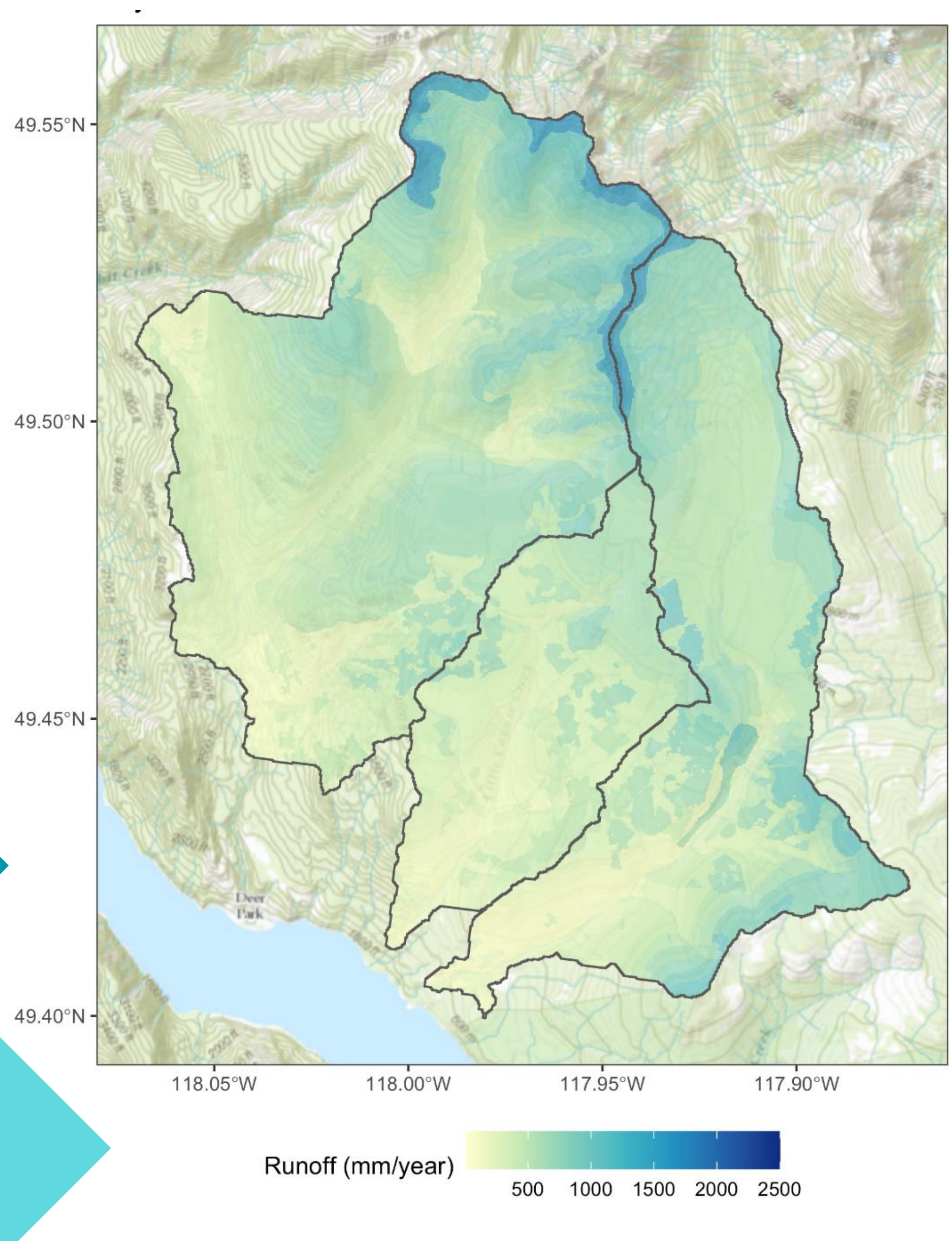
JUNE 2022

Hydrological Modeling to inform Forest Management



Selkirk College | SELKIRK INNOVATES

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On behalf of Selkirk College, I (we) acknowledge that we operate and serve learners on the unceded traditional territories of the Sinixt (Lakes), the Syilx (Okanagan), the Ktunaxa, and the Secwépemc (Shuswap) peoples.

Executive Summary

The move to risk-based decision frameworks for forest management in British Columbia's watersheds requires that information from professional assessments be presented in terms of changes in the likelihood or probability of occurrence of a harmful event. Traditionally, Equivalent Clearcut Area (ECA) calculations have been used in professional hydrological assessments and are one of the primary tools available to inform forest managers of the likelihood of harmful hydrological impacts of forest disturbance. These methods typically rely on broad regional assumptions, qualitative observations, and/or expert judgement, making it difficult to explicitly provide quantitative estimates of the change in the likelihood of occurrence of a harmful hydrological event due to forest disturbance. Here, a spatially explicit hydrological model has been developed to inform forest management in watersheds of the Southern Selkirk region. Since the process-based hydrological model uses land cover and weather data as inputs to simulate streamflow and other hydroclimatic variables, modifications to these input data such as harvest plans and/or climate change scenarios can be used to investigate how water resources in the watershed including potentially harmful hydrological events such as flooding may be impacted. The Southern Selkirk hydrological model was applied to four watersheds with diverse physical characteristics to investigate the effects of land cover (forest disturbance) and climate change on selected hydrologic metrics of concern.

Results, consistent with the outcomes of empirical based studies, emphasize that in addition to the amount of forest disturbance, watershed physical characteristics and topographic position of the disturbance influence the magnitude of hydrologic alteration in a watershed.

LANDCOVER EFFECTS

In Cayuse and Little Cayuse Creeks, the 25% low elevation and high elevation disturbance scenarios relative to the Year-2000 baseline produces similar increasing trends but almost twice the response in Little Cayuse Creek than in Cayuse Creek for all hydrological metrics investigated. The greater sensitivity to harvest levels in Little Cayuse likely attributes to the smaller watershed size and/or predominantly western slope aspect distribution which are the two main physical differences between the watersheds. The mitigating influence of watershed size is apparent when Forty-nine Creek and Coffee Creek are subject to similar levels of forest disturbance (~3%). In Forty-nine Creek the disturbance results in roughly twice the response compared to Coffee Creek which is over three times the size of Forty-nine Creek. The largest changes to water yield metrics (mean annual flow and summer low flows) are observed in the smallest watersheds in the study. Harvesting 31% and 29% respectively of Tribs 1 and 3 on Balfour Face results in the largest increases in mean annual flows (24% and 20%) and summer low flows (16% and 12%). However, the magnitude of the increase to both the 2-year and 100-year return period flows are similar in Balfour Face Trib 1 and Little Cayuse Creek. These annual flood metrics are more sensitive to high elevation snowmelt runoff which is lacking in the Balfour Face tributaries.

CLIMATE EFFECTS

In all watersheds, climate projections for the RCP 4.5 pathway have more substantial impacts on hydrological metrics of flow volume and timing of peak flows compared to landcover impacts but, depending on the watershed, forest disturbance can either exacerbate or mitigate these impacts. We also observe that climate change effects differ between watersheds for the near-term (2021-2050) and long-term (2051-2080) climate projections. For all watersheds mean annual flow initially decreases (2021-2050), and then increases for (2051 – 2080). Harvest scenarios mitigate decreases and amplify increases. Mean Aug-September summer low flows decrease for all watersheds but for Forty-nine Creek, Coffee Creek and Balfour Face the 2051-2080 period shows larger magnitude decreases. Harvest scenarios mitigate decreases except in Coffee Creek. Under all scenarios the 2-year peak flows decrease but these decreases are less in the 2051 – 2080 period except for Balfour Face where 2-year peak flow initially decrease and then increase in the later time period.

The ability of the model to investigate a range of input conditions including the cumulative effects of landcover and climate change is a substantial improvement over traditional ECA analyses that consider only the level of forest disturbance in the assessment of the likelihood of a harmful hydrological response in a watershed. Additionally, by replicating hydrologic processes and watershed function the model contributes to an improved process understanding and provides resource managers with quantitative outputs that feed into risk-based management decisions.
Further work could include a refining model parameterization to incorporate more stages of forest hydrological recovery, better process-representation, and data inputs during peak flow periods, and further empirical and conceptual (modeling) work to better understand the key factors determining late-summer streamflow. In addition, conceptual work should be completed to establish clear guidelines to determine baselines against which hydrologic change is measured and what level of hydrologic alteration is acceptable.

Contents

Introduction

Background

In forested snowmelt landscapes, vegetation can exert strong hydrological control on runoff processes, most notably by intercepting a fraction of incoming precipitation and by providing shade which slows spring snowmelt. These factors have high potential to modify the timing and quantity of water delivery from these systems. While they can affect streamflow throughout the year (Moore and Wodzell, 2005), vegetation changes can have particularly consequential effects on the frequency and magnitude of peak streamflow (Alila et al., 2009, Green and Alila, 2012; Schnorbus and Alila, 2013, McEachran et al., 2021). Changes to the frequency, magnitude and timing of peak streamflow can alter stream channel morphology, sediment transport characteristics and the occurrence of damaging floods in watersheds, ultimately affecting downstream communities, water users and aquatic ecosystem function and structure.

Forest hydrology research in Alberta and British Columbia has demonstrated that removal of forest vegetation generally increases snow accumulation and melt rates (Winkler et al., 2009; Ellis et al., 2010; Pomeroy et al., 2012), and consequently increases the average and peak streamflow originating from forested watersheds (Schnorbus and Alila, 2004; Green and Alila, 2012; McEachen, et al., 2021) . These studies have also identified that certain elevation zones contribute disproportionately to peak streamflow (Schnorbus and Alila, 2004; Schnorbus and Alila, 2013). Lower elevation areas typically contribute less total runoff, and this runoff also primarily occurs prior to freshet. By comparison, higher elevation areas receive more precipitation, generate substantially greater runoff, and snowmelt coincides with peak streamflow (Whitaker et al., 2002; Mahat and Anderson, 2013). Forest disturbance within this zone has greater potential to alter the quantity and timing of streamflow by decreasing vegetation interception and, as well, synchronizes and accelerates snowmelt in clearings within the area contributing most to the snowmelt dominated peak flow (Winkler et al., 2005; Ellis et al., 2010; Green and Alila, 2012). Because of this dynamic, accurate identification of this sensitive elevation-dependent zone is an integral component in evaluating the likelihood of change to water yields, timing of flows and peak flows related to forest disturbance.

Historically, Equivalent Clearcut Area (ECA) calculations and professional watershed and hydrological assessments have been the primary tools available to inform forest managers of the potential hydrological impacts of forest development or disturbance in a watershed. These methods typically rely on broad regional assumptions and/or on qualitative observations and expert judgement, making it difficult to explicitly provide quantitative estimates of the likelihood of change in hydrologic metrics (i.e., peak flow, water yield) due to forest disturbance. With the implementation of the Watershed Assessment and Management of Hydrologic and Geomorphic Risk in the Forest Sector Guidelines (EGBC/ABCPF, 2020) that requires the development of a risk management framework to guide forest development, forest managers require more explicit quantitative assessments of the potential for change in the occurrence of a harmful hydrological event. Process-based hydrological models present an alternative and/or complementary approach to established watershed assessment methods that can provide quantitative estimates of hydrologic change due to forest disturbance. Hydrological models vary greatly in their complexity, ranging from single lumped watersheds which simulate streamflow from simple empirical relationships to detailed spatially distributed models with physically based processrepresentations (Finger et al., 2015; Clark et al., 2017). Data requirements generally scale with model complexity, where simple models often have few data requirements, and more complex models may require very detailed model inputs. Correspondingly, although practitioners often lean towards less complex models, those that do not incorporate land cover and/or climate are not able to estimate the hydrologic effects of changes in land cover and climate. Likewise, very complex models have high data requirements which is often unavailable or requires a high degree of processing which may not be available or attainable for many projects.

This study presents a process-based hydrological modeling workflow for the purpose of informing forest management in watersheds. The modeling workflow incorporates the underlying hydrologic processes driving streamflow, incorporates climate and land cover, and has relatively modest data requirements, making it well suited for applications in low data environments where many forestry decisions are made in western Canada. Here the workflow is applied to simulate and quantify the effects of forest disturbance and climate change on the hydrology of several watersheds within the Southern Selkirk region of British Columbia. Results from this study provide a well-performing hydrological model that can reliably simulate streamflow and major hydroclimatic processes for watersheds throughout the Southern Selkirk region and can estimate hydrologic changes due to forest disturbance and climate change.

Methods

Research Team

Faculty researcher Kim Green, PhD, P.Geo., project lead, has been responsible for connecting with industry partners, organizing project meetings review of model outputs and production of the final project report. Matthew Chernos, MSc., P.Geo., Modeling geoscientist with MacDonald Hydrological Consultants Ltd (Cranbrook) undertook model development and analysis as well as assisted with reporting. Ryan MacDonald, PhD, PAg., senior watershed scientist with MacDonald Hydrological Consultants provided expertise in model development and reviewing model outputs.

Mr. Ron Palmer, RPF, Forestry Superintendent and Mr. Simon Martin, RFT Forestry Supervisor with Interfor Corp. (Castlegar), Mr. Gerald Cordeiro, Forestry Manager with Kalesnikoff Lumber Co. Ltd (Thrums), Mr. Adam Rodgers, RPF, Development Forester with Atco Wood Products Ltd (Fruitvale), and Mr. Bill Kestell, RPF, Woodlands Manager, with Porcupine Wood Products Ltd. (Salmo), have provided forest inventory databases, participated in numerous discussions and participated in developing model scenarios for the selected watersheds.

Watershed Selection

Watersheds for the modeling investigation are situated in the Selkirk Mountains of southern British Columbia and were selected by the industry partners. They include Cayuse Creek and Little Cayuse Creek, Forty-nine Creek, Duhamel Creek, and Coffee Creek/Balfour face (Figure 1). All four watersheds are considered high value for aquatic resources and provide a supply of consumptive-use water. As well, all watersheds have a long history of resource development including forestry dating to the early 1900s.

Three of the study watersheds (Cayuse, Duhamel and Coffee creeks) have experienced substantial recent wildfire disturbance.

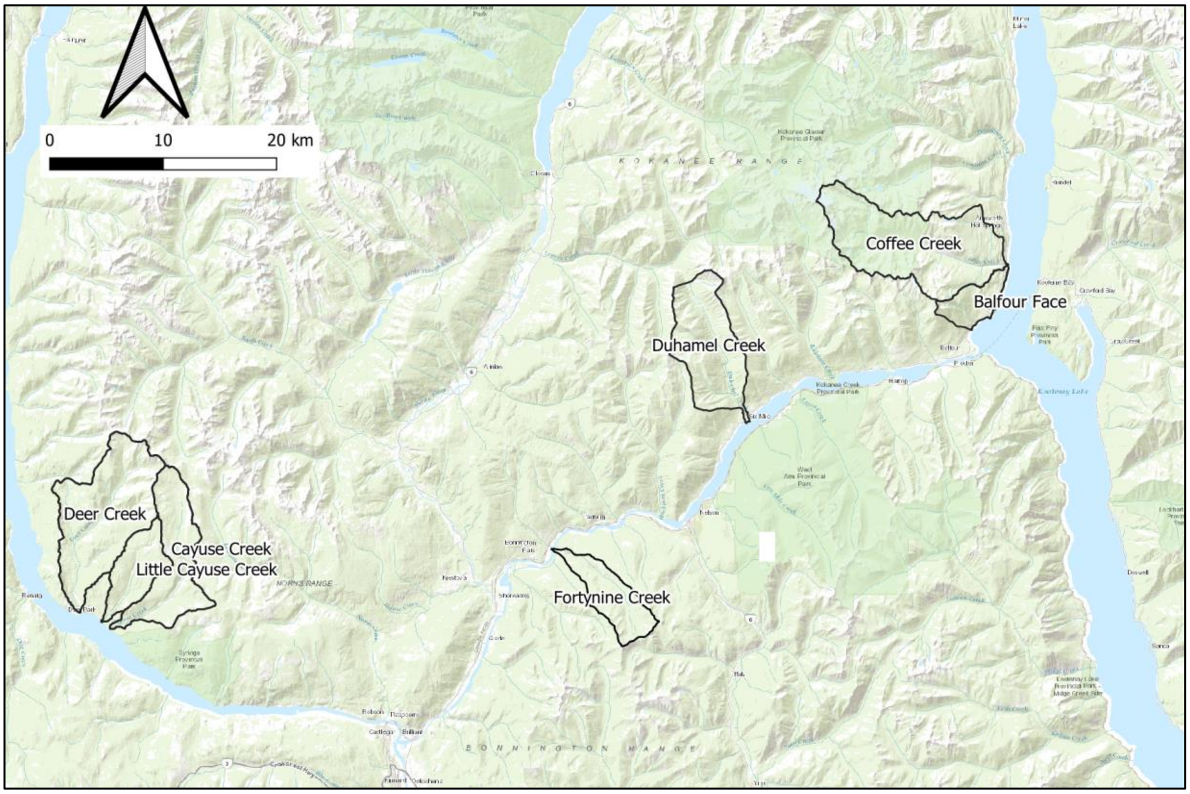

Figure 1. Location of project watersheds

Study Area

GEOLOGY AND SOILS

The southern Selkirk Mountains of southern British Columbia between Kootenay Lake and Arrow are characterized by steep, forested mountain watersheds that feed the Kootenay and Columbia rivers. Coarse textured igneous rocks of the Nelson Plutonic complex, gneiss and schist of the Valhalla metamorphic complex and volcanic and sedimentary rocks of the Rossland Group underly the region (Figure 2, BC Data Catalogue, Bedrock Geology, accessed through iMapBC, February 2022).

