We used the fraction of disturbed riparian area within the fundamental watershed and considered a fraction of 0 (i.e., no disturbance) to have a filtering capacity of 80% based on a conservative filtering efficiency for a healthy, 30 m wide riparian buffer (Quinn et al. 2020) and a fraction of 1 (i.e., full disturbance) to have no filtering capacity. This scaling from 0–80% was multiplied by our input concentrations so that an undisturbed riparian buffer filtered 80% of estimated inputs and a completely disturbed buffer had no filtering function.

Point source inputs were compiled by PAWPIT and included human activities of mines, pulp and paper mills, PCB owners, seafood processing facilities, solid waste, spills, wastewater treatment plants, wood waste, and other commercial facilities (ECCC 2022). Contaminated sites from the Federal Contaminated Sites Inventory were also evaluated by PAWPIT, but contained insufficient data to quantify releases (ECCC 2022). Concentrations of nutrients and pollution from point sources as identified by PAWPIT (ECCC 2022) were summed for each fundamental watershed (Fig. 15, step 4); nutrient point source inputs included ammonia, nitrates, and phosphates, and pollution included all other inputs except for those identified as 'other toxins' (ECCC 2022). The other toxins category included sedimentation input, which could not be differentiated from other inputs, so we did not include point sources of sedimentation. We explored the ability to identify the likelihood of pollutants to travel downstream versus settle in sediment (e.g., using octanol/water partition, logK_{OW}, or organic carbon partition coefficient, K_{OC}) (Quinn et al. 2020). This information was not readily available for many pollutants, but would improve future pollution estimation.

In the next step, we calculated the accumulated nutrient, pollution, and sedimentation loads for each stream reach by identifying and summing the loads for all fundamental watersheds within the catchment (Weller et al. 2023) (Fig. 17, step 5). We accounted for dilution of inputs by dividing each accumulated loading by modeled mean total annual stream flow for the historical time period (Vörösmarty et al. 2010) (Fig. 17, step 6; see full details of stream flow models in 'Climate Change Threats: Stream Flow'). This resulted in the final estimated load, where a score of 0 indicated no estimated load and a score of 1 indicated the highest estimated load across the FRB (Fig. 17, step 7).

The point and nonpoint source concentrations used here were the best available at the time of data collection. The nonpoint source contribution information is particularly known to have gaps as this was obtained from relatively limited literature and had required including studies in other parts of western North America (ECCC 2022). Concentration coefficients for some inputs may be missing for different land classes due to a lack of data, in which case the total input estimated for these land classes would be underrepresented. Another consideration is that the concentration coefficients for nonpoint sources are dependent on the surface runoff characteristics from the corresponding studies and may not fall within the bounds of the modeled runoff applied here; this mismatch could occur from seasonal or yearly variation. Addressing seasonal mismatch is not directly feasible without developing a seasonal timeseries of coefficients. Yearly mismatch can be somewhat addressed by matching modeled runoff using the same timeframe as that bounding the study dates, though this may be limited by available flow models. PAWPIT developed their own flow model to pair with the nonpoint source coefficients; however, we used different available models so that we could match both runoff and discharge estimates (see details in 'Climate Change Threats: Stream Flow'). These data are continuously being improved and using updated input data and flow models as they become available is recommended for future iterations of these threat scores. Finally, pollutants vary in their degree of impact to fish and the concentration at which they start to have an impact. For example, PAWPIT identified priority contaminants for Chinook to focus on those most likely to cause harm (ECCC 2022). This delineation is an important consideration for next phases of applying the pollution loading scores to estimate the effect of pollutants on fish.

2.3.2. Climate change threats

Climate change is creating shifts in long term average conditions and in the frequency and magnitude of extreme events which has multiple, interacting effects on fish and fish habitat. The primary climate-related variables of concern for fish and fish habitat are stream temperature and stream flow. Changes in air temperature and precipitation directly impact stream temperature and flow, and influence other driving forces that further affect these two variables such as forest fires (Beyene et al. 2022), glacier retreat (Pitman et al. 2020; Weller et al. 2023), and reduction of snowpack (Mote et al. 2003). Hydrologic droughts and floods are extreme events related to flow that have increased over recent years in the FRB and are expected to worsen (Brice et al. 2021). Earlier and longer hydrologic droughts are expected with reduction in cool-season precipitation stored as snowpack (Islam et al. 2017). Floods occur when there is a combination of high, spring-season flows and extreme precipitation events (Brice et al. 2021). Reduced precipitation as snow is expected to lead to more rapid, frequent, and earlier floods, followed by more severe summer droughts that may occur in the same year (Brice et al. 2021).

We compiled the best available and spatially comprehensive models of climate change related threats for flood risk, low and high stream flow, and high (i.e., summer) stream temperatures. Modeled projections represented climate averages (20–40 year averaged periods), and we present results for up to 2060 as a relevant timeframe for management (Dey et al. 2023). Predicted changes in fish habitat in BC based on stream temperatures and precipitation also show most of the change over the next century occurring by 2060 under Representative Concentration Pathway (RCP) 4.5 (Iacarella and Weller 2023; Weller et al. 2023). We provided separate scores for a 'middle of the road' and 'worst case' future climate scenarios using scenarios and Global Climate Models (GCMs) from Phase 5 and Phase 6 of the Coupled Model Intercomparison Project (CMIP5 and CMIP6, respectively). The 'middle of the road' scenario used RCP 4.5 (from CMIP5) or Shared Socioeconomic Pathway (SSP) 2–4.5 (from CMIP6). The 'worst case' scenario used RCP 8.5 or SSP5–8.5. Hereafter, the 'middle of the road' and 'worst case' scenarios are referred to as RCP 4.5 and RCP 8.5 for simplicity. Threat scores for each climate scenario were calculated using an ensemble average of climate projections from multiple GCMs; the set of GCMs included in the ensemble for each threat varied based on data availability (Appendix E). Other assessments of climate change effects (e.g., climate change vulnerability analyses) can also characterize projected variability or deviations from the mean when a higher temporal resolution is modelled, but we selected high spatial resolution over temporal resolution for our focus on stream reaches. The compiled models incorporated multiple elements of climate change effects (e.g., stream temperatures influenced by air temperature, precipitation, and glacier cover), but do not currently include all interacting climate-related effects (e.g., wildfires) or explicitly include interacting human-related threats (e.g., water extraction, riparian disturbance) (Schnorbus 2020; Mohanty and Simonovic 2021; Weller et al. 2023).

Climate change threat scores were transformed and scaled using the same methods as the human activity threat scores.

2.3.2.1. Flood risk

Flood risk was estimated as modeled overland water level (m) for streams within the overland inundation extent provided by Floodmapviewer (Mohanty and Simonovic 2021; Simonovic et al. 2023). Mohanty and Simonovic (2021) applied a catchment-based macro-scale flood model to Canada and downscaled resulting floodplain maps to a 1 km^2 resolution. Floodmapviewer was also used by DFO in fish and fish habitat reporting for the Ontario and Prairie Region using 100 and 200 year return periods (Dey et al. 2023). We focused on the 100 year return period under the CMIP6 ensemble of GCMs for RCP 4.5 and RCP 8.5 (Appendix E). For this threat, we calculated the change in overland water level between current conditions (1980–2019) and the projected time period of 2022–2060. We mapped raw change values, and used the absolute values of change for the cumulative threat scoring as either extensive increases or decreases in flood level can have negative impacts to fish habitat. A score of 0 indicated no projected change in flood levels and a score of 1 indicated the greatest amount of projected change (either increasing or decreasing in flood level) across the FRB. It is important to note that flood risk modeling has high levels of uncertainty and there are additional metrics, (e.g, other return periods, shifts in return period for a given magnitude of flood event) that would be beneficial to consider provided further development of such modeling efforts.

2.3.2.2. Stream flow

Stream flow is modeled using mechanistic hydrological models. The stream flow model outputs we used are from the Pacific Climate Impacts Consortium (PCIC) using a Variable Infiltration Capacity (VIC) model that incorporates components of runoff, evapotranspiration, and changes in water storage from snow, glaciers, soil, groundwater, and lakes; the glacier component was added by PCIC and accounts for glacier accumulation, melt, runoff, and change in glacier area (VIC-GL) (Schnorbus 2020). The VIC-GL model has been produced for gauged river basins in BC that drain to tide water and has a gridded resolution of 1/16° (approximately 30 km^2). Modelled total runoff and runoff components (e.g., surface runoff, baseflow, glacier outflow, etc.) are available as daily timeseries projected from 1945–2100 under multiple climate change scenarios.

Given our focus on stream reach resolutions, we used the VIC-GL model outputs for baseflow and surface runoff downscaled to the resolution of fundamental watersheds for the FRB. Downscaled surface runoff rates for fundamental watersheds were used in estimation of nonpoint source loads for the flow accumulated threats. Downscaled baseflow and surface runoff were summed and accumulated downstream to predict discharge (stream flow). The downscaling process required reducing the temporal resolution to monthly timescales to reduce inaccuracies. Ongoing work by PCIC to be delivered in 2026 will provide flow outputs at the resolution of fundamental watersheds for the same extent as the VIC-GL model, allowing further analysis with finer temporal resolutions.

The downscaling process was developed and conducted for DFO by Foundry Spatial, a software development company focused on water sustainability and hydrology research. We detail the downscaling method for stream discharge here for clarity (surface runoff was downscaled with the same method, but did not consider the upstream catchment or account for flow regulation).

First, the VIC-GL gridded daily baseflow and surface runoff variables were added to create gridded daily runoff in mm. The runoff grid was subset to the FRB extent and summarized as minimum, maximum, and mean total monthly, seasonal, and annual flow calculated across the historical period of 1981–2010. These summary gridded runoff values were then assigned to the fundamental watershed units based on the centroid of the watershed. Second, a gridded precipitation climatology (mm) for the historical period (1981–2010) from ClimateNA (400 m^2 grid) was assigned to the fundamental watershed units.

The downscaling method was to generate the minimum, maximum, and mean runoff for each fundamental watershed unit (Fig. 18). The method assumes that the spatial variability of precipitation is proportional to the variability of the PCIC downscaled runoff values. The equation for the downscaled gridded values (Yi) is:

$$Yi = r + (Xi - m1)$$

where m1 is the mean precipitation (mm) across a VIC-GL grid cell, r is the runoff value (mm) of the VIC-GL grid cell, and Xi is the mean precipitation (mm) of the watershed unit. In the case of transformed negative values (1–14% of watersheds depending on the month), the lowest positive transformed value within the VIC-GL grid cell was used instead. The runoff for each watershed unit was converted to a rate (m^3/s) using the watershed area and the unit of time (month, season, or annual). Stream discharge was then calculated by accumulating all runoff rates of the upstream watershed units within the catchment basin (Fig. 18).

Monthly stream flow estimates were adjusted for fundamental watersheds associated with six dams where flow regulation was tracked by nearby hydrometric stations with measurements post-1980. This was completed for

1. Skins Lake #3 Dam (a.k.a. Saddle Dam) at the Nechako Reservoir outlet,
2. Seton Main Dam at Seton Lake outlet,
3. Walden Power Dam at Cayoosh Creek,
4. Alouette Dam using a gauge on Alouette River 12 km downstream,
5. Coquitlam Dam using a gauge on Coquitlam River 12 km downstream, and
6. La Joie Dam at the Downton Lake outlet.

A correction factor was applied to the modeled streamflow estimates at the fundamental watersheds associated with these dams to adjust the modeled streamflow estimates to match the observed regulated streamflow. These regulation corrections were applied to the full time series of climate projections. The Nechako River fundamental watershed units between Kenney Dam and where the Cheslatta River meets the Nechako River were removed as there are engineered modifications to the drainage of the Nechako Reservoir into the Nechako River; these watershed units in the FWA are no longer accurate and were removed from the full analysis (n = 26).

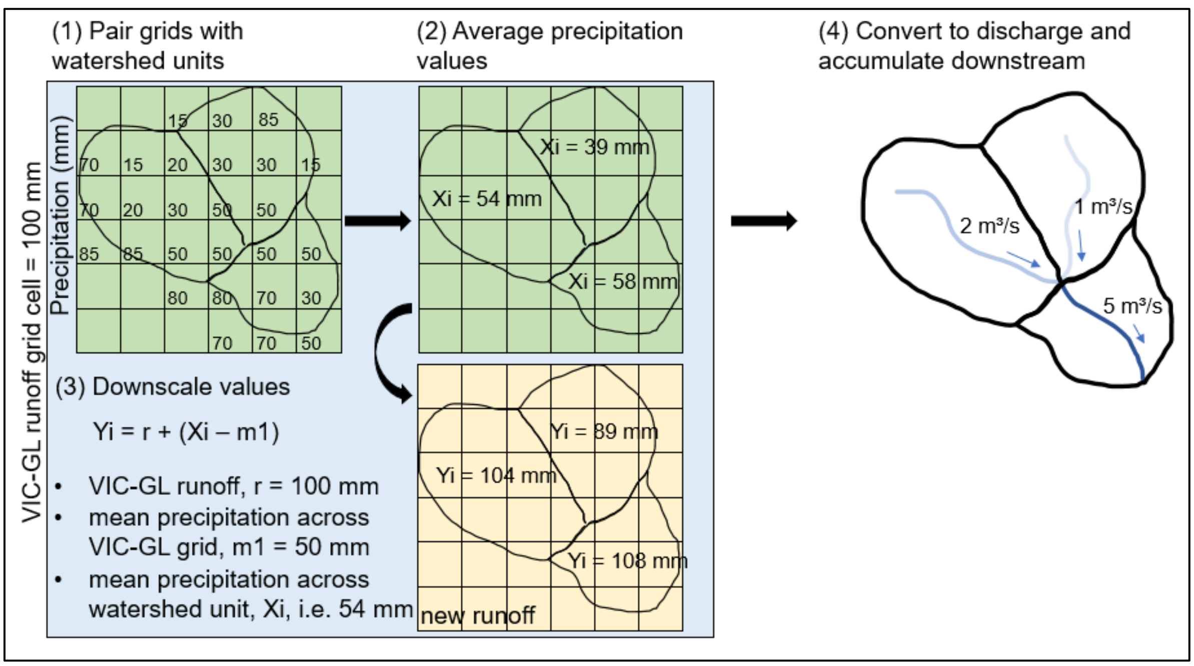

Figure 18. Method for downscaling stream runoff and assigning flow values to fundamental watersheds. (Foundry Spatial). Downscaled gridded values (Yi) are calculated from the runoff value (mm) of the VIC-GL grid cell (r), the mean precipitation (mm) across a VIC-GL grid cell (m1), and the mean precipitation (mm) of the watershed unit (Xi).

The downscaling process was applied to available layers for climate projections and produced as summaries of minimum, maximum, and mean total monthly, seasonal, and annual flow across climate average 20-year time periods (2020–2040, 2040–2060, 2060–2080, 2080–2100) using RCP 4.5 and 8.5 under six CMIP5-era GCMs (Appendix E).

Foundry Spatial compared downscaled results to the original PCIC VIC-GL model outputs, as well as to observed flow rates at 86 gauge stations across the FRB (Appendix F). Performance metrics comparing downscaled results to VIC-GL layers at the gauge stations across months indicated a high degree of congruency (mean performance metrics across months for downscaled outputs vs. VIC-GL: R^2 = 0.99, mean absolute percent error = 11.26%, and Nash-Sutcliffe efficiency = 0.98). Performance metrics of downscaled model results compared to gauge stations indicated overall high performance, with some cases of lower performance particularly for minimum August and September flows across the historical time period (1981–2010) (Appendix F, Table F1, Fig. F1).

For the current estimation of low and high stream flow threats, we used a variation of percent mean annual discharge (%MAD) as this is the standard metric used to determine flow rates of concern for fish habitat and water withdrawal allowance (Tennant 1976; Ptolemy and Lewis 2002). %MAD is generally calculated as the proportion of flow for a single day relative to the mean daily flow across a year. Given the downscaled temporal resolution, we used the average of mean total monthly flow values across the year ('MAD-monthly') for the historic time period and calculated %MAD-monthly for minimum and maximum monthly flows across each subsequent time period relative to the historic period. We focused our cumulative threat scoring for low stream flow using minimum August %MAD-monthly and high stream flow using maximum May %MAD-monthly based on visual inspection of timeseries of mean %MAD-monthly averaged across the FRB (Appendix F, Fig. F2); maps of shoulder months were provided for comparison. A low stream flow threat score of 0 indicated the highest projected minimum August %MAD-monthly flows and a score of 1 indicated the lowest projected flows; conversely, a high stream flow threat score of 0 indicated the lowest projected maximum May %MAD-monthly flows and a score of 1 indicated the highest project flows.

The Environmental Flow Needs Risk Assessment Framework conducted by the provincial government of BC similarly uses monthly means to calculate flow sensitivity of streams (Ministry of Forests, Lands, Natural Resource Operations and Rural Development [FLNRORD] 2022). Specifically, they calculate sensitivity based on long-term mean monthly discharge as a percentage of long-term mean annual discharge (MAD). This enables identification of sensitivity at different times of the year; long-term MAD on its own does not indicate sensitivity that may only occur during particular seasons (FLNRORD 2022). However, mean monthly values also obscure potentially important variation in daily flows that may impact fish and fish habitat. Future iterations of the flow threat scores may consider flow sensitivity metrics, and %MAD based on daily values would advance the current metrics once data are available. It is also important to consider for future development of stressor-response predictions, that there can be interacting effects between flow and in-stream habitat destruction, such as channelization, that will alter how different levels of flow impact fish and their habitat.

Stream flow is also influenced by land use practices, and in particular forest disturbances (see details in 'Threat Estimation: Human activity and landscape disturbances: Flow alteration'). These disturbances can have important effects on seasonal peak flows and low flows (Goeking and Tarboton 2020). Climate change is expected to generally increase the frequency and intensity of wildfires in Canada, as already seen in BC (Coogan et al. 2019), as well as expand the outbreak range of some forest pests (Pureswaran et al. 2018). The effect of these disturbances on stream flow depends on the remaining vegetation and regrowth over time (Coble et al. 2020; Goeking and Tarboton 2020). These interactions are highly complex to predict, but in general, climate change will alter stream flows through a variety of mechanisms including directly through climate shifts and indirectly from forest disturbances. Forest harvest practices further exacerbate changes to stream flows (Coble et al. 2020; Goeking and Tarboton

2020). Spatial intersection of cut-block areas with projected stream flow may be of interest to highlight where potential flow levels of concern overlap with current logging.

2.3.2.3. Stream temperatures

Stream temperature models are developed using either hydrological models or empirical statistical models. Hydrological models characterize the physical mechanisms of heat transfer and hydrology. These models may be better for projecting temperatures outside of current observed ranges owing to their mechanistic basis, but they are very data intensive and computationally challenging (Hague and Patterson 2014). Current initiatives for hydrological modeling in BC provide temperature predictions at grid resolutions of 1/4° (approximately 480 km^2; Islam et al. 2017) and 1/16° (Wanders et al. 2019; Schnorbus 2020), and at the resolution of a fundamental watershed using Raven Hydrological Framework models (Craig et al. 2020), though the latter is computationally intensive and not yet fully developed for BC at this time (M. Schnorbus, PCIC, pers. comm.). Conversely, statistical models fit relationships between environmental covariates and in situ water temperature data. These models can be defined at catchment scales for direct application to fundamental watersheds and stream reaches, and they are achievable at large spatial scales provided adequate in situ data coverage (Isaak et al. 2017; Weller et al. 2023). Water temperatures are most commonly collected in summer in BC, making statistical models more difficult to develop for winter temperatures to date.

High stream temperatures were represented using statistical models of August mean stream temperature, currently the most geographically extensive and high spatial resolution stream temperature layers for BC (Weller et al. 2023). August mean stream temperature had been selected as the modeled thermal metric for BC to match the largescale stream temperature modeling conducted in the Pacific Northwest (Isaak et al. 2016, 2017). August mean stream temperature is correlated with many thermal metrics for streams including thermal variability and magnitudes in other seasons (Isaak et al. 2018, 2020). Therefore, it is a useful metric for capturing thermal stress from high temperatures, as well as to distinguish streams with differing thermal regimes (Isaak et al. 2020; Isaak and Young 2023). The model was developed for stream reaches in BC with catchments at least 1 km^2 in size, based on available in situ data (generally 3rd order streams and higher; Weller et al. 2023). The model was fit to in situ temperature data from 562 stations with 1,544 station-years within a historical period of 1981–2020. Catchment-level variables included area, mean elevation, latitude, fractional lake cover, fractional glacier cover, mean August air temperature for the historical period, mean August air temperature anomaly (difference between the year of data and mean of the historical period), mean annual precipitation for the historical period, and mean annual precipitation anomaly (ratio of precipitation in a given year to the mean of the historical period). The model did not include land use or riparian cover as covariates; however, the model implicitly accounts for any human activity or landscape disturbance effect on water temperatures at the time of in situ data collection, whereas hydrological models must explicitly include this mechanism to predict temperatures based on altered landscapes. Model performance matched other published regional-scale statistical models (R^2 = 0.79, root mean square error = 1.53°C, mean absolute error = 1.18°C; Weller et al. 2023). August mean stream temperatures were projected for the same 20-year time periods as stream flow and included RCP scenarios 4.5 and 8.5 under 6 CMIP5-era GCMs (Appendix E) (Weller et al. 2023). We focused this threat score on absolute values rather than degree of change as this is likely to be most important for fish, particularly cold-water adapted anadromous salmonids. For instance, high elevation stream reaches are projected to have the greatest increases in-stream temperatures, but these temperatures are still low relative to lower elevation streams where Pacific salmon predominately exist

(Weller et al. 2023). Stream temperature threat scores from 0–1 indicated increasing projected temperatures.

2.4. CUMULATIVE THREAT SCORING

Many of the current freshwater-related cumulative effect assessments in BC apply thresholds or binned risk categories to human activity or threat scores, as developed above, followed by summation or a series of roll up rules for a final score (DFO 2022). Thresholds and binning are ideally obtained from stressor-response functions measured in the field or lab, or secondarily are developed through expert opinion. In practice, decisions around thresholds and binning have varied greatly among tools, and include binning based on data structure (e.g., percentiles), literature, or expert opinion (DFO 2022). We did not apply any expected stressor-response relationships, thresholds, or risk levels to the developed threat scores at this point; this will be developed in the next stage of research.

Multiple threats in a system may have effects that are additive, synergistic, or antagonistic. Meta-analyses on stressor interactions and cumulative effects have found that overall, antagonistic interactions are more prevalent, but that pair-specific meta-analyses on commonly studied combinations of stressors (e.g., nutrients and temperature) more frequently showed additive effects (Crain et al. 2008). Most cumulative effect assessments use additive scoring in part because there is limited understanding of interactive effects (Schäfer and Piggott 2018), and incorporating these effects can make models less tractable for management (MacPherson et al. 2024). For instance, the ‘Joe model’, developed for estimating cumulative effects on Trout populations in Alberta, uses an additive approach carried out as multiplying proportional stressor-response values (MacPherson et al. 2024). The cumulative risk of fishing-related incidental mortality of salmon was also found to be best represented by treating risk values as additive (i.e., multiplicative proportional responses) rather than as antagonistic or synergistic (Patterson et al. 2017). In a meta-analysis testing mortality predictions using five null models for cumulative effects, the simple addition, dominance, multiplicative, and concentration models underpredicted on average by 8.0%, 12.9%, 9.9%, and 6.9%, respectively, and stressor addition overpredicted by 5.7% (Dey and Koops 2021). We used the simple addition approach as there is general support for this being a reasonable expected biological response, it is commonly used and easily understood, and stressor-response relationships have not yet been applied to the threats presented here to more fully address this (Schäfer and Piggott 2018). We refer to the final score as a cumulative threat score, rather than a cumulative effect score in light of this assessment stage focusing on threat exposure, and not yet assessing the risk or effect of that exposure on fish.

Cumulative threat scores were developed separately for the human activity and climate change based threats. The human activity based cumulative threat score was applied to stream reaches in the FRB for which we could calculate all associated threats. Cumulative threat scores summarized for FWA watershed groups (n = 68 within the FRB) included all threats, whereas cumulative threat summaries focused on salmon CUs included anadromous fragmentation but not resident fragmentation and vice versa for those focused on SAR habitat. The climate change based cumulative threat scores were applied to all streams within catchments at least 1 km^2 in size based on the resolution of the stream temperature modeling (Weller et al. 2023). For the summary results and Thompson-Nicola EDU case study, we used the human activity based cumulative threat score calculated with a standard approach of adding the transformed and scaled scores. However, we also provide a comparative approach for the FRB that ranks the raw score estimates, scales the ranked values from 0–1, and then sums the ranked values. This approach creates more equivalence in individual threat contributions to the cumulative score as it removes some of the difference in score distributions (except it still retains 0 values as 0s), though it over-inflates differences between score levels (e.g., continuous scores of 1.2, 1.3, 5.0, 10.0 would be ranked as 1, 2, 3, 4). We then scaled both cumulative threat scores (i.e., continuous, transformed vs. ranked) from 0–1 to visually compare the two approaches.

Example summary graphs and maps were developed for an initial approach to visualizing results based on salmon CUs (only including streams below natural barriers for salmon), SAR extents, and FWA watershed groups. Tukey's box plots were produced to show distributions of cumulative and individual threat scores across streams associated with species extents. We mapped median values of human activity cumulative threat scores across streams within watershed groups. We also calculated the prevalence of each human activity and landscape disturbance input and mapped the most prevalent input within watershed groups. The metric of prevalence accounts for widespread occurrence but not intensity. We additionally graphed the mean proportion contribution of inputs (i.e., based on relative intensity for flow accumulated threats) for in-stream habitat destruction, riparian disturbance, nutrients, pollution, and sedimentation threats across streams within watershed groups (Fig. 19). The nonpoint source input of 'other non-urban' for flow accumulated threats was left out of the prevalence and proportion summaries as this category describes all land cover that did not otherwise have defined contribution coefficients (e.g., urban, forestry) and therefore was inherently the most dominant across the majority of watersheds.

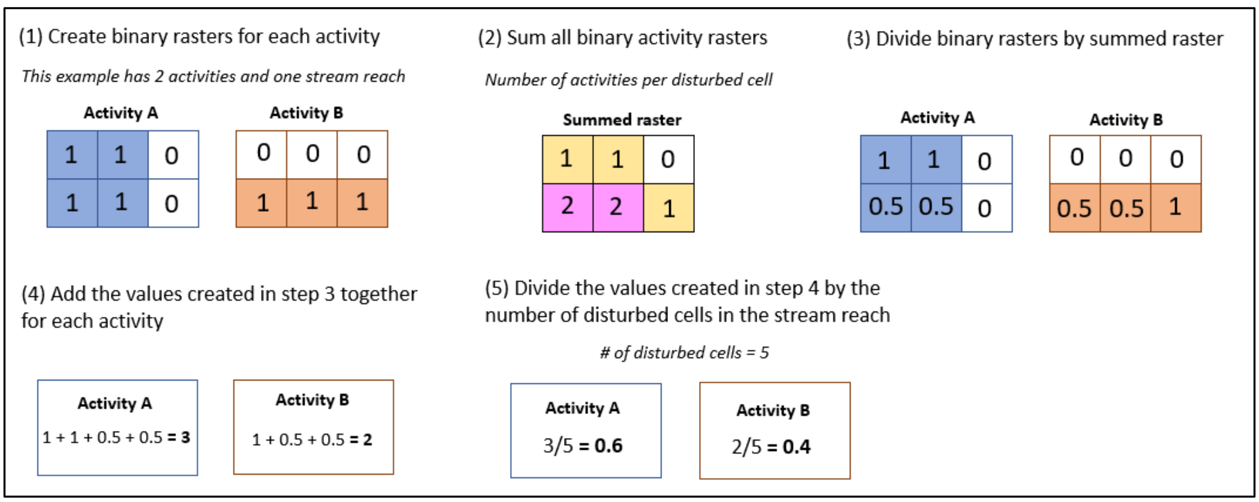

Figure 19. Calculation of proportion contributions of inputs based on threat estimates for in-stream habitat destruction and riparian disturbance.

2.5. TEMPORAL EVALUATION

We reviewed human activity and landscape disturbance data sources for the ability to evaluate change in threat scores over time. We showcased the data that have timeseries by providing example maps of differences between:

1. land use and land cover for 2018 (the earliest year with reliable data) and 2022 (the latest year available at the time of analyses),
2. forest fire perimeters from 2008–2018 and 2012–2022 (10-year time window matching land use and land cover years),
3. forestry cut blocks from 2008–2018 and 2012–2022, and
4. severe forest pest defoliation from 2008–2018 and 2012–2022.

Many of the other data sources do not have timestamps, and therefore are not conducive to historical timeseries analysis (Appendix C, Table C1). We did not re-run threat scores at this time as the best temporal evaluation will be to use these threat scores as a baseline and re-calculate with updated datasets moving forward.

2.6. THOMPSON-NICOLA EDU

For the Thompson-Nicola EDU case study, we developed examples of how the individual and cumulative threat scores can be applied to help inform restoration priority setting and management actions for salmon habitat. In particular, we focused on human activities and threats that may reasonably be mitigated, including riparian disturbance, water withdrawal, and longitudinal fragmentation. We identified overlap of these threats with two examples of ways to identify areas important to salmon:

1. using CU delineations and
2. using modeled environmentally favourable spawning habitat (Iacarella and Weller 2023).

Environmentally favourable spawning habitat for Pacific salmon within the EDU (Chinook, Coho, Pink, Sockeye) was previously estimated using Environmental Niche Models for ≥4th order stream reaches under current and future conditions (Iacarella and Weller 2023). Environmental Niche Models characterize the ecological niche and are not meant to specifically define the current distribution of a species; the focus of these models is large scale and on projecting shifts from climate change. Environmental favourability scores are calculated as a function of the probability of presence and prevalence of the species, where favourability scores greater than 0.5 indicate that local conditions lead to a probability of presence higher than expected based on overall prevalence (Iacarella and Weller 2023). These models were developed for BC to the southern US extent of ranges using spawning observations and primary environmental driving variables of August mean stream temperature, mean annual precipitation, distance to ocean and lakes (for Sockeye), stream gradient, and catchment area (Iacarella and Weller 2023). Models were fit using accessible stream reaches only and baseline environmental conditions (1981–2020) matching the timespan of salmon spawning observations. Future climate scenario comparisons were projected for 20-year time windows from 1981–2100 for all stream reaches (i.e., including inaccessible reaches and ≥4th order) (Iacarella and Weller 2023); all stream reaches were mapped when comparing between current and future projections. Juvenile rearing habitat was not captured in these models, which is another important salmon value to consider when planning habitat management and restoration.

We multiplicatively combined threat scores with modeled environmental favourability for salmon spawning to create composite scores that reflected a gradient of potential management implications (Fig. 20). For instance, a high threat score combined with a high favourable habitat probability identifies an area that warrants localized investigation and potential restoration or mitigation actions. Conversely, a low threat score combined with a low favourable habitat probability identifies an area that is less likely to need management attention based on this salmon value (i.e., predicted spawning habitat). Intermediate composite scores are best viewed separately to understand whether the area has a low threat score and high favourable habitat probability or the converse, which have different management implications (Fig. 20). When the two scores are varying in opposite directions (one is increasing across space and the other is declining), the highest scores would occur at intermediate values (e.g., 0.5 x 0.5 = 0.25) and the lowest scores would occur when one score is high and the other is low (e.g., 0.1 x 0.9 = 0.09). This is more informative than an additive approach to combining the scores as these scenarios would result in the same values across the gradient when adding (e.g., 0.5 + 0.5 = 1, 0.1 + 0.9 = 1). In the cases applied here, there were no 0 values. This multiplicative approach was applied to the human activity based cumulative threat scores, riparian input scores, and anadromous fragmentation scores. We also used a multiplicative approach to assess spatially coincident water withdrawals and low flow conditions. In this case, we overlaid the composite score with CU extents to reduce complexity, rather than also multiplying this composite score by modeled environmental favourability.

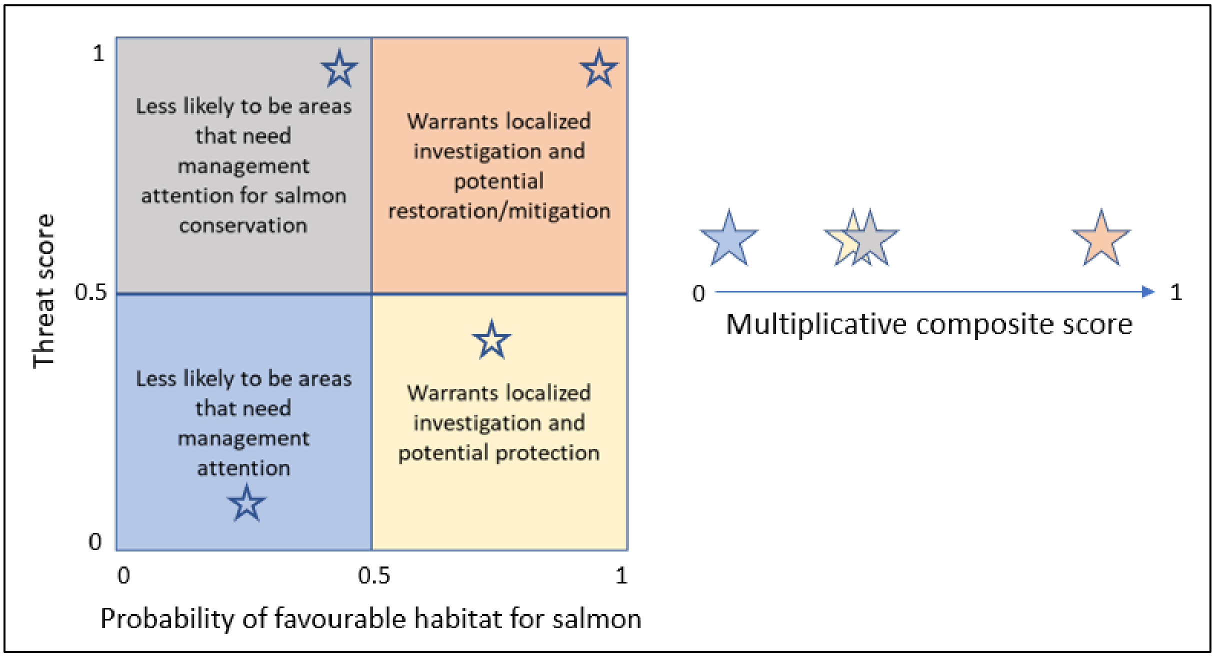

Figure 20. Rubric of potential management implications indicated by multiplicatively combining threat scores with salmon habitat values such as modeled favourable habitat. Star symbols along the multiplicative composite score gradient approximate their relative distribution from 0–1 based on the colour-coded rubric and example locations within.

For cumulative threat scores, we first applied the individual and cumulative threats to salmon CUs (only including stream reaches below natural barriers for salmon) and graphically indicated which CUs are predicted to experience higher threats, as was done for the FRB. We then multiplicatively combined the human activity based cumulative threat scores (excluding longitudinal fragmentation—resident) with environmental favourability scores (≥4th order streams) under baseline conditions (1981–2020) for accessible streams, current climate conditions (2001–2020) for all streams, and future climate conditions (2041–2060; RCP 4.5) for all streams ('cumulative threat composite score'). We used the median score within watershed groups to provide an indication of which watersheds have estimated high favourable habitat where there are also high cumulative threats. Results based on accessible streams were provided for an indication of current relative scores between watersheds and species, and results based on current and future climate conditions for all streams were provided for comparisons based on projected shifts in environmental favourability for salmon spawning and considering that some barriers (i.e., dams) may be mitigated.

We created a similar score for riparian inputs ('riparian input composite score') to help inform where riparian restoration may be needed based on

1. nonpoint source inputs of nutrients, pollution, and sedimentation and associated riparian disturbance levels and
2. environmental favourability for salmon spawning.