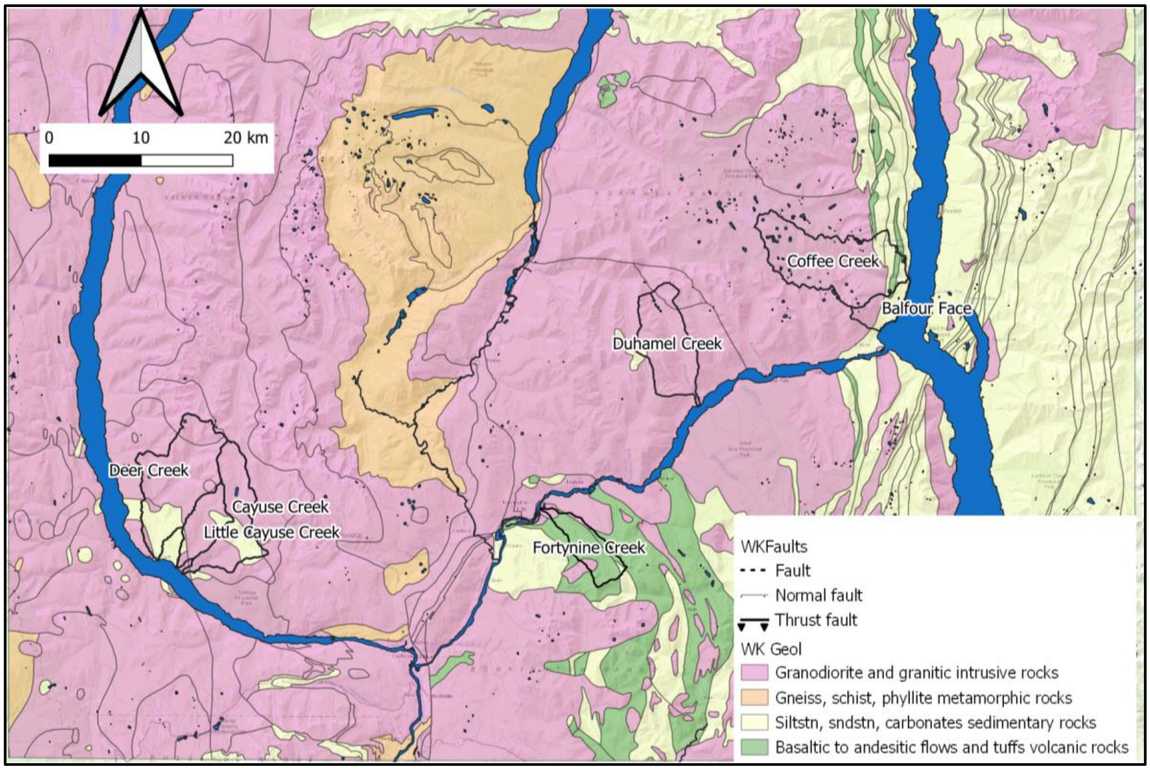

Figure 2. Bedrock geology of the project area (from iMapBC).

Glacial sediments and soils derived from these rock types include thin veneers of well-drained sands and gravels at upper elevations with thicker sandy to silty kame terrace deposits mantling the main tributary valleys. Thick deposits of sandy glaciofluvial and silt to clay glaciolacustrine sediments occur locally in the main valleys of Arrow Lake and the main valley and West Arm of Kootenay Lake.

CLIMATE

The 1961 to 1990 climate Normals indicate mean annual temperatures for the project area range from -3.1 C at the highest elevations to +8.0 C in the main valley bottoms (Figure 3). Mean annual precipitation also shows a strong vertical gradient from just over 500 mm annually near the valley bottoms to over 2100 mm at the highest elevations of the Selkirk Mountains (Figure 4) (Wang et al., 2016).

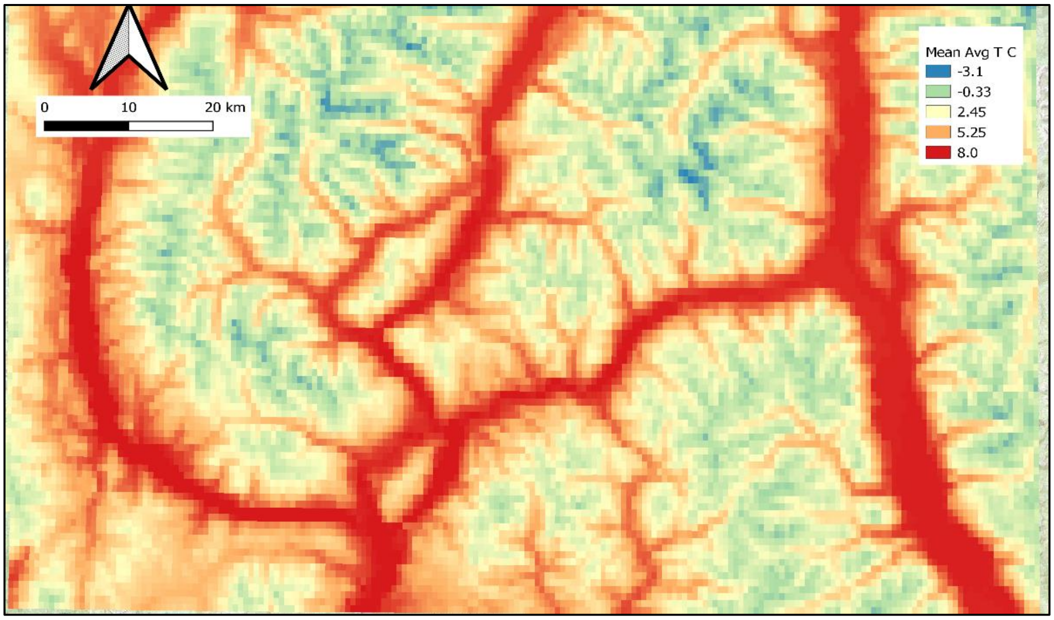

Figure 3. Mean annual temperature (Celsius) for the Southern Selkirk area (1961- 1990 Normals, from ClimateBC)

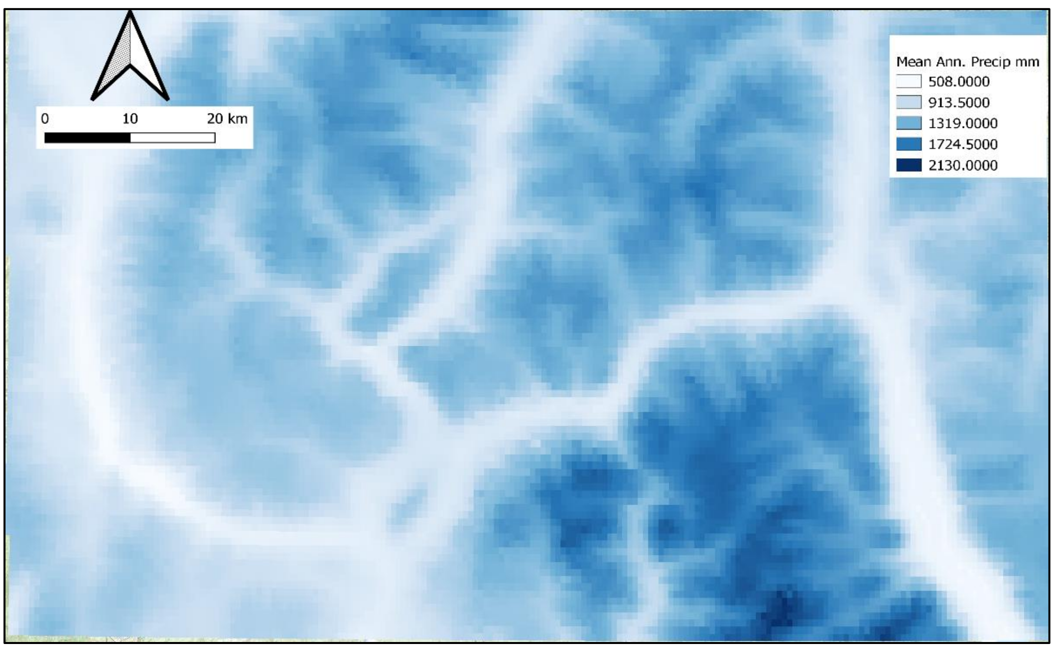

Figure 4. Mean annual precipitation for the Southern Selkirk area (1961 to 1990 Normals, from ClimateBC).

West to east air temperature and precipitation gradients exist in the project area with western Arrow Lakes watersheds generally warmer and drier than eastern Kootenay Lake watersheds (Figure 3 and Figure 4).

Watershed physical characteristics

ELEVATION AND AREA

Except for the two small tributaries in the Coffee Creek study area all of the watersheds included in this study are steep, forested, Southern Selkirk watersheds that flow from the high elevations of the Selkirk Mountains.

CAYUSE AND LITTLE CAYUSE CREEKS

Cayuse and Little Cayuse creeks flow south into Lower Arrow Lake (470 m) west of the community of Robson, BC from an elevation of 2200 and 2100 meters respectively. The southern extent of the Valkyr Range of the Selkirk Mountains forms the headwater of Cayuse and Little Cayuse creeks (Figure 5). Catchment areas range from 2655 hectares for Little Cayuse Creek, to 4857 hectares for Cayuse Creek. Both Cayuse Creek and Little Cayuse Creek have linear drainage patterns with a single main channel along the length of the watershed.

FORTY-NINE CREEK

Forty-nine Creek is a 2872-hectare watershed that flows northwest into the Kootenay River west of Nelson BC. Copper Mountain (2260 m) in the Bonnington Range defines the watershed headwaters. Two equal-sized headwater tributaries converge to form the mainstem channel below 1400 meters (Figure 5).

DUHAMEL CREEK

Duhamel Creek is a 5706-hectare watershed that flows southward to the west arm of Kootenay Lake from an upper elevation of 2355 meters at Mount Cornfield in the Kokanee Ranges. The watershed displays a linear drainage pattern with two tributaries flowing into the mainstem channel from the western side. Slopes on either side of Duhamel Creek are steep with many avalanche tracks descending from bedrock and colluvial cliffs at the uppermost elevations (Figure 5).

COFFEE CREEK – BALFOUR FACE

The Coffee Creek project area includes Coffee Creek and two of the small watersheds (Trib 1 and 3) that drain the Balfour Face area directly south of Coffee Creek. Coffee Creek is a 9521-hectare watershed that flows eastward to Kootenay Lake from the Kokanee Peak in the Kokanee Ranges. The watershed displays a linear drainage pattern with many small tributaries and avalanche paths entering along the length of the mainstem channel. Elevation ranges from just under 2800 meters in the Kokanee Range to 533 meters at Kootenay Lake (Figure 5). The Balfour Face watersheds which range in size from 11.3 to 23 hectares are much lower elevation with their upper elevation slopes at 1700 meters.

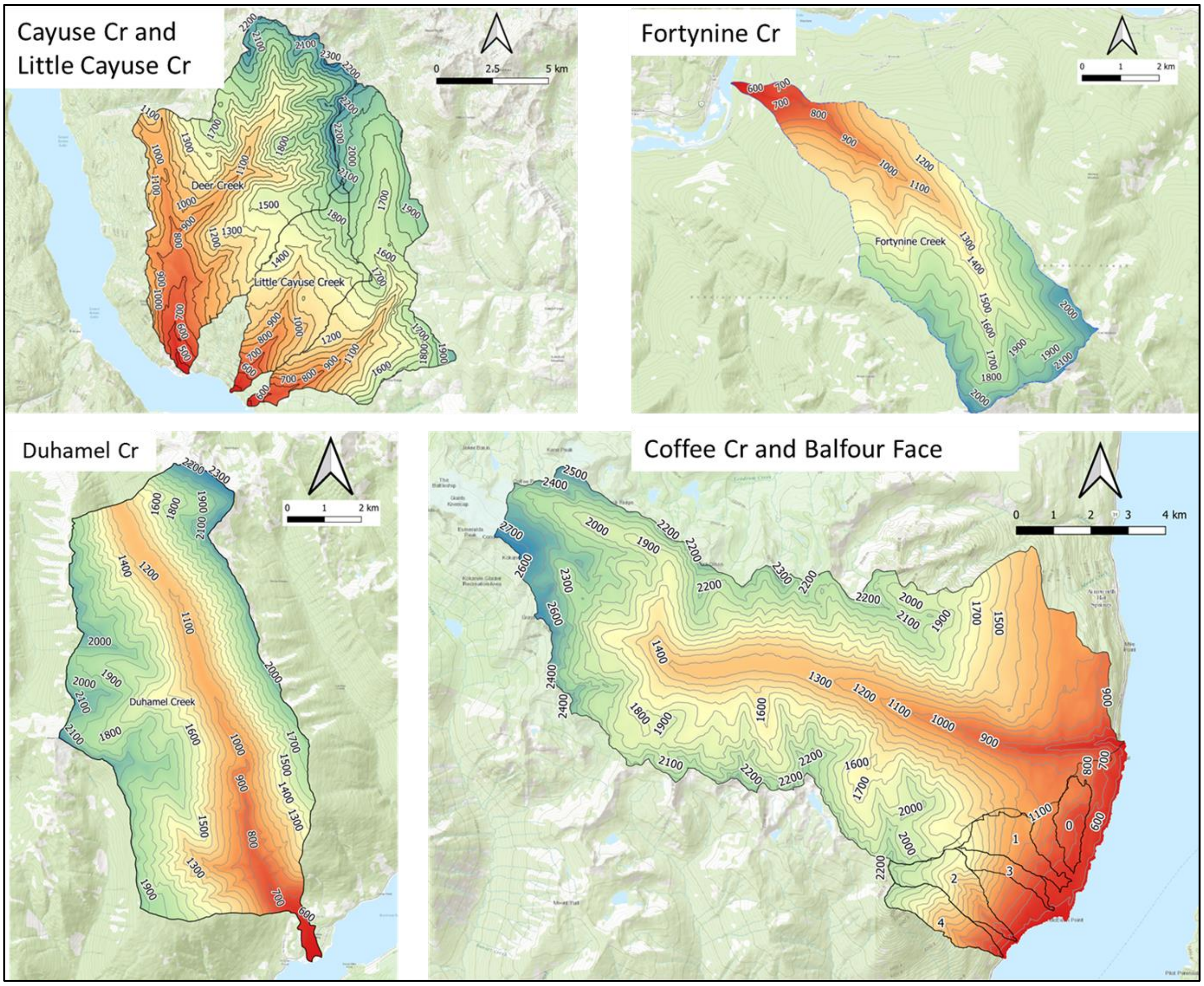

Figure 5. Elevation distribution in the study watersheds

ASPECT DISTRIBUTION

The study watersheds display a range of slope aspects. Relatively steep slopes throughout the watersheds results in less than 0.5% of 'flat' terrain which is less than 1% slope gradient in any of the watersheds.

CAYUSE AND LITTLE CAYUSE CREEKS

Little Cayuse Creek display a predominance of south, southwest and west aspect slopes while the slopes in Cayuse Creek include equal areas of east, southeast, south, southwest and west as well as northwest aspect slopes but lacking north and northeast aspects (Figures 6 and 7).

FORTY-NINE CREEK

Slope aspects in Forty-nine Creek are predominantly north-northeast and west-southwest with the headwater slopes displaying north and northwest aspect (Figure 6 and 7).

DUHAMEL CREEK

Slope aspects in Duhamel Creek are predominantly west-southwest and east-northeast (Figures 6 and 7). The western tributaries include south southeast and north aspects.

COFFEE CREEK AND BALFOUR FACE

A balanced distribution of north, northeast, south, southeast, and southwest aspect slopes are present in Coffee Creek while the Balfour Face watersheds are predominantly east and southeast aspect (Figure 6). A histogram of the aspect distributions in the study watersheds indicates that Cayuse Creek and Coffee Creek have the broadest aspect distributions with most aspects relatively equally represented. Forty-nine Creek and Duhamel Creek display aspect distributions dominated by two opposing aspects. Little Cayuse Creek and the Balfour Face tributaries display limited aspect distributions which are dominated by one or two main aspects (Figure 7)

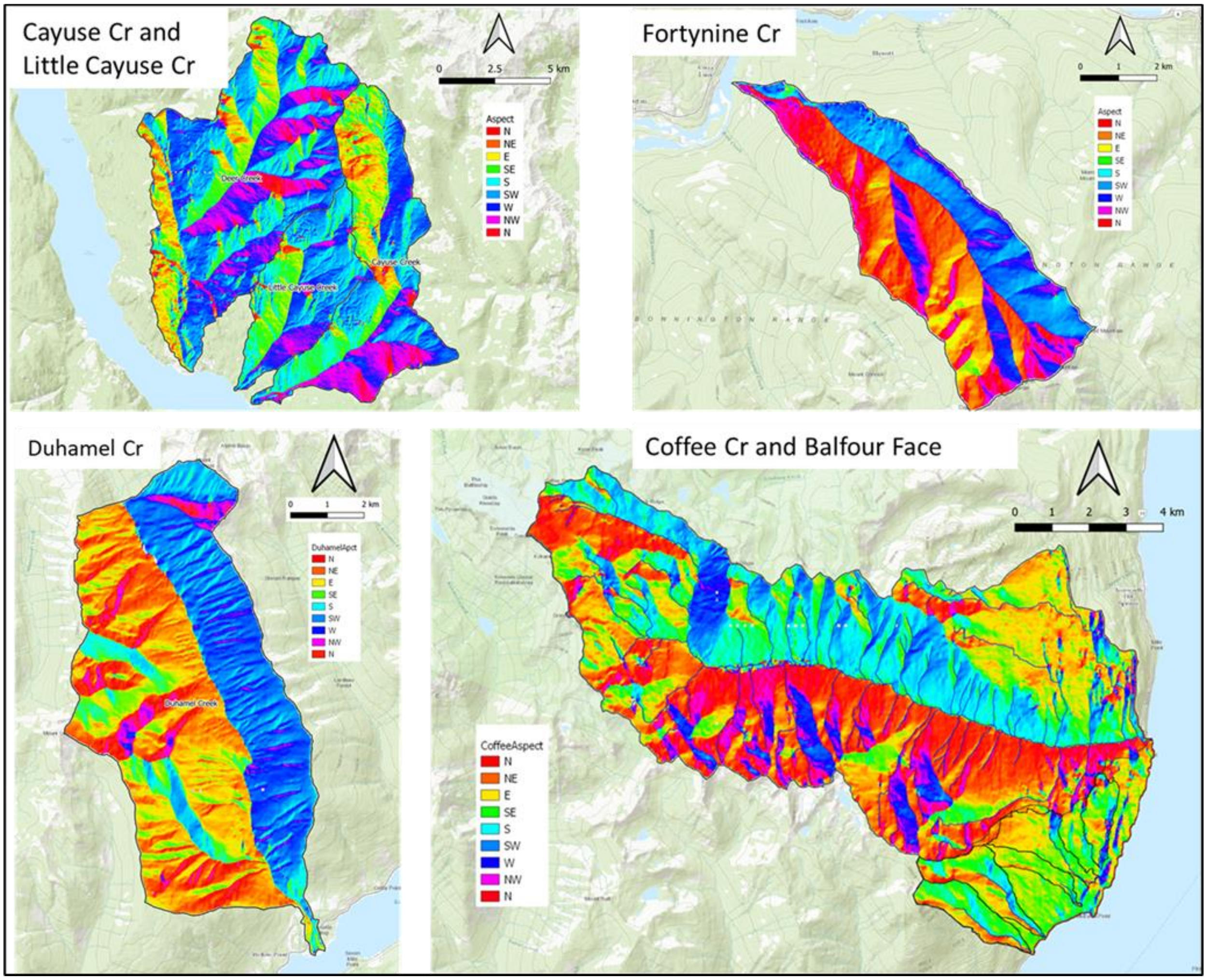

Figure 6. Aspect distribution in the study watersheds

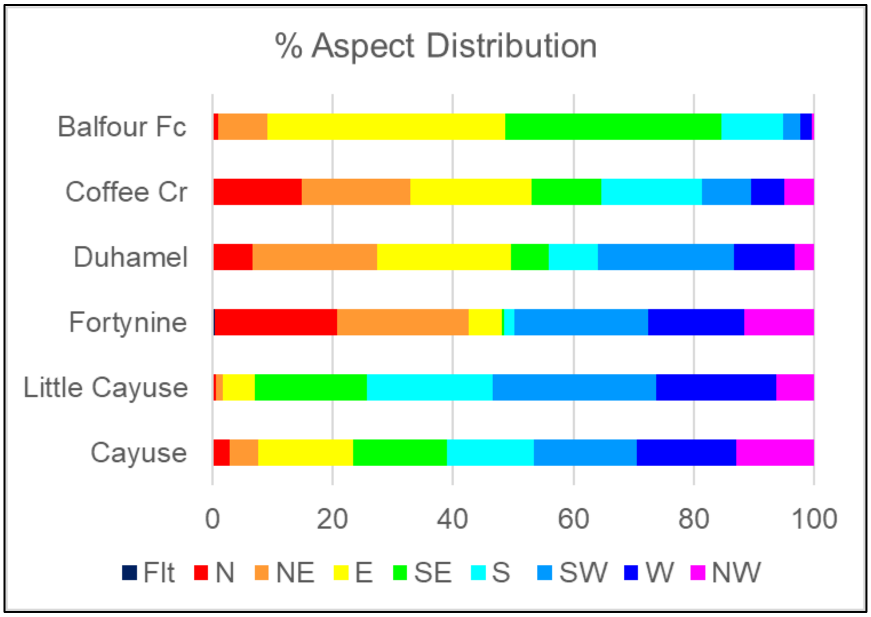

Figure 7. A comparison of aspect distributions across watersheds.

LANDCOVER CHARACTERISTICS

All study watersheds display predominantly forested landcover. Similar elevation distribution and regional climate across the Southern Selkirk results in relatively consistent forest stands that are characterized by western red cedar and hemlock at lower elevation and a broad mix of coniferous species including cedar, hemlock, Douglas fir, spruce, balsam fir and larch at mid- and upper elevations.

CAYUSE AND LITTLE CAYUSE CREEKS

Landcover in the Cayuse study area consists primarily of conifer forests classified within the Interior Cedar Hemlock (ICH) and Engelmann Spruce Subalpine Fir (ESSF) Biogeoclimatic zones (Figure 8). According to the Provincial Vegetation Resource Inventory (VRI) database (2020), the oldest mature stands are present in the ESSF zone at the uppermost elevations of the watersheds and along the riparian areas. Mid-1900s logging was concentrated in the broad, gentle gradient upper elevation basin of Cayuse Creek. Steep bedrock cliffs and colluvial slopes confine Cayuse Creek through the mid elevations.

FORTY-NINE CREEK

Landcover in the Forty-nine Creek watershed is coniferous forests classified as Interior Cedar Hemlock (ICH) and Engelmann Spruce Subalpine Fir (ESSF) Biogeoclimatic zones (Figure 8). According to the VRI, the oldest mature stands of balsam fir and hemlock occur in the upper watershed and along the riparian areas. Rocky subalpine areas are present at the uppermost steep slopes above 2000 meters.

DUHAMEL CREEK

Forests in Duhamel Creek are classified within the ICH and ESSF biogeoclimatic zones (Figure 8). The Provincial VRI database indicates most of the forest stands in Duhamel Creek are younger than 150 years with some older stands remaining in the riparian areas. This is due to the fact that Duhamel Creek was the focus of early 1900s logging activities that removed large volumes of wood from riparian forest and lower valley slopes. These forests are now mature second growth cedar-hemlock stands.

COFFEE CREEK AND BALFOUR FACE

Forests in Coffee Creek are classified within the ICH and ESSF biogeoclimatic zones (Figure 8). The uppermost elevations are classified as Interior Mountain-heather Alpine (IMA). The Provincial VRI database indicates the majority of the ICH forest stands in Coffee Creek are younger than 100 years and were the focus of early to mid-1900 logging. Balfour Face watersheds are primarily within the ICH biogeoclimatic zone.

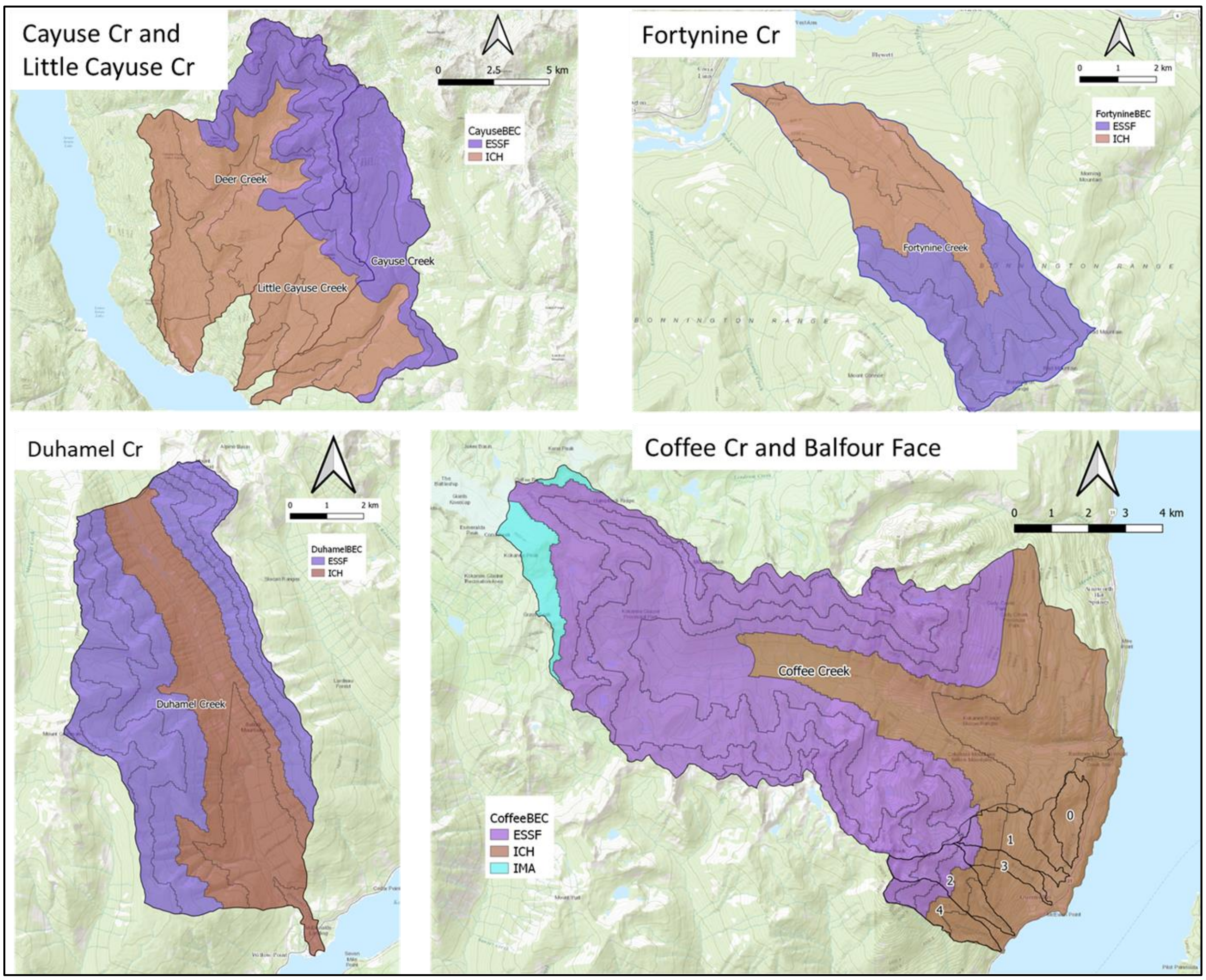

Figure 8. Biogeoclimatic zones of study watersheds

FOREST DISTURBANCE

Wildfire is one of the largest natural forest disturbance processes in the Selkirk Region. Three of the four study areas show a long history of wildfire disturbance with the oldest recorded fires dating to the 1920s. Logging has been ongoing in all of the study watersheds since the early to mid-1900s.

CAYUSE AND LITTLE CAYUSE CREEKS

Cayuse Creek and adjacent watersheds have experienced substantial forest disturbance over the past century. Two large forest fires occurred in Deer Creek in 2015, and 2018. Large fires also occurred in Cayuse Creek and Little Cayuse Creek in the early 1900s (Figure 9). Forest harvesting has been ongoing in these watersheds for the past century but only blocks later than the 1960s are recorded in the VRI. Mid-1900s logging occurred at the upper elevations of Cayuse Creek and Little Cayuse Creeks but these old blocks are not recorded in the Provincial VRI or consolidated cutblocks databases.

FORTY-NINE CREEK

The Provincial wildfire database indicates three small patches at lower elevations have experienced wildfire in the past several decades (Figure 9). Forty-nine Creek, is named for the ‘Forty-niners’ who arrived at the tail end of the California goldrush and mining related forest disturbance in the watershed dates back to the late 1800s.

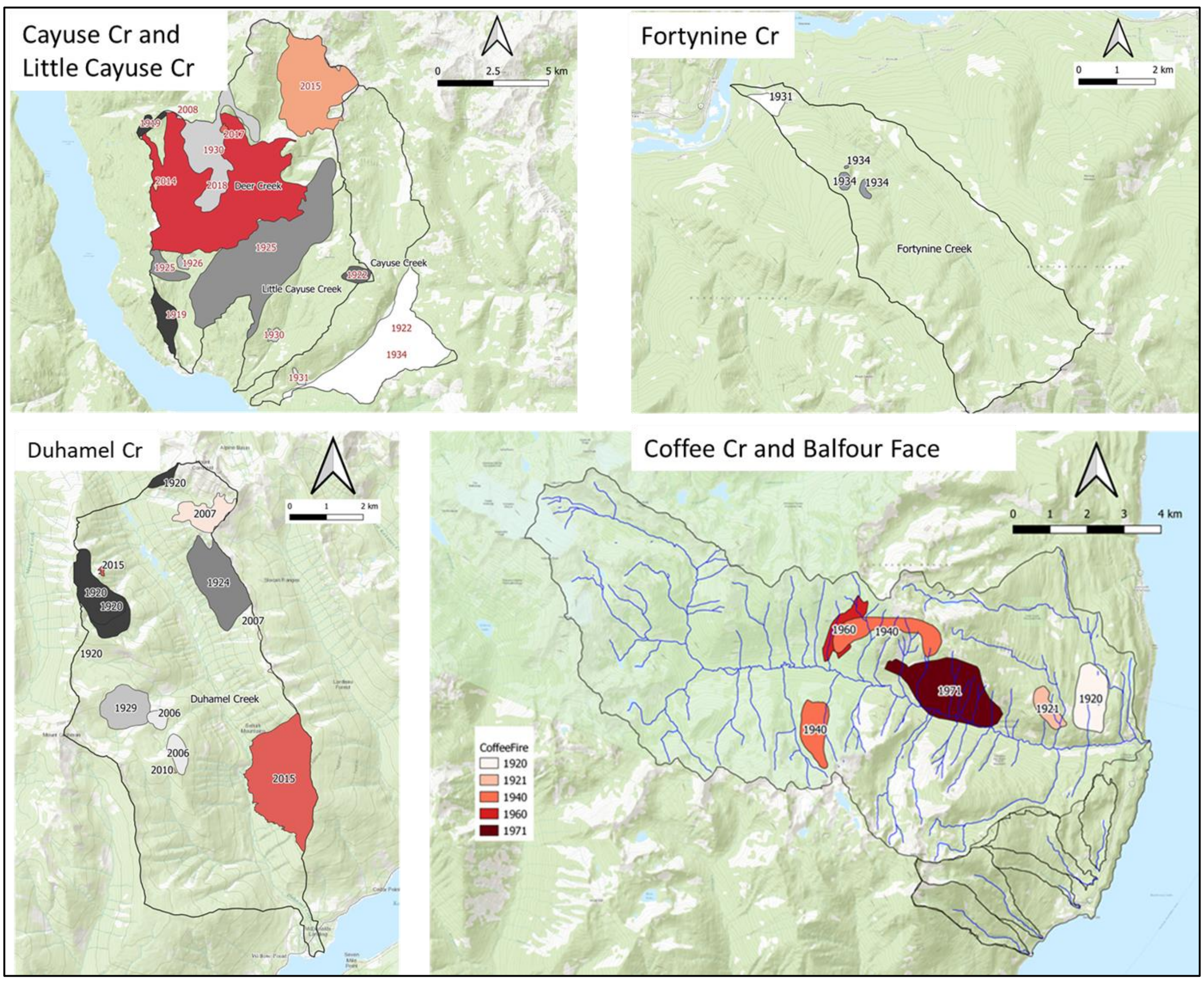

Figure 9: Wildfire disturbance themed by colour with red being the most recent fires and white the oldest fires

DUHAMEL CREEK

Satellite imagery reveals the scars of multiple forest fires on the hillsides of Duhamel Creek, some of which are recorded in the Provincial wildfire database. The most recent fire in 2015 burned a large area of forest from the southeastern slopes (Figure 9).

COFFEE CREEK AND BALFOUR FACE

The Provincial wildfire database indicates only limited fire disturbance located primarily on south aspect slopes in the eastern half of the watershed (Figure 9). No fires are recorded for Balfour Face but most of these slopes were burned in the early 1900s in association with early mining exploration activities and the hot and dry period of the 1930s.

Hydrological Modeling

A process-based hydrological model such as the HBV-EC model used in this study tracks the accumulation and runoff of precipitation inputs through a virtual representation of a watershed using a network of polygons referred to as Hydrological Response Units or HRU's. The model 'sees' the watershed as an interconnected network of HRUs and moves water through these HRUs to the streams by overland flow and subsurface flow. A graphical representation of the discretized HRU's for this study appears as a patchwork quilt with each HRU representing a distinct set of variables influencing precipitation accumulation/storage and runoff including, elevation, aspect, slope gradient and landcover (Figure 10**)**

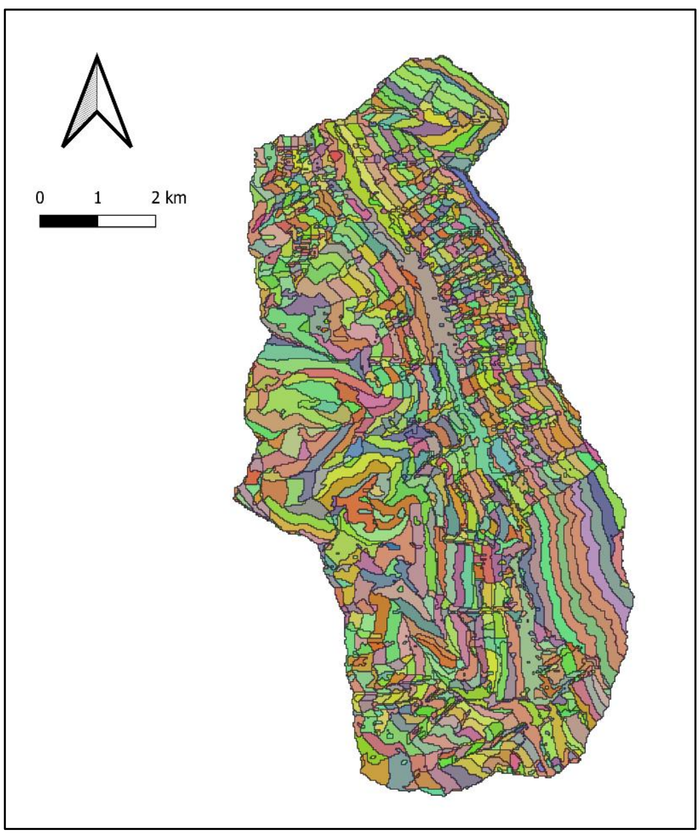

Figure 10. Graphical representation of the Hydrological Response Units (HRUs) defined in Duhamel Creek.

The semi-distributed hydrological model used in this study is an adapted version of the HBV-EC model, emulated within the Raven Hydrological Modeling Framework version 3.0 (Craig et al., 2020). The model simulates streamflow and other hydro-climatic variables (i.e. snowmelt, evaporation, etc.) at a daily timestep from 1980-2019. The model spatially distributes daily minimum and maximum air temperature and precipitation from all weather stations across the study region. Using a series of algorithms, the model simulates major hydrological processes including canopy interception, snow accumulation and melt, glacier melt, evaporation, soil infiltration, percolation, and baseflow, as well as surface runoff. Major processes are described below, while a comprehensive discussion of model algorithms can be found in Bergström (1992), Jost et al. (2012), and Chernos et al. (2020).