This score focused on the estimates of where nonpoint source inputs were greatest and riparian filtering capacity was potentially lost from riparian disturbance (e.g., results from Fig. 17 up to step 3). We only included streams with some associated riparian disturbance (riparian disturbance score >0). Point sources were not included in this score as it was assumed riparian filtering would not deter point source inputs. We multiplied the riparian input score (summation of scaled scores for nonpoint source inputs of nutrients, pollution, and sedimentation within the EDU) by the environmental favourability score for salmon spawning in accessible reaches under baseline conditions (1981–2020) and mapped results. The riparian input score relates to the filtering value of riparian buffers, but does not account for the function of riparian buffers in creating stream shade during summer months. Estimating loss of riparian stream shading to further inform restoration efforts can be achieved using high resolution remote sensing such as LIDAR (Seixas et al. 2018), and has also been estimated at a coarser resolution using satellite data (Iacarella et al. 2024).

We developed another score ('water resource composite score') for the combined occurrence of licensed water withdrawal (part of the flow alteration threat) and projected low stream flows under historic (1981–2010) and future conditions (2040–2060; RCP 4.5 and 8.5). We multiplied the inverse of the lowest minimum %MAD-monthly across the year for each stream reach by the associated licensed water withdrawal amounts within each fundamental watershed unit; a high score indicated low %MAD-monthly and high allowable water withdrawal. We then took $\log_{10}(x+1)$ to reduce skew and scaled to calculate a threat score. We overlaid this score with salmon CUs and visualized results with maps and graphs. The estimation of the water resource composite score would be improved by linking the monthly amount of water extraction to monthly flow levels. However, this information was not readily available to the extent needed, so the composite score calculation provided the highest values by linking the full allowed water extraction amount to the lowest flows across the year. Future iterations could estimate water withdrawal timing by binning by season based on the type of withdrawal (e.g., agricultural).

Lastly, we used a multiplicative score for the longitudinal fragmentation—anadromous species threat and environmental favourability for salmon spawning ('anadromous fragmentation composite score'). This score indicates which barriers are potentially blocking the greatest extent of favourable habitat. It uses the originally developed threat, but focuses the multiplicative score only on the portion of stream network from the initial dam to the next barrier (dam or natural) upstream. The mean spawning favourability scores of upstream reaches for each salmon species under current (2001–2020) and future climate conditions (2041–2060; RCP 4.5 and 8.5) were then multiplied by the stream length of these blocked network patches, and the log10(x) of this was normalized for the final anadromous fragmentation composite score. These results were visualized graphically.

3. RESULTS

3.1. HUMAN ACTIVITY AND LANDSCAPE DISTURBANCE THREATS

Human activity and landscape disturbance based threats were developed for 578,031 stream reaches (i.e., fundamental watersheds) of 644,594 (90%) in the FRB, representing 384,619 km of stream reaches, 87% of the length of the FRB network. The remaining 10% represented: watersheds in the US that were added to model drainage patterns across the entire FRB (Weller et al. 2023), watersheds that were too small to associate with the rasterized human activity and landscape disturbance data, watersheds without an associated stream reach, and watersheds with excluded stream reaches (e.g., lakes, subsurface flows).

Maps of threat scores for stream reaches showed geographic variation in intensity across the FRB depending on the threat (figure legends are scaled to highlight the gradient of scores particular to each threat; Figs. 21–30). AIS threat scores above 0 were largely contained to the lower Fraser River, with some patches in eastern FRB (Fig. 21). Higher flow alteration and latitudinal fragmentation threat scores generally followed the larger rivers including the Fraser, Thompson, and Nechako Rivers (Figs. 22, 24). In-stream habitat destruction and riparian disturbance had threat scores above 0 for most of the FRB, and the highest scores coincided with low to midrange elevations, particularly the interior plateau that runs from the northwest corner of the FRB to the southeast corner (Figs. 23, 27). Longitudinal fragmentation had higher scores along the interior plateau, around the lower Fraser River, and in the Nechako major watershed (Figs. 24, 25). High nutrient loading scores were found within the interior plateau, lower Fraser River, and upper reaches of the FRB (Fig. 28). Pollution loading scores were relatively low for most of the FRB, with higher concentrations around the lower Fraser River and central FRB (Fig. 29). Relatively high levels of human-derived sedimentation were estimated across the FRB (Fig. 30). Finally, the additive cumulative threat score highlighted high threat levels across the lower Fraser River and interior plateau (Fig. 31). The two approaches of summing threats for the cumulative scores (i.e., continuous, transformed scores vs. ranked scores) provided overall similar spatial patterns in score levels, with spatial differences primarily in areas with intermediate values (Fig. 32). There were also more values in the higher (scaled cumulative threat scores >0.5) and lower range (<0.08) using the ranking approach.

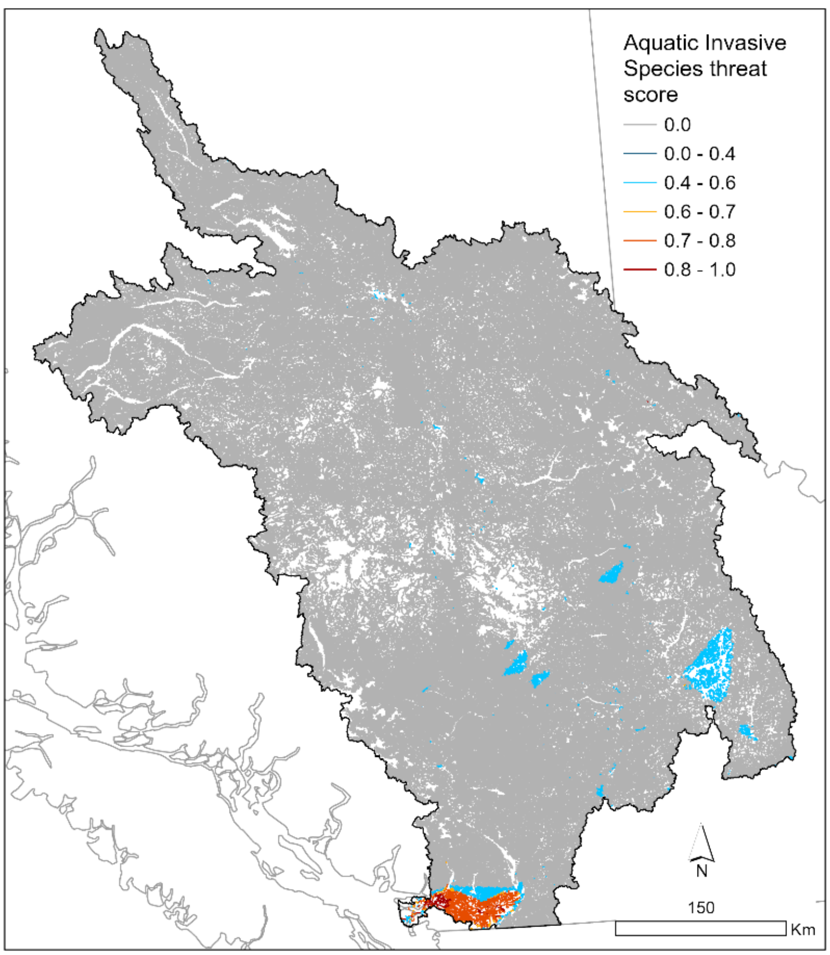

Figure 21. Aquatic Invasive Species threat exposure score. Transformed and scaled scores from 0–1 indicate increasing non-native species richness based on estimated distributions.

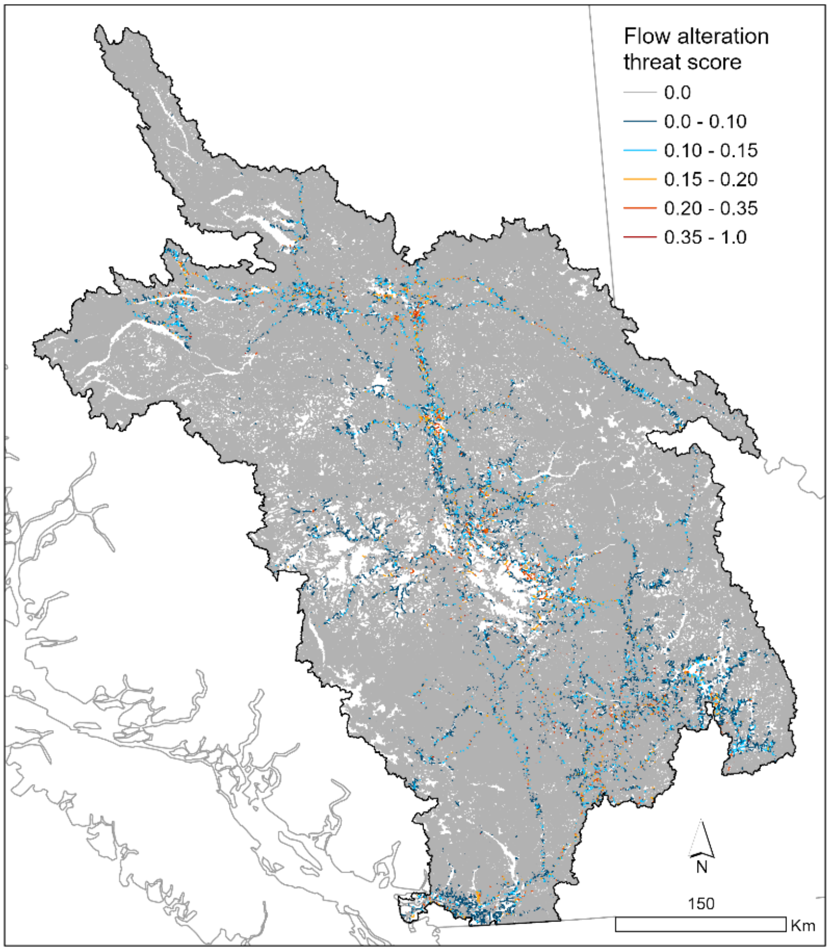

Figure 22. Flow alteration threat exposure score. Transformed and scaled scores from 0-1 indicate increasing estimated flow alteration from culverts (water velocity change), dams (water quantity change), and water extraction (water quantity change).

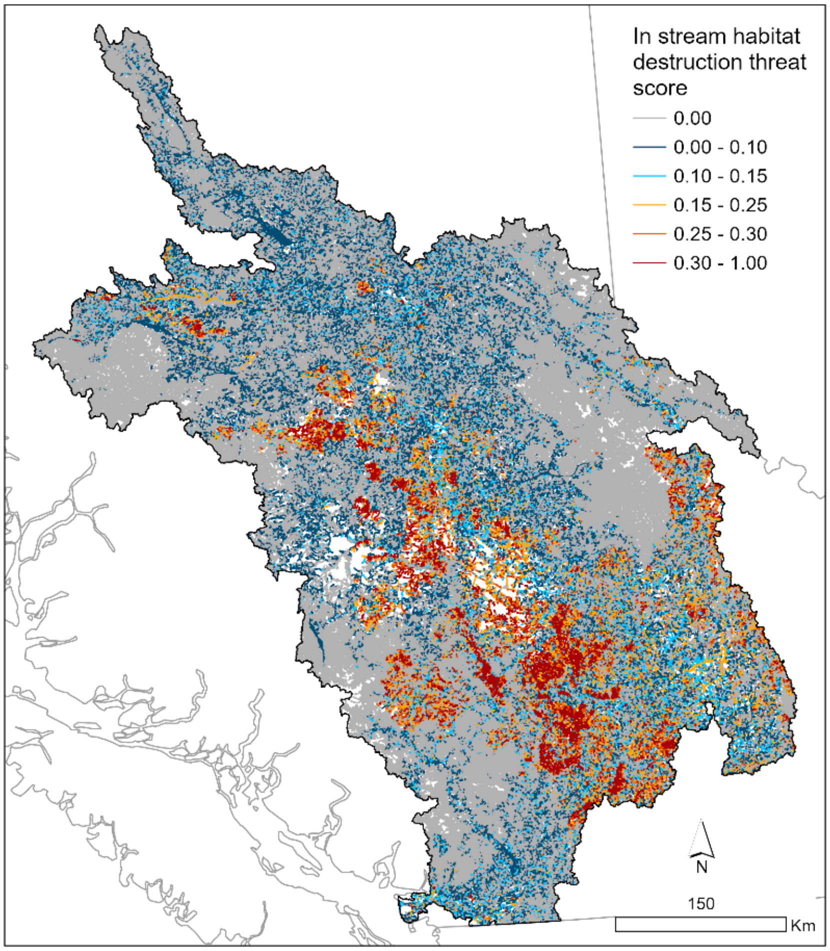

Figure 23. In-stream habitat destruction threat exposure score. Transformed and scaled scores from 0–1 indicate increasing in-stream habitat destruction estimated based on human activity and landscape disturbance footprints overlapping stream extents.

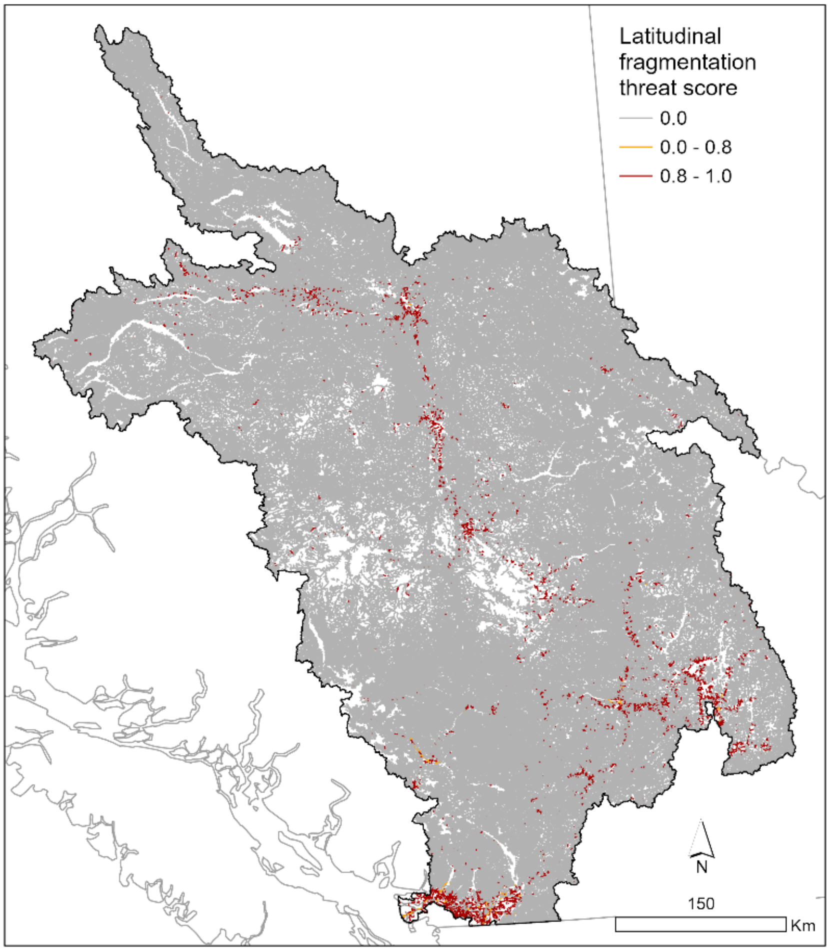

Figure 24. Latitudinal fragmentation threat exposure score. Transformed and scaled scores from 0–1 indicate greater potential disconnection from floodplain habitat from flood protection barriers and urban land use.

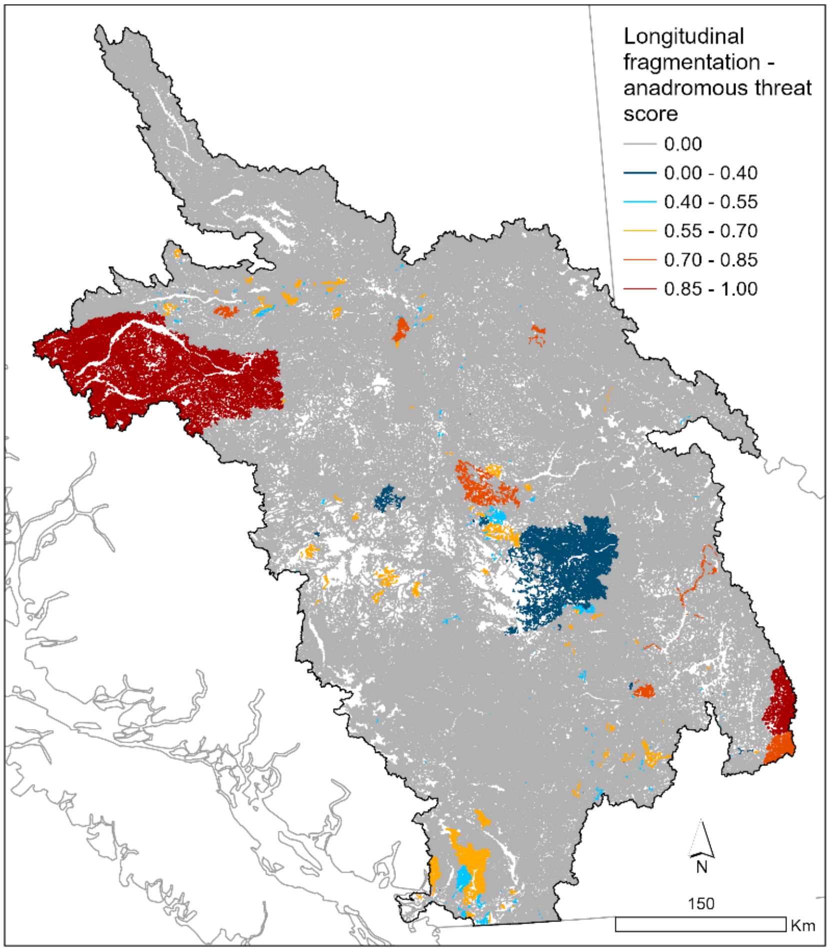

Figure 25. Longitudinal fragmentation – anadromous species threat exposure score. Transformed and scaled scores from 0–1 indicate greater lengths of blocked stream network based on the extent from the first full dam barrier upstream of ocean entry to the next barrier (dam or natural). Scores were applied to streams upstream of any subsequent dams, but below natural barriers.

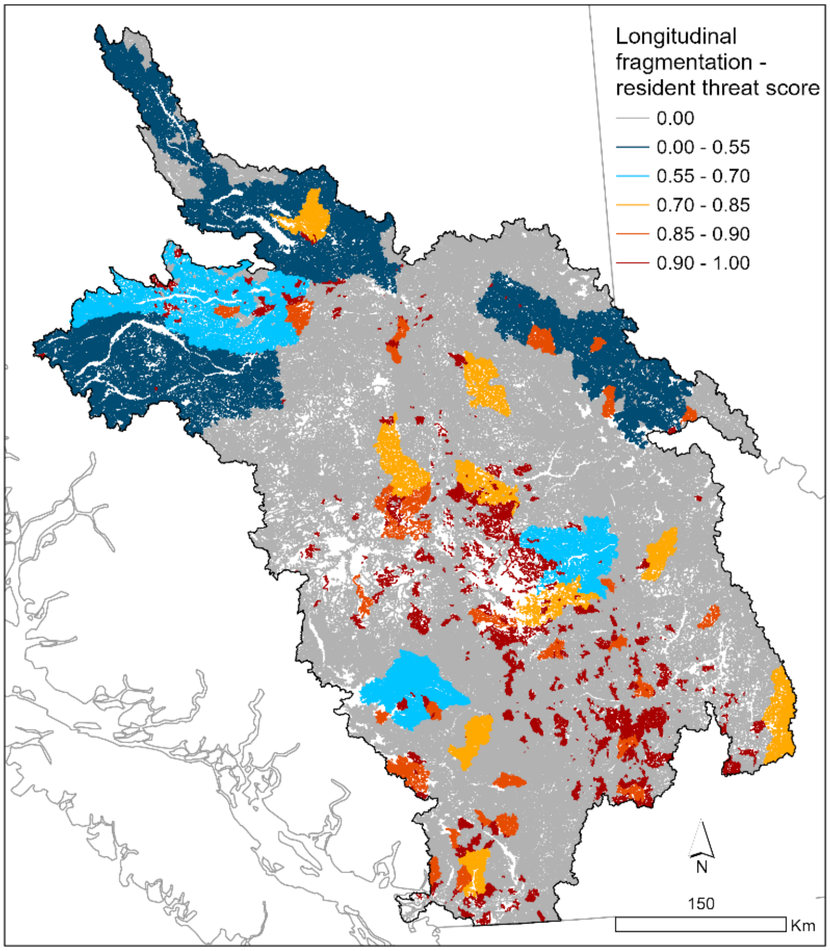

Figure 26. Longitudinal fragmentation – resident species threat exposure score. Transformed and scaled scores from 0–1 indicate shorter connected stream lengths between full barrier dams and natural barriers.

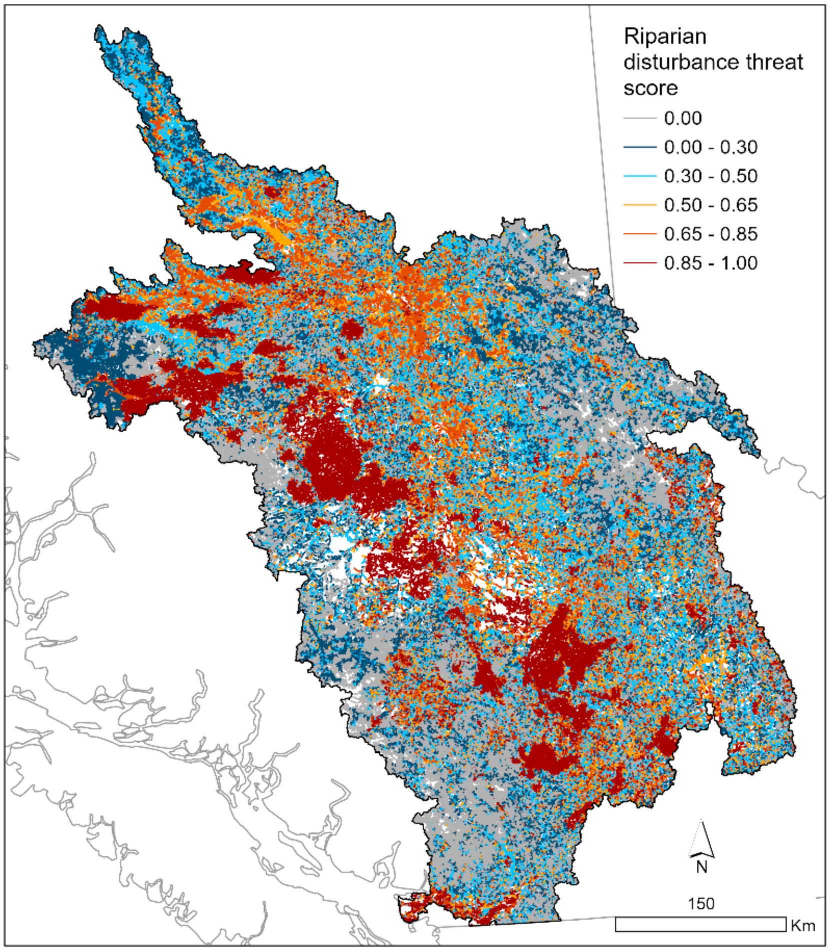

Figure 27. Riparian disturbance threat exposure score. Transformed and scaled scores from 0–1 indicate increasing riparian disturbance estimated based on human activity and landscape disturbance footprints overlapping riparian buffer extents (30 m from stream reaches).

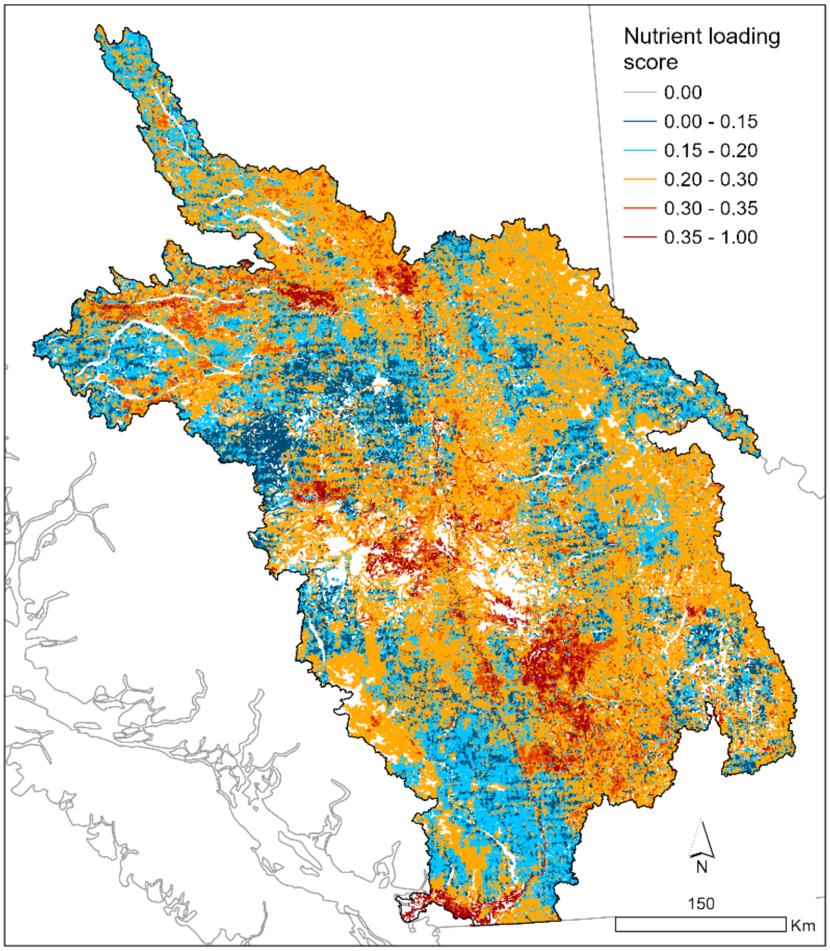

Figure 28. Human-derived nutrient loading score. Transformed and scaled scores from 0–1 indicate estimated increasing nutrient loading from point and nonpoint sources.

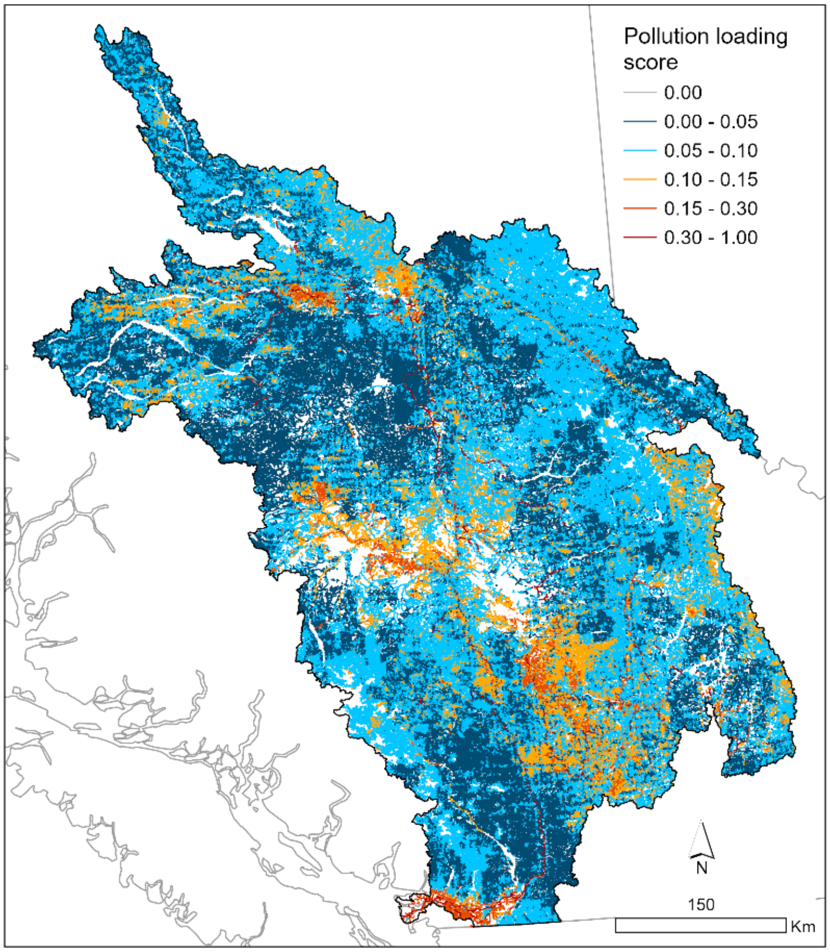

Figure 29. Pollution loading score. Transformed and scaled scores from 0–1 indicate estimated increasing pollution loading from point and nonpoint sources.

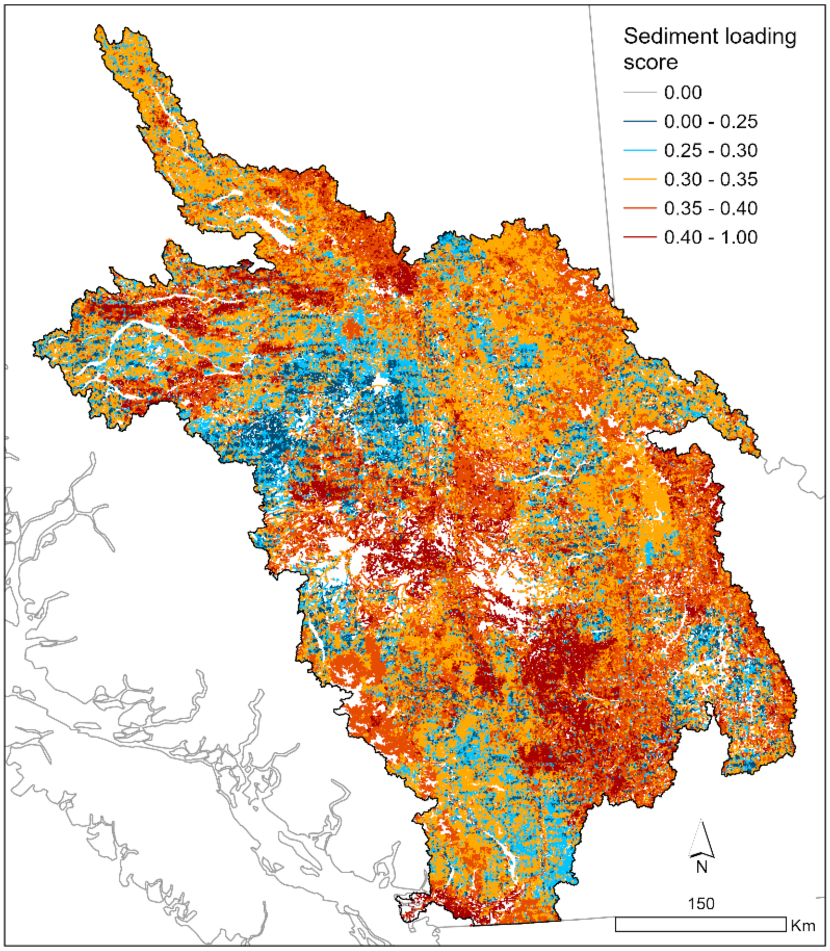

Figure 30. Human-derived sediment loading score. Transformed and scaled scores from 0–1 indicate estimated increasing sediment loading from point and nonpoint sources.

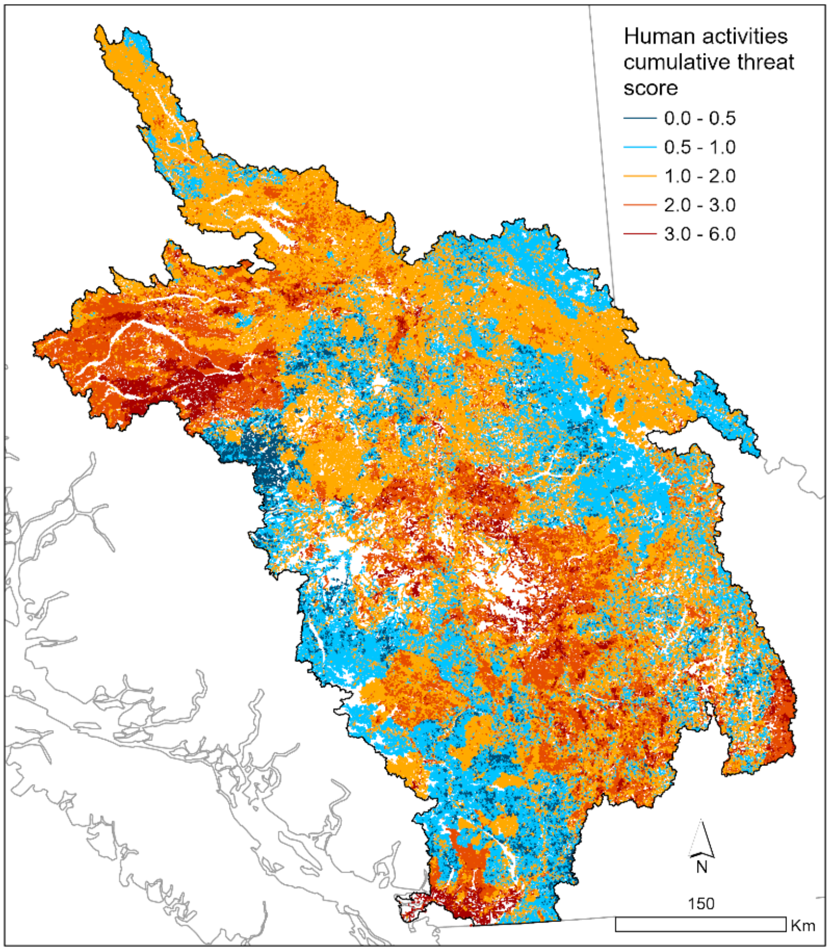

Figure 31. Human activity and landscape disturbance based additive cumulative threat score.

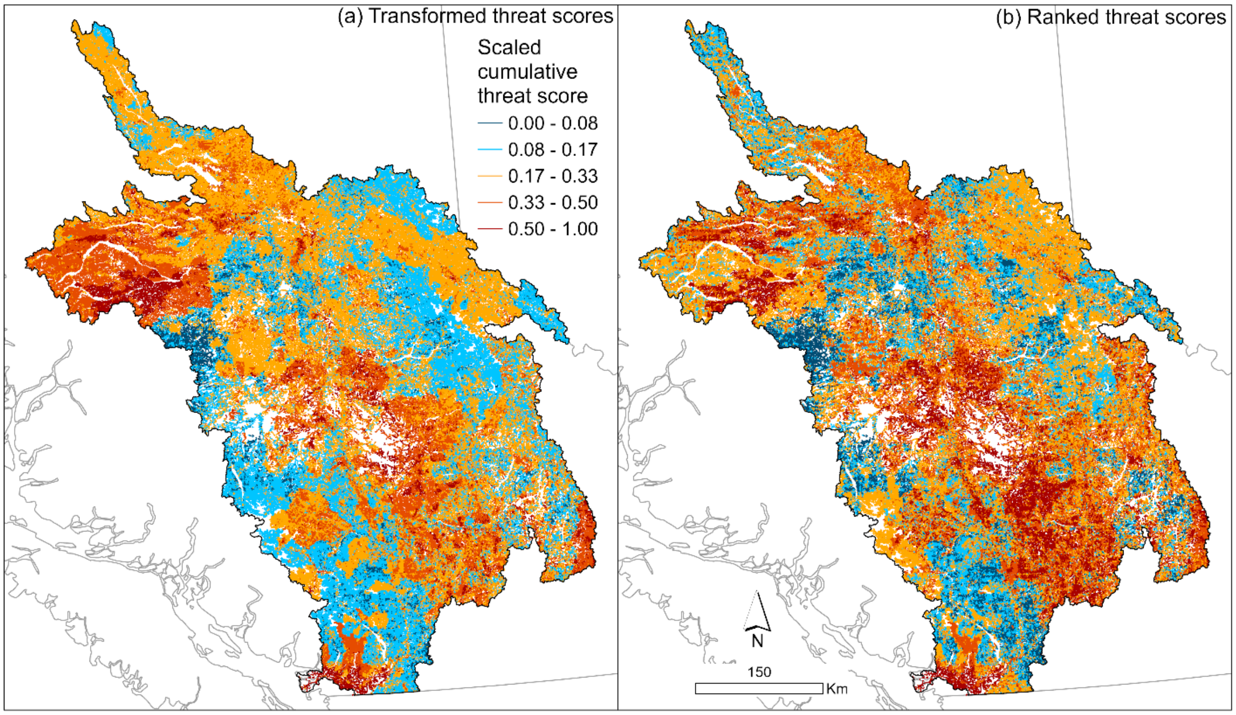

Figure 32. Scaled human activity and landscape disturbance based cumulative threat scores from summation of (a) continuous, transformed scores and (b) ranked scores. Legend symbols apply to both maps.