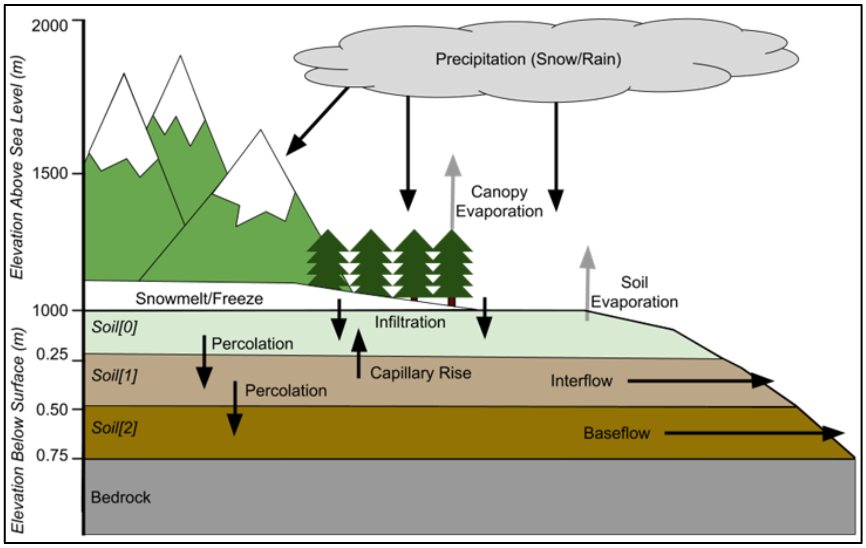

Figure 11. A visual representation of the HBV-EC model (from Craig et al., 2020)

In the hydrological model, water inputs occur as precipitation, which are partitioned into rain or snow following the HBV linear transition based on air temperature (Figure 11). Precipitation intercepted by the forest canopy is estimated as a function of Leaf-Area Index (LAI; Craig et al., 2020; Hedstrom and Pomeroy, 1998). Snowmelt is calculated using a spatially corrected temperature index model, which accounts for aspect, slope, and day length (Jost et al., 2012, Craig et al, 2020). Potential evapotranspiration is calculated using the Priestley–Taylor equation. Once water infiltrates a three-layer soil, it moves downwards through percolation and upwards through capillary rise. Soil water becomes surface runoff (i.e. streamflow) through (faster) interflow and (slower) baseflow pathways.

Data used in the model

To run the hydrological model, daily air temperature (maximum and minimum, °C) and precipitation (mm/day) are required. These data were collected from DayMet (Thornton et al., 2018) using the Single Pixel Extraction Tool to obtain observations from 1980-2019 for at a 0.15-degree resolution over the study area. Since DayMet data are based on a 1x1 km grid cell, reference elevations are obtained for each data point and are used to correct observations to HRU elevations using specified lapse rates (i.e. temperature and precipitation gradients) within the hydrological model (Figure 12).

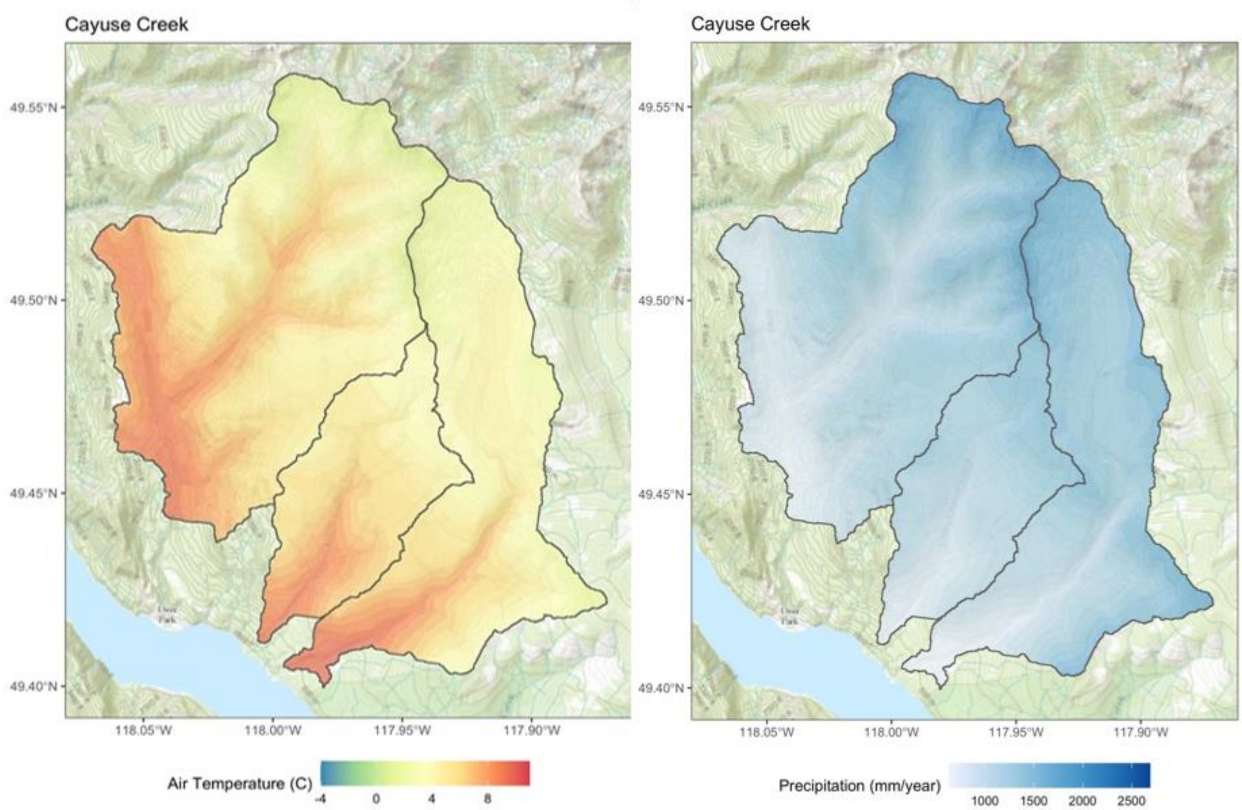

Figure 12. Model-generated average annual air temperature and precipitation for Cayuse Creek

Future climate change scenarios were generated from statistically downscaled climate scenarios obtained from Environment and Climate Change Canada (ECCC, 2021) under the representative concentration pathway (RCPs) 4.5, which corresponds to a scenario where carbon emissions stabilize by 2040. The RCP 4.5 Scenario applied the median projection from an equal-weighting ensemble forecast of 24 General Circulation Models (GCMs) from the Coupled Model Inter-comparison Project Phase 5 (CMIP5) from 2021-2100. Projections among climate models can vary because of differences in their underlying representation of earth system processes. Thus, the use of a multi-model ensemble approach has been demonstrated in recent scientific literature to likely provide better projected climate change information (Zhang et al., 2019, ECCC, 2021).

Daily future weather was generated by first bias-correcting projected climate values by calculating the change between simulated future air temperature and precipitation and historical (simulated). Each future month and year were then matched with a proxy month from the baseline (observed) period. These scaling factors for each month and year (i.e. fractional difference in precipitation and absolute difference in air temperature between the proxy and scenario) were then used these to correct the daily observed record for each climate scenario (Figure 14).

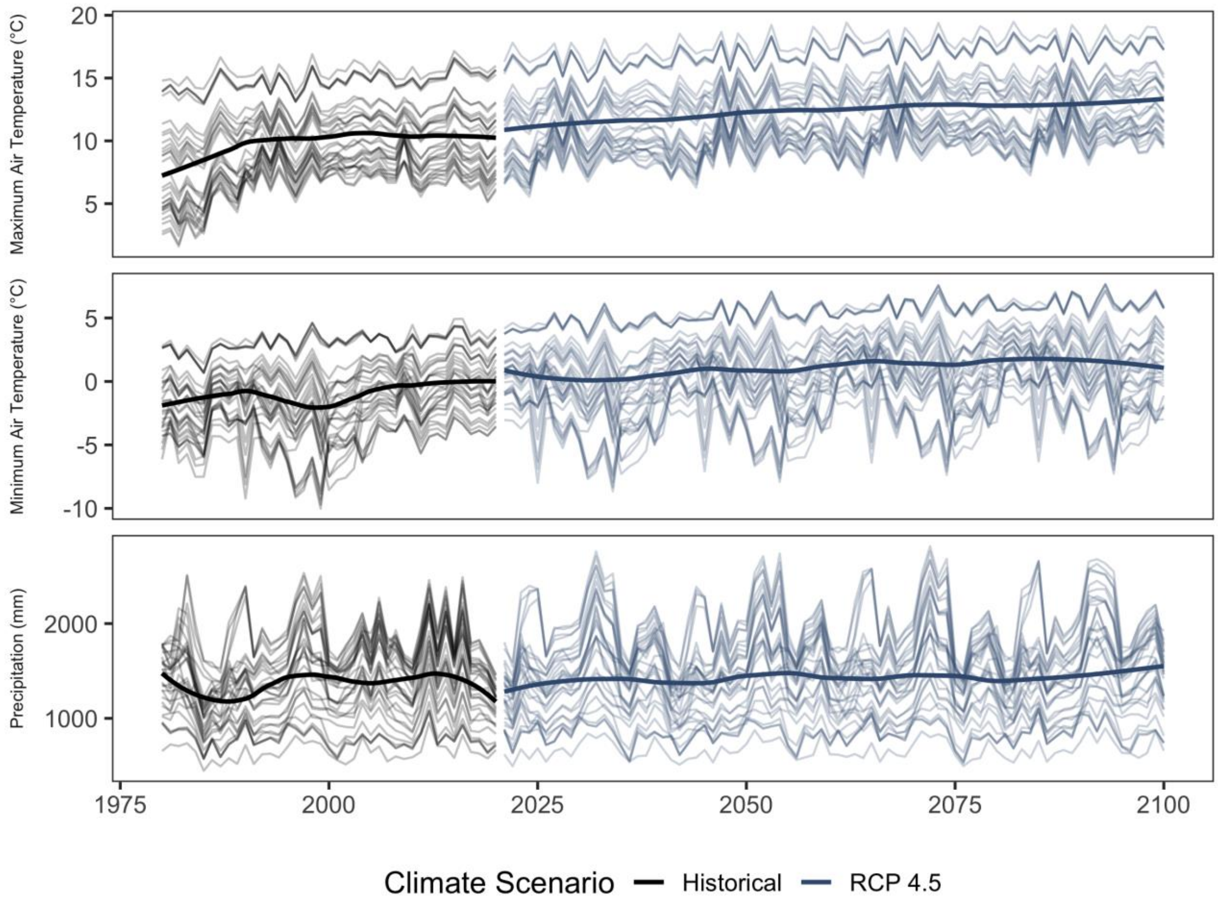

Figure 13. Time series of minimum, maximum air temperature and precipitation generated from climate models.

Monthly averages of the historical and projected temperature and precipitation daily time series shows the magnitude of change in the monthly averages of these climate variables (Figure 14). Of the three climate variables, precipitation for the winter months shows less change from historical conditions compared to minimum and maximum average monthly air temperatures but greater change during the spring freshet months of April and May.

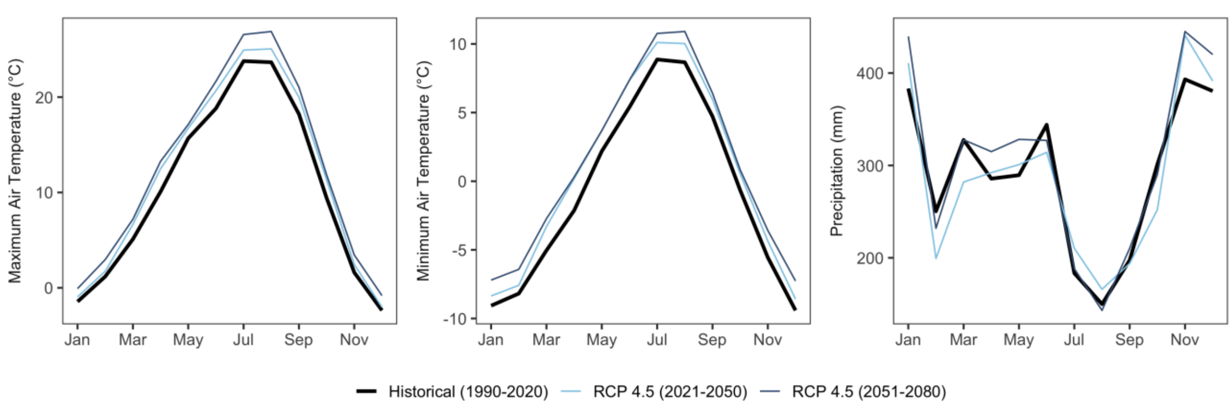

Figure 14. Average monthly climate under historical and future scenarios.

Streamflow (m^3/s) data were obtained from Water Survey of Canada (WSC) hydrometric stations Deer Creek at Deer Park (Stn 08NE087), and Duhamel Creek above Diversion (Stn 08NJ026) which have long-term records. In addition, several years of daily streamflow gauging was available for Coffee Creek (08NH101) (1988 – 1992). In total, three hydrometric sites were used in model calibration and verification (Table 1).

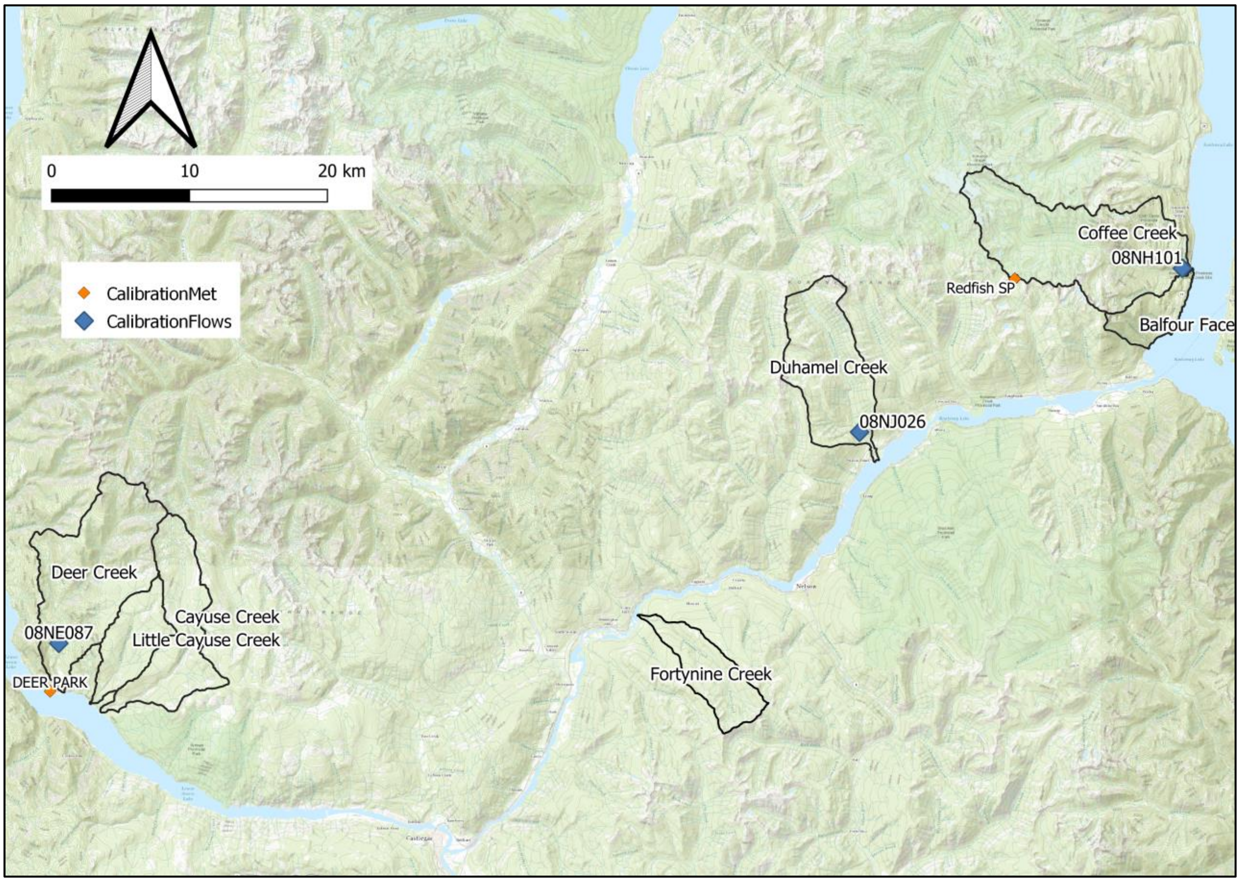

Figure 15. Model streamflow calibration against hydrometric and climate stations.

The model was further calibrated and verified using daily air temperature and precipitation observations from regional weather stations at Redfish and Deer Park, and snow water equivalent observations were obtained from the snow pillow site at Redfish Creek (Figure 16, Table 2).

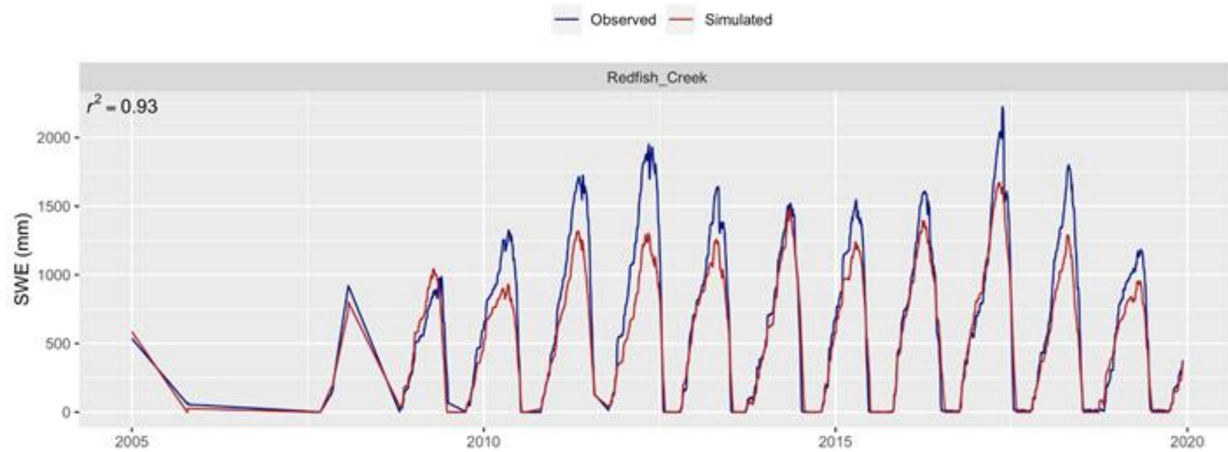

Figure 16. Snow water equivalent calibration against Redfish Creek snow pillow

Table 1. Hydrometric stations/sites used in this study. WSC corresponds to the Water Survey of Canada

Name	Station ID	Source	Period	Drainage Area (km^2)
Duhamel Creek	08NJ026	WSC	1996-2021	52.9
Coffee Creek	08NH101	WSC	1988-1992	87.3
Deer Creek	08NE087	WSC	1980-2021	81.6

Table 2. All weather and snow stations used for model verification in this study.