3.2. CLIMATE CHANGE THREATS

Climate change based threats were developed for 243,856 stream reaches (i.e., fundamental watersheds) of 644,594 (38%) in the FRB based on limitations to catchments of at least 1 km^2 in size. This represented 171,181 km of stream reaches, 39% of the FRB stream network length.

Flood risk as identified by overland water level indicated higher levels along the lower and upper Fraser River and upper tributaries of the Thompson, Nechako, and Stuart rivers under historic conditions (Fig. 33a). Increased overland water levels were projected for these same areas under future climate conditions, except for the upper Fraser River; the upper and central Fraser River, and Chilcotin River were projected to decrease in overland water level under RCP 4.5 (Fig. 33b). The most notable difference between RCP 4.5 and 8.5 was an increase in water level along the central Fraser River instead of a decrease (Fig. 33b–c).

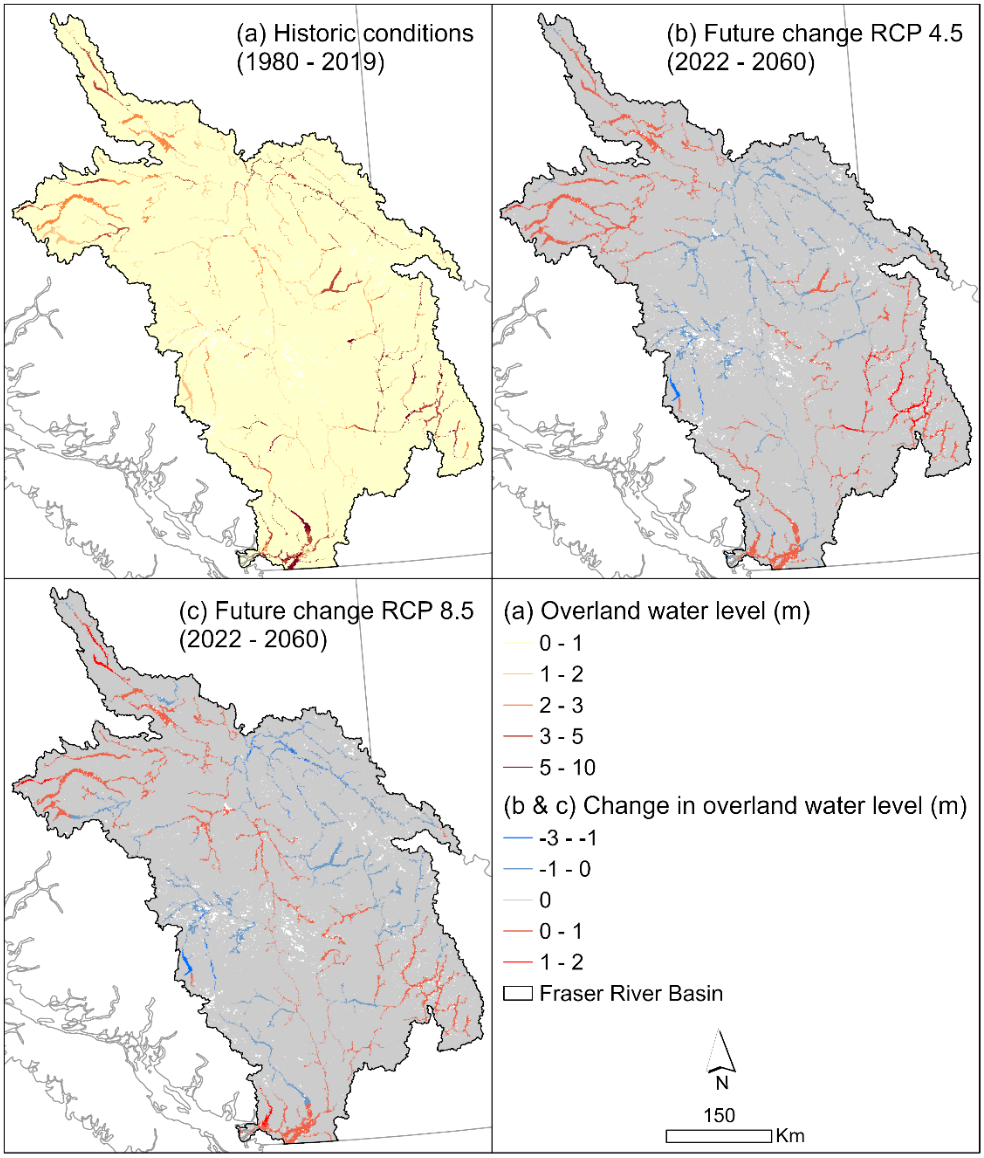

Figure 33. Flood risk threat based on modeled (a) historic overland water level (1980–2019) and projected change in overland water level (1980–2019 to 2022–2060) for a 100 year return period under (a) RCP 4.5 and (b) RCP 8.5. Absolute change in overland water level was transformed and scaled so that a higher score indicated greater change in overland water level (positive or negative).

Maps for minimum %MAD-monthly highlighted the lower and upper Fraser River as areas of low %MAD-monthly (<10%) (Fig. 34). The most notable change in August minimum %MAD-monthly from historic to future conditions was an expansion of low %MAD-monthly values in the southern FRB, with little difference between RCP 4.5 and 8.5 (Fig. 35). Maximum %MAD-monthly for May had the highest values in the northern FRB, with moderate %MAD-monthly values dispersed throughout the FRB; patterns in %MAD-monthly alternated between the shoulder months of April to June (Fig. 36). May maximum %MAD-monthly did not change substantially from historic to future conditions, and was similar between RCP 4.5 and 8.5 (Fig. 37).

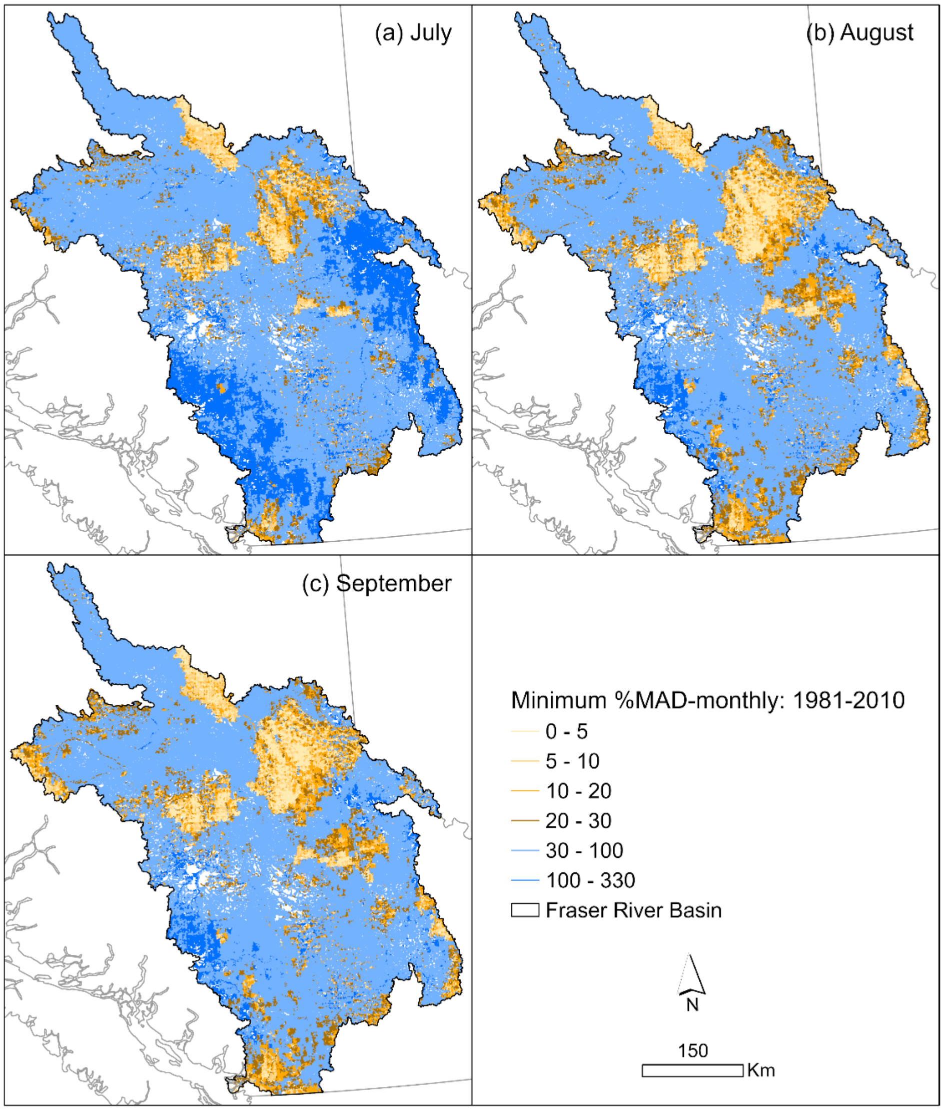

Figure 34. Modeled minimum monthly % MAD-monthly (calculated as mean monthly flow across the year) for climate average conditions from 1981–2010 for low flow summertime months: (a) July, (b) August, and (c) September.

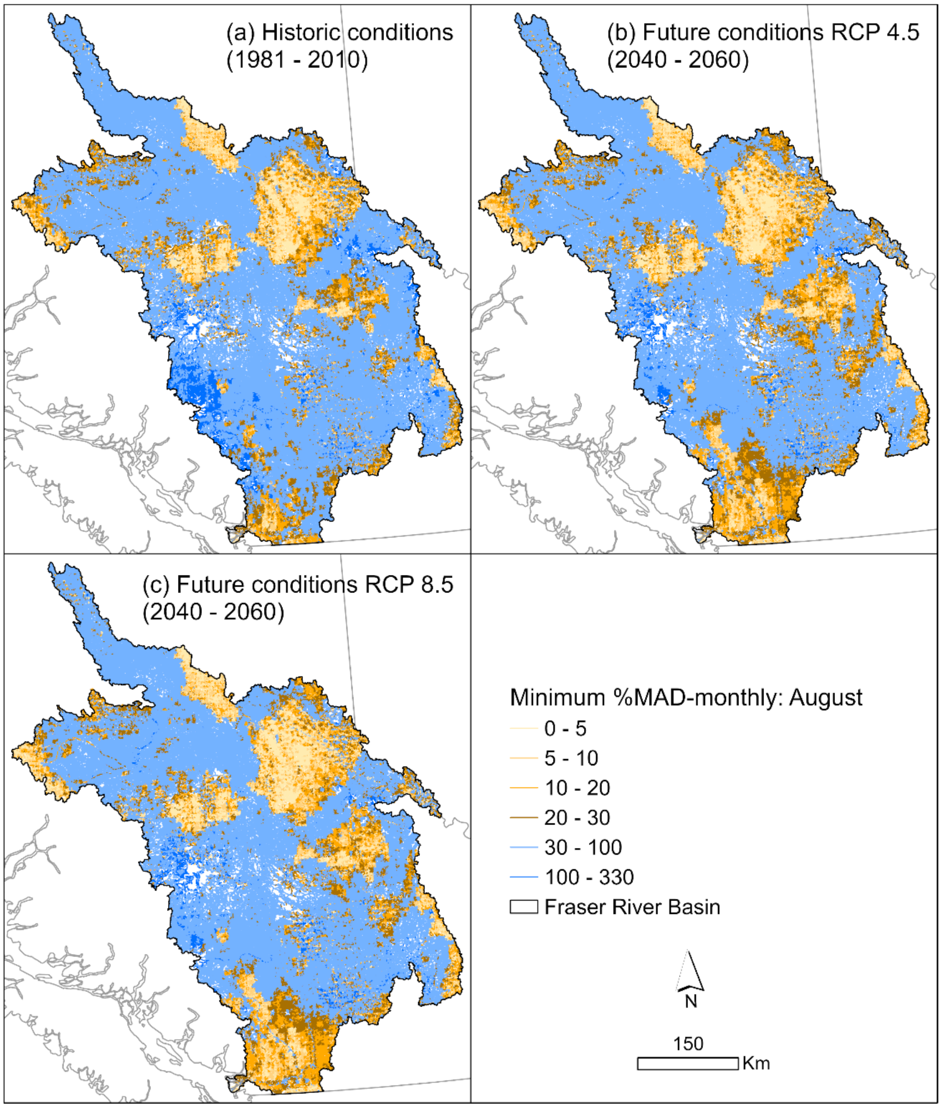

Figure 35. Low stream flow threat based on modeled minimum August %MAD-monthly (calculated as mean monthly flow across the year) for climate average conditions from (a) 1981–2010 and for 2040–2060 under (b) RCP 4.5 and (c) RCP 8.5. Future projected %MAD-monthly was calculated relative to the historic period (1981–2010). Low stream flow threat scores (based on mapped values shown here) were transformed and reverse-scaled from 0-1 so that a higher score indicated lower minimum flows.

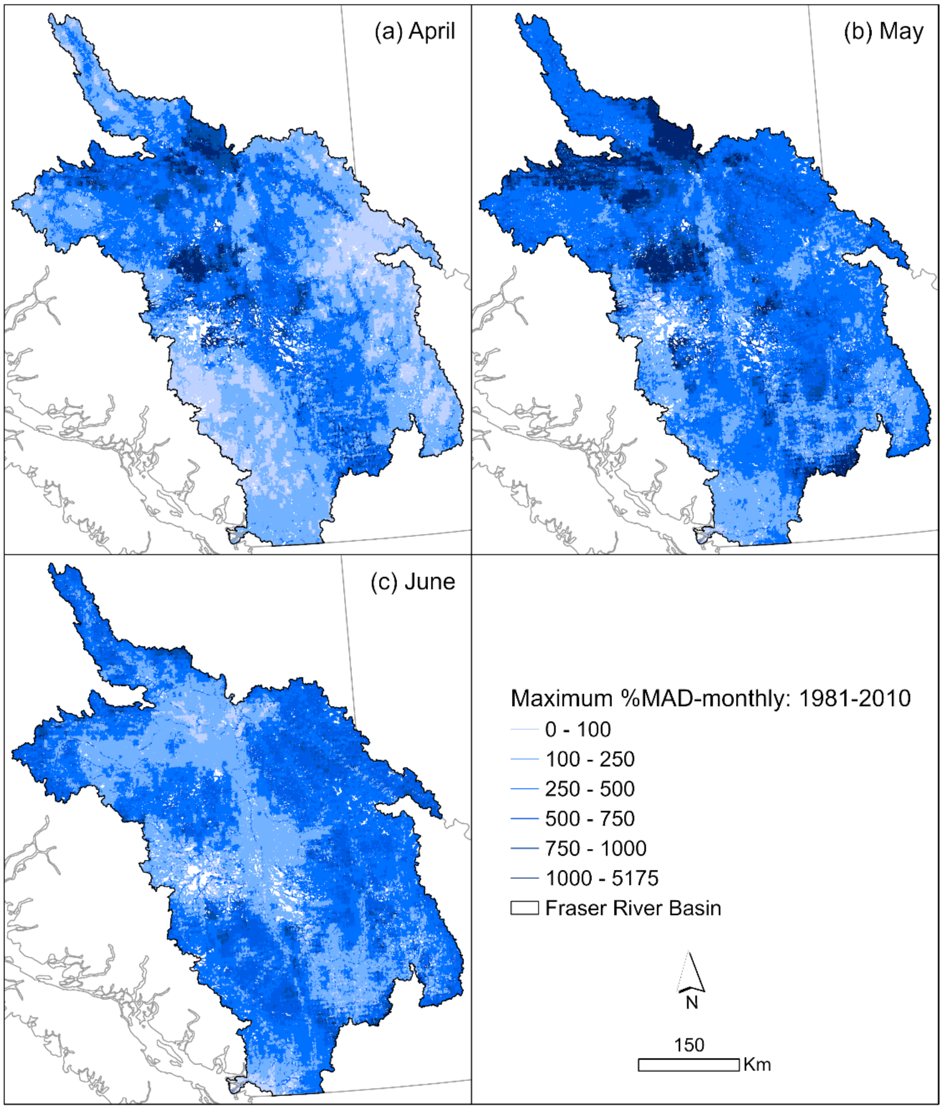

Figure 36. Modeled maximum monthly %MAD-monthly (calculated as mean monthly flow across the year) for climate average conditions from 1981-2010 for high flow months: (a) April, (b) May, and (c) June.

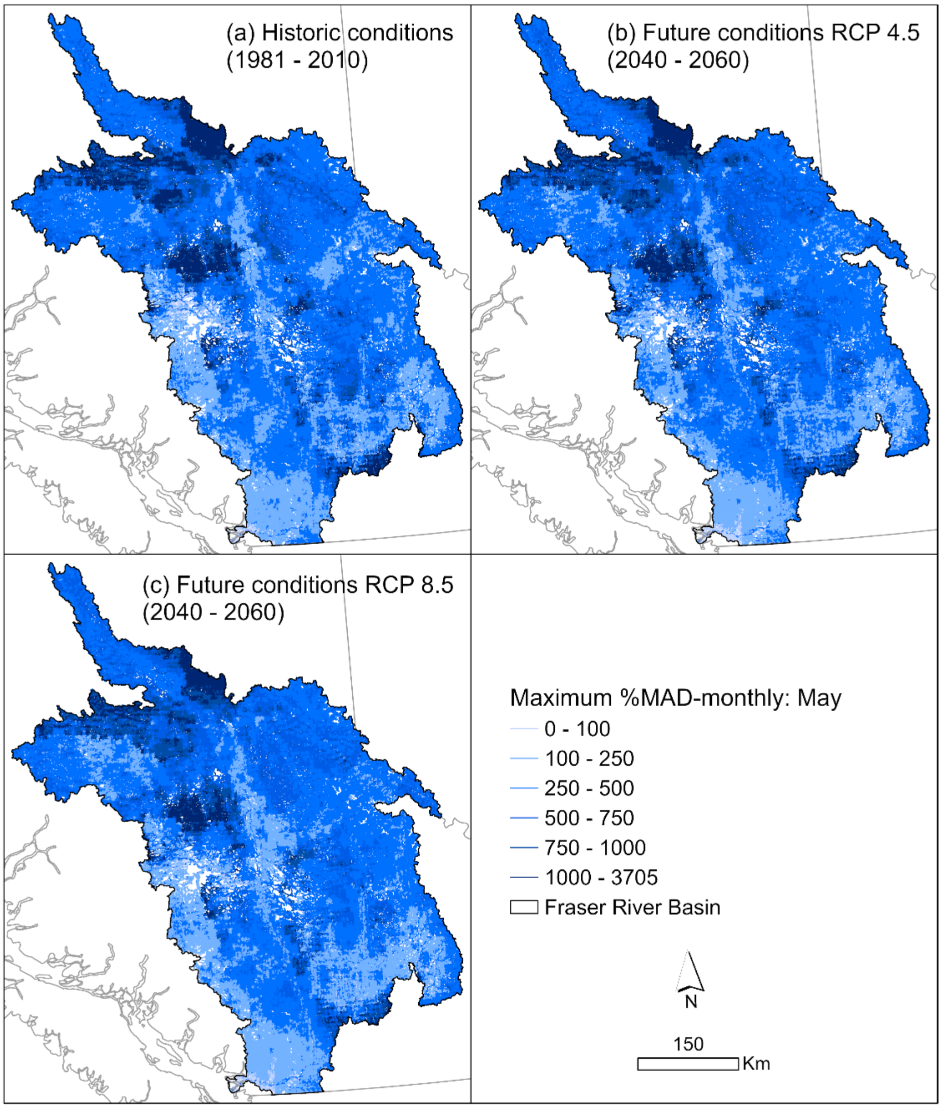

Figure 37. High stream flow threat based on modeled maximum May %MAD-monthly (calculated as mean monthly flow across the year) for climate average conditions from (a) 1981–2010 and for 2040–2060 under (b) RCP 4.5 and (c) RCP 8.5. Future projected %MAD-monthly was calculated relative to the historic period (1981–2010). High stream flow threat scores (based on mapped values shown here) were transformed and scaled from 0–1 so higher scores corresponded with higher maximum flows.

August mean stream temperatures were highest along the larger rivers, including the Fraser, Thompson, and Nechako rivers (Fig. 38a). Stream temperatures increased from current to future conditions, with high temperatures along the large rivers and streams within low to midrange elevations (Fig. 38b–c).

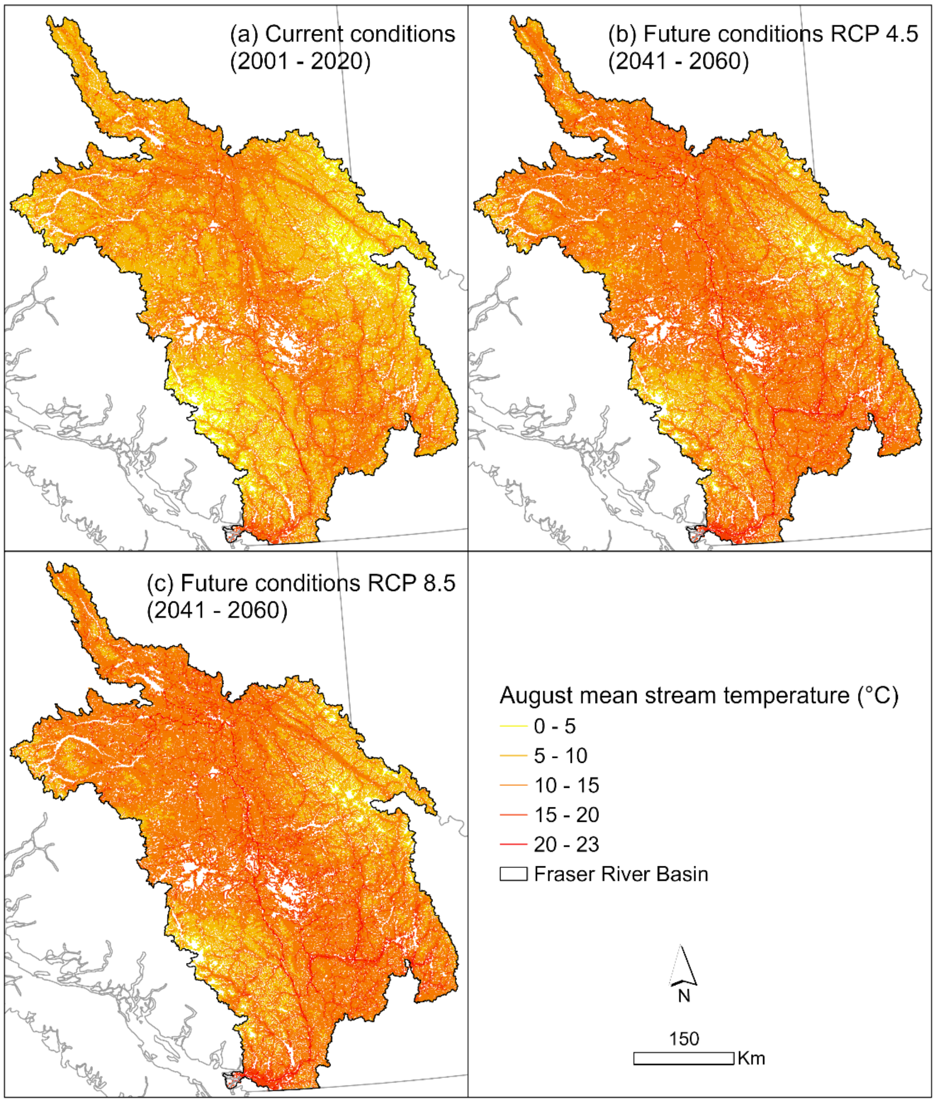

Figure 38. High stream temperature threat based on modeled August mean stream temperatures for (a) current conditions (2001–2020) and future conditions (2041–2060) under (b) RCP 4.5 and (c) RCP 8.5. Scaled high stream temperature threat scores from 0–1 indicate increasing temperatures.

The climate change cumulative threat score was highest along the entirety of the Fraser River and across the interior plateau, and low scores were generally restricted to the high elevation areas of the Coast and Rocky mountains (Fig. 39). Scores were higher under RCP 8.5 than 4.5 most notably in the southern FRB.

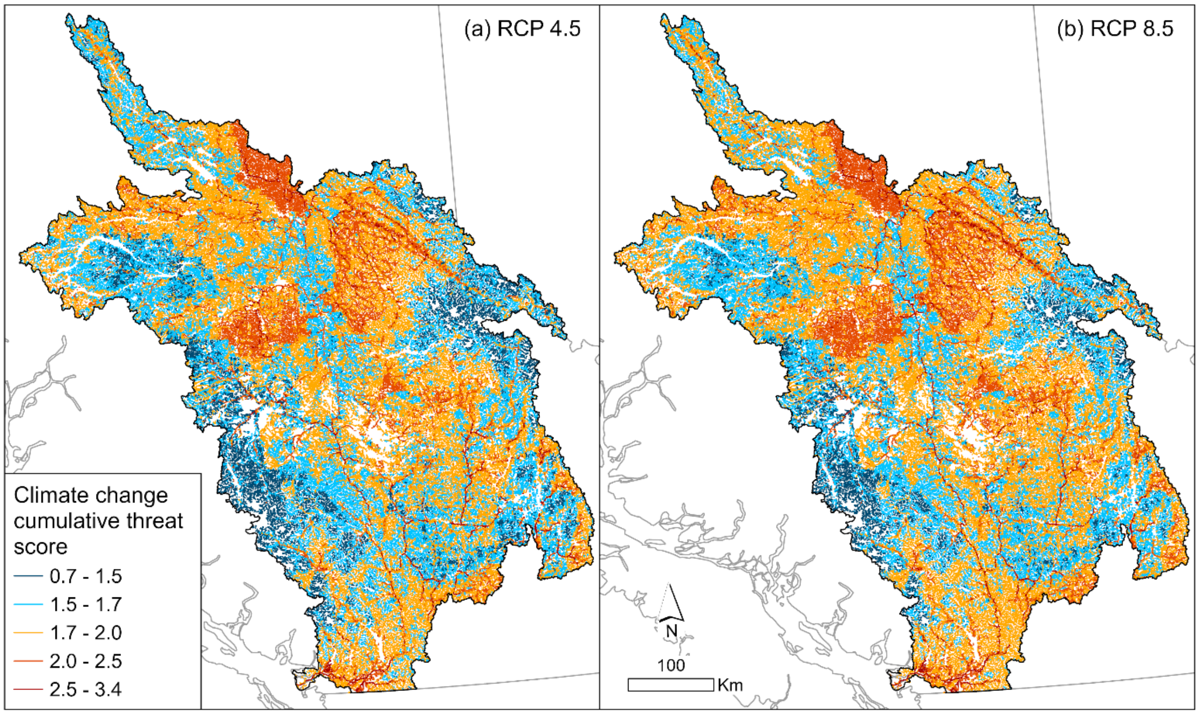

Figure 39. Climate change additive cumulative threat score for 2040–2060 under (a) RCP 4.5 and (b) RCP 8.5.

3.3. SUMMARIES

Human activity and landscape disturbance threat score distributions varied greatly, though many were dominated by 0 values with outliers at higher values, particularly for AIS, flow alteration, in-stream habitat destruction, latitudinal fragmentation, and longitudinal fragmentation – anadromous species. This indicates a majority of streams were not affected by these threats, and a small proportion were relatively highly affected (Fig. 40). Threats with higher median values were riparian disturbance, nutrients, pollution, and sedimentation. Nutrients, pollution, and sedimentation inherently had few 0 values as all land cover types were estimated to contribute some input, though this could be partially filtered by undisturbed riparian buffers and diluted by higher flow volumes. Climate change threat scores had median values that were lowest for flood risk owing to the restricted extents of modeled flood levels, whereas the other three metrics had mid-range median values (Fig. 33, 41). There tended to be a higher median high stream flow under RCP 8.5 than 4.5, and no notable difference between RCPs for the other threat scores (Fig. 41).

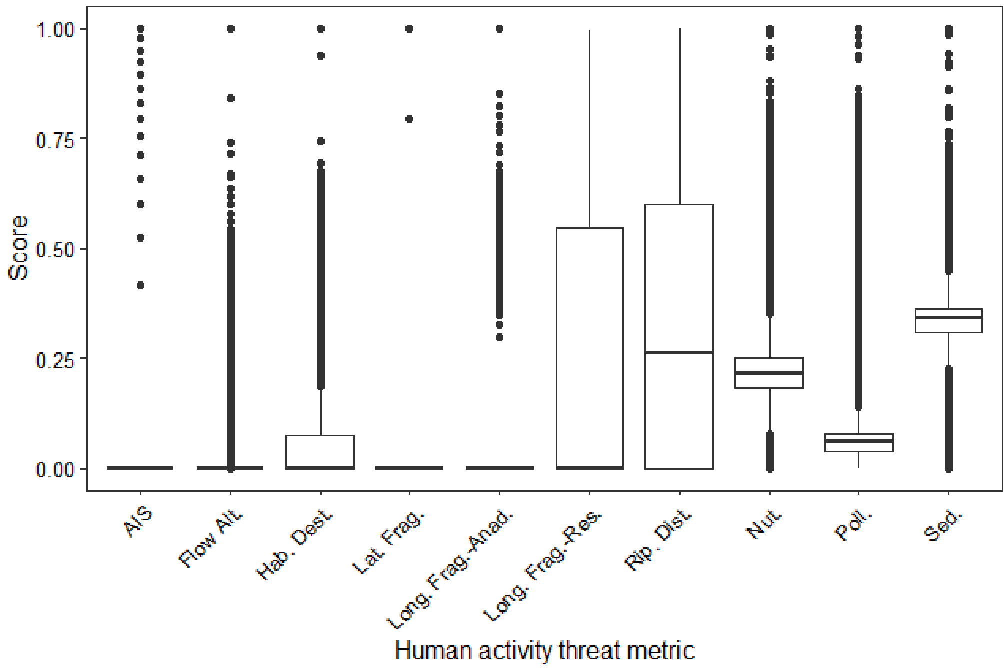

*Figure 40. Tukey's box-whiskers plots of the human activity and landscape disturbance based threats, including Aquatic Invasive Species (AIS), flow alteration (Flow Alt.), in-stream habitat destruction (Hab. Dest.), latitudinal fragmentation (Lat. Frag.), longitudinal fragmentation – anadromous (Long. Frag. - Anad.), longitudinal fragmentation – resident (Long. Frag. -Res.), riparian disturbance (Rip. Dist.), nutrients (Nut.), pollution (Poll.), and sedimentation (Sed.). The box plot line represents the median across stream reaches, the lower and upper hinges represent 25th and 75th percentiles, respectively, and outliers are points above or below 1.5 * the inter-quartile range.*

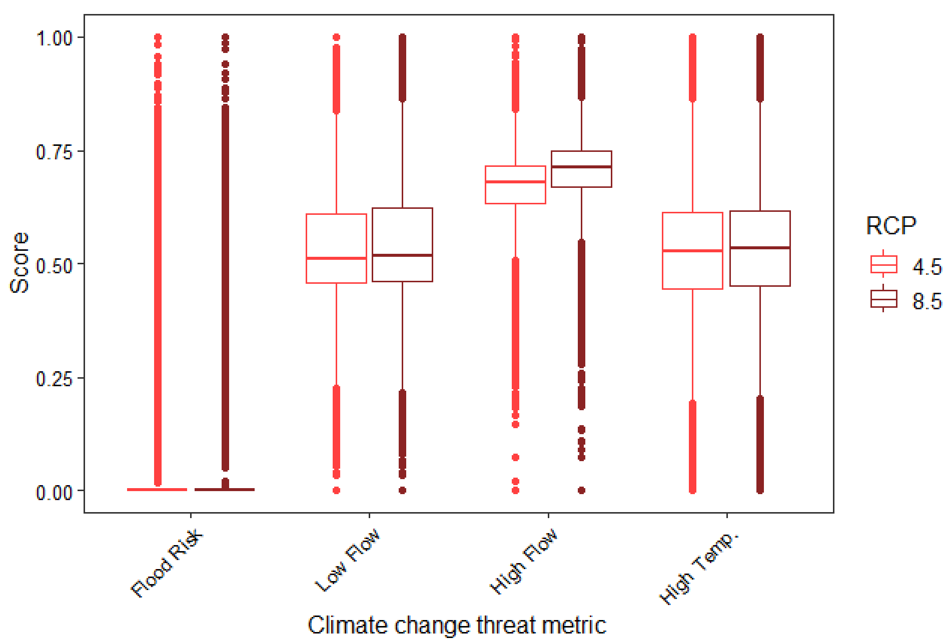

Figure 41. Tukey's box-whiskers plots of the climate change based threat scores for 2040–2060 under RCPs 4.5 and 8.5. Higher scores indicate projected greater absolute flood level change ('flood risk'), lower minimum August %MAD-monthly stream flows ('low flow'), higher maximum May %MAD-monthly stream flows ('high flow'), and higher August stream temperatures ('high temp.').

Median cumulative threat scores for human activity and climate change based threats were generally similar across salmon species and in relation to all streams in the FRB (Fig. 42). However, median human activity cumulative threat scores for Chinook CUs not at risk tended to be higher relative to other CUs and to all streams in the FRB, and median climate change cumulative threat scores tended to be higher for Sockeye CUs not at risk. Among individual CUs, the Endangered Sockeye Cultus – Late Timing (SEL-03-02) CU and Momich Lakes – Early Summer Timing population (SEL-09-xx) had particularly high median human activity cumulative threat scores (Appendix G, Fig. G1). The Threatened Sockeye North Barriere – Early Summer Timing CU (SEL-10-03) also had the highest median climate change cumulative threat score (Appendix G, Fig. G2). Median human activity cumulative threat scores for SAR extents were notably higher relative to all streams for Coastrange Sculpin, Green Sturgeon, Nooksack Dace, and Salish Sucker (Fig. 43). Median climate change cumulative threat scores were more similar, except Mountain Sucker and White Sturgeon extents in particular had higher median scores relative to all streams (Fig. 43).

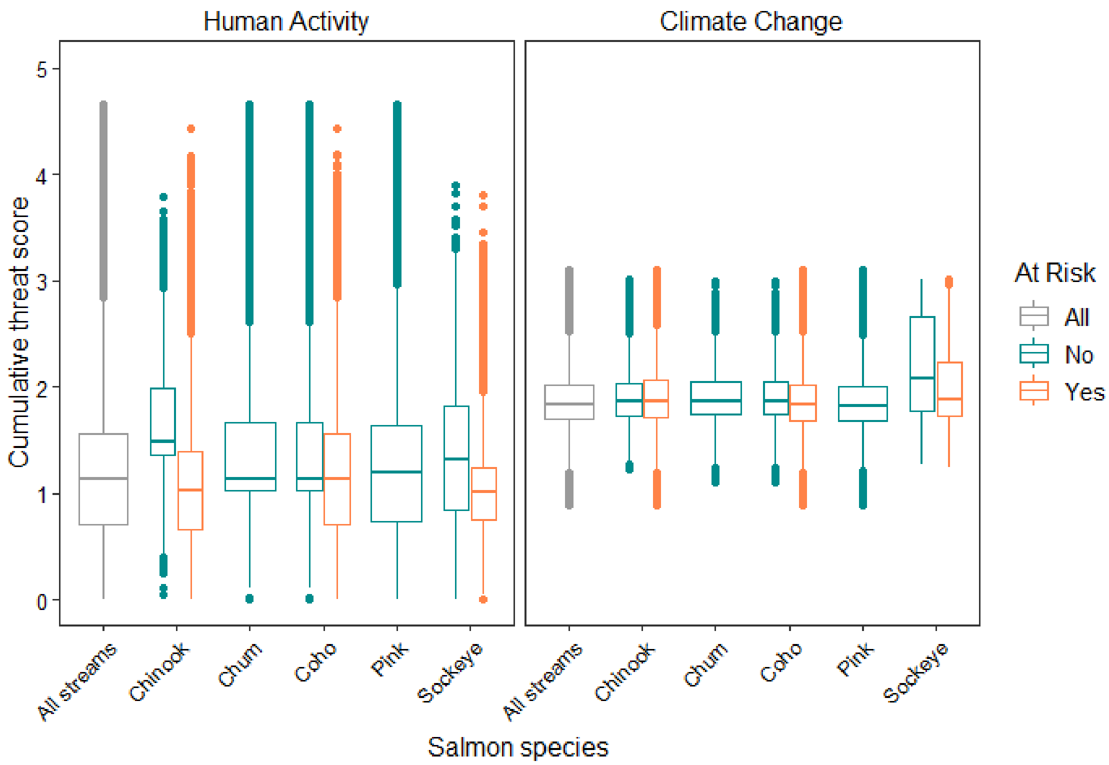

Figure 42. Tukey's box-whiskers plots of the cumulative threat scores from human activity and landscape disturbance based threats (left panel) and climate change based threats (right panel) for all streams in the FRB and for streams within salmon CUs (only including streams below natural barriers for salmon). CUs identified as Special Concern, Threatened, or Endangered by COSEWIC were distinguished from those not at risk.

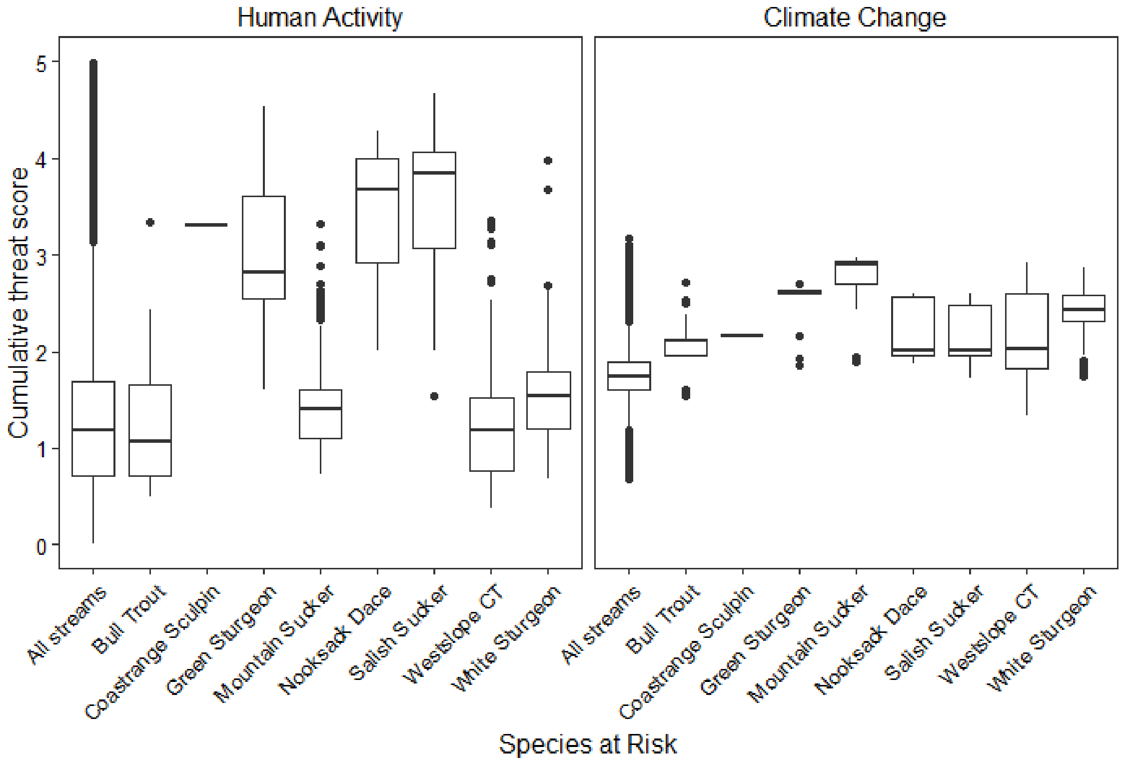

Figure 43. Tukey's box-whiskers plots of the cumulative threat scores from human activity and landscape disturbance based threats (left panel) and climate change based threats (right panel) for all streams in the FRB and delineated stream habitats of fish SAR.

Corresponding with the human activity cumulative threat scores, median values of individual threats tended to be similar across salmon species and in relation to all streams in the FRB (Fig. 44). However, the median riparian disturbance threat score for the Chum CU and Coho CUs not at risk were lower relative to other CUs and all streams in the FRB. In addition, the median longitudinal fragmentation – anadromous species threat score for the Chinook, Chum, and Coho CUs not at risk were higher relative to other CUs and all streams in the FRB. Median values for SAR extents differed most for threats of AIS, latitudinal fragmentation, riparian disturbance, nutrients, and pollution (Fig. 45). Overlap with higher AIS, latitudinal fragmentation, and riparian disturbance threat scores was greatest for Coastrange Sculpin, Green Sturgeon, Nooksack Dace, and Salish Sucker extents. Median nutrient loading scores tended to be highest for Nooksack Dace and Salish Sucker, and pollution scores tended to be highest for these two species, as well as for Green Sturgeon, Mountain Sucker, and White Sturgeon (Fig. 45).

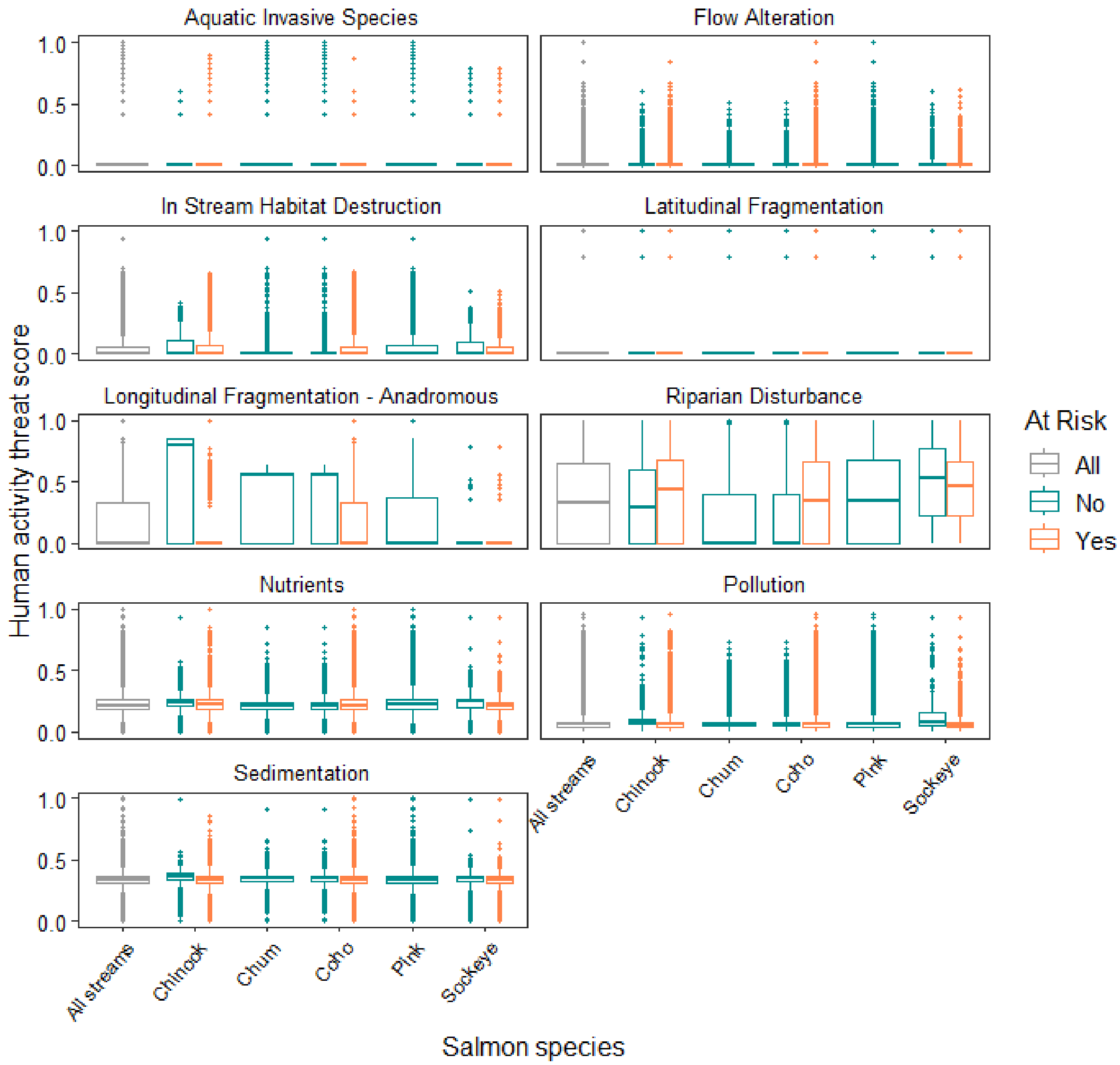

Figure 44. Tukey's box-whiskers plots of the human activity and landscape disturbance based threats for all streams in the FRB and for streams within salmon CUs (only including streams below natural barriers for salmon). CUs identified as Special Concern, Threatened, or Endangered by COSEWIC were distinguished from those not at risk (see Appendix G, Fig. G1 for individual CU results).

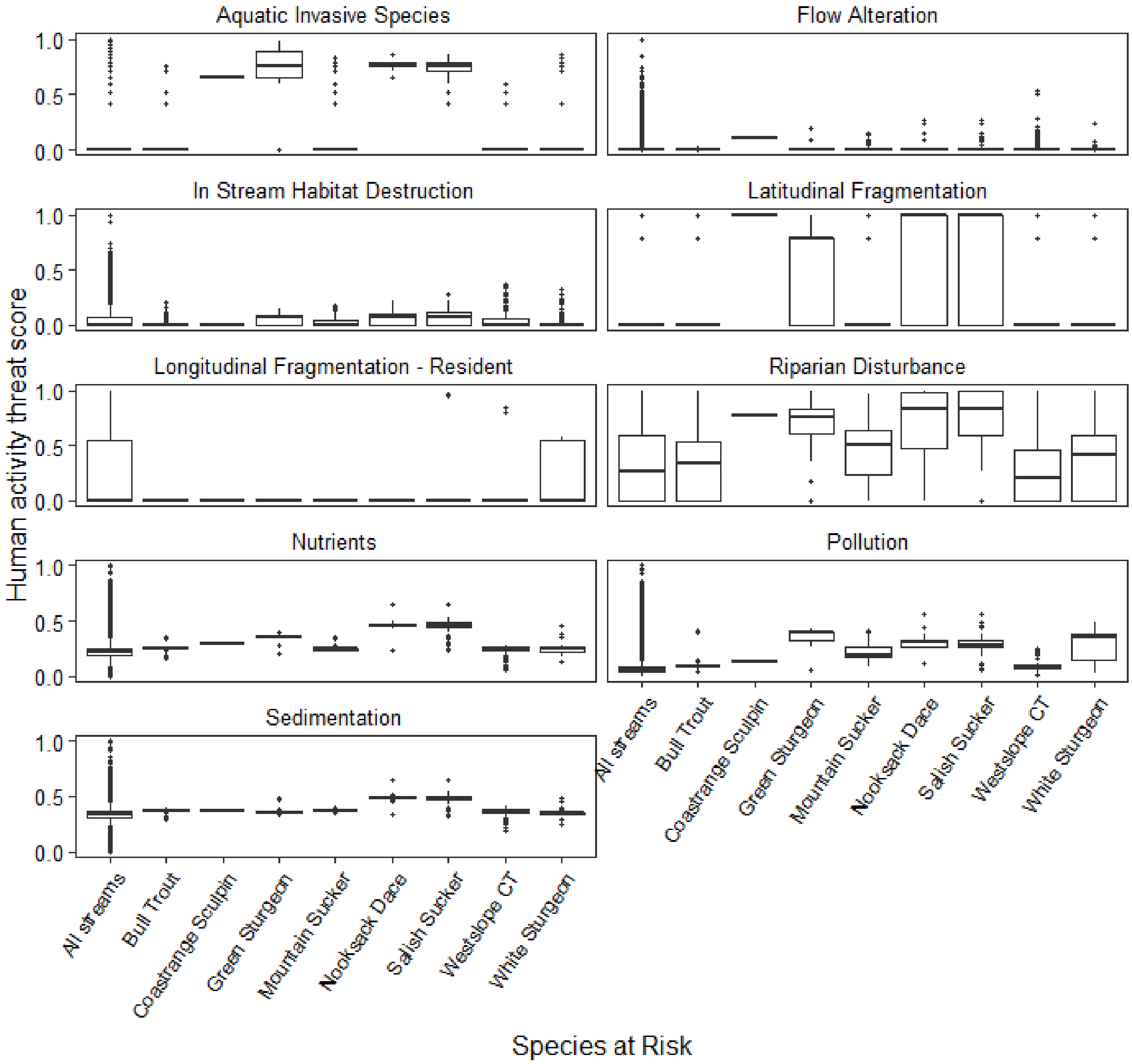

Figure 45. Tukey's box-whiskers plots of the human activity and landscape disturbance based threats for all streams in the FRB and delineated stream habitats of fish SAR.

Median values for individual climate change based threats varied across salmon CU species (Fig. 46). Relative comparisons of CU exposure to low and high stream flow threats were generally inversed as CUs exposed to low minimum flows (i.e., higher score for low stream flow threat) were less exposed to high maximum flows (i.e., higher score for high stream flow threat). Most notable trends were higher median low stream flow scores (i.e., lower minimum flow) for the Chum CU and Coho CUs not at risk and higher median stream temperature for Sockeye CUs not at risk (Fig. 46). Median flood change was highest for Mountain Sucker, followed by Green Sturgeon, White Sturgeon, and Bull Trout (Fig. 47). Low stream flow threat median values were highest (i.e., lower minimum flows) for Coastrange Sculpin, Nooksack Dace, and Salish Sucker relative to other SAR and all streams across the FRB. SAR extents tended to be similarly or less exposed to high stream flow threat compared to all streams. Finally, median stream temperature was notably higher for Coastrange Sculpin, Green Sturgeon, Mountain Sucker, Nooksack Dace, and White Sturgeon relative to all streams (Fig. 47).

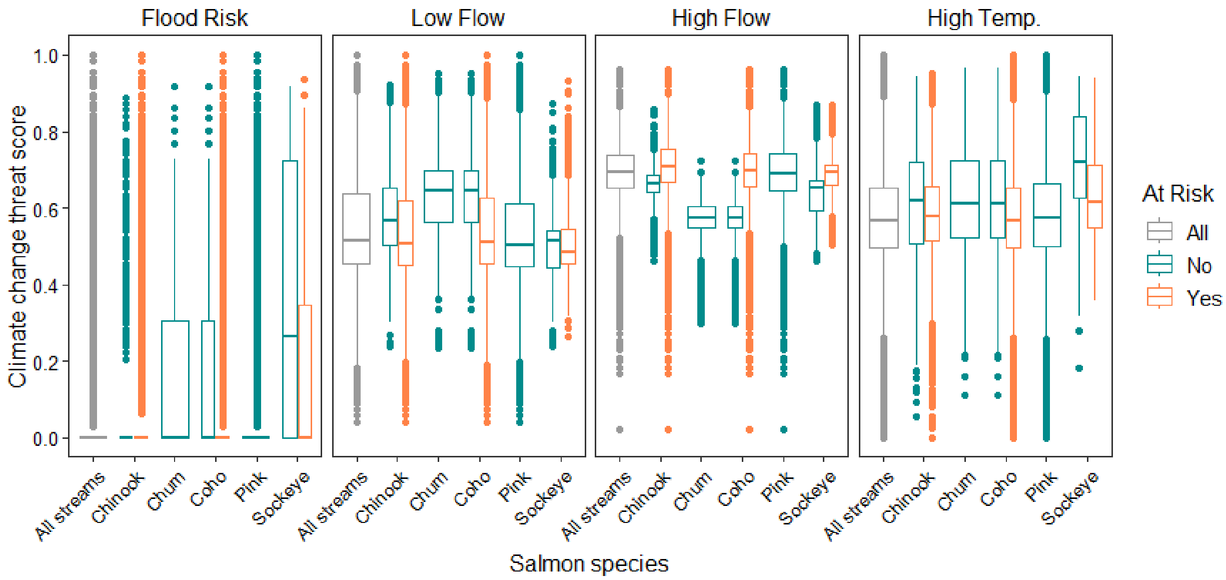

Figure 46. Tukey's box-whiskers plots of the climate change based threats for 2040–2060 under RCP 4.5 for all streams in the Fraser River Basin and for streams within salmon CUs (only including streams below natural barriers for salmon). CUs identified as Special Concern, Threatened, or Endangered by COSEWIC were distinguished from those not at risk (see Appendix G, Fig. G2 for individual CU results). Higher scores indicate projected greater absolute flood level change ('flood risk'), lower minimum August %MAD-monthly stream flows ('low flow'), higher maximum May %MAD-monthly stream flows ('high flow'), and higher August stream temperatures ('high temp.').

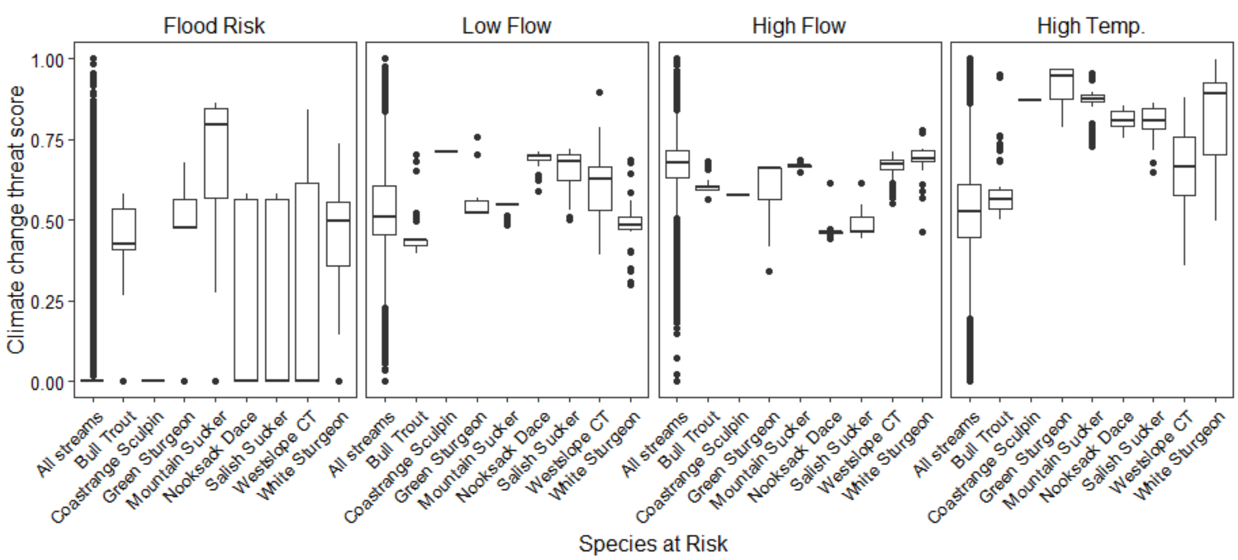

Figure 47. Tukey's box-whiskers plots of the climate change based threats for 2040–2060 under RCP 4.5 for all streams in the Fraser River Basin and delineated stream habitats of fish SAR. Higher scores indicate projected greater absolute flood level change ('flood risk'), lower minimum August %MAD-monthly stream flows ('low flow'), higher maximum May %MAD-monthly stream flows ('high flow'), and higher August stream temperatures ('high temp.').

Median human activity cumulative threat scores by watershed groups highlighted the interior plateau and the Lower Fraser watershed group as areas with the highest summed threats.

Those with the highest median cumulative threats were Nicola River, Guichon Creek, and San Jose River, from 1st to 3rd across watersheds. Within watershed groups across the FRB, the most prevalent activities or disturbances that contributed to threats based on identified occurrence as relevant for each individual threat score were roads, followed by dams and forest pest defoliation, and next by forest fires (Fig. 48b). The occurrence of an activity or disturbance as identified for each threat was based on its presence within a focal area for a stream reach for localized threats (e.g., flow alteration, riparian disturbance, in-stream habitat destruction), its presence upstream of a focal stream for flow accumulated threats (e.g., sedimentation, nutrients, pollution), or its presence downstream of a focal stream for longitudinal fragmentation for anadromous species.

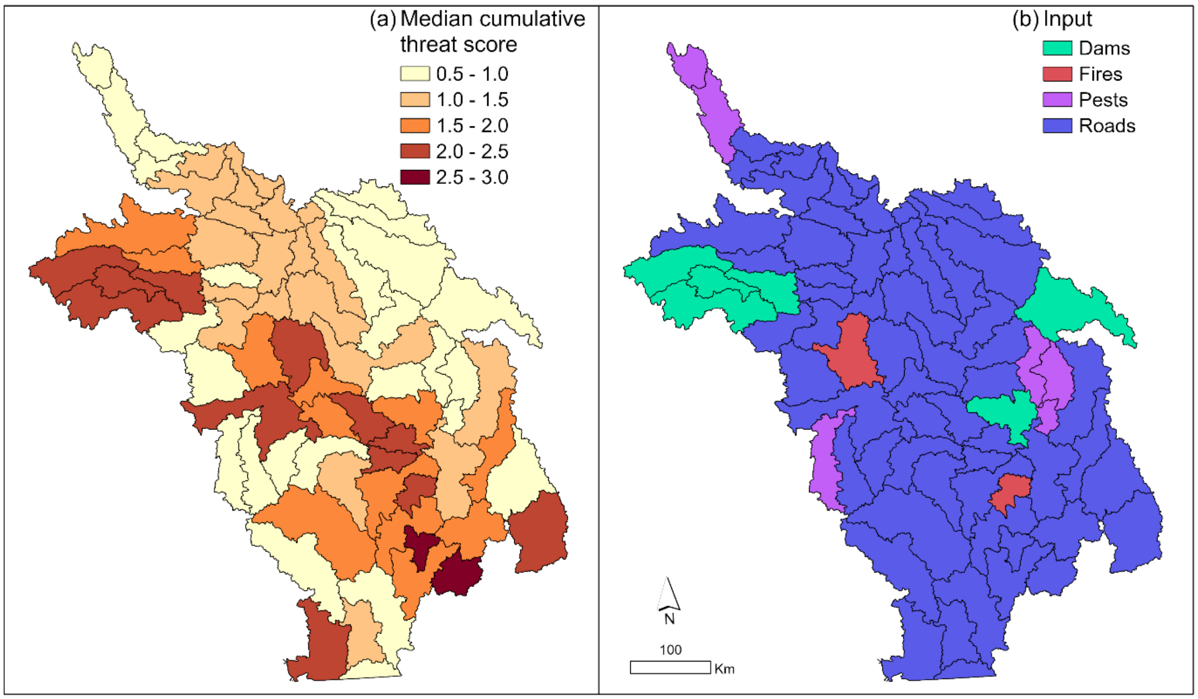

Figure 48. Summary results for watersheds groups indicating (a) the median cumulative threat score for human activity and landscape disturbance based threats and (b) the most prevalent activity or disturbance contributing to threats across streams based on its occurrence upstream, downstream, or within a focal area of a stream reach as relevant for each individual threat score.

The proportion contribution of inputs for threats with several human activity and landscape disturbance sources indicated which contributed most within watershed groups (Fig. 49). Culverts, rangeland, and roads were dominant for in-stream habitat destruction scores, and forest fires, forest pest defoliation, rangeland, and roads were most important for comprising the riparian disturbance scores (Fig. 49a,b). Fires and roads were primary contributors to nutrient and sedimentation threat scores; forest pest defoliation was also important for nutrients, and forestry was important for sedimentation (Fig. 49c,e). Agriculture and urban land uses frequently comprised a higher contribution to pollution threat scores, though multiple other inputs also had an influence depending on the watershed group (Fig. 49d). The land class category of ‘other non-urban’ made up a majority of the mean contribution for the flow accumulated threats, particularly pollution, despite a low concentration coefficient owing to the high prevalence of this category across streams (Fig. 49c–e).

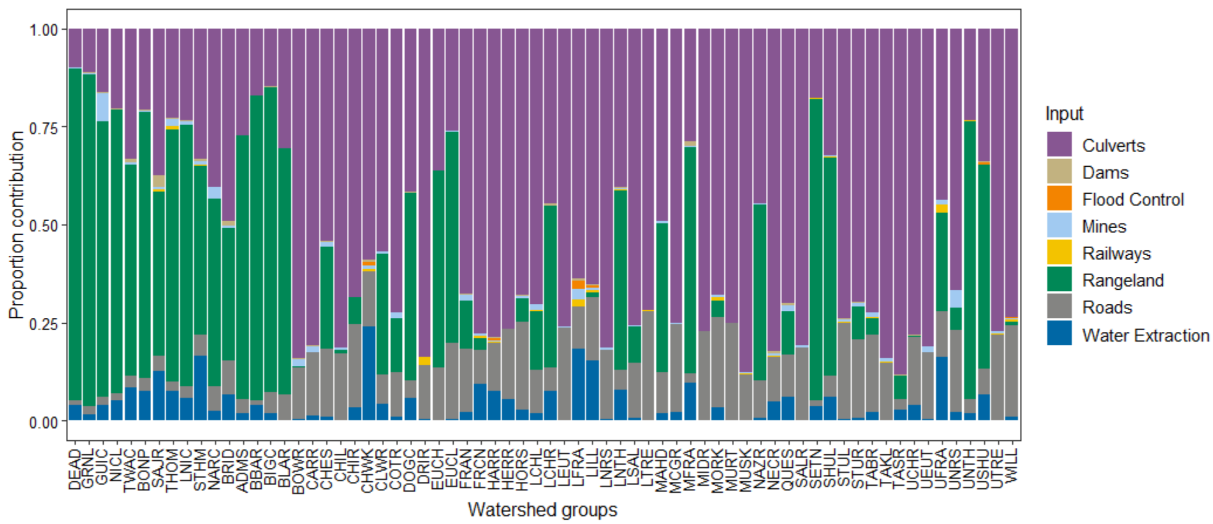

Figure 49a. Mean proportions of human activity and landscape disturbance inputs across streams within watershed groups for in-stream habitat destruction. Watershed groups are ordered by the median value of the threat from highest to lowest, followed by alphabetically when necessary. See Appendix A, Table A1 for the watershed group abbreviations ('codes').

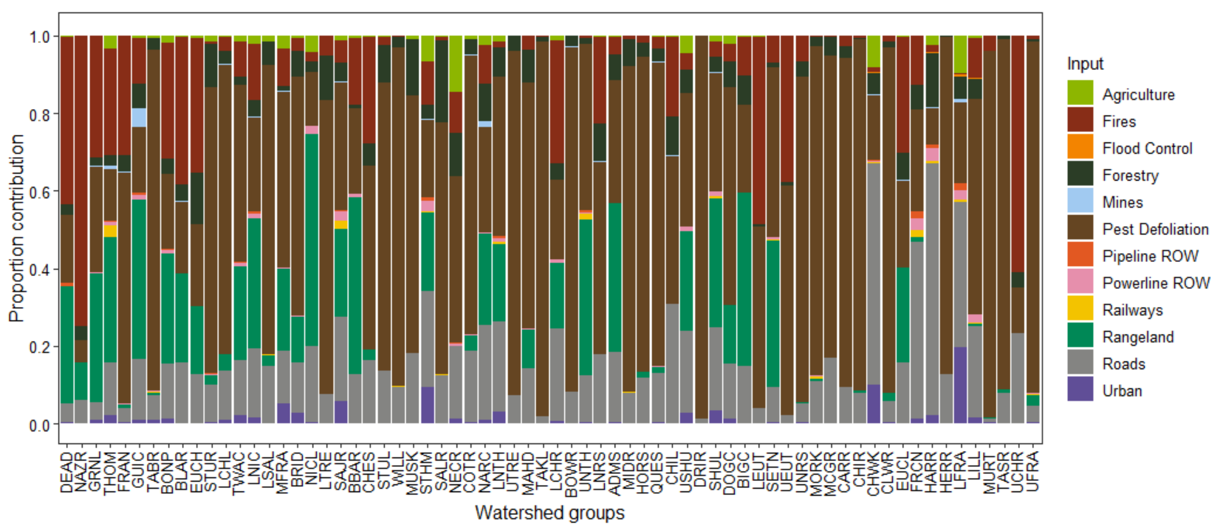

Figure 49b. Mean proportions of human activity and landscape disturbance inputs across streams within watershed groups for riparian disturbance. Watershed groups are ordered by the median value of the threat from highest to lowest, followed by alphabetically when necessary. See Appendix A, Table A1 for the watershed group abbreviations ('codes').

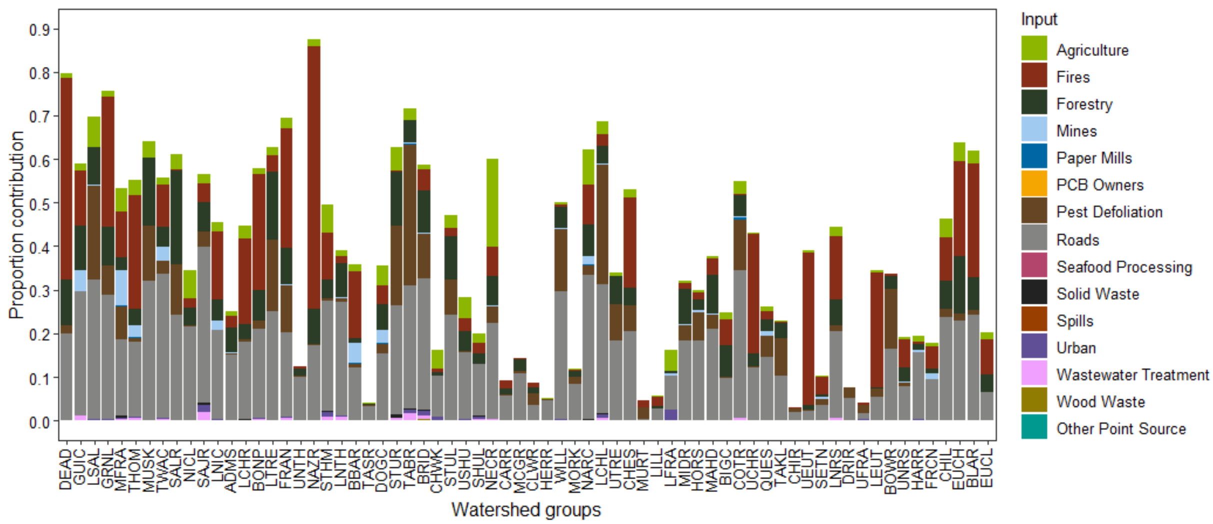

Figure 49c. Mean proportions of human activity and landscape disturbance inputs across streams within watershed groups for nutrient loading. Watershed groups are ordered by the median value of the threat from highest to lowest, followed by alphabetically when necessary. The land use class of 'other non-urban' was left out for visualizing other inputs, but makes up the remainder of the contributions. See Appendix A, Table A1 for the watershed group abbreviations ('codes').

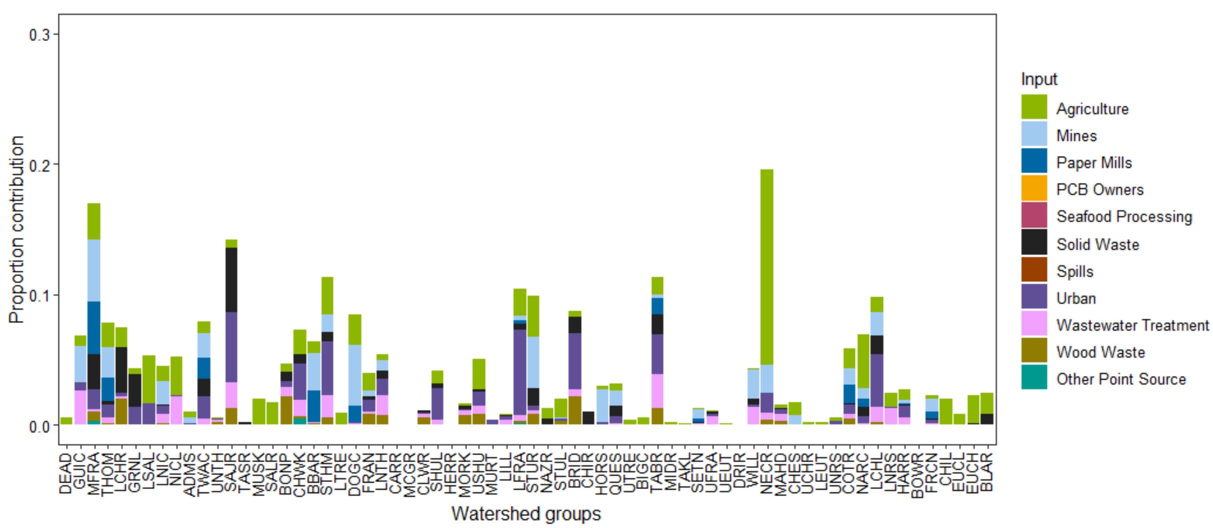

Figure 49d. Mean proportions of human activity and landscape disturbance inputs across streams within watershed groups for pollution loading. Watershed groups are ordered by the median value of the threat from highest to lowest, followed by alphabetically when necessary. The land use class of 'other non-urban' was left out for visualizing other inputs, but makes up the remainder of the contributions. See Appendix A, Table A1 for the watershed group abbreviations ('codes').

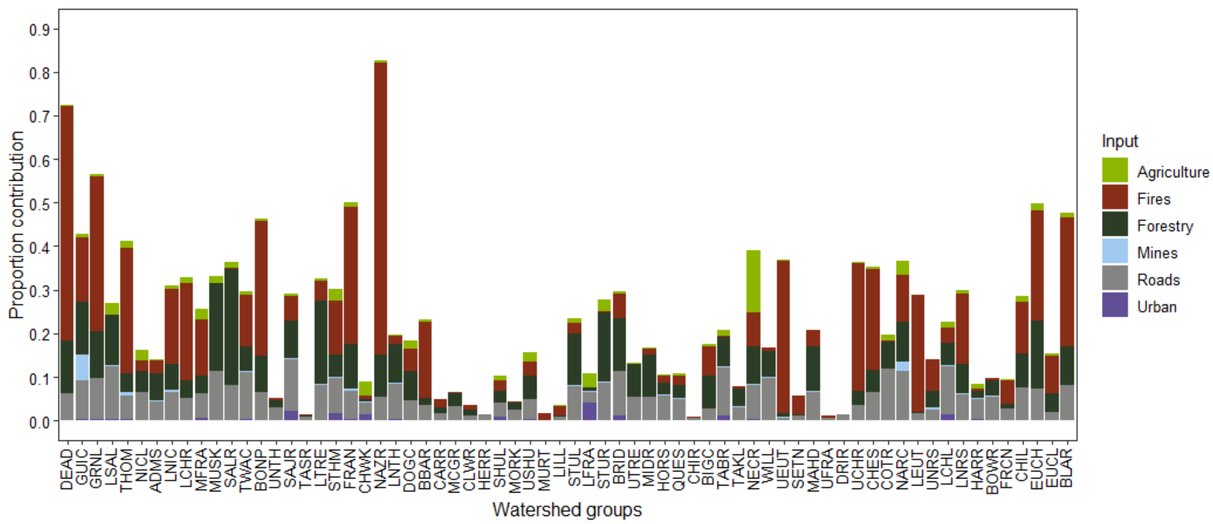

Figure 49e. Mean proportions of human activity and landscape disturbance inputs across streams within watershed groups for sedimentation loading. Watershed groups are ordered by the median value of the threat from highest to lowest, followed by alphabetically when necessary. The land use class of 'other non-urban' was left out for visualizing other inputs, but makes up the remainder of the contributions. See Appendix A, Table A1 for the watershed group abbreviations ('codes').