Station Name	Station ID	Longitude	Latitude	Elevation (m)	Network	Data Type
Deer Park	1142400	-118.05	49.42	485	EC	Weather Station
Redfish Creek	2D14P	-117.08	49.68	2,104	FLNRO-WMB	Snow Pillow

Hydrological Response Unit delineation

The study watersheds were discretized using hydrological response units (HRUs) based on the unique overlay of elevation bands, hillshade, land cover, and sub-basin. We derived 100 m elevation bands using the Canadian Digital Elevation Data digital elevation model (DEM; Natural Resources Canada, 2016). Hillshade is calculated using the `hillshade` function in the R `raster` package (Hijmans, 2020), which incorporates the slope and aspect of each grid cell. Land cover was obtained from Baseline Thematic Mapping Present Land Use Version 1 (https://openmaps.gov.bc.ca/geo/pub/WHSE_BASEMAPPING). We further aggregated land cover into the following classes: Agriculture, Alpine, Shrub, Burn, Disturbed Forest, Young Forest, Mature Forest, Lake, Wetlands, Developed. In addition, Mature Forest was divided into the two prevalent Biogeoclimatic (BEC) zones in the region: Interior Cedar Hemlock (ICH) and Engleman Spruce Subalpine Fir (ESSF) which allows for adjustment of snow interception and shading associated with different forest species. Finally historical vegetation disturbance was accounted for using BC Government's Fire Perimeter and Consolidated Cutblocks data layers, accessed through the bcdata R package (Teucher et al., 2021). Areas within 30 years of disturbance date were treated as "Disturbed Forest" while forest more than 30, but less than 60 years since disturbance were treated as "Juvenile

Forest". The Provincial datasets did not capture some of the older, poorly regenerated cut blocks and manual adjustments were needed in Cayuse and Little Cayuse creeks following a visual inspection of current satellite imagery.

MODEL CALIBRATION

To optimize model representation of key hydrologic processes and streamflow, model parameters were calibrated in a stepwise manner following Chernos et al. (2017) and originally adapted from Stahl et al. (2008). First, air temperature and precipitation lapse rates were calibrated to regional weather stations, then snowmelt parameters are modified to follow empirical values obtained from regional snowmelt and glacier mass balance observations. Finally, vegetation interception and soil routing parameters are calibrated to streamflow observations. Final calibrations were completed by a combination of manual methods and automated calibration. Automated calibration of some parameters is undertaken using OSTRICH calibration software (Matott, 2017), using the Dynamically Dimensioned Search (DDS) algorithm to finalize parameter values. Model parameters were calibrated to the 2010-2019 period using the Duhamel Creek and Deer Creek hydrometric stations. Model performance was verified over the remaining record (prior to 2010) for Duhamel and Deer creeks as well as the short record (1988-1992) available at Coffee Creek.

While calibration was able to constrain the value of most model parameters, some parameters are relatively insensitive, such that changing their value does not substantially alter streamflow simulations. In some cases, this is because the model parameter does not affect a dominant hydrologic process in the watershed (for example, capillary rise as a soil water process). In other cases, particularly, for land cover specific model parameters, the parameter is insensitivity because little of that land cover type exists in the sub-basin. For example, since Duhamel Creek contains minimal Juvenile Forest over the calibration period, it is difficult to calibrate the interception parameters for this land cover class. In these cases, model parameters were finalized to ensure conceptual and physical realism (i.e. to ensure Juvenile stands intercept more precipitation than Disturbed (i.e. open) stands, but less than Mature forest).

LAND COVER SCENARIOS

Since the hydrological model uses land cover and weather data as inputs to simulate streamflow (and other hydroclimatic variables), modifying these input data can be used to investigate how those changes will impact water resources in the watershed. The possibilities for scenario analysis are essentially limitless, and can include specific management plans or configurations, weather or climate patterns, or combinations of both. Here we investigate two conceptual landcover disturbance scenarios requested by the forest managers.

Baseline forest conditions against which to measure hydrological disturbance was the focus of some deliberation amongst industry partners. For this project hydrological disturbance is measured against the year 2000 baseline landcover but is also compared against the 2020 end of year landcover conditions. The project team agreed that a more realistic baseline condition would be the forest conditions that existed in the past several decades (i.e., 1970s) before intensive forestry activities began in a watershed. The task of defining historical landcover polygons for these watersheds was discussed but determined to be beyond the scope of this project. Land cover scenarios are described in **Error! Reference source not found.** and shown in greater detail in Figures 19, 21, 23 and 25.

Table 3. Percent of watershed with disturbed forest for each land cover scenario investigated in this study.

Forest Disturbance Scenarios

Percent of watershed with forest disturbed (cut or burned) within last 25 years (not ECA)

Watershed	Baseline (2000)	Current Conditions	Scenario A	Scenario B
Little Cayuse Creek Near Deer Park	14.6%	7.7%	29.1%	32.1%
Forty-Nine Creek Near Blewett	12.4%	10.3%	12.3%	13.4%
Cayuse Creek Near Deer Park	12.1%	11.5%	30.3%	33.9%
Deer Creek At Deer Park	11.1%	61.0%	60.9%	60.9%
Coffee Creek Near Ainsworth	5.4%	5.7%	8.6%	8.6%
Duhamel Creek Above Diversions	2.1%	12.2%	14.0%	18.0%
Coffee South Face	1.3%	6.3%	12.2%	12.2%
Coffee South Face Trib 2	0.1%	2.4%	2.4%	2.4%
Coffee South Face Trib 0	0.0%	42.4%	42.4%	42.4%
Coffee South Face Trib 1	0.0%	13.7%	44.7%	44.7%
Coffee South Face Trib 3	0.0%	2.9%	31.9%	31.9%
Coffee South Face Trib 4	0.0%	17.7%	17.7%	17.7%

Study Results

Model Parameterization

Model parameterization relied on a combination of calibration using independent weather and snowpack data and conceptual understanding of the dynamics of vegetation regrowth. A comprehensive list of model parameters is provided in

Table 4. Notable parameter values include that snow in Mature Forest is assumed to melt at a slower rate than open areas (0.80 in ICH, 0.85 in ESSF), while this difference is less pronounced in Juvenile Forest. Likewise, forest cover fractions are higher in mature forest classes, relative to juvenile and disturbed forest. Finally, although maximum annual leaf-area-index (LAI) values are the same between forest age classes, Disturbed Forest varies seasonally with winter values half their summer value, reflecting that much of recently disturbed forests consist of deciduous shrubs.

Table 4. Final model parameters used in the south Selkirk hydrological model.

Process	Description	Parameter	Value	Units
Orographic Corrections	Adiabatic Lapse Rate	Alapse	6.5	°C/km
	Precipitation Lapse Rate	Plapse	6.0	mm/day/km
Rain-Snow Partitioning	Transition Temperature	Snw1	1.0	°C
	Mixed-Range	Snw2	2.0	°C
Snowmelt	Global Snowmelt Factor	K_factor	2.75	mm/°C /day
	Mature Forest correction (ICH)	Forest_corr	0.70	fraction
	Mature Forest correction (ESSF)	Forest_corr	0.75	fraction
	Juvenile Forest correction	Leaf_corr	0.85	fraction
	Aspect/Slope correction	Acor	0.2	fraction
	Minimum Melt (winter)	Min_melt	0.0	mm/°C/day
	Refreeze factor	Refreeze	2.0	mm/°C/day
Leaf Area Index*	Disturbed Forest	Cut_LAI	4.5	unitless
	Juvenile Forest	ForestY_LAI	4.5	unitless
	Mature Forest	Forest_LAI	4.5	unitless
Vegetation/Canopy Coverage	Disturbed Forest	Cut_Cov	0.50	fraction
	Juvenile Forest	ForestY_Cov	0.60	fraction
	Mature Forest (ICH)	Forest_Cov	0.85	fraction
	Mature Forest (ESSF)	Decid_Cov	0.75	fraction
Infiltration	HBV Beta	HBV_B0	0.5	unitless
Percolation	Surface Soil	Perc0	4.0	mm/day
	Soil Layer 1	Perc1	4.0	mm/day
Capillary Rise	Surface Soil	Cap0	4.0	mm/day
Baseflow	Soil 1 K	Base_K1	0.05	unitless
	Soil 1 N	Base_N1	1.12	unitless
	Soil 2 N	Base_N2	1.12	unitless
	Soil 2 Max Rate	Base_MAX2	7.0	mm/day

**Indicates maximum annual LAI value; Shrub/Wetland, Disturbed Forest, and Grassland values vary seasonally with lower values during the winter.*

Model Performance

Simulated daily air temperature, total monthly precipitation, and daily SWE closely followed observed values from independent weather stations throughout the study region. Daily maximum air temperatures had r^2 values ranging from 0.75 to 0.98. Monthly precipitation r^2 values ranged from 0.45 to 0.90 with four out of five sites over 0.70. It should be noted that these weather stations are likely not fully independent since some are likely inputs into the DayMet grid (Thornton et al., 2020) used in this study. Daily total SWE was well simulated at Redfish Creek snow pillow (r^2 = 0.94, PBIAS = -16%).

Streamflow simulations demonstrated strong performance in reproducing observations from Coffee Creek, Duhamel Creek and Deer Creek WSC hydrometric stations although peak flows are generally under-estimated (Figure 17). Performance was similar between the calibration period (2010-2019) and verification period (1988-2009). Nash-Sutcliffe Efficiency (NSE), ranging up to 1 (perfect simulation) was between 0.72-0.84 at all hydrometric gauges (

Table 5). Overall, the model displays minimal bias between simulated and observed streamflow, with a moderate positive bias (i.e. over-simulation) at Deer Creek and a moderate negative bias at Duhamel Creek and Coffee Creek (Figure 17).

Table 5. Model performance statistics for the calibration and verification periods.

Site	Period	NSE	PBIAS
Coffee Creek Near Ainsworth	Verification	0.79	-11.8%
Deer Creek At Deer Park	Calibration	0.80	12.7%
Deer Creek At Deer Park	Verification	0.72	4.8%
Duhamel Creek Above Diversions	Calibration	0.84	-19.3%
Duhamel Creek Above Diversions	Verification	0.79	-21.2%

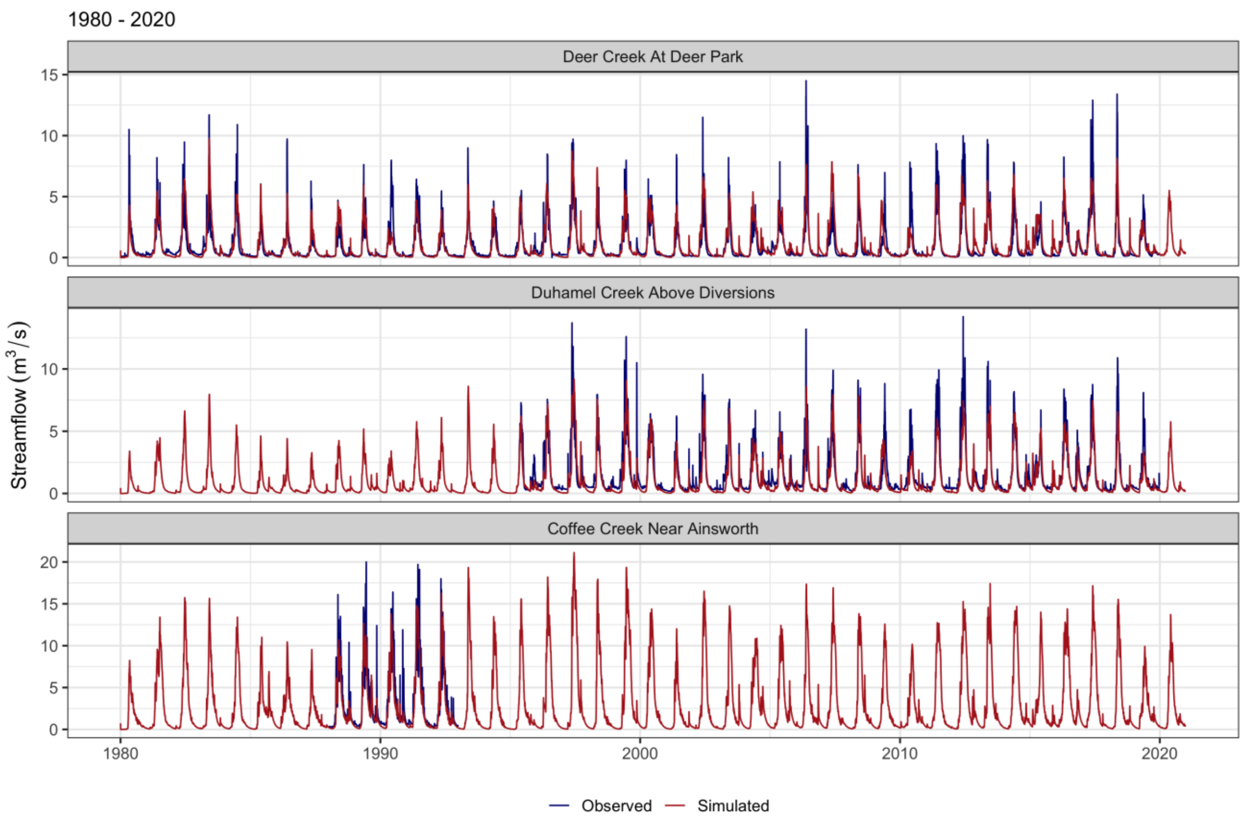

Figure 17. Daily hydrograph for three sites with hydrometric records that were used for model calibration.

HYDROLOGICAL BASELINE CONDITIONS

Streamflow in all study watersheds follows a strongly snowmelt driven pattern. Flows are low during the winter months as snow accumulates, and increases sharply during the spring, coinciding with snowmelt, particularly at upper elevations. Streamflow decreases into July, with only small increases in flow coinciding with large rainfall events. In Coffee Creek, high flows persist longer into the summer due to glacier melt from its upper reaches providing additional water inputs. Spatially, runoff is generally substantially greater at higher elevations, with ridgetops and alpine areas approaching 2000 mm of runoff annually. Conversely, lower elevations and valley bottoms can produce less than 500 mm per year on average. This dynamic reflects the relatively steep precipitation gradient in the region, where upper elevations receive substantially more precipitation (estimated at 3.5 mm/day/km in the model) and greater evaporation at lower elevations due to warmer air temperatures (Figure 18).

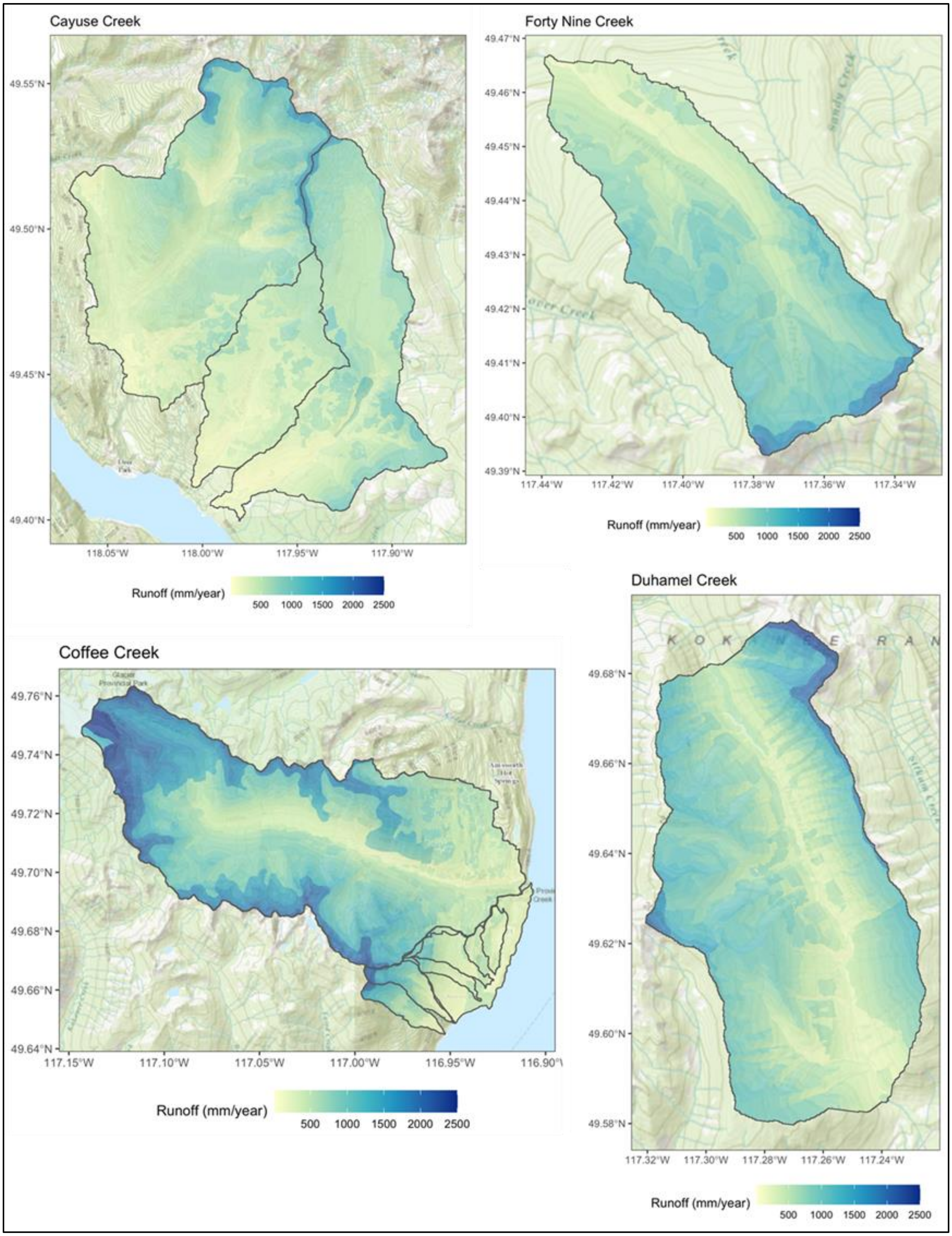

Figure 18. Mean Annual Runoff (mm/year) over the historical study period (1990-2019) for all watersheds modelled in this study.