3.4. TEMPORAL EVALUATION

A comparison of land cover and land use from 2018–2022 largely showed shifts between areas identified as trees and rangeland across the FRB (Fig. 50). For instance, large patches within and surrounding the Thompson River major watershed indicated shifts from trees to rangeland, and within the Nechako River major watershed shifts from rangeland to trees (Fig. 50c–d). Forest related activities and disturbances all occurred within the interior plateau (Figs. 51–53). Fires from 2008–2022 had new occurrences within the 2012–2022 timeframe (i.e., post-2018) primarily within and surrounding the Thompson River major watershed (Fig. 51). Forestry cut blocks had interspersed shifts in extent between the two 10-year timeframes (Fig. 52). New occurrences of severe forest pest defoliation within the 2012–2022 timeframe (i.e., post-2018) primarily occurred around the central interior plateau and the Stuart River major watershed, whereas pest defoliation in the Thompson River major watershed mostly occurred prior to 2012 (Fig. 53).

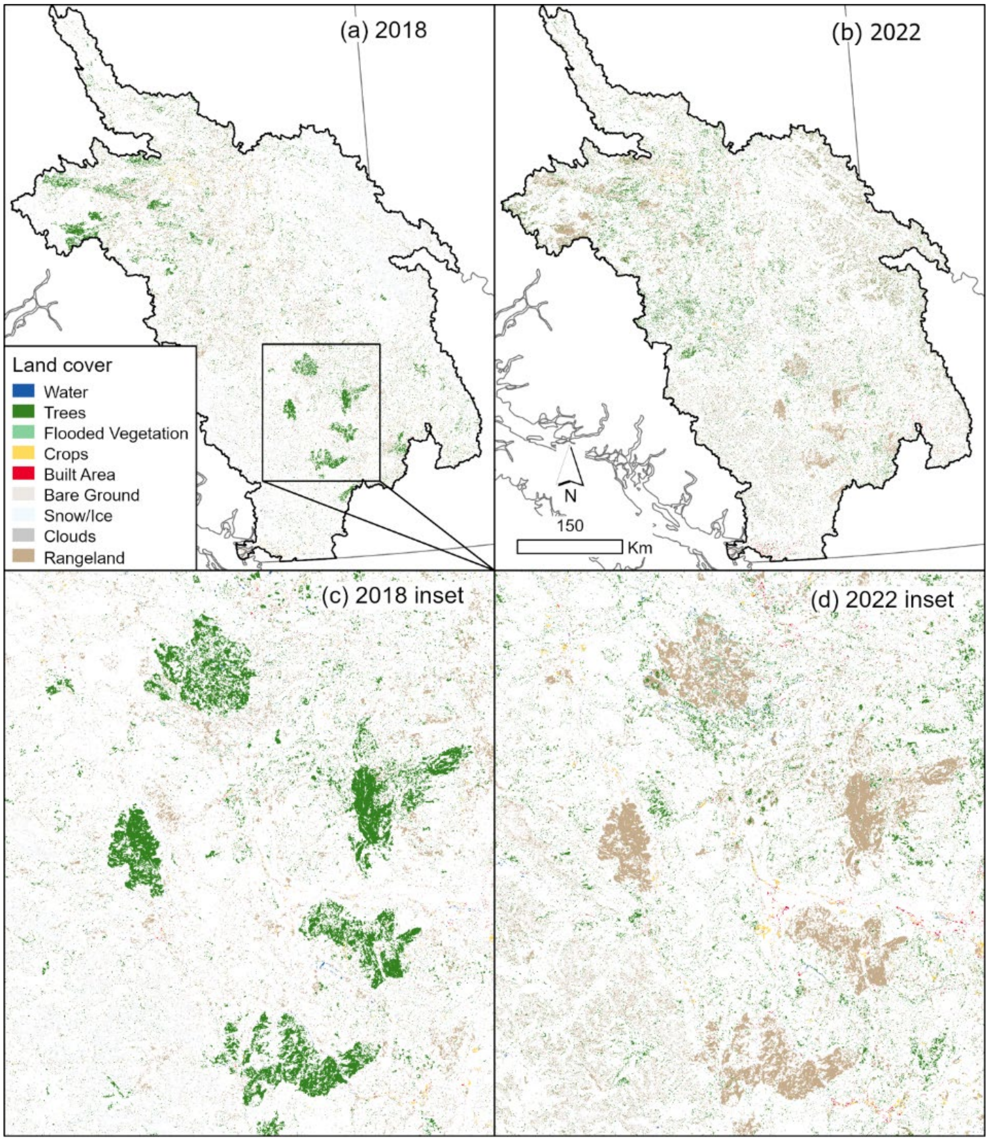

Figure 50. Temporal changes in land cover and land use from (a) 2018 to (b) 2022, showing grid cells that change land cover type between years, and a zoomed in extent highlighting changes from (c) 2018 to (d) 2022.

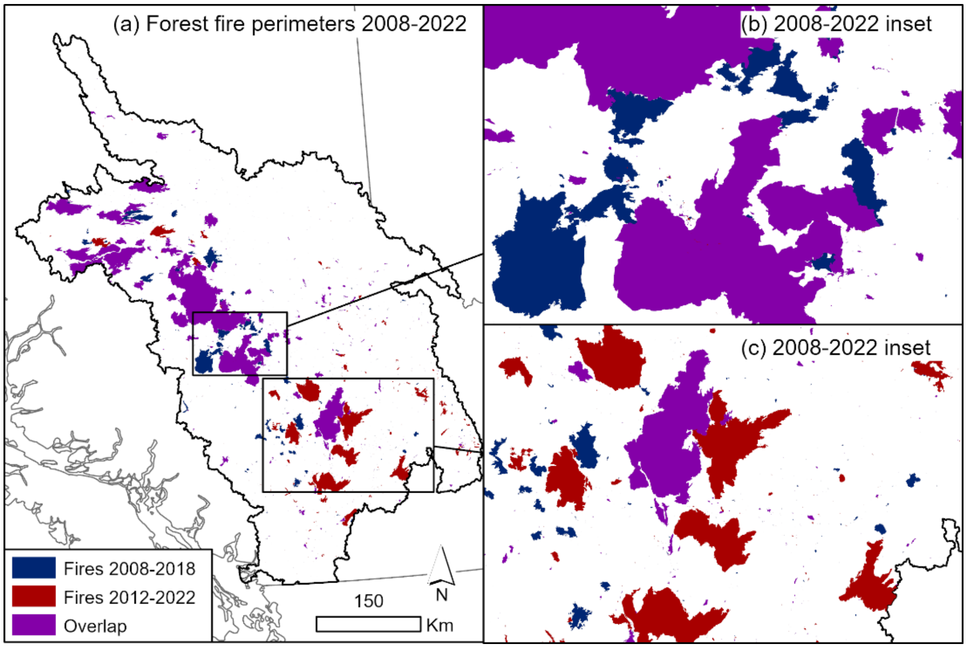

Figure 51. Temporal changes in forest fires perimeters using 10-year time windows. Forest fire perimeters are shown for (a) the FRB for 2008–2018 and 2012–2022 with areas of overlap indicated, and (b–c) two zoomed in extents to highlight change.

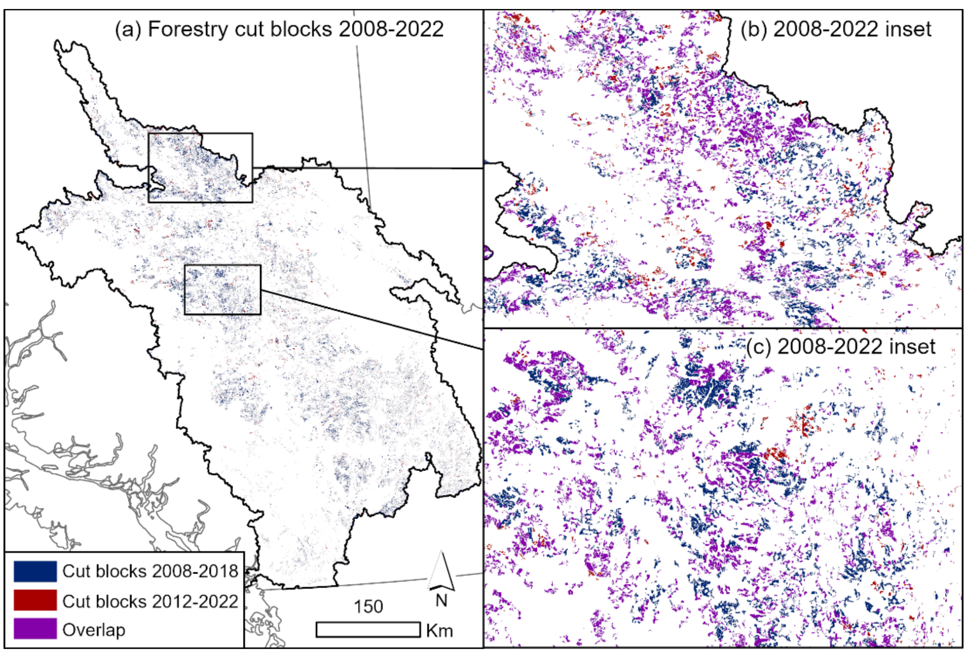

Figure 52. Temporal changes in forestry cut blocks using 10-year time windows. Forestry cut block areas are shown for (a) the FRB for 2008–2018 and 2012–2022 with areas of overlap indicated, and (b–c) two zoomed in extents to highlight change.

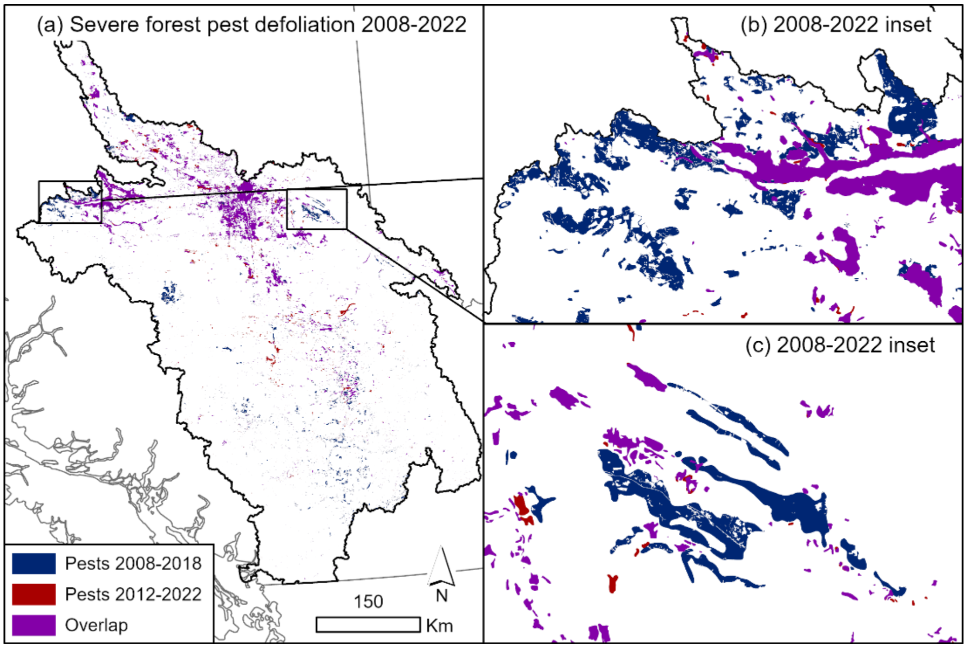

Figure 53. Temporal changes in severe forest pest defoliation using 10-year time windows. Areas with severe forest pest defoliation are shown for (a) the FRB for 2008–2018 and 2012–2022 with areas of overlap indicated, and (b–c) two zoomed in extents to highlight change.

3.5. THOMPSON-NICOLA EDU

Within the Thompson-Nicola EDU, there are eight Chinook Salmon CUs (5 identified as Endangered by COSEWIC), three Coho Salmon CUs (all Threatened), one Pink Salmon CU (not at risk), and five Sockeye Salmon CUs (1 Special Concern, 1 Threatened, and 1 Endangered; note, the Endangered Momich Lakes-Early Summer population is referred to here as a CU for simplicity) (Fig. 54).

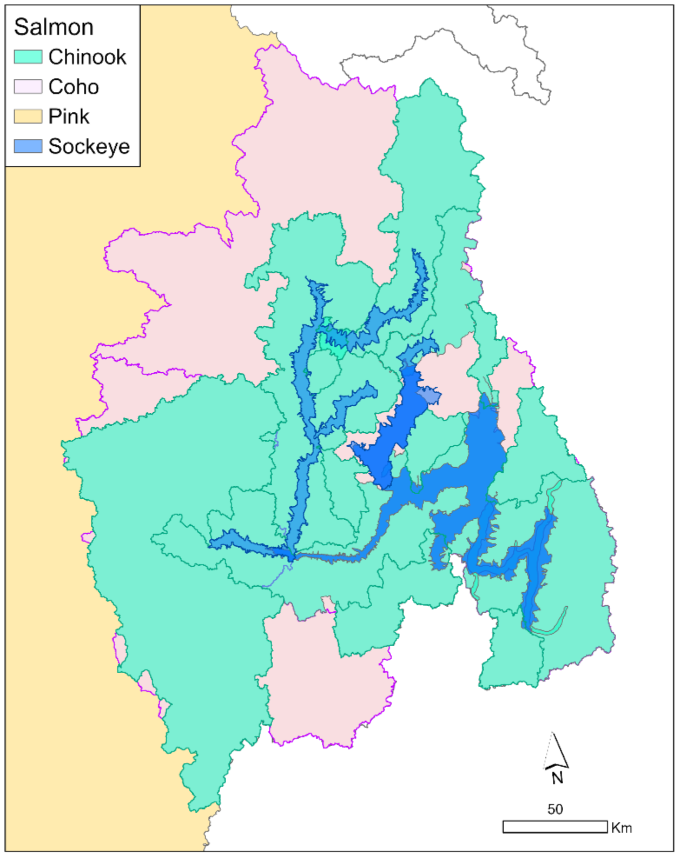

Figure 54. Pacific salmon CUs within the Thompson-Nicola EDU and those identified as Special Concern, Threatened, or Endangered by COSEWIC (note, the Pink CU covers the extent of the EDU).

Median cumulative threat scores for human activity and landscape disturbance based threats and climate change based threats were generally similar across salmon species in the Thompson-Nicola EDU. However, the median human activity cumulative threat tended to be highest for Chinook and Sockeye CUs not at risk and the climate change cumulative threat tended to be highest for Sockeye CUs (Fig. 55). Across individual CUs, Endangered Chinook and Threatened Coho Lower Thompson CUs (CK-17 and CO-07, respectively) tended to have higher median scores for in-stream habitat destruction and riparian disturbance (Fig. 56). Threatened Sockeye North Barriere – Early Summer Timing CU (SEL-10-03) had relatively high median scores for each of the climate change threats (Fig. 57).

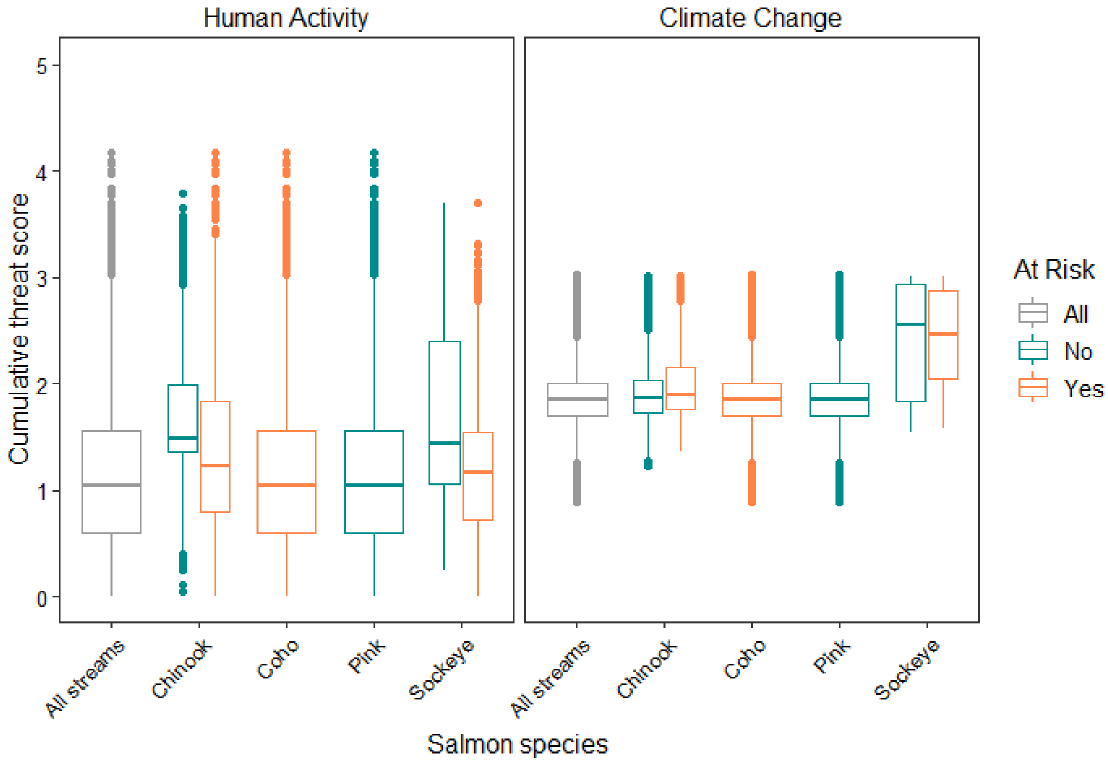

Figure 55. Tukey's box-whiskers plots of the cumulative threat scores from human activity and landscape disturbance based threats (left panel) and climate change based threats (right panel) for all streams in the Thompson-Nicola EDU and for streams within salmon CUs of the EDU (only including streams below natural barriers for salmon). CUs identified as Special Concern, Threatened, or Endangered by COSEWIC were distinguished from those not at risk.

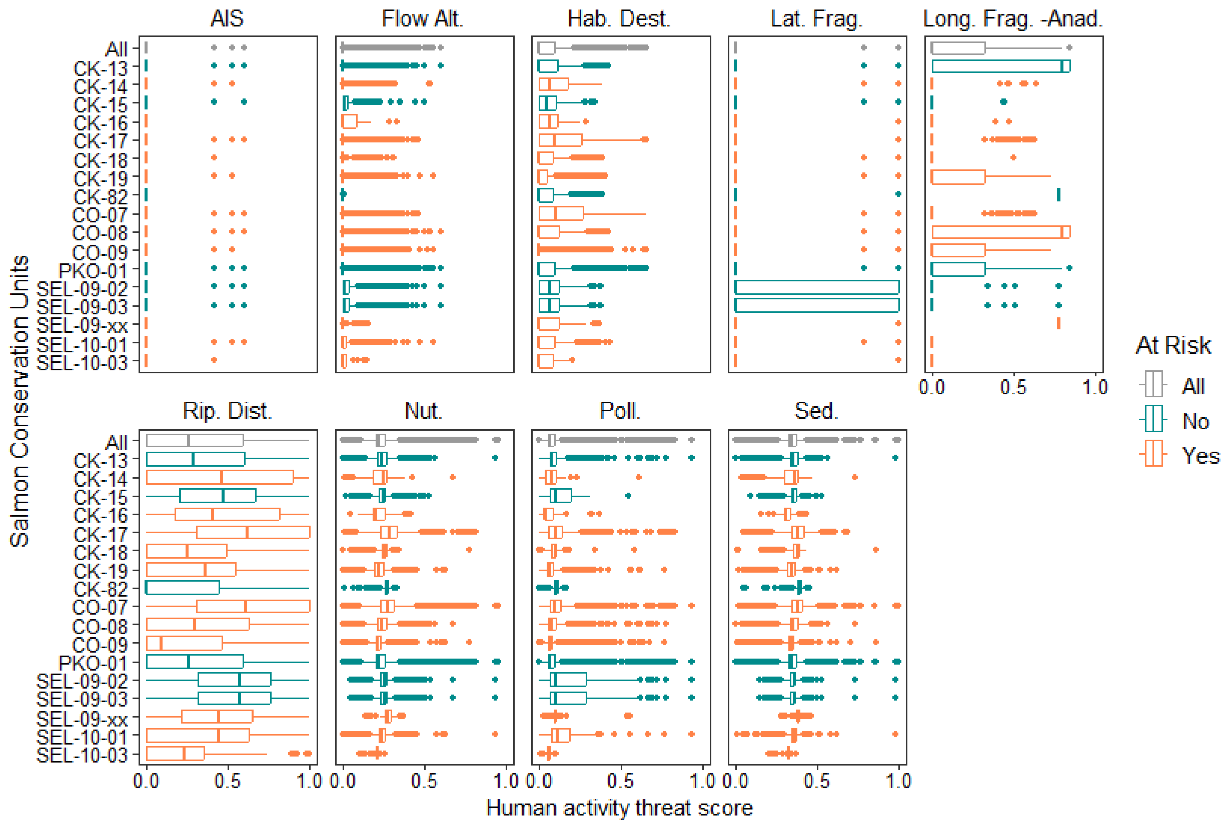

Figure 56. Tukey's box-whiskers plots of the human activity and landscape disturbance based threats for all streams in the Thompson-Nicola EDU and for streams within salmon CUs (only including streams below natural barriers for salmon), including: Aquatic Invasive Species (AIS), flow alteration (Flow Alt.), in-stream habitat destruction (Hab. Dest.), latitudinal fragmentation (Lat. Frag.), longitudinal fragmentation – anadromous (Long. Frag. - Anad.), riparian disturbance (Rip. Dist.), nutrients (Nut.), pollution (Poll.), and sedimentation (Sed.). CUs identified as Special Concern, Threatened, or Endangered by COSEWIC were distinguished from those not at risk. CUs included Chinook (CK), Coho (CO), Pink – Odd (PKO), and Sockeye – Lake (SEL).

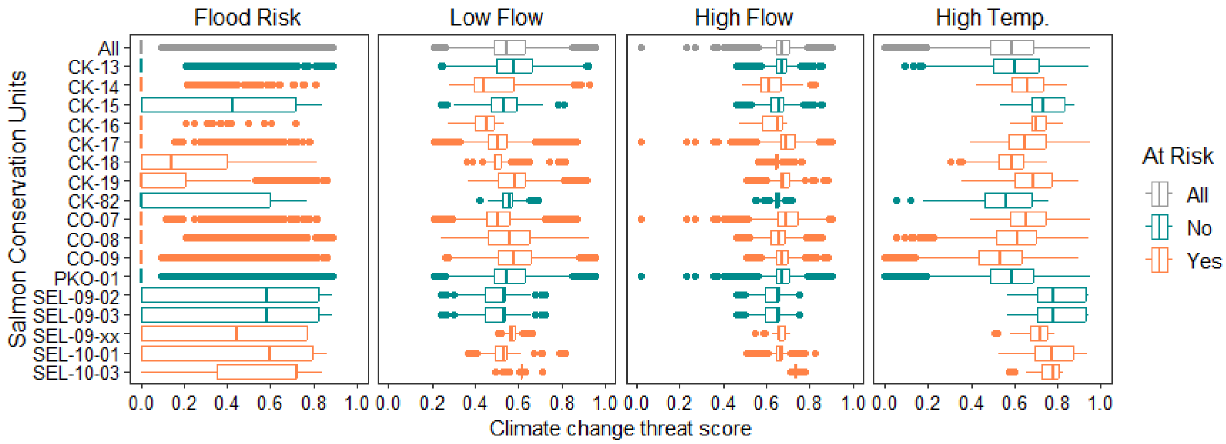

Figure 57. Tukey's box-whiskers plots of the climate change cumulative threat score and component metrics for 2040–2060 under RCP 4.5 for all streams in the Thompson-Nicola EDU and for streams within salmon CUs (only including streams below natural barriers for salmon). Higher scores indicate projected greater absolute flood level change ('flood risk'), lower minimum August %MAD-monthly stream flows ('low flow'), higher maximum May %MAD-monthly stream flows ('high flow'), and higher August stream temperatures ('high temp.'). CUs identified as Special Concern, Threatened, or Endangered by COSEWIC were distinguished from those not at risk. CUs included Chinook (CK), Coho (CO), Pink – Odd (PKO), and Sockeye – Lake (SEL).

Median cumulative threat composite scores within watershed groups based on the multiplicative value of human activity cumulative threats and favourable spawning habitat under current and future conditions indicated overall higher scores for Sockeye (Fig. 58). Relative differences in scores between species and timeframes within watersheds are reflective of higher or lower predicted spawning favourability as the cumulative threat scores are the same for these comparisons; differences between watersheds are from a combination of differences in cumulative threats and spawning favourability. Higher probability of environmental favourability for spawning may or may not overlap current CU extents as these models match environmental conditions of stream reaches with conditions of where spawning has been observed, but do not include other limiting factors that may determine distributional constraints. In addition, model projections included currently inaccessible streams to help inform potential barrier remediation. Watershed groups that were considered inaccessible based on ≥4th order streams were Bridge Creek, Green Lake, and Murtle Lake (Fig. 58). Considering all streams, the greatest shifts in median composite scores from current to future climate conditions (i.e., based on changes in predicted spawning favourability), focusing on watershed groups that are currently accessible, were increases in Upper North Thompson River for Chinook (median score change = 0.14), Bonaparte River for Pink (0.06), and Deadman River for Sockeye (0.11), and a decrease in Thompson River for Coho (-0.06). Watershed groups with the highest median scores generally remained the highest between current and future conditions. Watershed groups that had consistently high composite scores under both current and future conditions across salmon (including all streams) were Adams River and Deadman River (Fig. 58).

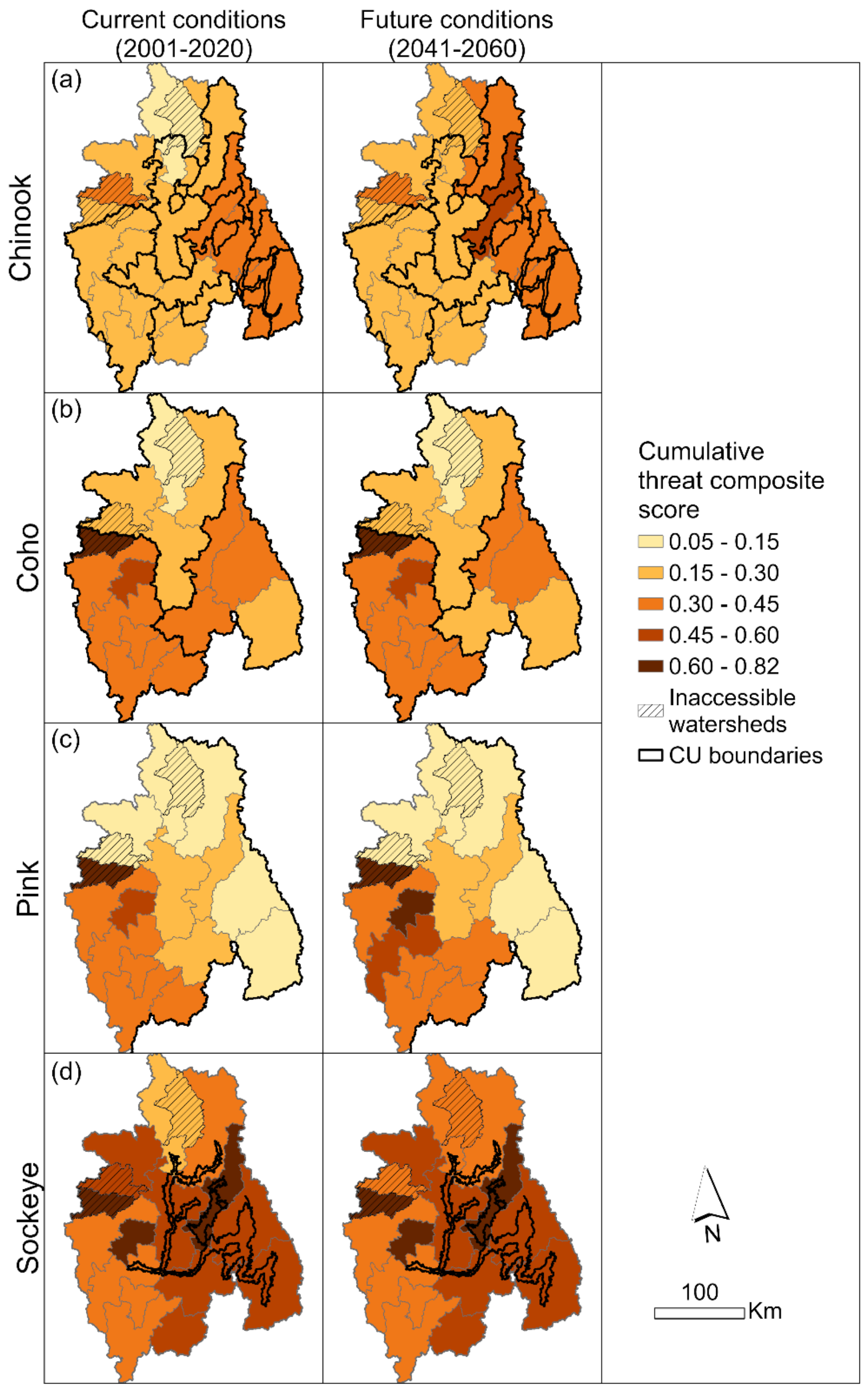

Figure 58. Median cumulative threat composite scores for watershed groups in the Thompson-Nicola EDU based on the multiplicative value of human activity and landscape disturbance based cumulative threats and modeled environmental favourability for spawning (row a) Chinook, (b) Coho, (c) Pink, and (d) Sockeye Salmon. Modeled environmental favourability probabilities used in the composite score were based on projected (column a) current and (b) future conditions for all stream reaches (≥4th order) including inaccessible streams from dams and natural barriers. Watershed groups that are largely inaccessible are identified by hatched lines, and salmon CU boundaries in black outlines.

The riparian input composite score indicated where high estimated inputs of nonpoint sources of nutrients, pollution, and sedimentation based on land use and riparian disturbance corresponded with high predicted spawning favourability for salmon (Fig. 59). Nonpoint source inputs were estimated to be highest along the eastern edge of the Thompson-Nicola EDU (Fig. 59a). Riparian input composite scores were highest along the North Thompson River, Eagle River, and Shuswap River, particularly for Chinook, Coho, and Sockeye (Fig. 59b–e).

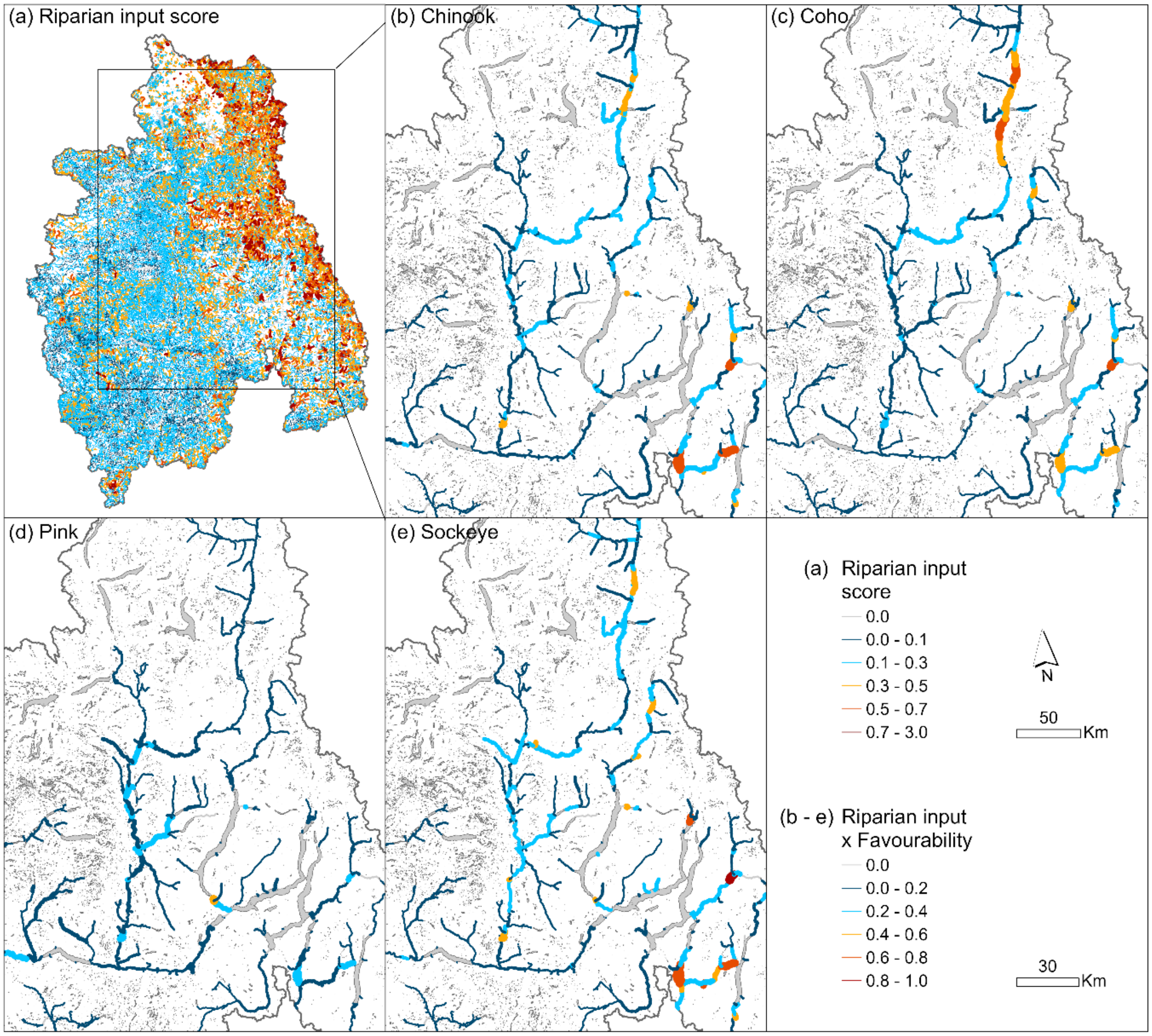

Figure 59. Riparian input composite score (a) based on nonpoint source inputs and riparian disturbance scores. The riparian input score multiplied by modeled environmental favourability for salmon spawning (baseline conditions 1981–2020) indicated accessible stream reaches where high riparian input values coincided with high environmental favourability for (b) Chinook, (c) Coho, (d) Pink, and (e) Sockeye Salmon. Stream lines are scaled to highlight those with higher scores.

Evaluation of the water resource composite score showed that locations of licensed water withdrawal generally corresponded with streams that had higher minimum %MAD-monthly flows in the Thompson-Nicola EDU (Fig. 60a). The multiplicative composite score indicated a gradient of streams with low to high values based on the distribution of values in the EDU, and some that increased under future climate conditions (Fig. 60c–d). Watershed groups with the highest water resource composite scores were distinguished for CUs and at risk status of each salmon species and indicated that the South Thompson River watershed was the only one with high average scores across all species (Fig. 61). The Thompson River watershed extent that overlapped Sockeye CUs not at risk had the highest composite score owing to high water withdrawal allowances, with a lower but still notable score for Sockeye CUs at risk. As similarly shown in the map (Fig. 60a), the lowest minimum flow values tended to correspond with lower water withdrawal allowances (Fig. 61). Water resource composite scores increased slightly between historic (1981–2010) and future climate conditions (2040–2060) from lower minimum %MAD-monthly values, but did not change which watersheds had higher scores (Appendix H, Figs. H1, H2).