To investigate the effect of land cover and climate scenarios several streamflow variables were selected that correspond to potentially harmful hydrological events of interest to forest managers. These variables include (1) the timing of peak flows that is important to aquatic ecosystems, (2) mean annual flow which is representative of annual water yield, (3) August – September low flows which are critical to aquatic ecosystems as well as the security of water supplies, (4) the 2-year return period peak flow which is geomorphically significant in the maintenance of channel morphology and (5) the 100-year return period flood representative of more extreme, floods that can harm property and human life (

Table 5).

The 2-year and 100-year return period flood magnitudes are estimated by fitting the 30-year time series of mean daily annual peak flow for using a log-normal distribution in the Fitdistrplus package in R (Delignette-Muler and Dutang, 2015).

Table 5. Hydrologic indicators used to identify changes in hydrologic regime and function.

Variable	Description
Peak flow timing	The average Julian day of peak daily streamflow in a calendar year, representative of the timing of spring snowmelt-driven runoff.
Mean Annual Flow	The average annual streamflow, representative of the amount of water passing through this point in a calendar year.
Aug-Sept Low Flow	The average August-September streamflow, representative of conditions following snowmelt, which has historically coincided with summer low flows and heightened risk of droughts, degraded water quality, and water scarcity.
2-year Peak Flow	The average annual peak flow (annual likelihood of occurrence of 0.5 or 50%. This peak flow is typically a bank-full discharge and associated with maintaining sediment transport processes and channel morphology.
100-Yr Return Period Flood	The flood magnitude that has an annual likelihood of occurrence of 0.01 or 1%. It is estimated by undertaking a frequency analysis of the time series of annual peak flows. This hydrologic metric provides insight regarding the influence of disturbance on extreme floods.

Model outputs

CAYUSE CREEK

The scenarios proposed in Cayuse Creek and Little Cayuse Creek are intended to investigate high elevation versus low elevation forest disturbance (Figure 19). Scenario A involves clearing of 25% of the mature stands in the lower half of the watersheds below the H50 elevation while Scenario B explores clearing of 25% of mature forests in the upper half of the watersheds. Deer Creek is included in the figures as it is used in the model calibration process (Figure #) but no additional disturbance was simulated in this sub-basin within these scenarios.

The hydrological response in Cayuse and Little Cayuse creeks is investigated relative to year 2000 baseline landcover and current climate conditions as well as for conditions of a changing climate consistent with projections for the RCP 4.5 pathway (keeping landcover static). The outcomes for the scenarios are presented in Tables 6 and 7, and Figure 20.

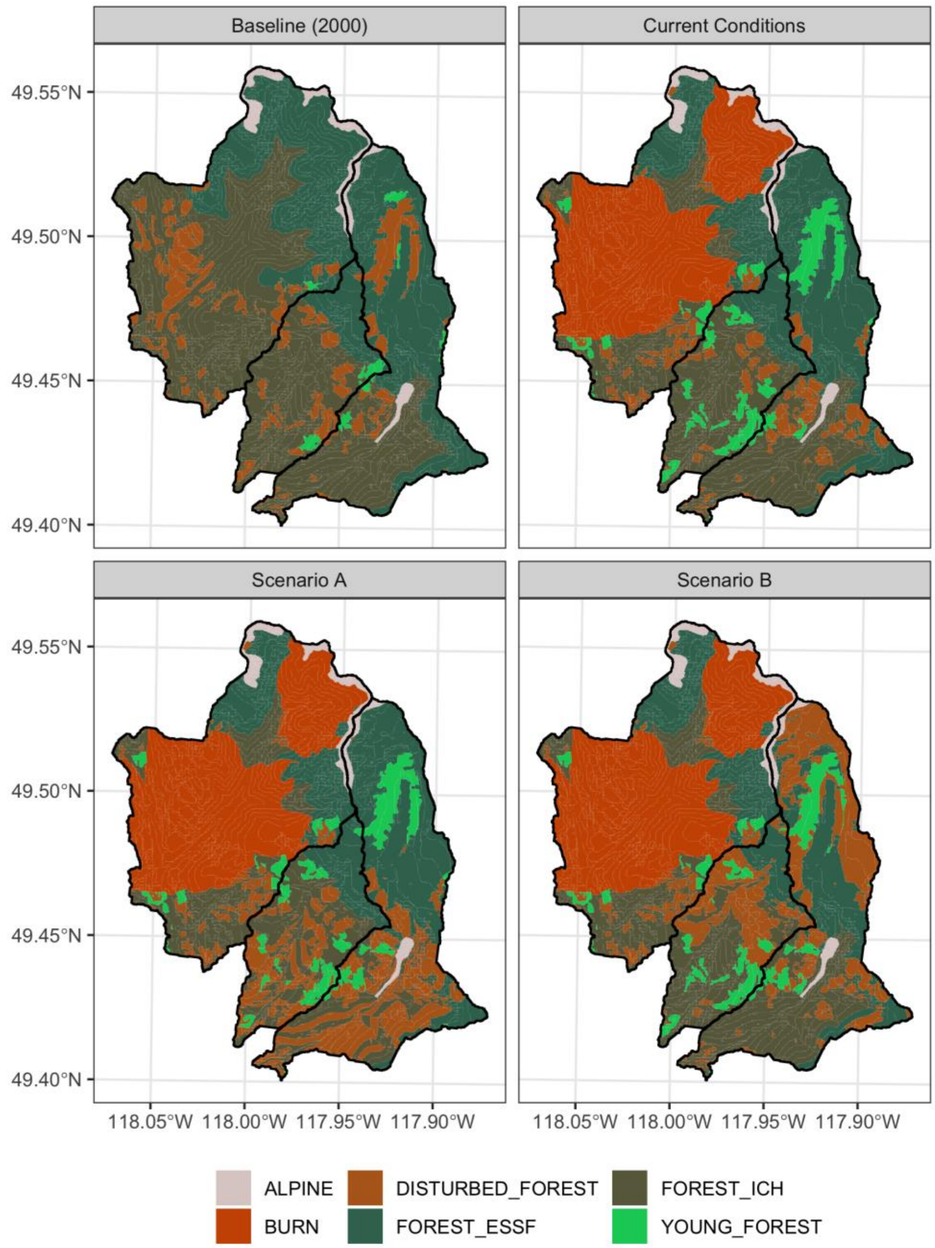

Figure 19. Forest cover scenarios for Cayuse Creek and Little Cayuse Creek.

LANDCOVER EFFECTS

Application of 25% lower (A) and upper (B) disturbance scenarios in Cayuse Creek show a substantial change in all hydrological metrics except for timing of peak flows. Harvesting of the lower elevations increases mean annual flow (i.e. mean water yield) by 9% and by 12% following harvesting of upper elevations relative to baseline conditions. Summer low flows also increased for Scenarios A and B by 6% to 7%, respectively. The largest alteration to hydrological metrics is observed with the elevation of the 2-year (average annual) flood by over 16% for Scenario B but only 5% for the low elevation disturbance scenario. The 100-year (extreme) floods are less elevated, but the upper elevation 25% scenario increases the magnitude by 8% which is a significant increase in magnitude of an extreme flood event and would also result in a large increase in frequency of larger than average flood events. In contrast a 1% increase in the magnitude of extreme floods for the low elevation forest disturbance Scenario A is minimal.

Table 6. Cayuse Creek landcover and climate scenarios model outputs.

Hydrologic Change Consequence Table

Cayuse Creek Near Deer Park

Land Cover Scenario	Mean Annual Flow	Summer Low Flow	2-year Peak Flow	100-year Peak Flow	Peak Flow Timing
1990-2019					
Current Conditions	2%	1%	1%	−0%	0.3
Scenario A	9%	6%	5%	1%	−0.3
Scenario B	12%	7%	16%	8%	−0.1
2021-2050					
Baseline (2000)	−8%	−25%	−10%	2%	−13.3
Current Conditions	−7%	−24%	−10%	2%	−13.3
Scenario A	−0%	−20%	−6%	3%	−15.3
Scenario B	3%	−18%	3%	11%	−13.9
2051-2080					
Baseline (2000)	6%	−26%	−4%	−11%	−21.4
Current Conditions	7%	−25%	−3%	−11%	−20.8
Scenario A	14%	−22%	−1%	−10%	−22.5
Scenario B	18%	−20%	10%	−4%	−20.4

All indicators reflect percentage change in hydrologic indicators relative to Baseline (2000) except Peak Flow Timing which is the absolute change in days.

CLIMATE EFFECTS

Under the future climate change scenario, warming air temperatures in the watershed are projected to lead to a reduction in the winter snowpack, both due to more precipitation falling as rain as well as earlier and more rapid snowmelt in the spring. The effects of climate change on the hydrological metrics observed for the 2021-2050 period of the RCP 4.5 pathway are generally contrary to the effects of forest cover disturbance, particularly for baseline, current and low elevation Scenario A. Mean annual flow and summer low flows show substantial decreases in the first thirty-year period for all scenarios while the 2-year flood decreases for current and Scenario A forest conditions. The slight moderating effect of high elevation forest disturbance in Scenario B is due to the combined effects of the precipitation gradient (i.e. more precipitation at higher elevations) combined with decreased forest interception but this is also the cause of the substantial increase in the 100-year flood for Scenario B in this climate scenario. With a shift to predominantly winter rainfall, the longer-term climate impacts (2051-2018) equate to increases in mean annual flow, but summer low flows may decrease up to 26% given the trend to hotter, drier summers. Additionally, the annual maximum peak flow may occur, on average, over 20 days earlier for all landcover scenarios compared to current conditions.

LITTLE CAYUSE CREEK

LANDCOVER EFFECTS

Changes in Hydrological indicators observed in response to low (Scenario A) and high elevation forest disturbance (Scenario B) in Little Cayuse Creek are generally larger than those observed in Cayuse Creek (Table 7). Mean annual flows increase by 13% for low elevation (A) disturbance and 18% for high elevation (B) forest disturbance. Increases in summer low flows range from 9% (A) to 12% (B), increases in 2-year peak flows range from 7% (A) to 22% (B) and increases in 100-year floods range from 4% (A) to 14% (B), These changes are almost twice the magnitude for a given hydrological metric compared to Cayuse Creek. Little Cayuse Creek peak flow timing advanced on average by 2.5 days for high elevation (B) forest disturbance scenario.

Table 7. Little Cayuse Creek model outputs

Hydrologic Change Consequence Table
Little Cayuse Creek Near Deer Park

Land Cover Scenario	Mean Annual Flow	Summer Low Flow	2-year Peak Flow	100-year Peak Flow	Peak Flow Timing
1990-2019					
Current Conditions	–0%	–0%	1%	1%	0.0
Scenario A	13%	9%	7%	4%	–0.9
Scenario B	18%	12%	22%	14%	–2.5
2021-2050					
Baseline (2000)	–7%	–25%	–13%	15%	–14.9
Current Conditions	–7%	–25%	–13%	15%	–14.9
Scenario A	5%	–18%	–7%	17%	–17.0
Scenario B	10%	–14%	5%	26%	–18.0
2051-2080					
Baseline (2000)	9%	–25%	–3%	2%	–16.2
Current Conditions	9%	–26%	–2%	3%	–16.3
Scenario A	22%	–19%	3%	4%	–19.2
Scenario B	27%	–16%	13%	11%	–19.2

All indicators reflect percentage change in hydrologic indicators relative to Baseline (2000) except Peak Flow Timing which is the absolute change in days.

CLIMATE EFFECTS

Like Cayuse Creek, climate change effects are likely to be substantially larger and generally contrary to landcover effects, particularly for mean annual flow, summer low flows and 2-year peak flow. Cumulatively, forest cover disturbance and climate change appear to be more mitigative for water yield metrics in Little Cayuse Creek except for extreme floods (100-year flood) which show an increase of 26% with high elevation forest disturbance combined with climate change.

MEAN DAILY STREAMFLOW

Visualization of the changes to the mean daily streamflow in Cayuse Creek and Little Cayuse creeks given landcover disturbance and climate change is provided in Figure 20. In all scenarios, baseline conditions are associated with the highest average daily streamflows during the peak flow period decreases in average summer flows (Table 7) across all watersheds are alarming and highlights the potential for substantially decreased water supplies in all three watersheds during the months with greatest demands. In Cayuse Creek the mean flows during the freshet are seen to decrease while the peak period widens and shifts to the right. The climate effect becomes more pronounced in the post-2050 time period and, as well, winter low flows increase in magnitude. The climate effects in Little Cayuse appear to have the opposite effect with the peak period becoming narrower.

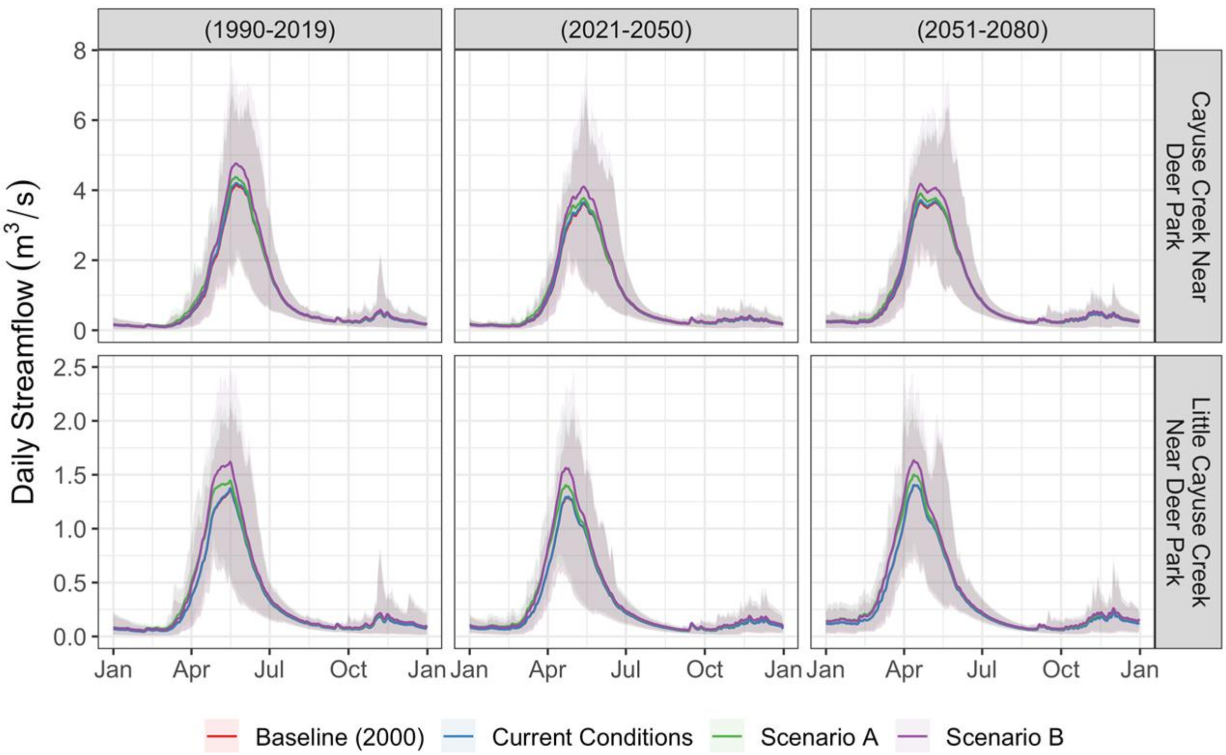

Figure 20. Mean daily streamflow in Cayuse and Little Cayuse creeks for current and future climate projections.

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FORTY-NINE CREEK

The scenarios for Forty-nine Creek are intended to investigate hydrological response of additional harvest in a watershed where existing levels of forest disturbance are approaching Provincial harvest thresholds of 25% as determined through an ECA calculation. Scenario A involves the harvest of four low elevation blocks representing 2% of the watershed area while Scenario B includes the harvest of four high elevation blocks representing 3.1 % of the watershed area (Figure 21).

LANDCOVER EFFECTS

The application of the hydrological model to the scenarios in Forty-nine Creek indicate that neither the low elevation nor the high elevation harvest scenarios substantially alters current hydrological response in Forty-nine Creek (Table 8). Small increases in mean annual flow (i.e., annual water yield) are indicated by the model with Scenario B increasing the mean annual flow by 3% relative to baseline (Table 8). Slightly higher (1%) increases in the 2-year flood and the 100-year flood magnitude are also observed for Scenario B compared to baseline and Scenario A.