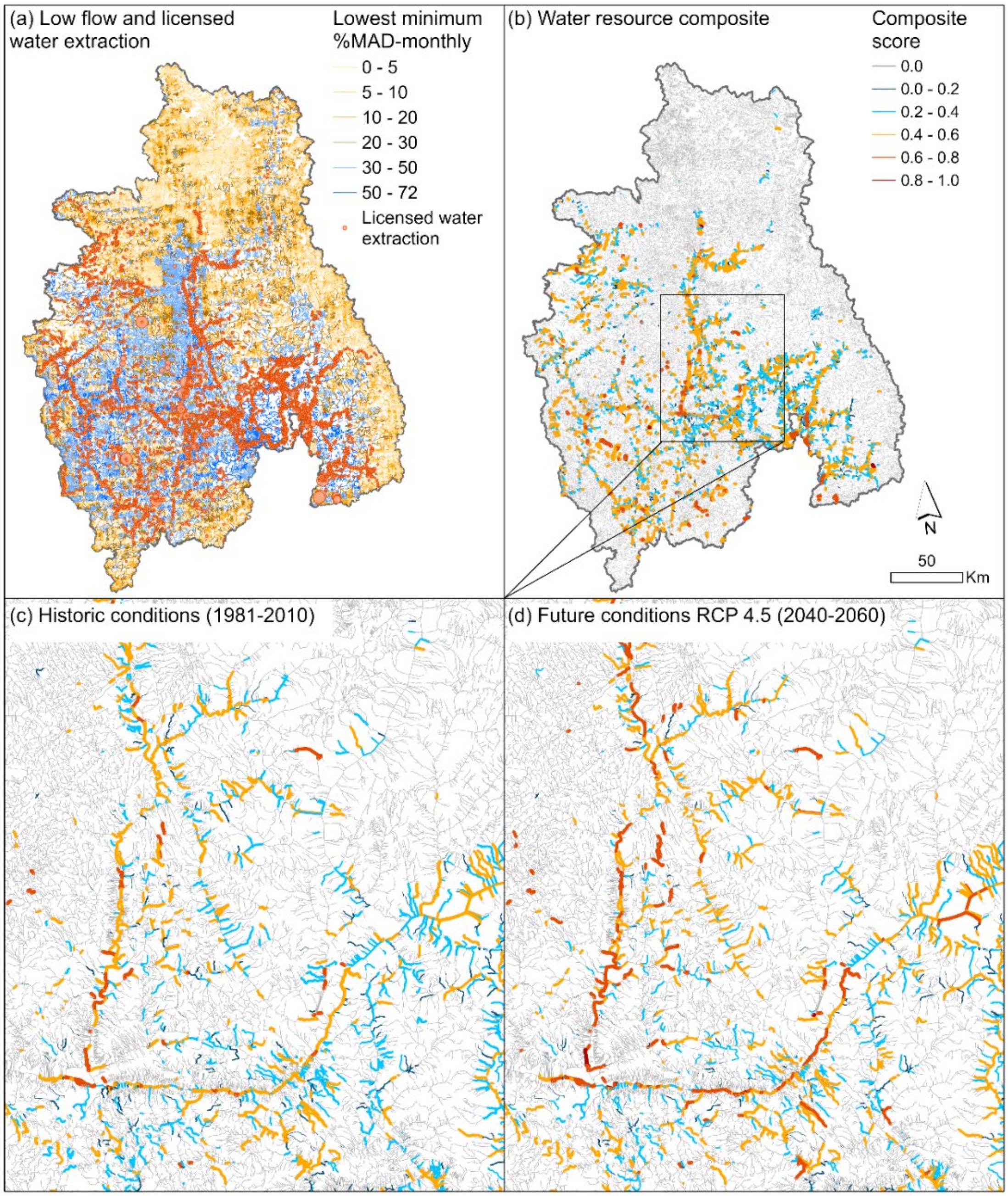

Figure 60. Map of (a) the lowest minimum %MAD-monthly flow across the year for each stream reach under historic conditions (1981–2010) and licensed water extraction amounts (proportional symbols based on allowable amount, m^3/year). The water resource composite score (b) was based on a multiplicative score between the inverse of lowest minimum %MAD-monthly and licensed water extraction. A zoomed in view of results for (c) historic and (d) future climate conditions (2040–2060). Stream lines in b–d are scaled to highlight those with higher scores.

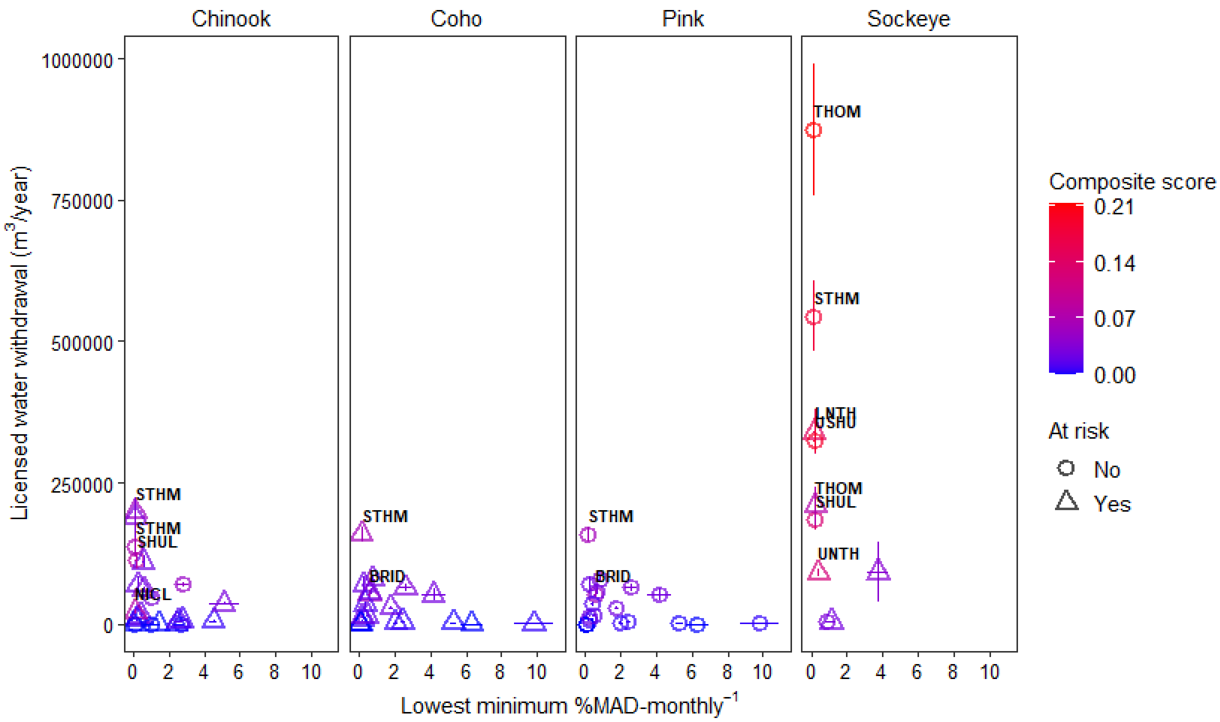

Figure 61. The water resource composite score based on the inverse of the lowest minimum %MAD-monthly flow (i.e., a higher value equates to lower flow) under historic conditions (1981–2010) and licensed water extraction amounts within the Thompson-Nicola EDU. Streams scores were averaged by watershed groups and associated salmon CUs distinguished by at risk status. Watersheds groups with a mean composite score greater than 0.05 are labeled, and include Bridge Creek (BRID), Lower North Thompson River (LNTH), Nicola River (NICL), Shuswap Lake (SHUL), South Thompson River (STHM), Thompson River (THOM) and Upper North Thompson River (UNTH). Points for both axes are mean ± 1 SE.

The anadromous fragmentation composite score identified several areas that had high amounts of blocked stream network with moderate probability of being favourable spawning habitat for salmon (Fig. 62). Blocked favourable habitat under current and future conditions was highest in the Upper Shuswap watershed group, followed by Adams River, for all salmon species (Fig. 62; Appendix H, Figs. H3, H4). Composite scores for individual dams and each salmon species indicated 3–6 focal dams per species; many of these higher score dams were the same across species and climate scenarios, including the Cherry Creek Pond Dam, Sugar Lake Dam, and a dam in the Rivers and the Peaks municipality (Fig. 63).

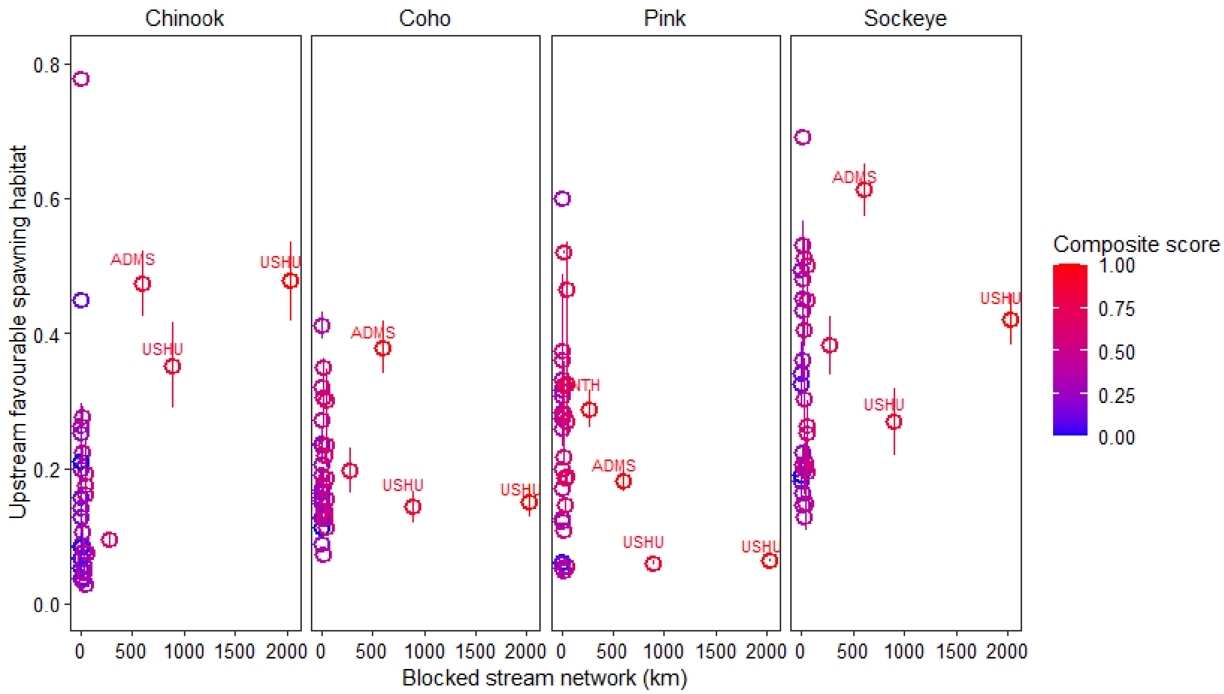

Figure 62. The anadromous fragmentation composite score based on the amount of blocked stream network upstream of an initial dam to subsequent barriers (natural or dams) and the corresponding upstream mean modeled favourable spawning habitat within the Thompson-Nicola EDU. Favourable spawning habitat is for current climate conditions (2001–2020); future projections are in Appendix H (Figs. H3, H4). Watersheds groups are labeled for blocked streams with composite scores greater than 0.85, and include Adams River (ADMS), Lower North Thompson River (LNTH), and Upper Shuswap (USHU). Points are mean ± 1 SE.

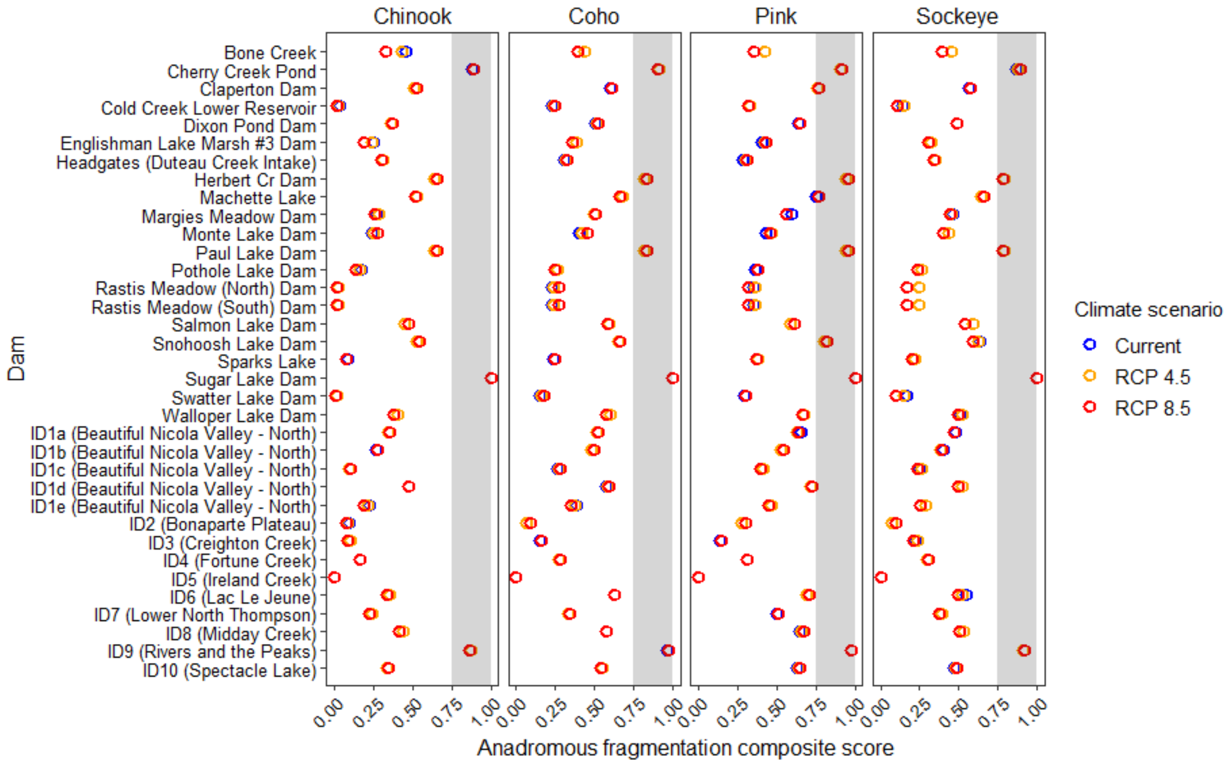

Figure 63. Anadromous fragmentation composite score for dams that are the first to block upstream passage in the Thompson-Nicola EDU. Composite scores change with climate scenarios for current (2001–2020) and future time periods (2041–2060) as changes in favourable habitat for salmon spawning are predicted to occur based on projected water temperature and precipitation. Grey areas highlight the dams with highest scores.

4. DISCUSSION

4.1. OVERVIEW

The cumulative threat assessment for the FRB provided estimations of threats that are directly linked to fish and fish habitat and can be used to inform management actions by:

1. evaluating threats identified as important by FFHPP and COSEWIC, including climate change,
2. creating a methodology that accounted for water flow and downstream effects (i.e., flow accumulated threats),
3. conducting the analyses at the scale of streams for finer resolution that can then be summarized at various watershed levels as needed,
4. identifying overlap of salmon and SAR extents, and
5. estimating threats at the level of influence on fish and fish habitat (e.g., sedimentation) while also evaluating which inputs (e.g., roads) contribute to these threats for potential mitigation or restoration.

These attributes are components of the criteria that have been proposed as important for determining the suitability of geospatial tools for reporting on the status of threats and the state of fish habitat (DFO 2022). The criteria that have not yet been fully addressed, but are in scope for continuation and development of the methodology provided here, are to cover a greater extent of the Pacific Region, reassess indicators to evaluate change over time, and develop a cumulative effect score based on quantified biological responses (i.e., stressor-response curves) or expert opinion (see “Future Evaluation”) (DFO 2022).

The cumulative threat results indicated the highest cumulative threat scores around the lower Fraser River and along the interior plateau of the FRB for both human activity and landscape disturbance based threats and climate change based threats. These summary scores were especially driven by riparian disturbance, nutrients, and sedimentation for the human activity based threats and high stream temperatures for the climate change based threats as those with the highest median scores. Roads were the most frequent input that influenced human activity based threats across the FRB, and contributed consistently to in-stream habitat destruction, riparian disturbance, nutrients, and sedimentation. Other important inputs to these threats were forest fires, forest pest defoliation, rangeland, and forestry. This combination of results provides information on where estimated threats to fish and fish habitat are high and the key drivers behind these threats.

Median threat scores were compared across salmon CUs and SAR extents relative to each other and to all streams across the FRB. Scores that tended to differ from all streams indicated that a species extent had a higher or lower exposure to individual or cumulative threats because of its location within the FRB. In particular, higher median human activity threat scores for an at risk species extent may provide some insight as to which threats are limiting the species most, though a closer link to the effect on the species requires information on responses to the threats (i.e., stressor-response curves). The finding that generally SAR with limited ranges (i.e., Coastrange Sculpin, Green Sturgeon, Nooksack Dace, and Salish Sucker) had higher median human activity cumulative threat scores relative to all streams in the FRB corresponded with the status of these species as at risk. Median human activity threat scores tended to be more similar among salmon species and relative to all streams, though a few of the Threatened and Endangered Sockeye CUs had notably higher median threat scores. The individual CU results may be more informative than the summary comparisons of salmon CUs at risk and not at risk as these groupings encompass large spatial extents that inherently capture a greater range of threat scores across streams. Any similarity in scores indicates that one CU may not be more exposed to a threat than another CU, but these relative comparisons do not imply that the estimated threats are not impacting the CUs. In addition, a more fine-tuned evaluation for salmon could focus on specific spawning locations of interest to determine relative threat levels for those areas, which is more aligned with the SAR focal extents (Boyd et al. 2022). We used salmon CUs instead of spawning extents for this evaluation as geospatial delineations of spawning extents are not fully resolved, though PSE also provides spawning extents from a compilation of observational data and expert elicitation (PSF 2021). The human activity threat scores provided an indication of threats that may be currently limiting populations, whereas the climate change threat scores estimated threats that these species may be facing by 2060. Identification of which species use areas that are projected to have higher climate change based threats can indicate which may be most at risk from these pressures, and may be currently experiencing shifts in conditions. For instance, Mountain Sucker extent had the highest median climate change cumulative threat score, with relatively high individual scores for each of the climate change threats compared to the other SAR. Linking these threats to species-specific responses would enable further understanding of how each species may respond to these projected changes. For anadromous species, more detailed understanding of projected climate change impacts can be achieved through analyses such as life cycle modeling that links projected climate variables to appropriate timing windows and locations of life history stages (Crozier et al. 2021).

4.2. COMPARISON TO OTHER RELEVANT ASSESSMENTS

Other assessments of cumulative threats that span the FRB include the Pacific Salmon Explorer, WWF-Canada Watershed Reports, and Global Threats to Human Water Security and River Biodiversity ('RiverThreat'; Vörösmarty et al. 2010; DFO 2022).

PSE used human activity and landscape disturbance inputs to represent categories of human development footprint, hydrological process, vegetation quality, fish passage/habitat connectivity, surface erosion, water quantity, and water quality; these were then binned into low, moderate, and high risk cumulative pressure ratings (PSF 2021). The assessment was conducted using 1:20,000 scale FWA Assessment Watersheds across BC salmon bearing watersheds. The general pattern of risk across the FRB largely matched the human activity based cumulative threat scores provided here, with similarly higher scores along the lower Fraser River and the interior plateau. The most notable differences were in our higher scores in the southwestern portion of the Nechako River major watershed and the southeastern extent of the South Thompson River watershed where PSE had identified low risk. In these areas, we estimated high threat scores for longitudinal fragmentation, riparian disturbance, nutrients, and sedimentation. Riparian disturbance was the most directly comparable threat between this assessment and PSE, and showed differences where PSE had estimated higher risk scores around Quesnel River and upper Fraser River major watersheds. We used similar human activity and landscape disturbance inputs, and the same 30 m buffer for riparian zones, but applied a more restrictive cut-off for forestry (10 years vs. 60 years) which may have influenced this difference (PSF 2021). Binning and visualization methods, as well as resolution (stream reaches versus assessment watersheds), may also drive differences in observed spatial patterns.

WWF assessed threats of alteration of flows, pollution, habitat loss, habitat fragmentation, overuse of water, invasive species, and climate change, and binned these into threat level categories of very low to very high. Threats were evaluated at the level of sub-drainages across Canada, with four in the FRB (Lower and Upper Fraser, Thompson, and Nechako). Results from WWF were difficult to compare to results provided here owing to the large difference in resolution. For instance, their cumulative threat score was rated as high and the climate change threat score was rated as moderate for all four sub-drainages. The most similar scoring was in the high threat level of invasive species in the Lower Fraser sub-drainage, where we estimated highest AIS threat levels within the Lower Fraser watershed group in particular. Despite the challenge in making direct comparisons, WWF was ranked highest in the evaluation of which geospatial tools were most optimal for reporting on the status of threats and the state of fish habitat, of those available in 2022 (DFO 2022). This was based on a combination of the relevance of threats assessed, spatial coverage, data inputs, and methodology (DFO 2022).

RiverThreats was ranked second in the review of geospatial tools, and used methods that we adopted and expanded on here (Vörösmarty et al. 2010; DFO 2022). Specifically, our longitudinal fragmentation – resident species threat score used the same approach of quantifying the 'swimmable area' between barriers, though RiverThreats only used large dams and did not account for natural barriers (Vörösmarty et al. 2010). They also incorporated downstream effects of inputs using flow routing and estimated dilution by dividing accumulated inputs by mean annual discharge rates (Vörösmarty et al. 2010), as done here for the flow accumulated threats. The resolution of RiverThreats is fairly coarse (0.5° grid, ~55 km), but tended to have similarly high river biodiversity cumulative effect scores around the lower Fraser River and central parts of the interior plateau of the FRB. Similar to PSE, their cumulative effect score had lower values in the southwestern portion of the Nechako River major watershed than ours, which may in part be from our additional score for longitudinal fragmentation – anadromous species which was high in this area, and our accounting for forest fires in the riparian disturbance threat score which they did not include as an input in their catchment disturbance score (Vörösmarty et al. 2010).

Each of these geospatial tools provide useful information depending on the context, scale, and spatial extent of interest. The methodology and data inputs of these tools, and others including the BC Cumulative Effects Framework (Provincial Aquatic Ecosystems Technical Working Group 2020), were reviewed and considered in the development of the cumulative threat assessment presented here (DFO 2022). The current cumulative threat assessment was inspired from a recognized need for a combination of finer spatial resolution specific to freshwater features, threats linked to DFO needs for managing salmon and SAR and reporting on the state of fish and fish habitat, further advancement of threat estimation based on developments in data availability, and more detailed consideration of water flow and downstream effects.

4.3. APPLICATION TO THE THOMPSON-NICOLA EDU

We provided example applications of the threat scores and associated inputs for informing management and prioritization decisions for salmon habitat in the Thompson-Nicola EDU, particularly in the context of climate change. Matching the FRB summaries, the individual and cumulative threat scores were summarized for streams within salmon CUs and below natural barriers to highlight results within the EDU. For instance, median climate change threat scores for flood risk, low stream flow, and high stream temperatures tended to be higher for at risk Sockeye Salmon CUs. We then paired different threat scores, inputs, and salmon values (i.e., CU extents, favourable spawning habitat) to highlight streams and watershed groups with higher estimated threat exposures relevant to salmon. This showcased how these sources of information can be combined and viewed to make predictions across a region that can help inform management and restoration actions at large spatial scales. First, the cumulative effect composite score showed where cumulative threats and modeled favourable environmental conditions for salmon spawning intersected. This was summarized at a watershed group level to highlight watersheds that have high estimated threats and predicted salmon values. The Adams and Deadman River watershed groups were generally identified to have higher median scores under current and future climate conditions across salmon species in the EDU. Second, we created a riparian input composite score to indicate potential priority streams for riparian restoration based on estimated nonpoint source inputs, riparian disturbance, and modeled favourable spawning habitat. This identified streams along the eastern edge of the EDU with highest scores. Third, we estimated where the water resource composite score was greatest based on licensed water withdrawal allowance and low stream flows under current and future conditions. We graphically visualized which salmon species and watershed groups had higher exposures based on CU extents and found the South Thompson River watershed had high scores across salmon species. Finally, we calculated the anadromous fragmentation composite score as the correspondence between the amount of stream network blocked by an initial dam and the modeled favourable spawning habitat of that blocked network to help identify dams with the largest estimated impact to salmon habitat extent. We summarized these results by salmon species, watershed groups, and dams. Overall, the Upper Shuswap and Adams River watersheds, and the Cherry Creek Pond Dam, Sugar Lake Dam, and a dam in the Rivers and the Peaks municipality had high fragmentation composite scores across salmon species and climate change scenarios. This score focused on dams identified as full barriers, though dams recorded as partial barriers and culverts can greatly impede passage for salmon and can be considered in future iterations of this score. The riparian input, water resource, and anadromous fragmentation composite scores were developed to provide information on specific human activities and landscape disturbances that are of management interest and may be feasible to mitigate or restore.

Further iterations of threats and inputs combined with these and other salmon values can be applied as different management opportunities and priorities arise. In particular, juvenile rearing habitat was not captured as an important salmon value at this point. Known locations of juvenile rearing or other types of models of potential habitat use by salmon such as intrinsic potential models (also known as habitat suitability index models) can be applied to represent other streams that may be important for management and restoration. Intrinsic potential models for salmon in BC have been developed by the Canadian Wildlife Federation (Rebellato et al. 2022). In addition, region-specific models and local data are available for the Thompson-Nicola EDU and important to use in combination with these results as the methodology and data used here were restricted to what could be applied uniformly across the FRB.

4.4. UNCERTAINIES AND LIMITATIONS

There are some common uncertainties associated with generating geospatial cumulative effect assessments. A few uncertainties associated with general approaches to assessing stressors or threats to a focal ecosystem component include: whether the input layers should be treated as of equal importance; whether there is a uniform distribution of stressors within a gridded format (i.e., raster); where focal assessment units are located within a grid cell of raster-based data; and how scores are transformed and normalized (Halpern and Fujita 2013). We treated input layers with equal importance except for the pollution, nutrient, and sedimentation loadings where we were able to use estimations of input based on the activity or land use. The 10 m resolution grid cell for land cover, land use, and landscape disturbance layers corresponded well with the extent of fundamental watersheds (i.e., the primary focal habitat), as well as with the size of common human activities and disturbances such as roads. However, there were some cases where a grid cell would overlap with only a portion of a fundamental watershed and that grid would then be attributed to the watershed in entirety. More can be done to address this issue such as accounting for the relative proportion of that cell in the watershed, however this would add more complexity to the analysis which was currently deemed to outweigh the benefit. The biggest challenge in attributing inputs and threats to streams (i.e., the secondary focal habitat) was for those that were associated with two or more fundamental watersheds. This occurs for larger streams (e.g., Fraser River, Thompson River) where the local watershed of a stream reach is composed of multiple fundamental watersheds that include the river surface area on either side of the stream centreline and drainage area from both left and right banks; the fundamental watersheds for smaller streams include the entire surface area that drains into a reach. For these larger streams, we needed to attribute inputs from both sides which required additional processing steps. An additional uncertainty is in the accuracy of FWA stream network delineations; known issues include overestimates of headwater streams in the interior regions and underestimates in coastal regions, which will be important to consider when applying this assessment to other basins. On the ground actions following these results may need to overlay results with satellite imagery (such as Google Earth) to fully determine where streams align.

In assembling a global map for human impacts to marine ecosystems, Halpern et al. (2008a) transformed and rescaled drivers to allow for direct comparisons. Halpern and Fujita (2013) later suggested that preserving skew in the stressors is justified as it represents real differences between stressor levels. We chose to transform threats as presence/absence based threats had much more frequent high values (e.g., AIS threat) than those based on concentrations or extent (e.g., pollution). However, inherent differences in scores influenced their contribution to the cumulative threat. In particular, stream temperature had higher scores than the other climate change based threats and thus contributed more to the climate change cumulative threat score. The ranked cumulative threat score provided a comparative approach that better reduced the differences across threat score distributions, but over or underrepresented differences between score values within threats. The geospatial patterns between both cumulative threat score approaches were broadly similar. We focused our result summaries on the individual threat scores alongside the cumulative threats as the vulnerability to these threats, and subsequent weightings or response curves to produce a cumulative effect score (Halpern and Fujita 2013) has not yet been addressed.

Another uncertainty associated with these geospatial analyses is that the derived scores are often based on proxies rather than direct measures (DFO 2022). We sought to create more direct correspondence between the proxies and fish habitat to reduce some of this uncertainty, for instance by using input values for nutrients, pollution, and sedimentation collected by ECCC (2022) and other known sources, rather than simply associating terrestrial human activity footprints with fish habitat. ECCC's pollutant data PAWPIT are estimates based on available monitoring data and include extrapolations to fill gaps, and therefore also have uncertainties and are subject to change as more data become available. We also incorporated some of the mechanisms involved in how human activities and landscape disturbances contribute to threats to fish habitat, though these were based on generalized approximations. For instance, the degree that riparian buffers, runoff, and stream flow influence sedimentation in a stream is context-dependent and could only be represented at this point with simple relationships. Some threats have less uncertainty in this regard, for instance riparian disturbance based on satellite data and known land use footprints, or longitudinal fragmentation based on dams and natural barriers that have been assessed as blocks to fish passage. However, data sources may also contain errors, for instance there are associated error rates in land use classification from satellite imagery depending on the applied algorithm, and some dams identified as barriers have not been verified. Uncertainty in the flow accumulated threats can be quantified with in situ data provided an adequate time series of sampling, though such data are currently limited (see "Future Evaluation"). Uncertainty in the flow alteration threat could also be quantified where there are time series records of stream flow before and after flow alteration; this would be mostly limited to locations of gauge stations.

We identified uncertainties and limitations for each threat, as well as the ability to extend the threat assessments to other basins in the Pacific Region (Table 2). Qualitative confidence ratings were also applied to each threat based on the identified uncertainties and limitations, following categories used in the Risk Assessment Method for salmon. Confidence ratings were identified as low for five threats (data exist but are considered poor or conflicting), medium for four threats (data exist but there are some key gaps), and high for four threats (data exist and are considered sound) (Table 2). Further work to quantify confidence intervals for threat scores would be beneficial. Sensitivity analysis can be conducted to determine how assumptions or applied values influenced threat scores, for instance, when there is a range of reasonable expectations for an input into a threat or when there are multiple modeled inputs included in a single score. Examples of this could include weighting in-stream habitat destruction activities differently based on expert elicitation versus treating them as equally destructive, or testing a range of plausible coefficients for non-point source sediment loadings from land use. Such iterations of scoring would indicate the degree to which these decisions change the scores, which is particularly pertinent if the relative comparisons across streams shift.

Table 2. Uncertainties, limitations, ability to extend the methodology for the rest of the Pacific Region, and confidence ratings for each estimated threat. Confidence ratings include low (data exist but are considered poor or conflicting), medium (data exist but there are some key gaps), and high (data exist and are considered sound); major deciding factors for ratings are in parentheses.

Uncertainties	Limitations	Extension	Confidence rating
Focal Ecosystem Components			
• FWA stream reach delineations have inaccuracies • Species at Risk habitat delineations may not fully encompass their habitat use	• Steelhead was not included based on initial scoping, but would be beneficial to include in future assessments as a species with populations assessed by COSEWIC as Endangered	• Feasible for BC • National Hydrographic Network could be used for Yukon with additional processing and preparation of fundamental watersheds	Medium (based on uncertainty in capturing full Species at Risk habitat extents)
Aquatic Invasive Species			
• Approximated polygon distributions of each species' range based on observations and 10 km search radius; the true distribution of each species is unknown • Determination of Aquatic Invasive Species status versus non-native species (i.e., no recorded impact) • Impact of each species on focal ecosystem components not fully known	• Only species observations from opportunistic surveys available • Further delineation of each species' distribution (i.e., from species distribution models) would improve accuracy of this score • Limited information on each non-native species and interactions with focal ecosystem components	• Feasible for BC • Need equivalent data for Yukon	Medium (based on uncertainty in capturing full AIS distributions)
Longitudinal Fragmentation			
• Steep slopes may be a natural barrier for other species, but were only for Pacific salmon • Blocks to passage from culverts not known for all culverts in FRB, and was not included in the threat scoring • Possible passage over dams and natural barriers that were included as blocks to passage	• Limited knowledge on slopes as barriers for resident fishes, and would require species-specific threat scores • Limited assessment of culverts as barriers for the extent of the FRB • Blocks to passage from culverts not included	• Feasible for BC • Need equivalent data for Yukon	Medium (based on conservative assessment using only dams as full barriers)

Uncertainties	Limitations	Extension	Confidence rating
• Partial barriers may fully block passage depending on the context, but were not included in the threat scoring	• Lack of detailed information on dams identified as partial barriers		
Latitudinal Fragmentation			
• Degree to which floodplain control infrastructure limits latitudinal movement from a given stream reach	• Simple presence/absence assessment of association of flood controls with stream reaches • Amount of floodplain habitat connected to a given stream reach not yet delineated • Did not yet consider other features that could limit latitudinal movement (e.g., roads, railways) • Spatial data on channelization are not available and therefore not represented aside from those accounted for by the urban land cover and flood control infrastructure layers	• Feasible for BC • Need equivalent data for Yukon • Need to consider other transect lengths used to capture flood control infrastructure when applying to other basins	Low (based on lack of association to lateral habitat)
In-Stream Habitat Destruction			
• Human activities were all treated equally with no current assessment of intensity • Forestry and oil and gas roads data were based on tenures (i.e., roads may not have been built or may be decommissioned); roads may be present on the landscape that were not captured by this dataset	• No current delineation of which activities may be more harmful to in-stream habitat than others • Activities on private land were not explicitly included, but were largely represented by the other included human activity and land cover layers based on visual inspection of layers	• Feasible for BC • Need equivalent data for Yukon	High (based on robust and comprehensive data inputs for evaluating presence of disturbance)
Flow Alteration			

Uncertainties	Limitations	Extension	Confidence rating
• Human activities all treated equally, but likely have variable contributions • Water withdrawal is based on licensed maximum allowances, actual amount withdrawn is unknown • Withdrawals include both groundwater and surface water, which may have differing impacts on flow that were not considered • Downstream and upstream effects of dams and water extraction not accounted for • Other land uses, in particular forest disturbances, can have important effects on stream flow that were not included	• No current designation or consistent data on characteristics that make dams and culverts more impactful to flow regimes • Data on amount of water withdrawn is not available • Data on unlicensed domestic water withdrawal (e.g., fire prevention, private dwelling) in BC are not available • Currently no general relationship to account for upstream/downstream effects of dams and water withdrawal on flow • Ideally apply data on intensity of forest fires and harvest, and general relationships, to account for effect of forest disturbances on flow alteration	• Feasible for BC • Need equivalent data for Yukon	Low (based on lack of information for water withdrawals, i.e., how much is withdrawn and association with seasonal flow levels)
Riparian Disturbance			
• Human activities were all treated equally with no current assessment of intensity • Relevant fire and forestry timeline to include depends on riparian function of interest • Forestry and oil & gas roads data were based on tenures (i.e., roads may not have been built or may be decommissioned); roads may be present on the landscape that were not captured by this dataset • Riparian buffer based on standard of 30 m but other buffer distances	• Currently limited assessments of buffer widths necessary to maintain different riparian functions depending on the system • Riparian zone based on static stream and river shorelines (does not account for any migration in river position over time) • Activities on private land were not explicitly included, but were largely represented by the other included human activity and	• Feasible for BC • Need equivalent data for Yukon • Need to consider differences in riparian recovery times (e.g., from forest disturbance) for other basins/climates	High (based on robust and comprehensive data inputs for evaluating presence of disturbance and focused currently on the riparian function of filtering)

Uncertainties	Limitations	Extension	Confidence rating
can be important and is dependent on the system • Level of forest pest defoliation that should be considered a disturbance depends on the riparian function of interest	land cover layers based on visual inspection of layers • Not a full assessment of disturbance to all riparian functions; currently focused on filtering capacity		
Nutrients			
• Land use inputs are likely context-dependent, but were applied as a single concentration coefficient (and accounting for runoff rates) • Point source input effluent loads were estimated based on available environmental monitoring, and estimates were made based on correlations to fill data gaps (ECCC 2022) • Non-point source coefficients were derived from limited literature including from the Western US (ECCC 2022) • Concentration coefficients for nutrient inputs from forest related disturbances (cut blocks, fires, pest defoliation) were estimated based on relative effect compared to 'Other Non-Urban' classification • Relevant fire and forestry timeline to consider can be variable • Forestry and oil and gas roads data are based on tenures (i.e., roads may not have been built or may be decommissioned); roads may be present on the landscape that were not captured by this dataset	• Limited literature and data on land use inputs to derive contribution coefficients • Dependent on extent of PAWPIT (ECCC 2022) data and high resolution hydrological layers	• Need high resolution hydrological layers for other basins (see 'stream flow' threat) • Provided hydrological layers, feasible for the FRB, Vancouver Island, Haida Gwaii, and coastal watersheds based on PAWPIT (ECCC 2022) extent	Low (based on incomplete nonpoint source input information and generalized assumptions for downstream accumulation and riparian filtering)

Uncertainties	Limitations	Extension	Confidence rating
• More complex context-dependencies in riparian filtering capacity not accounted for • More complex and localized settling dynamics not accounted for • Uses runoff and stream flow from hydrological models that were downscaled with associated uncertainty			
Pollution			
• Land use inputs are likely context-dependent, but were applied as a single coefficient (and accounting for runoff rates) • Point source input effluent loads were estimated based on available environmental monitoring, and estimates were made based on correlations to fill data gaps (ECCC 2022) • Non-point source coefficients were derived from limited literature including from the Western US (ECCC 2022) • Did not include air releases as deposition rates to a given stream reach were uncertain • Contributions of pollutants from river sediments were not included (ECCC 2022) • More complex context-dependencies in riparian filtering capacity not accounted for • More complex and localized settling dynamics not accounted for	• Limited literature and data on land use inputs to derive contribution coefficients • Dependent on extent of PAWPIT (ECCC 2022) data and high resolution hydrological layers	• Need high resolution hydrological layers for other basins (see 'stream flow' threat) • Provided hydrological layers, feasible for the FRB, Vancouver Island, Haida Gwaii, and coastal watersheds based on PAWPIT (ECCC 2022) extent	Low (based on incomplete nonpoint source input information and generalized assumptions for downstream accumulation and riparian filtering)

Uncertainties	Limitations	Extension	Confidence rating
• All pollutants were treated as exposure only, but their impacts on fish and ecosystem health vary			
Sedimentation			
• Land use inputs are likely context-dependent, but were applied as a single coefficient (and accounting for runoff rates) • Relevant fire and forestry timeline to include can be variable • Forestry and oil & gas roads data are based on tenures (i.e., roads may not have been built or may be decommissioned); roads may be present on the landscape that were not captured by this dataset • More complex context-dependencies in riparian filtering capacity not accounted for • More complex and localized settling dynamics not accounted for • Non-point source coefficients were derived from limited literature including from the Western US (ECCC 2022)	• Limited literature data on land use inputs to derive contribution coefficients • Less literature and data available for sedimentation than for nutrients and pollution • Dependent on extent of PAWPIT (ECCC 2022) data and high resolution hydrological layers	• Need high resolution hydrological layers for other basins (see 'stream flow' threat) • Provided hydrological layers, feasible for the FRB, Vancouver Island, Haida Gwaii, and coastal watersheds based on PAWPIT (ECCC 2022) extent	Low (based on incomplete nonpoint source input information and generalized assumptions for downstream accumulation and riparian filtering)
Flood Risk			
• Based on models for the extent of Canada with associated uncertainty (Mohanty and Simonovic 2021) • Models produced at coarser resolution compared to other used data layers (1 km^2)	• Limited use for finer resolution inquiry • Does not assess the change in probability of occurrence for a flood of a given magnitude • Metric based on a single return period	• Feasible for all Pacific Region based on model extent	Low (based on high uncertainty associated with flood projections)

Uncertainties	Limitations	Extension	Confidence rating
• Flood models considered highly uncertain			
Stream Flow – High and Low			
• Based on hydrological models (Schnorbus 2020) with associated uncertainty and some months performing better than others • Some uncertainty in downscaling the models, though a close correspondence was found between the original and downscaled resolutions • Correction factor used to adjust stream flow predictions at major dams where flow regulation was monitored, not adjusted for dams without associated hydrometric data	• Downscaling currently only done for the FRB • %MAD calculated based on monthly instead of daily values given current data constraints • Does not include extreme events such as atmospheric rivers or droughts	• Need high resolution hydrological layers for other basins • Finer scale models (fundamental watershed resolution) underway by PCIC for salmon bearing watersheds in BC, with an estimated timeline for delivery of 2026	High (well-established models with validated downscaling method)
Stream Temperature			
• Based on statistical stream temperature models with associated uncertainty (Weller et al. 2023) • Implicitly includes effect of land use disturbances on stream temperatures based on model fitting to in situ data, but does not explicitly model these effects	• Models developed for catchments at least 1 km^2 in size based on available in situ data (generally 3rd order streams and higher; Weller et al. 2023). • Does not include extreme events such as heat domes.	• Feasible for BC based on model extent • Need more extensive in situ stream temperature data for Yukon to produce and validate models	High (validated models that perform well relative to other largescale temperature models)

Data limitations prevented evaluation of some threats listed in the FFHPP policy (DFO 2019a) and guide[1]. We provide a brief overview of each threat as it relates to freshwater fish and fish habitat, as well as potential avenues and limitations for assessment using geospatial methods:

1. **Overexploitation of fish and provincially managed species:** Overexploitation of fish and provincially managed species is a key threat to consider for fished species (Post et al. 2015). Estimating overexploitation requires evaluation of sustainable yields and catch data (de Kerckhove et al. 2015). Comprehensive freshwater catch data are currently not available or accessible at broad spatial scales in BC.
2. **Change in aquatic habitat and vegetation:** Change in aquatic habitat and vegetation can affect availability of refugia and prey for fish. Unshaded habitats with greater macrophyte production can lead to higher densities of salmon and their prey compared to unvegetated habitats (Riley et al. 2009; McCormick and Harrison 2011). A greater number and different composition of fish species has also been found to occur in clearer water, vegetated habitats than in turbid, unvegetated habitats (Miller et al. 2018). Underwater aquatic vegetation has been successfully assessed geospatially using remote sensing methods in clear shallow waters; deep or turbid waters obscure reflectance of underwater vegetation making it difficult to detect and identify (Rowan and Kalacska 2021). There is a large variety of acoustic (e.g., echo-sounders) and electromagnetic sensors (e.g., bathymetric LiDAR) being deployed to test applications of mapping and identifying underwater vegetation (Rowan and Kalacska 2021). While these methods show great promise for fish habitat assessments, they are currently often limited to smaller spatial scales owing to intensive data processing, and the equipment can be cost prohibitive.
3. **Change in dissolved oxygen:** Low DO levels, and specifically hypoxic events, are a major concern for migrating and rearing salmon (Sergeant et al. 2023), as well as resident freshwater fishes including SAR in BC (Rosenfeld et al. 2021). Recent efforts to model DO and apply modeled relationships across a large spatial extents include (1) evaluation of statistical models and scaling laws for watersheds across the contiguous US (Abdul-Aziz and Gebreslase 2023) and (2) relative estimates of hypoxia vulnerability in association with high salmon densities near hatcheries in Alaska (Sergeant et al. 2023). In the US, DO was largely predicted by water temperature and secondarily by pH and TP (Abdul-Aziz and Gebreslase 2023). The importance of water temperature relates to lower solubility of oxygen and higher rates of microbial respiration at higher temperatures. Nutrient controls (TP and total nitrogen, TN) were less dominant in vegetated lands (53% of the watersheds represented in the study), and likely would be more important in modelling for agricultural lands (35% of watersheds; Abdul-Aziz and Gebreslase 2023). In Alaska, hypoxia vulnerability was found to be strongest in low-gradient stream reaches regardless of water temperature owing to low reaeration rates (Sergeant et al. 2023). Conducting an extensive geospatial modeling effort of hypoxia vulnerability for BC may be feasible using some combination of the parameters in these two models, but requires extensive DO in situ data for modeling and validation, high resolution flow layers, and stream channel attributes that are at various stages of development and refinement for BC. Spatially continuous measures of TP, TN, and pH are not available, though human-derived nutrient input estimates from the nutrient threat score may be useful. Such work is being explored within the Freshwater Ecosystems Section (DFO).
4. **Change in food supply:** Change in food supply is traditionally measured from site samples and is not commonly geospatially-derived. One study estimated prey availability for sturgeon across a watershed by interpolating between in situ samples (Spindler et al. 2012); however, interpolation is a very simplified way to obtain spatially continuous estimates. In addition,

there are many factors that can influence food supply so it may not be a threat that can be well represented by a few metrics.

5. **Change in noise:** Anthropogenic noise is known to affect the physiology and behavior of many aquatic organisms, though the effect of noise pollution in freshwater is relatively understudied compared to marine systems (Risch and Parks 2017; Mickle and Higgs 2018). A review on freshwater noise effects on fish captured studies on noise originating from boats, road traffic (i.e., along bridges), aquaculture production, and trawling. Acute noises from activities such as pile driving are a common focus of noise impacts; however, vessel traffic noise is considered the most pervasive noise pollution in aquatic systems and overlaps with frequencies of hearing and vocalizations of many aquatic organisms (Mickle and Higgs 2018). Urbanized areas can also lead to consistent noise in freshwater, though lower in magnitude than boats (Kuehne et al. 2013). Underwater acoustic environments in Washington lakes with greater than 50% impervious surface within a 10 km radius were found to exceed Environmental Protection Agency thresholds for 'outdoor annoyance and disruption' during daytime hours (Kuehne et al. 2013). Thus, obtainable metrics for chronic noise in freshwater include high-use bridge crossings and urban land cover; vessel traffic is another important metric, though vessel traffic data for freshwater are not readily available.
6. **Change in light:** Light pollution, in particular artificial light at night, can alter physiological, functional, and behavioural responses of freshwater organisms and have cascading ecosystem effects (Hölker et al. 2023). Direct and indirect light (i.e., 'skyglow') can have different effects depending on the properties of the light interacting with the freshwater system (e.g., attenuation, polarization) and the biota in the system; for instance, primary production may decrease or increase depending on the strength of artificial light (Hölker et al. 2023). Global light pollution is captured to an extent by satellites, but satellites cannot detect light emitted horizontally (e.g., by buildings) or blue light by light-emitting diodes (LEDs) which are contributing to an estimated 10% yearly increase in artificial light (Falchi and Bará 2023). Satellite data could be used to partially estimate this threat for freshwater BC, though this would be a simple association that does not account for different properties of light and how this may influence freshwater systems.
7. **Change in electromagnetic field:** The geomagnetic field is important for physiological and behavioral responses of many fish species, influencing processes such as migration and egg emergence (Putman et al. 2014, 2018; Fey et al. 2019). Underwater cables and freshwater renewable energy devices can alter electromagnetic fields which may impact egg and larval development (Fey et al. 2019), as well as swimming behavior and distribution (Bevelhimer et al. 2013). Spatial information on underwater cables is not currently accessible, but would help provide an indicator of the potential presence of this threat.

4.5. FUTURE EVALUATION

The cumulative threat assessment presented here provides a foundation for continued development of freshwater cumulative effect assessments to help inform management actions and reporting on the state of fish and fish habitat for the Pacific Region. Next steps for this cumulative threat assessment include expansion to other parts of the Pacific Region, reassessing the threats in a few years to evaluate change over time, linking the effect of threats on focal ecosystem components for cumulative effect evaluation, and validation of estimated individual and cumulative threats and effects.

An important criteria for reporting on the status of threats to the state of fish habitat is spatial coverage for the Pacific Region. The ability to extend the methodology to other parts of the Pacific Region largely centre around availability of information and data (Table 2). The threats that are most limited for extension to other basins in BC are those that require hydrological layers at a fundamental watershed resolution—nutrients, pollution, sedimentation, low stream flow, and high stream flow. Such layers are currently being produced by PCIC for all salmon bearing watersheds in BC, with expected availability in 2026 (M. Schnorbus, PCIC, pers. comm.). Nutrients, pollution, and sedimentation also require point and nonpoint source estimates from PAWPIT, which have now been developed for the FRB, Vancouver Island, Haida Gwaii, and coastal watersheds (ECCC 2022). Conversely, these three threats can be estimated using simpler methods such as originally produced for the Fraser Valley, BC (Boyd et al. 2022) which could then be more readily extended across BC. In that first iteration, we used catchment area to account for dilution instead of stream flow and used extents of human activities and landscape disturbances as a proxy for contributions without any source concentration information (Boyd et al. 2022). The method presented here is an advancement to provide more detailed and informed estimates, and would be preferable to use over the first iteration when possible. The other threats rely on data that are readily available for the rest of BC, but the availability of these data for the Yukon has not been assessed here. In addition, stream temperature models have been produced for the full extent of BC (Weller et al. 2023), but are not yet feasible using a statistical approach in the Yukon owing to limited availability of in situ temperature data. Method decisions made for the FRB will also need to be verified when extending to other basins; for instance, the recovery time of riparian areas from forest disturbance varies across basins and climates. The ability to extend the assessment of each threat for the Pacific Region is further detailed in Table 2.

The ability to reassess threats temporally is feasible moving forward using the threat scores provided here as a baseline. The data layers with available timeseries that would permit retrospective or future assessments were for land cover and land use, and forest related layers for fires, cut blocks, and pest defoliation. These data layers feed into threats of in-stream habitat destruction, latitudinal fragmentation, riparian disturbance, nutrients, pollution, and sedimentation. Many of the other data layers are updated regularly, but they are often not associated with timestamps based on when development occurred so retrospective analysis is not feasible (Appendix C, Table C1). However, threats can be reassessed in the future using these updated data layers (with the caveat that new additions to datasets may also be from previously missing developments that are not new on the landscape). An exception is for point source inputs for nutrients and pollution which were taken directly from PAWPIT (ECCC 2022); updated assessments would require updates to PAWPIT, or linking these estimates with any changes in associated human activities (e.g., mines, seafood processing, wood waste, etc.). We also used the BC Cumulative Effects Framework integrated roads and mining data layers completed in 2022 for our assessment as they combined and removed duplication from multiple road datasets (digital road atlas, forestry roads, and oil & gas roads), and assembled various types of mines from two data sources. The original data sources for roads are updated and could be used moving forward if the BC Cumulative Effects Framework data are not updated, however other sources for mining may need to be used as they do not appear to be updated.

Extending the cumulative threat score developed here to a cumulative effect score requires information on the relative impact of each threat to the focal ecosystem component. Threat scores can be weighted based on expert opinion of how vulnerable the ecosystem component is to each threat (Halpern et al. 2008b; Vörösmarty et al. 2010). A more fine-tuned approach would be to use stressor-response curves that delineate non-linear responses of focal ecosystem components across a range of threat levels (Rosenfeld et al. 2022; MacPherson et al. 2024). Stressor-response curves are traditionally generated through experiments, field studies, and modeled relationships, though methods to derive these relationships through expert elicitation have also been developed (DFO 2019b; MacPherson et al. 2024). We sought to create threat scores that would be conducive to stressor-response curve development by estimating threats that directly affect fish and fish habitat, to the extent that was feasible. For instance, relating stream ecosystem responses to human-derived nutrient inputs is more meaningful than relating responses to the proportion of agriculture in a watershed, a mapping exercise that is more readily achieved but one step further removed. Development of the estimated pollutant loadings into effect scores for fish will require scoring the various pollutants separately as they have different magnitudes of effects on fish depending on the type and the concentration.

Validation is an important step of most modeling exercises, though is often not a standard component of cumulative effect assessments (Halpern and Fujita 2013). Validation may be done for the threat estimates and for the predicted response of the focal ecosystem component. Threats that are derived from satellite imagery or datasets on land use footprints, such as riparian disturbance, are less necessary to validate unless the data sources are not reliable. Conversely, validation of threats that involve applied relationships and estimations, such as the flow accumulated threats, would be beneficial. For instance, ECCC (2022) conducted a contaminant load analysis at FRB water monitoring stations and compared the resulting loads to their estimated releases. They found multiple pollutants (e.g., metals, PCBs, PAHs) were higher in the contaminant load analysis than in the estimated releases, and attributed this in part to missing sources such as releases from sediments and deposition from air (ECCC 2022). Our pollution estimates are therefore likely underestimated to a similar extent since we used their estimated releases. This could mean that pollution has a more important role in the cumulative threat score than currently captured. In another case, comparisons of PSE-derived human pressure indicators to salmon spawner abundance found weak and variable relationships (Peacock et al. 2023). Conversely, evidence for biotic homogenization of freshwater fish diversity from cumulative pressures in the FRB was found from modeled relationships between fish species compositions within the freshwater assessment watersheds to the same pressure indicators (Iacarella 2022). The complexity of salmon population exposure to freshwater habitat conditions may lead to weak relationships, whereas fish communities (comprised primarily of resident species) assessed at a matching landscape scale appear to be more tightly linked to human pressures; this highlights the importance of matching biological characteristics and scale in expected outcomes of validation.

At this current stage of assessment, the individual and cumulative threat scores presented here provide useful information on estimated threat exposure to fish and fish habitat at a high resolution and across a large extent of BC. This information can contribute to targeting areas for more in depth field assessments, reporting on the status of threats to the state of fish and fish habitat, prioritization and decision making frameworks, and management and restoration planning.

5. ACKNOWLEDGMENTS

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APPENDIX A. ASSESSMENT UNITS

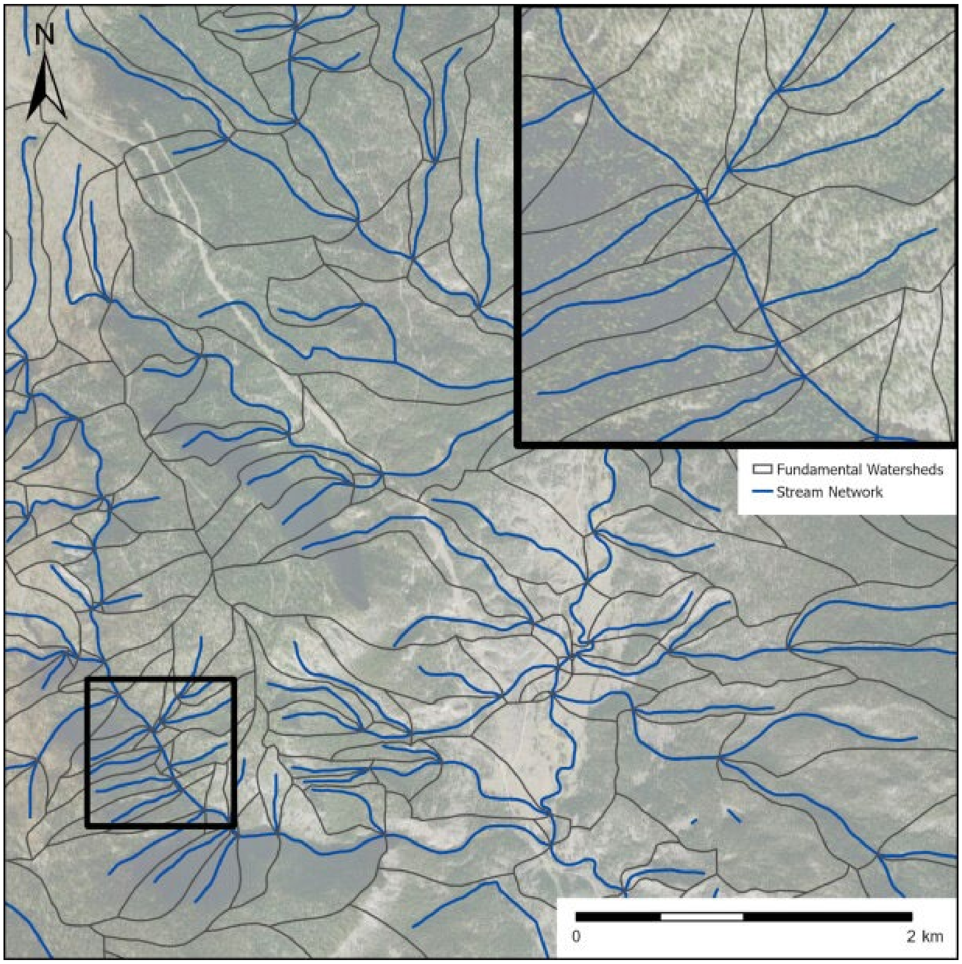

Figure A1. Example of the FWA stream network and associated fundamental watersheds used to assess threats.

Table A1. FWA watershed group codes and names.

Code	Name	Code	Name
ADMS	Adams River	LSAL	Lower Salmon River
BBAR	Big Bar Creek	LTRE	Lower Trembleur Lake
BIGC	Big Creek	MAHD	Mahood Lake
BLAR	Blackwater River	MCGR	McGregor River
BONP	Bonaparte River	MFRA	Middle Fraser
BOWR	Bowron	MIDR	Middle River
BRID	Bridge Creek	MORK	Morkill River
CARR	Cariboo River	MURT	Murtle Lake
CHES	Cheslatta River	MUSK	Muskeg River
CHIL	Chilako River	NARC	Narcosli Creek
CHIR	Chilko River	NAZR	Nazko River
CHWK	Chilliwack River	NECR	Nechako River
CLWR	Clearwater River	NICL	Nicola River
COTR	Cottonwood River	QUES	Quesnel River
DEAD	Deadman River	SAJR	San Jose River
DOGC	Dog Creek	SALR	Salmon River
DRIR	Driftwood River	SETN	Seton Lake
EUCH	Euchiniko River	SHUL	Shuswap Lake
EUCL	Euchiniko Lake	STHM	South Thompson River
FRAN	Francois Lake	STUL	Stuart Lake
FRCN	Fraser Canyon	STUR	Stuart River
GRNL	Green Lake	TABR	Tabor River
GUIC	Guichon Creek	TAKL	Takla Lake
HARR	Harrison River	TASR	Taseko River
HERR	Herrick Creek	THOM	Thompson River
HORS	Horsefly River	TWAC	Twan Creek
LCHL	Lower Chilako River	UCHR	Upper Chilcotin River
LCHR	Lower Chilcotin River	UEUT	Upper Eutsuk Lake
LEUT	Lower Eutsuk Lake	UFRA	Upper Fraser River
LFRA	Lower Fraser	UNRS	Upper Nechako Reservoir
LILL	Lillooet	UNTH	Upper North Thompson River
LNIC	Lower Nicola River	USHU	Upper Shuswap
LNRS	Lower Nechako Reservoir	UTRE	Upper Trembleur Lake
LNTH	Lower North Thompson River	WILL	Willow River

APPENDIX B. SPECIES AT RISK AND SALMON DESIGNATABLE UNITS

Table B1. Fish Species at Risk and Special Concern, Threatened, or Endangered salmon Conservation Units (CUs) with important habitat in the Fraser River Basin. Information is from COSEWIC reports; categorized threats were those specifically identified for a population, but are not considered exhaustive or exclusive to that population.

Species	Population	COSEWIC Status	Categorized Freshwater Environmental Threats
Bull Trout	South Coast British Columbia	Special Concern	• Aquatic Invasive Species • Fishing (by-catch) • Habitat degradation
Coastrange Sculpin	Cultus Lake	Endangered	• Aquatic Invasive Species • Changes in flow regime – low flow (climate change) • Changes in temperature – high temperature (climate change) • Pollution
Green Sturgeon	All	Special Concern	• Fishing (by-catch) • Flow alteration • Pollution • Sedimentation
Mountain Sucker	Pacific	Special Concern	• Aquatic Invasive Species • Changes in flow regime – low flow (climate change) • Changes in temperature – high temperature (climate change) • Flow alteration • Habitat degradation • Pollution • Sedimentation
Nooksack Dace	All	Endangered	• Aquatic Invasive Species • Changes in flow regime – low flow (climate change) • Habitat degradation • Pollution • Riparian disturbance
Salish Sucker	All	Threatened	• Aquatic Invasive Species • Fragmentation • Habitat degradation • Pollution • Sedimentation
Westslope Cutthroat Trout	Pacific	Special Concern	• Changes in flow regime – low flow (climate change) • Changes in temperature – high temperature (climate change)

Species	Population	COSEWIC Status	Categorized Freshwater Environmental Threats
			• Fishing (catch and release) • Fragmentation • Habitat degradation • Hybridization with native species
White Sturgeon	Lower Fraser River	Threatened	• Fishing (by-catch, catch and release) • Fragmentation • Habitat degradation • Pollution • Prey declines • Riparian disturbance • Sedimentation
White Sturgeon	Upper Fraser River	Endangered	• Flow alteration • Pollution • Sedimentation
Chinook Salmon	All relevant populations	–	• Changes in flow regime (climate change) • Changes in temperature – high temperature (climate change) • Fishing (overharvest) • Hatcheries
Chinook Salmon	CK-03: Lower Fraser River Fall 0.3 (DU2)	Threatened	• Habitat degradation (estuarine)
Chinook Salmon	CK-04: Lower Fraser River Spring 1.3 (DU3)	Special Concern	None specified (see threats for all populations)
Chinook Salmon	CK-05: Lower Fraser River-Upper Pitt, Summer 1.3 (DU4)	Endangered	None specified (see threats for all populations)
Chinook Salmon	CK-06: Lower Fraser River Summer 1.3 (DU5)	Threatened	• Habitat degradation
Chinook Salmon	CK-07: Maria Slough Summer 0.3 (DU6)	Endangered	• Changes in flow regime – low flow (climate change) • Pollution
Chinook Salmon	CK-08: Middle Fraser – Fraser Canyon Spring 1.3 (DU7)	Endangered	None specified (see threats for all populations)

Species	Population	COSEWIC Status	Categorized Freshwater Environmental Threats
Chinook Salmon	CK-09: Middle Fraser River – Portage Fall 1.3 (DU8)	Endangered	• Habitat degradation
Chinook Salmon	CK-10: Middle Fraser River Spring 1.3 (DU9)	Endangered	• Habitat degradation • Pollution
Chinook Salmon	CK-11: Middle Fraser River Summer 1.3 (DU10)	Threatened	• Flow alteration • Pollution
Chinook Salmon	CK-12: Upper Fraser River Spring 1.3 (DU11)	Endangered	• Aquatic Invasive Species • Avalanches/landslides • Changes in flow regime (climate change) • Habitat degradation (climate change) • Sedimentation
Chinook Salmon	CK-14: South Thompson Summer 1.3 (DU13)	Endangered	• Aquatic Invasive Species • Avalanches/landslides • Changes in flow regime – low flow (climate change) • Changes in temperature – high temperature (climate change) • Habitat degradation (climate change) • Hatcheries • Pollution
Chinook Salmon	CK-16: South Thompson – Bessette Creek Summer 1.2 (DU14)	Endangered	• Aquatic Invasive Species • Avalanches/landslides • Changes in flow regime (climate change) • Changes in temperature – high temperature (climate change) • Flow alteration • Habitat degradation (climate change) • Pollution • Riparian disturbance
Chinook Salmon	CK-17: Lower Thompson Spring 1.2 (DU15)	Endangered	• Aquatic Invasive Species • Avalanches/landslides • Changes in flow regime (climate change) • Changes in temperature – high temperature (climate change) • Habitat degradation (climate change)

Species	Population	COSEWIC Status	Categorized Freshwater Environmental Threats
Chinook Salmon	CK-18: North Thompson Spring 1.3 (DU16)	Endangered	• Avalanches/landslides • Aquatic Invasive Species • Changes in flow regime (climate change) • Changes in temperature – high temperature (climate change) • Habitat degradation (climate change)
Chinook Salmon	CK-19: North Thompson Summer 1.3 (DU17)	Endangered	None specified (see threats for all populations)
Coho Salmon	All relevant populations	–	• Aquatic Invasive Species • Changes in temperature – high temperature (climate change) • Fishing (overharvest) • Habitat degradation
Coho Salmon	CO-05: Fraser Canyon (DU4)	Threatened	None specified (see threats for all populations)
Coho Salmon	CO-07: Lower Thompson (DU6)	Threatened	None specified (see threats for all populations)
Coho Salmon	CO-08: South Thompson (DU7)	Threatened	None specified (see threats for all populations)
Coho Salmon	CO-09: North Thompson (DU8)	Threatened	None specified (see threats for all populations)
Coho Salmon	CO-48: Interior Fraser (DU5)	Threatened	None specified (see threats for all populations)
Sockeye Salmon	All relevant populations	–	• Changes in temperature – high temperature (climate change) • Fishing (overharvest) • Flow alteration • Fragmentation • Pollution • Riparian disturbance
Sockeye Salmon	SEL-07-01: Bowron - Early Summer Timing (DU2)	Endangered	None specified (see threats for all populations)
Sockeye Salmon	SEL-03-02: Cultus, Late Timing (DU6)	Endangered	None specified (see threats for all populations)

Species	Population	COSEWIC Status	Categorized Freshwater Environmental Threats
Sockeye Salmon	SEL-06-07: Francois/Fraser Summer Timing (DU7)	Special Concern	None specified (see threats for all populations)
Sockeye Salmon	SEL-03-03: Harrison – Downstream Migrating – Late Timing (DU9)	Special Concern	None specified (see threats for all populations)
Sockeye Salmon	SEL-03-04: Harrison – Upstream Migrating – Late Timing (DU10)	Endangered	None specified (see threats for all populations)
Sockeye Salmon	SEL-10-01: Kamloops – Early Summer Timing (DU11)	Special Concern	• Changes in temperature – high temperature (climate change) • Pollution
Sockeye Salmon	SEL-04-01: Lillooet/Harrison – Late Timing (DU12)	Special Concern	• Habitat degradation
Sockeye Salmon	SEL-05-02: Nahatlatch – Early Summer Timing (DU13)	Special Concern	None specified (see threats for all populations)
Sockeye Salmon	SEL-10-03: North Barriere – Early Summer Timing (DU14)	Threatened	None specified (see threats for all populations)
Sockeye Salmon	SEL-06-10: Quesnel – Summer Timing (DU16)	Endangered	• Changes in temperature – high temperature (climate change) • Fishing (overharvest) • Pollution
Sockeye Salmon	SEL-06-11: Seton – Late Timing (DU17)	Endangered	• Avalanches/landslides • Fishing (overharvest) • Pollution
Sockeye Salmon	SEL-06-14: Takla/Trembleur – Early Stuart Timing (DU20)	Endangered	• Changes in flow regime (climate change) • Changes in temperature – high temperature (climate change) • Fishing (overharvest)
Sockeye Salmon	SEL-06-13: Takla/Trembleur/Stuart – Summer Timing (DU21)	Endangered	None specified (see threats for all populations)

Species	Population	COSEWIC Status	Categorized Freshwater Environmental Threats
Sockeye Salmon	SEL-06-16: Taseko - Early Summer Timing (DU22)	Endangered	None specified (see threats for all populations)
Sockeye Salmon	SER-02: Widgeon Creek (DU24)	Threatened	None specified (see threats for all populations)
Sockeye Salmon	SEL-09-xx: Adams Lake – Early Summer Timing (DU199)	Endangered	None specified (see threats for all populations)

APPENDIX C. DATA INFORMATION

Table C1. Data information for human activity and landscape disturbance based threats.

Data input	Feature type	Threat contribution	Inclusion criteria	Update frequency	Timestamp	Source
Culverts	Points	In Stream Habitat Destruction, Flow Alteration	Used modelled BC fish passage culverts and Ministry of Transportation (MOT) culverts for In-Stream Habitat Destruction. Used MOT culverts for Flow Alteration.	Ongoing (modelled culverts); Ongoing (MOT culverts)	Date of field assessment (modelled culverts); None (MOT culverts)	BC MOT Culverts; Hillcrest Geographics BC Fish Passage - Modelled Culverts (bcfishpass on Github)
Dams	Points and polygons	In Stream Habitat Destruction, Longitudinal Fragmentation - Resident, Longitudinal Fragmentation - Anadromous, Flow Alteration	Used dam points and BC Cumulative Effects Framework (BC CEF) dam polygons for In-Stream Habitat Destruction. Used only active dams for Flow Alteration and dams identified as full barriers for Longitudinal Fragmentation.	Ongoing (CABD updated multiple times per year); No current updates (BC CEF completed in 2022)	Construction date; Date of data update (CABD); Date of data acquisition (BC CEF)	Used data: CWF Canadian Aquatic Barriers Database (CABD); BC Cumulative Effects Framework – Human Disturbance; Original Data: BC Dams
Flood control infrastructure	Lines	Riparian Disturbance, In-Stream Habitat Destruction, Latitudinal Fragmentation	All included.	Ongoing (updated every 10 years).	Survey date	BC Flood Protection Works - Structural Works
Forestry cut blocks	Polygons	Riparian Disturbance, Nutrients, Sedimentation	Subset to 2012–2022. (Extent of forest reserves removed from cut block polygons.)	Annual	Harvest year; Date of feature addition to the dataset	Harvested Ares of BC (Consolidated Cutblocks)

Data input	Feature type	Threat contribution	Inclusion criteria	Update frequency	Timestamp	Source
Forest fires	Polygons	Riparian Disturbance, Nutrients, Sedimentation	Subset to 2012–2023.	Annual	Fire year; Date of feature addition to the dataset	BC Fire Perimeters – Current; BC Fire Perimeters – Historical
Forest pest defoliation	Polygons	Riparian Disturbance, Nutrients	Subset to 2012–2022. Excluded animal damage and abiotic factors. A minimum cut-off of severe pest defoliation was used for Nutrients.	Annual	Date of occurrence	BC Pest Infestation Polygons
Land class: Agriculture	Raster	Riparian Disturbance, Nutrients, Pollution	2022 raster.	Annual	Image year	Sentinel-2 Land Use / Land Cover
Land class: Other non-urban	Raster	Nutrients, Sedimentation	2022 raster.	Annual	Image year	Sentinel-2 Land Use / Land Cover
Land class: Rangeland	Raster and polygons	Riparian Disturbance, In-Stream Habitat Destruction	2022 raster. Rangeland raster data was masked to only include areas that overlap with BC Range Pasture Polygons.	Annual	Image year	Sentinel-2 Land Use / Land Cover; BC Range Pasture Polygons
Land class: Urban	Raster	Riparian Disturbance, Nutrients, Pollution, Latitudinal Fragmentation	2022 raster.	Annual	Image year	Sentinel-2 Land Use / Land Cover
Mining	Polygons	In-Stream Habitat Destruction, Riparian Disturbance, Sedimentation, Nutrients	Included mines within 30 m of streams for In-Stream Habitat Destruction.	No current updates (completed in 2022); Can	Date of data acquisition	BC Cumulative Effects Framework – Human Disturbance

Data input	Feature type	Threat contribution	Inclusion criteria	Update frequency	Timestamp	Source
				use other data sources		
Natural fish barriers	Points	Longitudinal Fragmentation - Anadromous, Longitudinal Fragmentation - Resident	Gradients barriers 15% for Longitudinal Fragmentation - Anadromous. For Longitudinal Fragmentation - Resident, only included natural barriers that were located on stream reaches connected to a dam.	Ongoing (updated multiple times per year)	None	Hillcrest Geographics BC Fish Passage (bcfishpass on Github)
Non-native species	Points	Aquatic Invasive Species	Subset to 1980–2023.	Ongoing (multiple times a year)	Date of occurrence	Aquatic Invasive Species of British Columbia
Pipeline ROW	Polygons	Riparian Disturbance	Roads were excluded by BC Cumulative Effects Framework.	Annual	Date of data update	Used data: BC Cumulative Effects Framework, Human Disturbance; Original data: BC Energy Regulator (BCER) Oil and Gas Surface Land Use
Point source nutrients and pollution	Points	Nutrients and Pollution	Removed ‘other toxins’ category as it included sediments. Used high release estimates, which included a detection limit value.	No current updates (completed in 2022)	None	Pollutants Affecting Whales and their Prey Inventory Tool (PAWPIT)
Powerline ROW (right of way)	Polygons	Riparian Disturbance	Buffered to 12.5 m by BC Cumulative Effects Framework.	Ongoing (not modified since 2018)	Date of feature addition to the dataset	Used data: BC Cumulative Effects

Data input	Feature type	Threat contribution	Inclusion criteria	Update frequency	Timestamp	Source
						Framework, Human Disturbance; Original data: GeoBC BC Transmission Lines
Railways	Lines	Riparian Disturbance, In-Stream Habitat Destruction	Rail crossings only for In-Stream Habitat Destruction.	Ongoing (not modified since 2015)	Date of feature addition to the dataset	GeoBC GeoBase National Railway Network (NRWN)
Roads	Lines	Riparian Disturbance, Sedimentation, Nutrients, Pollution, In-Stream Habitat Destruction	Road crossings only for In-Stream Habitat Destruction. All roads were included for other threats.	No current updates (completed in 2022); Can use original data sources which are updated	Date of data acquisition; Forestry roads tenure date; Permit approval date for oil & gas roads	BC Cumulative Effects Framework, Integrated Roads
Water extraction	Points and lines	In-Stream Habitat Destruction, Flow Alteration	Included only active water extraction licenses (points) for Flow Alteration. Water extraction infrastructure (lines; pipes, pumps, etc.) were used for In-Stream Habitat Destruction.	Ongoing (water extraction licenses updated every 2 days)	Licence status date	BC Water Rights Licences - Public; BC Water Licensed Works - Lines

APPENDIX D. FLOW ALTERATION SCORES

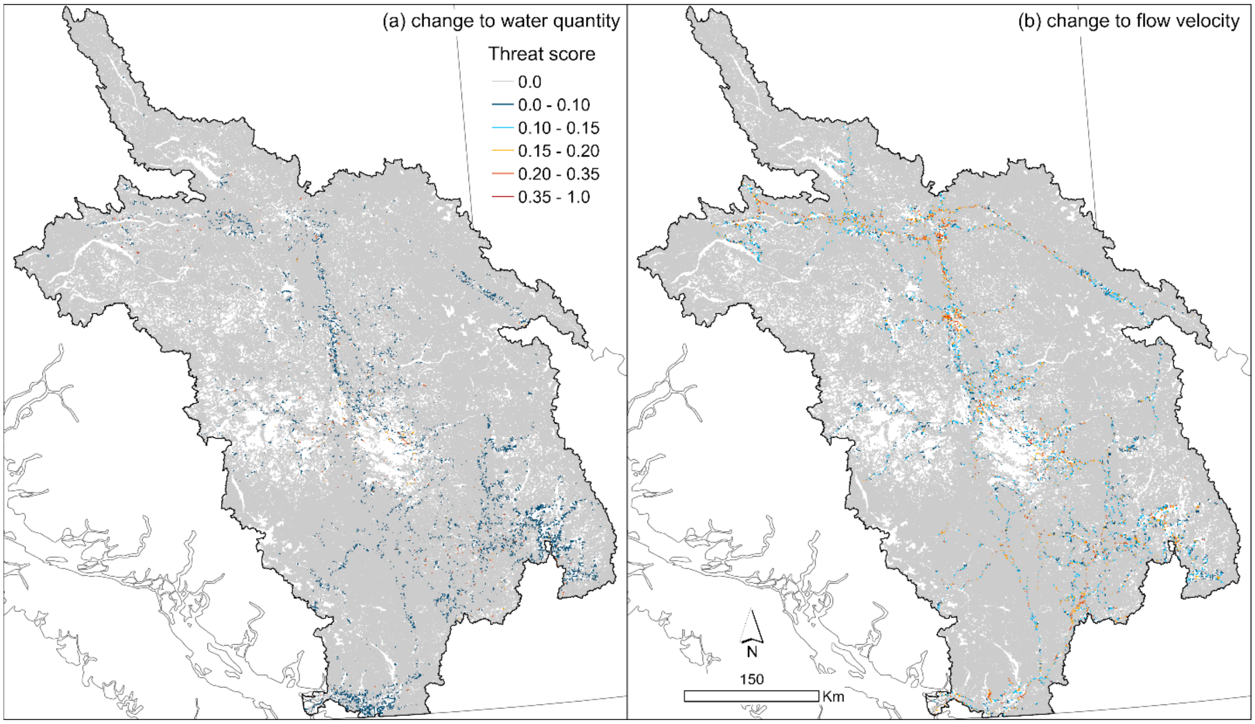

Figure D1. Flow alteration scores based on change to (a) water quantity from water extraction licenses and dams and (b) flow velocity from culverts.