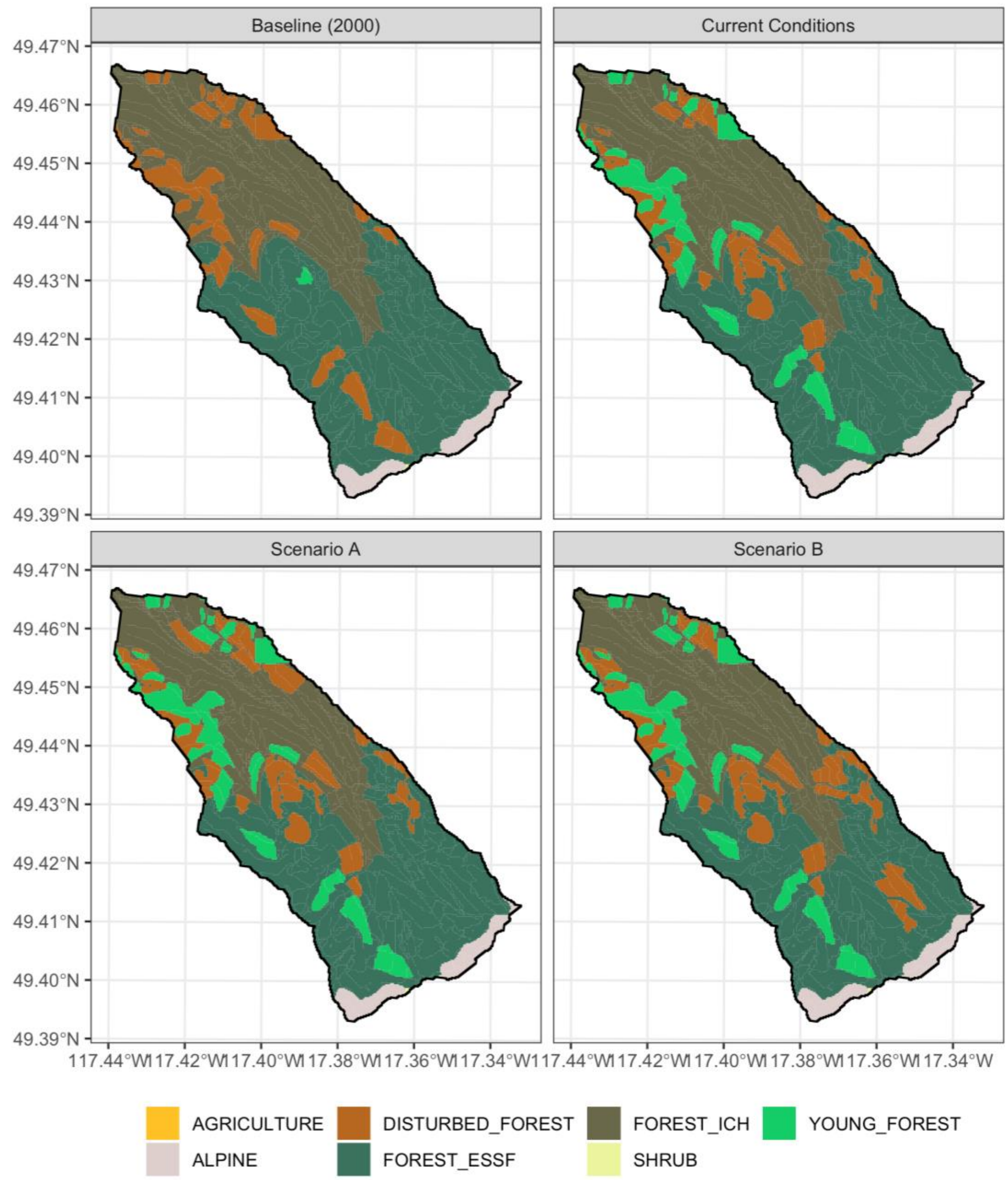

Figure 21. Forty-nine Creek land cover disturbance and additional harvest scenarios.

CLIMATE EFFECTS

The trends given projected climate change are more substantial and indicate decreases in mean annual flow and major decreases in summer low flows, average annual peak flows (2-year return period) and shifts to earlier peak flows (Table 8).

Notably, there is very little change in the magnitude of the 100-year flood (i.e., extreme floods) with climate change in the 2021 – 2050 period which may reflect that, currently, these events are primarily spring rainstorms coinciding with peak snowmelt generated floods and this will continue to be the dominant mechanism in the next few decades. As with Cayuse Creek, the higher elevation harvest scenario (B) results in slightly higher changes in the hydrological metrics, since upper elevations receive more precipitation, and therefore more precipitation reaches the forest floor in disturbed (open) areas.

Table 8. Forty-nine Creek Model outputs.

Hydrologic Change Consequence Table
Forty-Nine Creek Near Blewett

Land Cover Scenario	Mean Annual Flow	Summer Low Flow	2-year Peak Flow	100-year Peak Flow	Peak Flow Timing
1990-2019					
Current Conditions	1%	1%	1%	1%	−0.4
Scenario A	2%	1%	1%	1%	−0.4
Scenario B	3%	1%	2%	2%	−0.8
2021-2050					
Baseline (2000)	−10%	−27%	−14%	−0%	−13.6
Current Conditions	−8%	−26%	−13%	1%	−14.4
Scenario A	−8%	−26%	−13%	1%	−14.4
Scenario B	−7%	−25%	−12%	2%	−14.5
2051-2080					
Baseline (2000)	4%	−31%	−10%	−9%	−23.1
Current Conditions	5%	−30%	−9%	−8%	−23.5
Scenario A	5%	−30%	−9%	−8%	−23.5
Scenario B	6%	−29%	−8%	−7%	−23.6

All indicators reflect percentage change in hydrologic indicators relative to Baseline (2000) except Peak Flow Timing which is the absolute change in days.

MEAN DAILY STREAMFLOW

Plots of the mean daily streamflow for the scenarios compared to baseline for current and future climate conditions shows an negligible change in daily streamflow between harvest scenarios but a subtantial decrease in peak streamflow between current climate and projected climate conditions (Figure 22). The broadening of the hydrograph and progressive leftward shift for the two climate projections is due to the increased occurrence of winter rain and rain-on-snow triggered peak flows. Increases in October through March low flows are also evident with climate change compared to the 1990-2019 climate conditions.

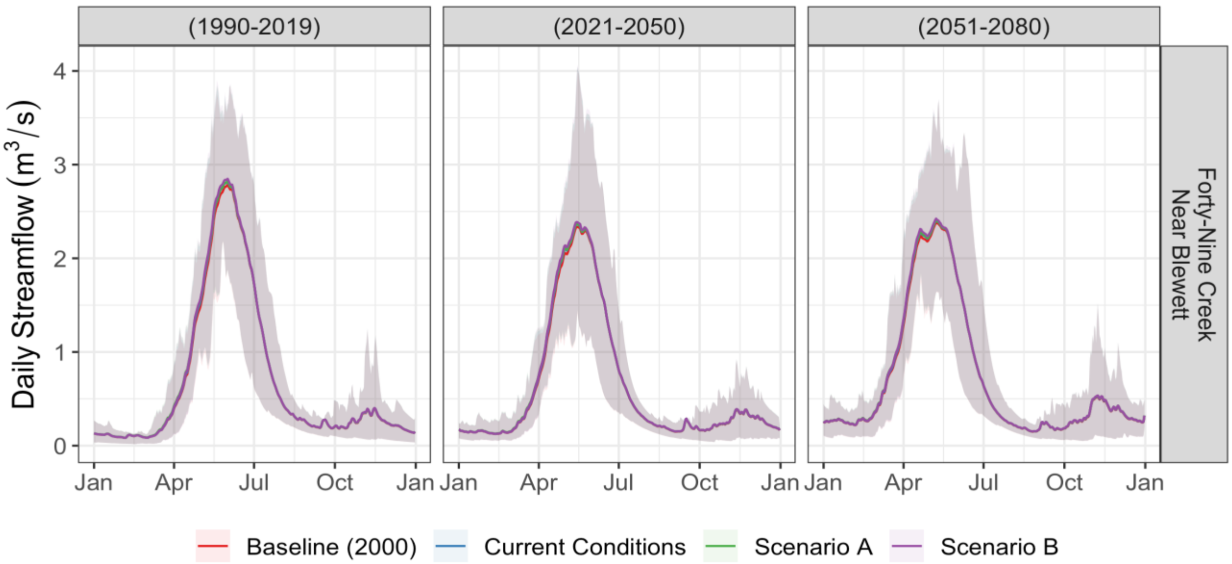

Figure 22. Mean annual hydrographs for baseline, current conditions, and forest cover disturbance scenarios for three time periods including current and projected RCP4.5.

DUHAMEL CREEK

The scenarios developed for Duhamel Creek are designed to investigate the hydrological impacts of low versus high level forest development scenarios in a watershed that has experienced a range of past forest disturbances including a recent large wildfire (Figure 23).

Scenario A is a conservative forest disturbance scenario of 1.8% of the watershed area distributed across lower elevation slopes while Scenario B is a higher level of disturbance at 5.2% of the watershed area concentrated mostly at mid elevations on the west side of Duhamel Creek.

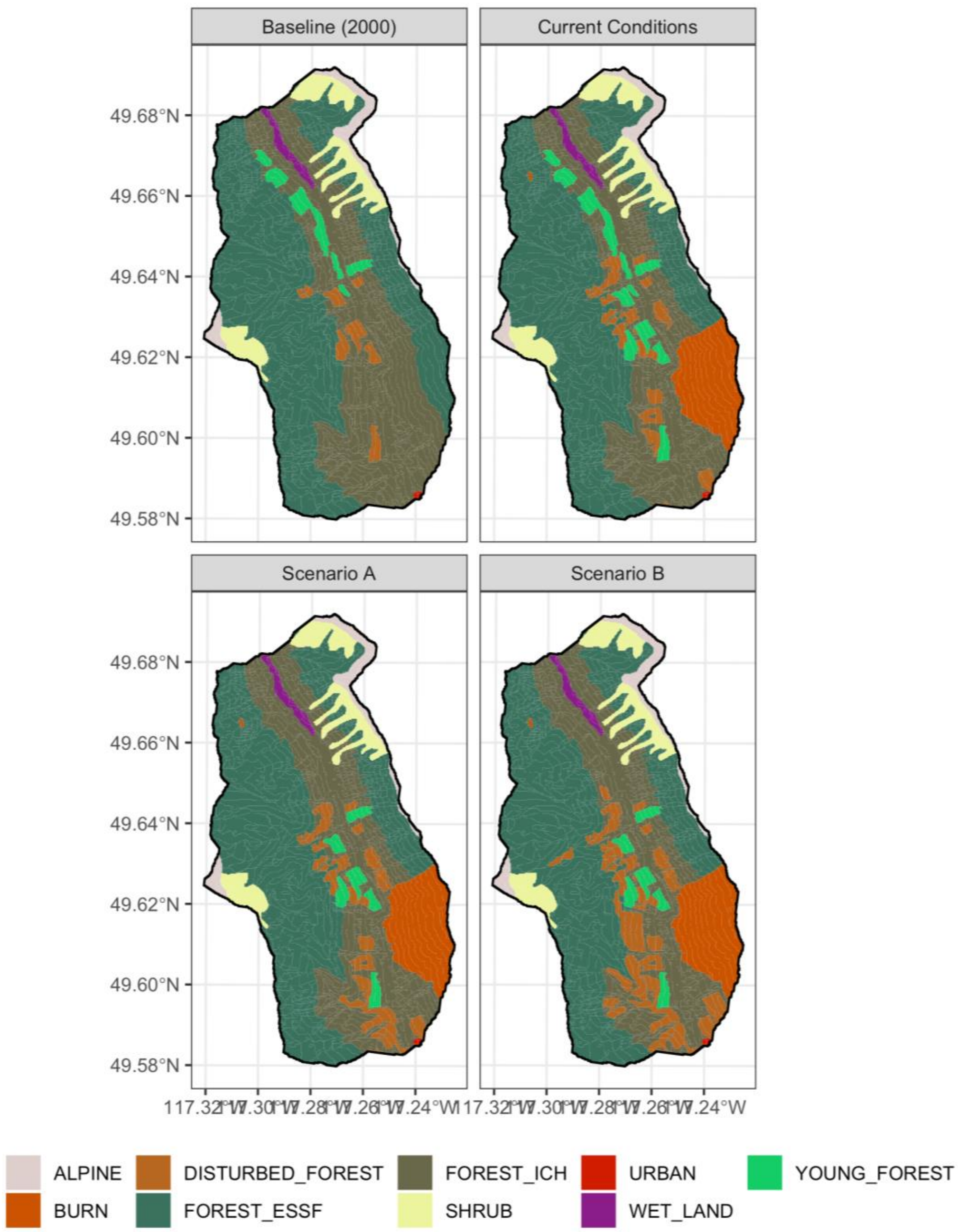

Figure 23. Duhamel Creek Historical, Current landcover and model scenarios.

LANDCOVER EFFECTS

The application of the hydrological model to the scenarios in Duhamel Creek indicates for 'Current' and Scenario A there is a 4% increase in mean annual flow relative to the year 2000 baseline condition which is likely primarily due to the 2015 fire disturbance. Scenario A results in no change in hydrological indicators relative to 'Current' conditions while Scenario B results in a small (1%) increase in all of the hydrological indicators relative to both the baseline and Current conditions (Table 9). The timing of peak flows indicates that for current and Scenario B landcover conditions peak flow is advanced on average by just over a day but for Scenario B there is no change relative to year 2000 baseline. The disparity in the effect of landcover disturbance on timing of peak flows reflects the advancing melt of high elevation openings which do not factor into Scenario A.

Table 9. Model outputs for Duhamel Creek

Hydrologic Change Consequence Table
Duhamel Creek Above Diversions

Land Cover Scenario	Mean Annual Flow	Summer Low Flow	2-year Peak Flow	100-year Peak Flow	Peak Flow Timing
1990-2019					
Current Conditions	4%	1%	1%	1%	–1.1
Scenario A	4%	1%	1%	1%	0.0
Scenario B	5%	2%	2%	2%	–1.1
2021-2050					
Baseline (2000)	–7%	–24%	–13%	15%	–16.0
Current Conditions	–3%	–22%	–12%	15%	–16.5
Scenario A	–3%	–22%	–12%	16%	–16.5
Scenario B	–2%	–22%	–11%	16%	–17.4
2051-2080					
Baseline (2000)	9%	–23%	–4%	8%	–25.7
Current Conditions	12%	–22%	–2%	8%	–26.2
Scenario A	12%	–22%	–2%	8%	–26.2
Scenario B	14%	–21%	–2%	8%	–26.2

All indicators reflect percentage change in hydrologic indicators relative to Baseline (2000) except Peak Flow Timing which is the absolute change in days.

CLIMATE EFFECTS

The changes in hydrological metrics given projected climate change are much more substantial in Duhamel Creek compared to landcover effects and, as with both Cayuse Creek and Forty-nine Creek, indicate that relative to 2000 baseline conditions, the Current and both disturbance Scenarios A and B result in a relatively smaller decreases in mean annual flows given shorter term climate projections but increases in mean annual flow of between 9% (baseline) and 14% (Scenario B) given the longer-term RCP 4.5 projections (2051 – 2080). Summer low flows display large decreases of up to 24% for all forest conditions considered with the RCP 4.5 projections. The 2-year (average annual) peak flow decreases in magnitude between 11% and 13% in the 2021 to 2050 period with the smallest decrease associated with the more extensive harvest scenario reflecting the mitigating effects of increased precipitation inputs at the higher elevation with forest removal. The mitigating effects of high elevation harvesting are not extended to extreme floods (100-year flood) which display the largest increases for high elevation harvest in Scenario B. As with Forty-nine Creek, the increase in extreme flood magnitude reflects an increase in the frequency of precipitation during the spring freshet, particularly for the 2021-2050 period. The decreased snowpack projected in the longer-term (2051 to 2080) has a dampening influence on extreme flood response for that time period.

For both the short and long-term time periods, the RCP 4.5 projections result in an advance of up to 26 days in the timing of the annual peak flows.

Mean daily streamflow

The simulated hydrographs for Duhamel Creek show the minimal difference in mean daily streamflow for the landcover scenarios but, similar to Cayuse Creek, show a decrease in magnitude and a broadening of the hydrograph as well as a prominent shift to the left for both climate periods. In addition, the elevation of daily streamflow during the winter period associated with increased runoff is clear for the 2051 – 2080 period (Figure 24).

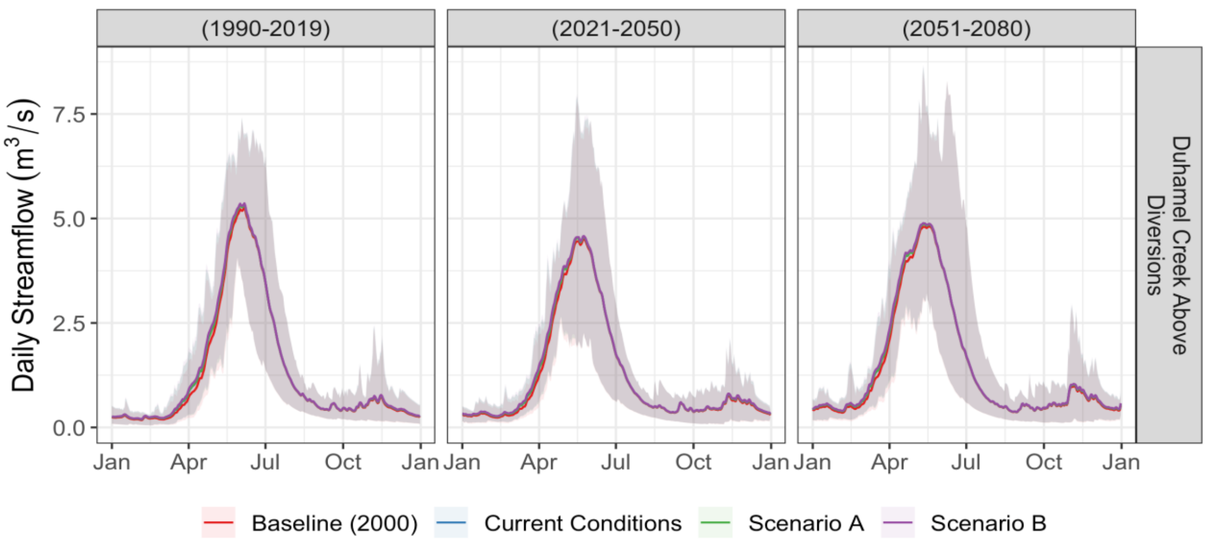

Figure 24. Mean daily streamflow in Duhamel Creek for current and future climate projections.

COFFEE CREEK/BALFOUR FACE

The scenarios developed for Coffee Creek/Balfour face are designed to investigate the hydrological impacts of forest development in small versus large watersheds. At 9521 hectares, Coffee Creek is the largest watershed in the study area, while the watersheds of Balfour Face at 11 hectares (Trib 3) to 23 hectares (Trib 1) are the smallest watersheds. Only Balfour tributaries 1 and 3 (See Figure 25) are affected by the forest development with removal of 31% of Trib 1 and 29% of Trib 3 included in the scenario. In Coffee Creek the harvest scenario represents forest disturbance of 2.9% of the watershed area.