APPENDIX E. GLOBAL CLIMATE MODELS

Table E1. Global Climate Models (GCMs) contributing to the ensemble averages used for calculation of Climate Change Threats. Flood Risk GCMs were from Coupled Model Intercomparison Project Phase 6. Stream Flow and Steam Temperature GCMs were from Coupled Model Intercomparison Project Phase 5.

Flood Risk	Stream Flow	Stream Temperature
MIROC6	ACCESS1-0	CanESM2
BCC-CSM2-MR	CanESM2	CSIRO-Mk3-6-0
CanESM5	CCSM4	GFDL-CM3
MRI-ESM2-0	CNRM-CM5	HadGEM2-ES
NIMS-KMA.KACE-1-0-G	HadGEM2-ES	MIROC-ESM
MPI-ESM1-2-LR	MPI-ESM-LR	MPI-ESM-LR
INM-CM5-0	–	–
INM-CM4-8	–	–
MPI-ESM1-2-HR	–	–
CMCC.CMCC-CM2-SR5	–	–
CCCR-IITM.IITM-ESM	–	–
IPSL.IPSL-CM6A-LR	–	–
NorESM2-MM	–	–
NorESM2-LM	–	–
EC-Earth-Consortium.EC-Earth3	–	–
CSIRO-ARCCSS.ACCESS-CM2	–	–
GFDL-CM4	–	–

APPENDIX F. STREAM FLOW PERFORMANCE METRICS

Performance metrics were calculated by Foundry Spatial comparing downscaled stream flow to 86 hydrometric gauge stations across the FRB. As the downscaled flow closely matched the original VIC-GL results ($R^2 = 0.99$), these metrics generally indicate the performance of the original model (Schnorbus 2020). Modeled total annual stream flow corresponded well with observed total annual flow (Table F1). Across months and metrics (minimum, maximum, mean), August and September minimum flow had the most deviation from observed flow (Table F1). Mean absolute error and percent error varied spatially across the FRB, with some higher relative error in the central area of the basin particularly in Fall and Winter months (Fig. F1).

Table F1. Performance results of downscaled stream flow from VIC-GL model compared to observations from 86 hydrometric gauge stations.

Time scale	R^2			Mean Absolute Error			Mean Absolute Percent Error			Nash-Sutcliffe Efficiency		
	Min	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**	**Min**	**Max**	**Mean**
January	0.97	0.93	0.95	7.58	32.70	11.74	0.54	0.58	0.39	0.97	0.95	0.97
February	0.87	0.90	0.89	9.48	40.85	14.32	0.56	0.72	0.43	0.92	0.93	0.94
March	0.68	0.95	0.95	11.48	37.83	12.11	0.56	0.68	0.38	0.86	0.95	0.97
April	0.82	0.92	0.99	17.69	72.05	18.69	0.58	0.49	0.42	0.91	0.86	0.99
May	0.82	0.89	0.99	54.13	154.59	40.67	0.68	0.48	0.45	0.91	0.82	0.99
June	0.88	0.95	0.99	72.96	139.36	44.30	0.51	0.39	0.33	0.93	0.91	0.99
July	0.60	0.93	0.99	78.01	138.37	31.69	0.66	0.58	0.38	0.84	0.88	0.99
August	0.35	0.95	0.95	63.96	79.29	46.24	0.85	0.51	0.49	0.79	0.92	0.96
September	0.34	0.98	0.97	38.44	43.78	25.28	0.79	0.46	0.43	0.79	0.97	0.98
October	0.81	0.95	0.99	18.88	47.34	14.91	0.58	0.41	0.36	0.90	0.92	0.99
November	0.76	0.97	0.93	17.68	37.03	25.82	0.55	0.53	0.45	0.88	0.98	0.96
December	0.87	0.93	0.95	11.29	33.64	15.36	0.55	0.54	0.45	0.93	0.96	0.97
Winter	0.90	0.96	0.95	10.02	25.41	12.27	0.56	0.47	0.40	0.94	0.97	0.97
Spring	0.84	0.94	0.99	33.48	58.66	18.76	0.48	0.38	0.36	0.91	0.9	0.99
Summer	0.86	0.98	1.00	56.31	70.91	25.89	0.52	0.37	0.30	0.92	0.97	1.00
Autumn	0.58	0.98	0.96	28.22	26.06	24.17	0.62	0.41	0.41	0.84	0.98	0.97
Annual	0.93	0.98	0.99	25.64	26.32	18.20	0.35	0.26	0.25	0.95	0.98	0.99

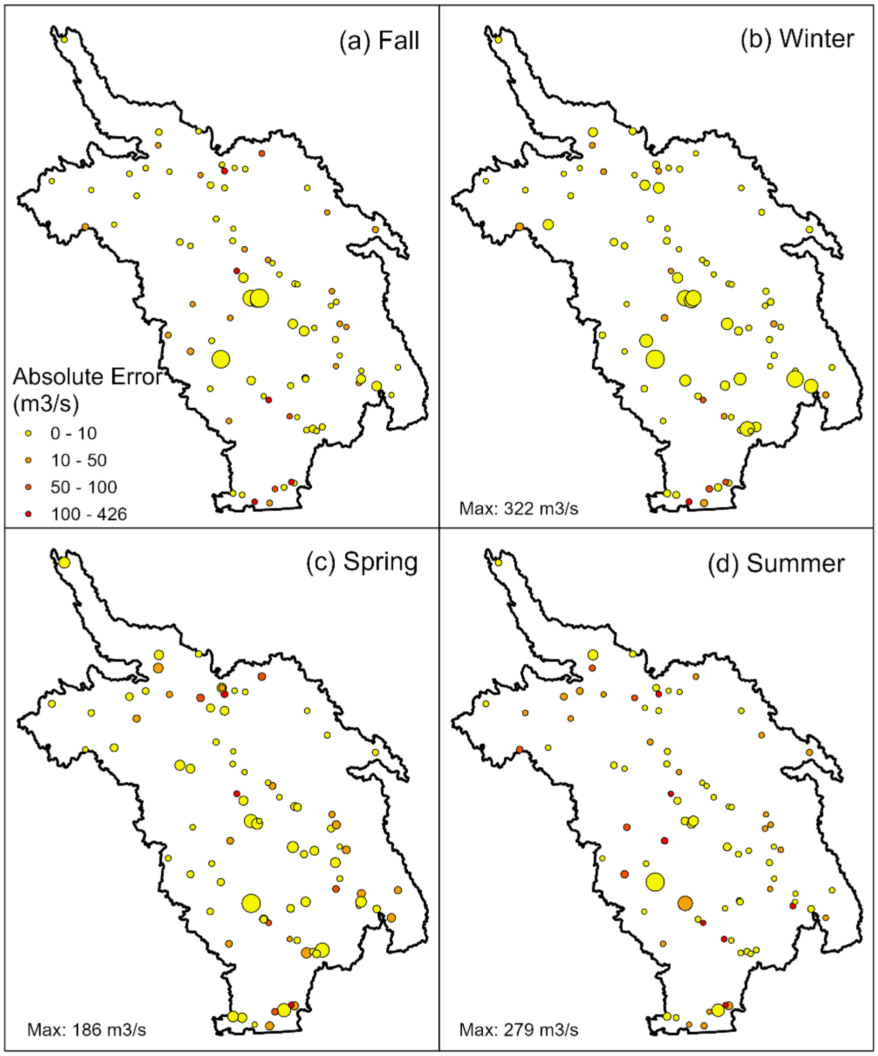

Figure F1. Mean absolute error of downscaled mean seasonal stream flow (m^3/s) for 86 hydrometric gauge stations. Symbol size varies based on mean absolute percent error.

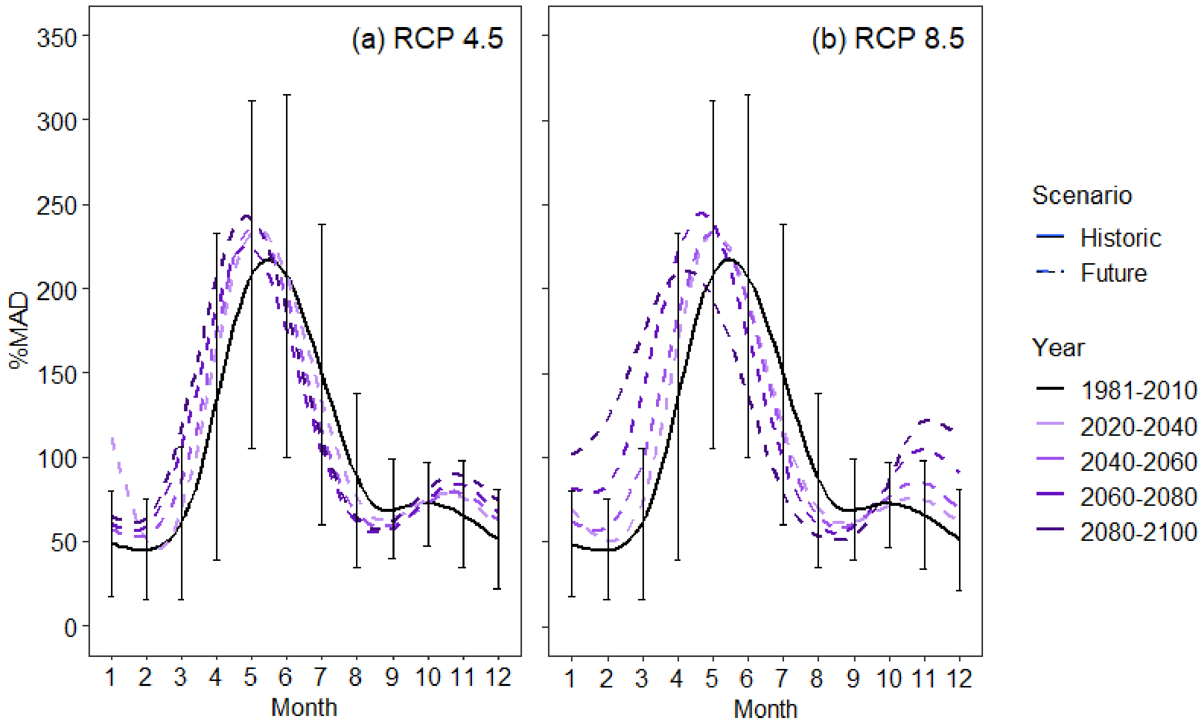

Figure F2. Timeseries of percent mean annual discharge (%MAD, calculated using monthly values) based on modeled stream flow for historic and future climate conditions under (a) RCP 4.5 and (b) RCP 8.5. %MAD for months in future periods is calculated based on the historic period MAD. Standard deviation is shown for the historic period to indicate the amount of variation across Fraser River Basin streams.

APPENDIX G. CUMULATIVE THREAT SCORES BY SALMON CONSERVATION UNIT

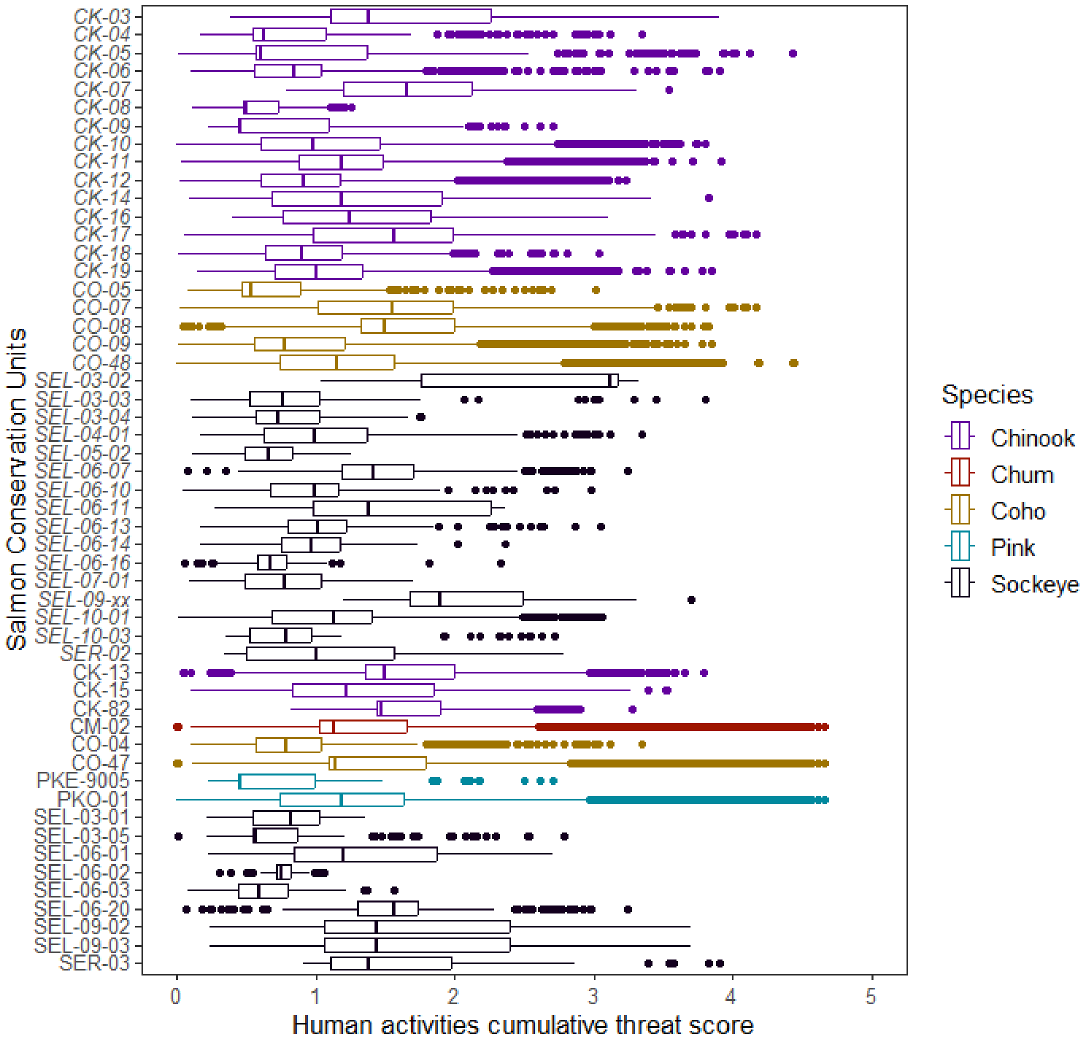

*Figure G1. Tukey's box-whiskers plots of the human activities cumulative threat score for each salmon Conservation Unit (CU) in the Fraser River Basin (only including streams below natural barriers for salmon). Those identified as Special Concern, Threatened, or Endangered ('at risk') by COSEWIC are in italics. CUs included Chinook (CK), Coho (CO), Pink – Even (PKE), Pink – Odd (PKO), Sockeye – Lake (SEL), and Sockeye – River (SER). The box plot line represents the median across stream reaches, the lower and upper hinges represent 25th and 75th percentiles, respectively, and outliers are points above or below 1.5 * the inter-quartile range.*

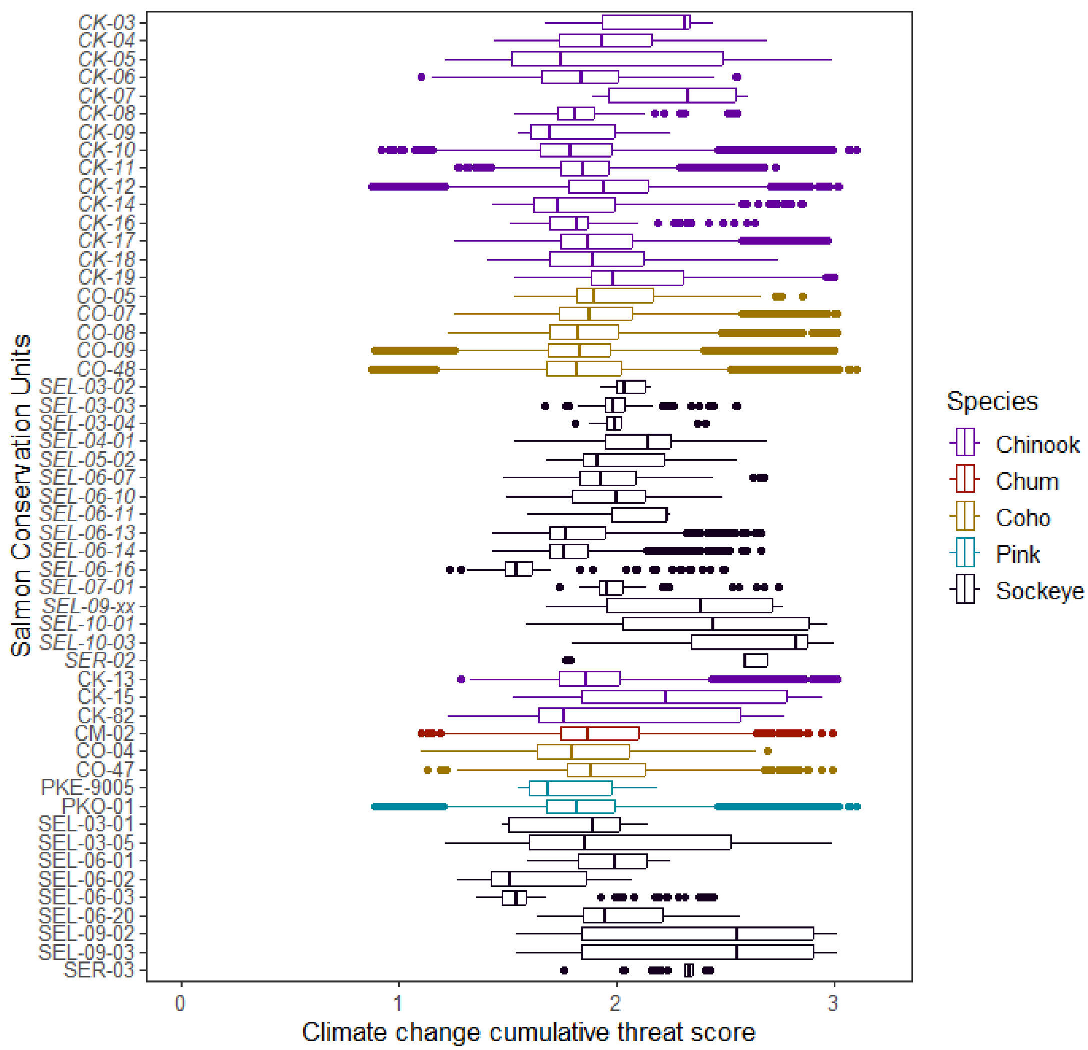

*Figure G2. Tukey's box-whiskers plots of the climate change cumulative threat score for 2040–2060 under RCP 4.5 for each salmon Conservation Unit (CU) in the Fraser River Basin (only including streams below natural barriers for salmon). Those identified as Special Concern, Threatened or Endangered ('at risk') by COSEWIC are in italics. CUs included Chinook (CK), Coho (CO), Pink – Even (PKE), Pink – Odd (PKO), Sockeye – Lake (SEL), and Sockeye – River (SER). The box plot line represents the median across stream reaches, the lower and upper hinges represent 25th and 75th percentiles, respectively, and outliers are points above or below 1.5 * the inter-quartile range.*

APPENDIX H. PROJECTED RESULTS FOR THE THOMPSON-NICOLA

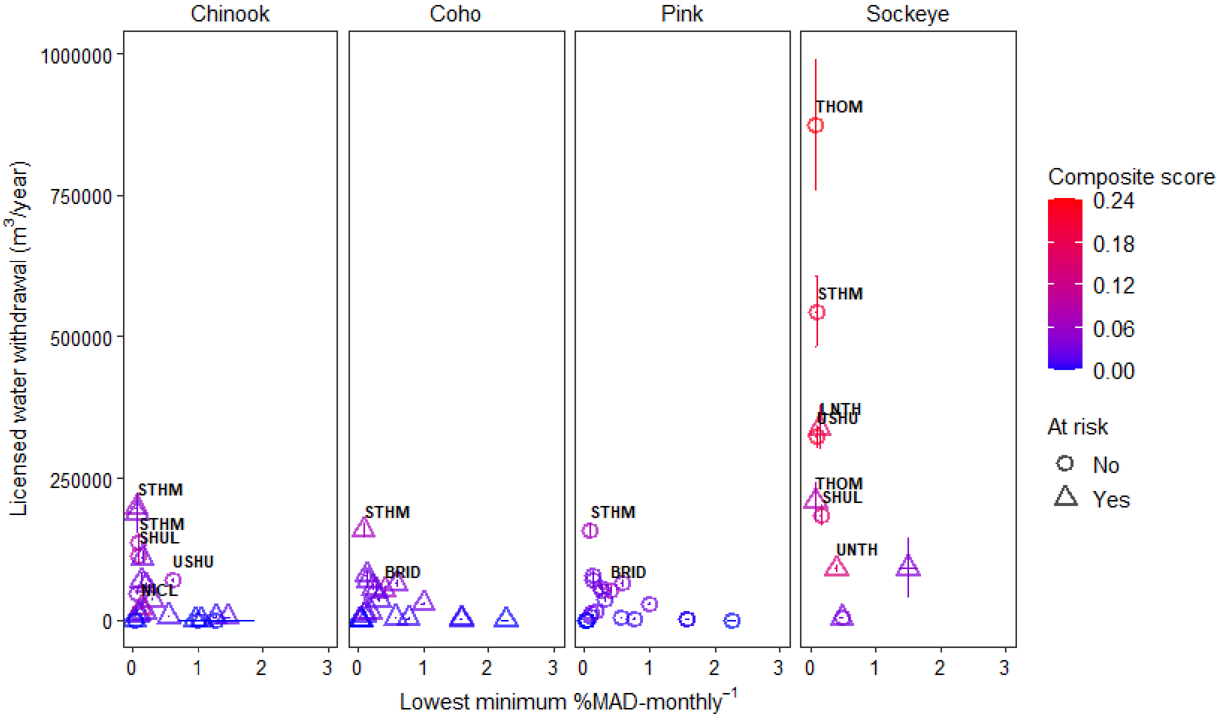

Figure H1. The water resource composite score based on the inverse of the lowest minimum %MAD-monthly flow under future climate conditions (2040–2060) for RCP 4.5 and licensed water extraction amounts within the Thompson-Nicola EDU. Streams scores were averaged by watershed groups and associated salmon CUs distinguished by at risk status. Watershed groups and salmon CUs with a mean composite score greater than 0.05 are labeled, and include Bridge Creek (BRID), Lower North Thompson River (LNTH), Nicola River (NICL), Shuswap Lake (SHUL), South Thompson River (STHM), Thompson River (THOM), and Upper North Thompson River (UNTH). Points for both axes are mean ± 1 SE.

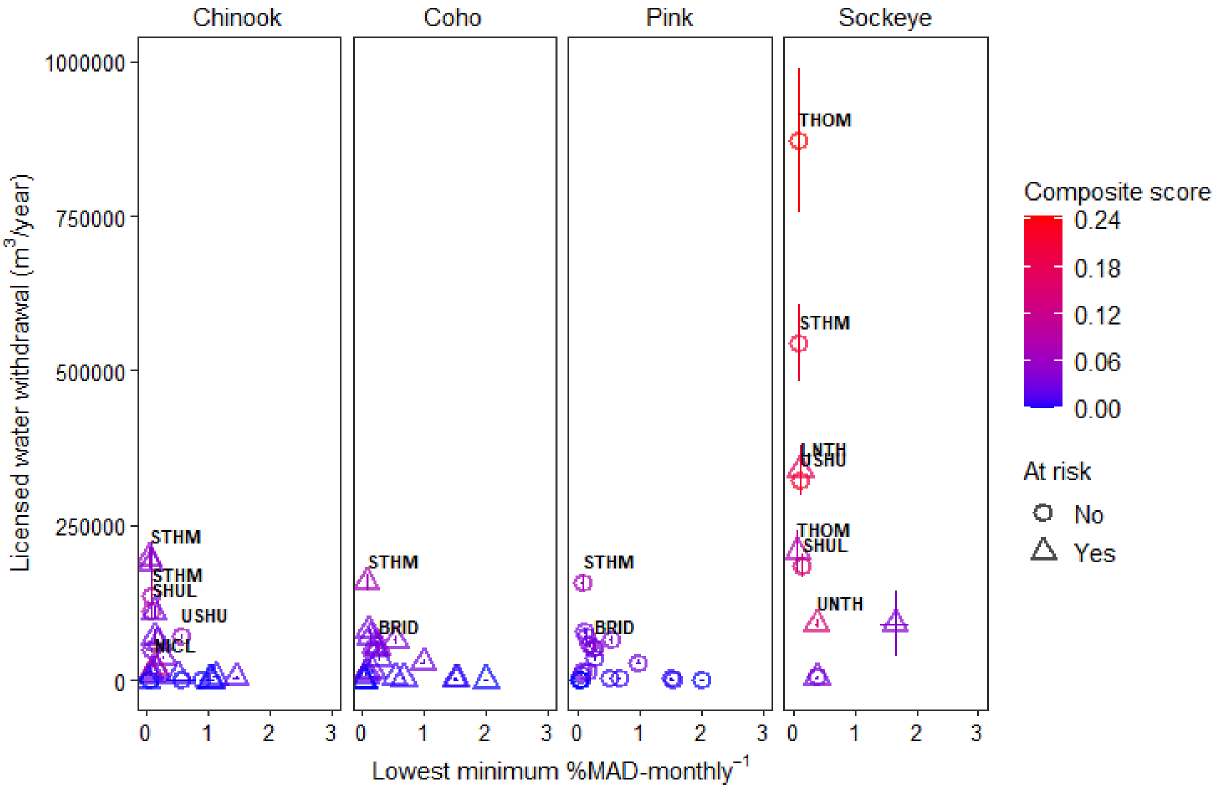

Figure H2. The water resource composite score based on the inverse of the lowest minimum %MAD-monthly flow under future climate conditions (2040–2060) for RCP 8.5 and licensed water extraction amounts within the Thompson-Nicola EDU. Streams scores were averaged by watershed groups and associated salmon CUs distinguished by at risk status. Watershed groups and salmon CUs with a mean composite score greater than 0.05 are labeled, and include Bridge Creek (BRID), Lower North Thompson River (LNTH), Nicola River (NICL), Shuswap Lake (SHUL), South Thompson River (STHM), and Thompson River (THOM). Points for both axes are mean ± 1 SE.

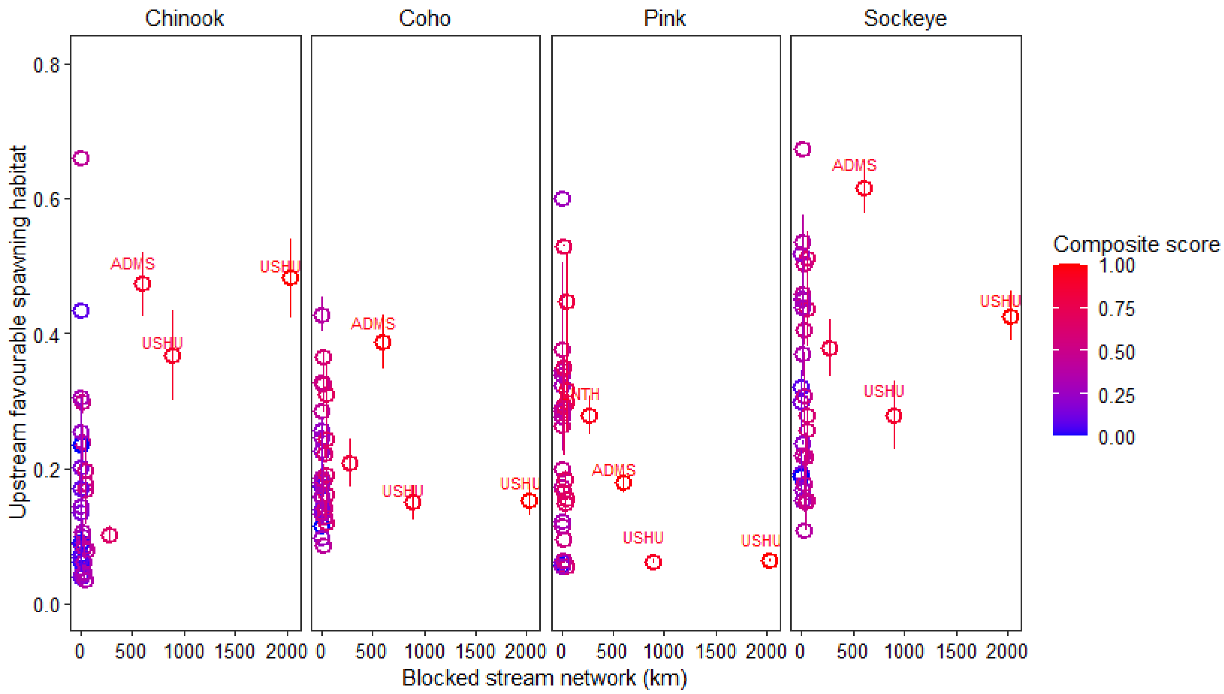

Figure H3. The anadromous fragmentation composite score based on the amount of blocked stream network upstream of an initial dam to subsequent barriers (natural or dams) and the corresponding upstream mean modeled favourable spawning habitat for the Thompson-Nicola EDU. Favourable spawning habitat is for future conditions, RCP 4.5 2041–2060. Watershed groups are labeled for blocked streams with a composite score greater than 0.85, and include Adams River (ADMS), Lower North Thompson River (LNTH), and Upper Shuswap (USHU). Points are mean ± 1 SE.

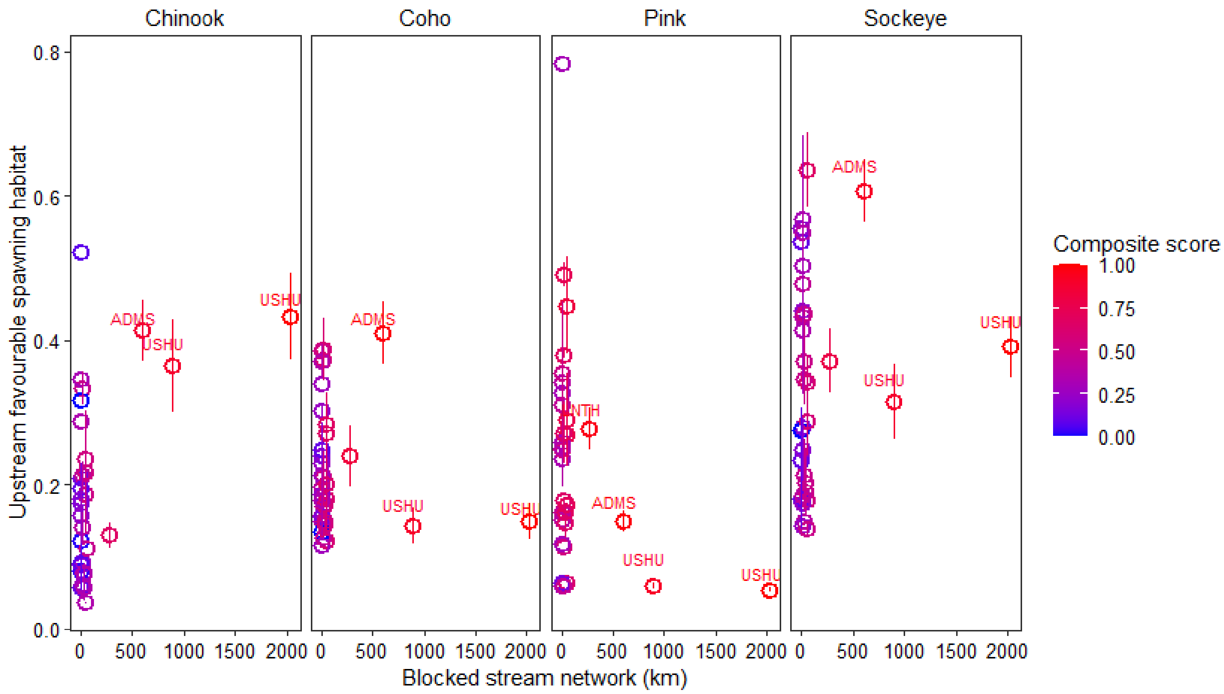

Figure H4. The anadromous fragmentation composite score based on the amount of blocked stream network upstream of an initial dam to subsequent barriers (natural or dams) and the corresponding upstream mean modeled favourable spawning habitat for the Thompson-Nicola EDU. Favourable spawning habitat is for future conditions, RCP 8.5 2041–2060. Watershed groups are labeled for blocked streams with a risk score greater than 0.85, and include Adams River (ADMS), Lower North Thompson River (LNTH), and Upper Shuswap (USHU). Points are mean ± 1 SE.