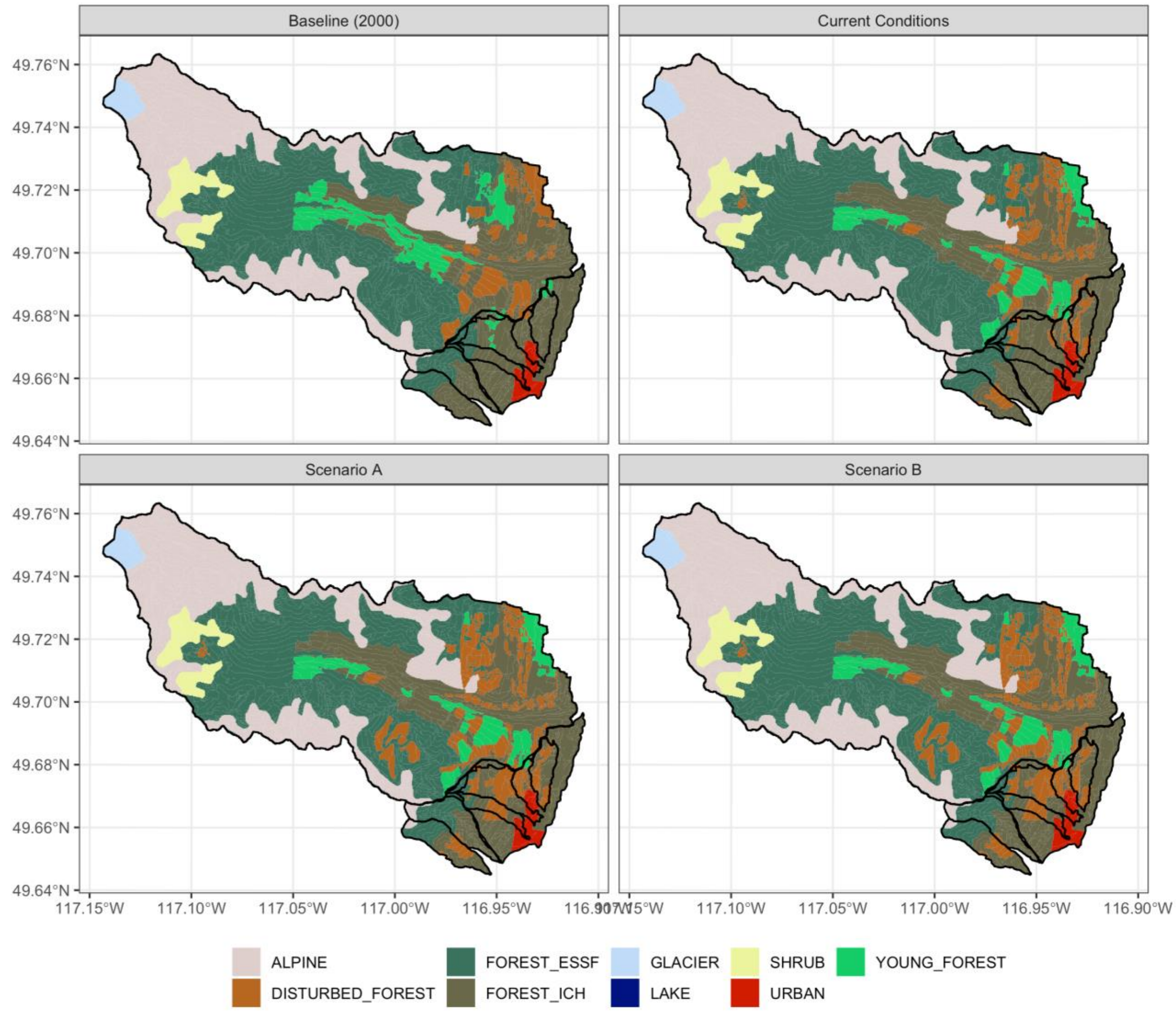

Figure 25. Coffee Creek and Balfour Face landcover scenarios

LANDCOVER EFFECTS

The forest removal of 2.9% concentrated on upper elevation, north aspect slopes of Coffee Creek has no substantial effect on any of the hydrological metrics considered in this study (Table 10). However, landcover effects are very substantial in both Trib1 and Trib 3 (Table 11 and 12). Harvesting of 31% of Trib 1 results in an increase for all runoff metrics and advancement of peak flows by over 10 days relative to year 2000 baseline conditions. Mean annual flow and the 2-year peak flow show the greatest increases of 24% and 22% respectively. Summer low flows and extreme floods (100-year flood) are both elevated by 16% relative to year 2020 baseline. In Trib 3 the scenario of 29% harvest is situated at the mid-elevations and results a 20% elevation of mean annual flow and a 12% increase in summer low flow. In this small tributary the 2-year peak flow is elevated by 8% while the 100-year event is only elevated by 5%. Peak flow timing in Trib 3 is advanced by 3 days on average given the landcover scenario.

Table 10. Coffee Creek landcover and climate change model outputs.

Hydrologic Change Consequence Table

Coffee Creek Near Ainsworth

Land Cover Scenario	Mean Annual Flow	Summer Low Flow	2-year Peak Flow	100-year Peak Flow	Peak Flow Timing
1990-2019					
Current Conditions	–0%	–0%	0%	0%	0.0
Scenario A	1%	0%	1%	1%	0.0
Scenario B	1%	0%	1%	1%	0.0
2021-2050					
Baseline (2000)	–1%	–8%	–6%	15%	–14.9
Current Conditions	–1%	–8%	–6%	16%	–14.9
Scenario A	–1%	–7%	–6%	16%	–14.9
Scenario B	–1%	–7%	–6%	16%	–14.9
2051-2080					
Baseline (2000)	10%	–11%	–1%	15%	–20.2
Current Conditions	10%	–11%	–1%	15%	–20.2
Scenario A	10%	–11%	–1%	15%	–21.9
Scenario B	10%	–11%	–1%	15%	–21.9

All indicators reflect percentage change in hydrologic indicators relative to Baseline (2000) except Peak Flow Timing which is the absolute change in days.

Table 11. Balfour Face Trib 1 landcover and climate change model outputs

Hydrologic Change Consequence Table

Coffee South Face Trib 1

Land Cover Scenario	Mean Annual Flow	Summer Low Flow	2-year Peak Flow	100-year Peak Flow	Peak Flow Timing
1990-2019					
Current Conditions	5%	3%	6%	1%	–0.7
Scenario A	24%	16%	22%	16%	–10.7
Scenario B	24%	16%	22%	16%	–10.7
2021-2050					
Baseline (2000)	–4%	–9%	–10%	24%	–10.5
Current Conditions	1%	–5%	–4%	25%	–17.3
Scenario A	18%	9%	5%	31%	–20.3
Scenario B	18%	9%	5%	31%	–20.3
2051-2080					
Baseline (2000)	12%	–17%	0%	13%	–4.0
Current Conditions	16%	–13%	6%	15%	–3.2
Scenario A	34%	–1%	16%	18%	–19.0
Scenario B	34%	–1%	16%	18%	–19.0

All indicators reflect percentage change in hydrologic indicators relative to Baseline (2000) except Peak Flow Timing which is the absolute change in days.

Table 12. Balfour Face Trib 3 landcover and climate change model outputs

Hydrologic Change Consequence Table
Coffee South Face Trib 3

Land Cover Scenario	Mean Annual Flow	Summer Low Flow	2-year Peak Flow	100-year Peak Flow	Peak Flow Timing
1990-2019					
Current Conditions	2%	1%	3%	1%	0.1
Scenario A	20%	12%	8%	5%	–3.0
Scenario B	20%	12%	8%	5%	–3.0
2021-2050					
Baseline (2000)	–4%	–8%	–10%	24%	–13.3
Current Conditions	–3%	–6%	–7%	25%	–13.3
Scenario A	14%	6%	–3%	25%	–20.8
Scenario B	14%	6%	–3%	25%	–20.8
2051-2080					
Baseline (2000)	11%	–16%	–2%	15%	–14.8
Current Conditions	12%	–14%	1%	16%	–14.8
Scenario A	29%	–4%	6%	15%	–18.0
Scenario B	29%	–4%	6%	15%	–18.0

All indicators reflect percentage change in hydrologic indicators relative to Baseline (2000) except Peak Flow Timing which is the absolute change in days.

CLIMATE CHANGE EFFECTS

Coffee Creek displays the smallest changes in hydrological metrics associated with climate change projections of the four study areas as well as some contrasting responses. 2021 to 2050 RCP 4.5 projections result in decreases in mean annual flows (1%), summer low flows (7%-8%) and the 2-year peak flow (6%) but an increase in the 100-year flood of 16%. Additionally, peak flows are advanced by just under 15 days. The longer-term (2051 – 2080) projections result in an increase in mean annual flows (10%) and a decrease in summer low flows (11%) and 2-year peak flows (1%). Extreme 100-year floods remain elevated (15%) and peak flow timing shows greater advancement to 21.9 days earlier compared to year 2000 baseline. The climate change related decrease in summer low flows and 2-year peak flows in Coffee Creek is almost assuredly under-estimated since the hydrological model does not account for future retreat of Kokanee Glacier in the Coffee Creek headwaters. Glacier melt is an important contributor of late summer streamflow in Coffee Creek and with increasing air temperatures, increased melt is expected in the coming decades. However, glacial resources are non-renewable, and increased melt rates will likely lead to further reduction in the size of the glacier, limiting further glacial contributions to streamflow, particularly during the late summer. The elevated magnitude of the extreme floods (100-year floods) reflects a shift to rain-on-snow dominated flooding in the high elevation regions.

Balfour Face tributaries show the greatest response to climate change of all of the study watersheds. The largest climate responses are seen in the extreme 100-year floods which increase by 25% for current conditions and up to 31% for the harvest scenario in Trib 1. Given current and baseline conditions, summer low flows and 2-year peak flows are projected to decrease in both watersheds but the harvest scenario reverses the response and results in small increases which relates to the increased soil water infiltration following decreased canopy interception in the openings. The timing of peak flows is advanced by just over 20 days on average for both tributaries in the 2021-2050 scenario and up to 19 days in the 2051-2080 scenario.

MEAN DAILY STREAMFLOW

The mean daily streamflow hydrographs for Coffee Creek show no obvious difference between current, baseline and landcover scenarios but, consistent with other watersheds in this study, show a decrease in magnitude and a broadening of the hydrograph as well as a shift to the left for both near- and long-term climate periods (Figure 26). The elevation of daily streamflow during the winter months associated with increased winter precipitation is not as prominent in Coffee Creek as in other watersheds in this study.

Much larger changes are evident in the mean daily streamflow due to landcover change in Trib 1 and Trib 3 on Balfour Face (referred to in figures as Coffee Face) compared to Coffee Creek. In addition, the climate related elevation in winter flows is more prominent, particularly for the post-2050 period. As with other watersheds the hydrographs flatten slightly and shift to the left with the trend to more late winter to spring rainfall; however, these low elevation watersheds currently experience more rainfall runoff events than other watersheds in the study so the relative change in the mean daily streamflow with climate change is not as obvious.

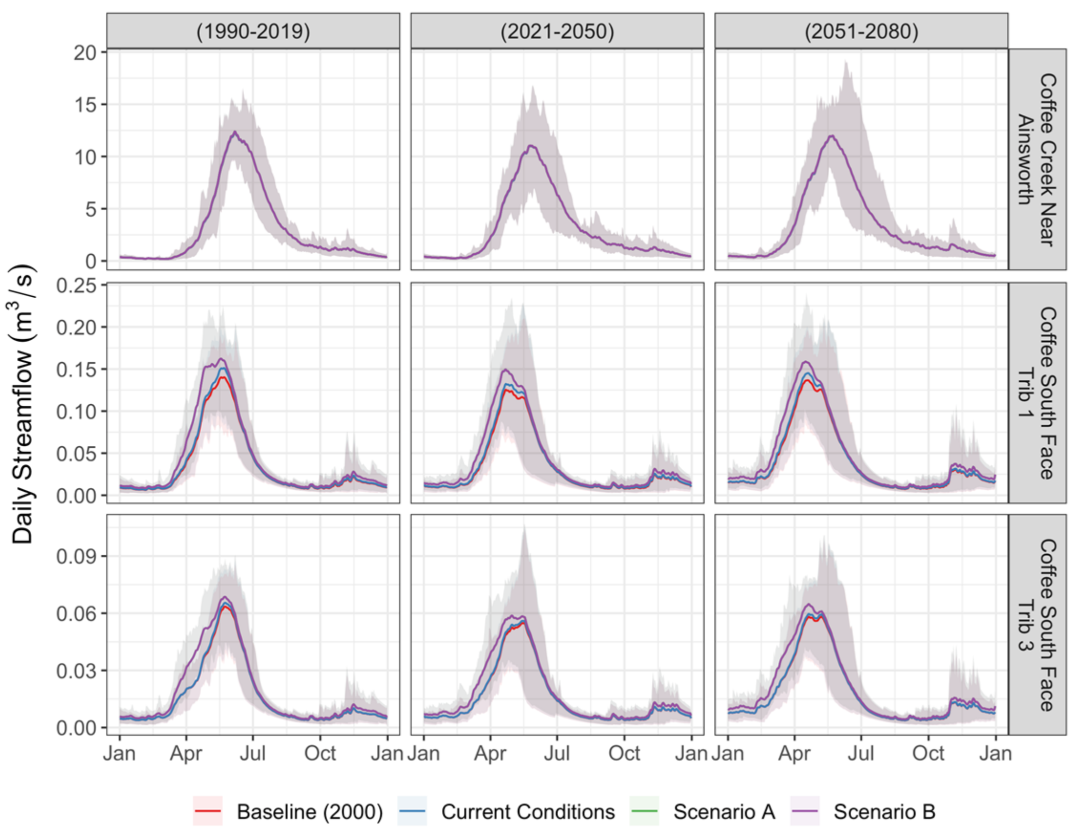

Figure 26. Mean daily streamflow in Coffee Creek and Balfour Face (aka Coffee face) Trib 1 and Trib 3 for current and future climate projections.

Discussion of Outcomes of Scenario Analysis

LANDCOVER CHANGE

Landcover and climate scenario analysis are undertaken using a modified version of the HBV-EC model, emulated within the Raven Hydrological Modeling Framework, for seven watersheds of the Southern Selkirk region that range in size, elevation, aspect distribution, and current landcover. When considered individually the model provides a watershed-specific process understanding of the linkage between forest cover and processes of precipitation input and runoff. Collectively, the modeling outcomes provide general insights regarding the influence of watershed physical characteristics on watershed response potential.

In Cayuse and Little Cayuse Creeks, the 25% low elevation and high elevation disturbance scenarios relative to the Year-2000 baseline produces similar increasing trends but almost twice the response in Little Cayuse Creek than in Cayuse Creek for all of the hydrological metrics investigated. The greater sensitivity to harvest levels in Little Cayuse likely attributes to the smaller watershed size and/or predominantly western slope aspect distribution which are the two main physical differences between the watersheds.

The more conservative forest disturbance scenarios of between 2% and 6%, investigated in Forty-nine, Duhamel and Coffee creeks result in small changes in the hydrological metrics, however, in both Forty-nine and Duhamel Creeks the higher elevation disturbance scenarios create slightly larger hydrological responses. These outcomes suggests that small increases in forest disturbance, when balanced across elevations and aspects can reduce the potential for hydrological impacts, however, high elevation harvest has a much greater impact on hydrological response in a watershed than low elevation harvest.

The mitigating influence of watershed size is apparent when Forty-nine Creek and Coffee Creek are subject to similar levels of forest disturbance (~3%). In Forty-nine Creek the disturbance results in roughly twice the response compared to Coffee Creek which is over three times the size of Forty-nine Creek.

The largest changes to water yield metrics (mean annual flow and summer low flows) are observed in the smallest watersheds in the study. Harvesting 31% and 29% respectively of Tribs 1 and 3 on Balfour Face results in the largest increases in mean annual flows (24% and 20%) and summer low flows (16% and 12%). However, the magnitude of the increase to both the 2-year and 100-year return period flows are similar in Balfour Face Trib 1 and Little Cayuse Creek. These annual flood metrics are more sensitive to high elevation snowmelt runoff which is lacking in the Balfour Face tributaries.

The outcomes with respect to the magnitude and direction of alteration of hydrological processes predicted by the model are generally consistent with those identified in published scientific studies that investigating the influence of forest removal on the magnitude of floods of a give frequency, annual water yield and timing of peak flows (Winkler et al., 2009, Moore and Scott, 2005, Green and Alila, 2012). In addition, the influence of watershed physical characteristics of elevation and aspect distribution and watershed size in mitigating or amplifying hydrological response observed here are consistent with the conceptual understanding of these factors presented in Green and Alila (2012). The consistent increases observed in summer low flows following harvest, due to increased soil infiltration and slower delivery to the stream channel, contradicts empirical observations presented in a recent study in BC that show decreases in summer low flows (Scherer and Pike, 2003)

CLIMATE CHANGE

In all watersheds, climate projections for the RCP 4.5 pathway have more substantial impacts on hydrological metrics of flow volume and timing of peak flows compared to landcover impacts but, depending on the watershed, forest disturbance can either exacerbate or mitigate these impacts. We also observe that climate change effects differ between watersheds for the near-term (2021-2050) and long-term (2051-2080) climate projections (Table 11).

climate change effects:

- Mean Annual Flow: For all watersheds, mean annual flow initially decreases (2021-2050), and then increases for (2051 – 2080). Harvest scenarios mitigate decreases and amplify increases.
- Mean Aug-September Summer Low Flow: decrease for all watersheds but for Forty-nine Creek, Coffee Creek and Balfour Face the 2051-2080 period shows larger magnitude decreases. Harvest scenarios mitigate decreases except in Coffee Creek. In Coffee Creek, future glacier retreat is likely to exacerbate this late summer flow reduction but is not accounted for in the hydrological model.
- 2- Year Peak flow: Decrease under all scenarios but these decreases are less in the 2051 – 2080 period except for Balfour Face where 2-year peak flow initially decrease and then increase in the later time period.
- 100-Year Peak flow: This metric displays the greatest variability with projected climate change. Little Cayuse, Duhamel and Balfour Face show large increases in the near-term and smaller increases over the long term. Cayuse Creek and Forty-nine Creek shows increases and then decreases in this metric over time. Coffee Creek shows increases of similar magnitude over time.
- Timing of Peak flow: significantly earlier under all scenarios, more pronounced for the later time period in Cayuse Creek, Forty-nine Creek, Duhamel Creek and Coffee Creek.

Table 13. Trends in hydrological metrics with climate change for two periods 2021-2050 (first column) and 2051-2080 (second column). Heavier arrows indicate at least 4% percent greater difference in the magnitude of the change for a given metric between the two time periods.

Hydrological Metric	Cayuse Creek		Little Cayuse Cr		Forty-nine Cr		Duhamel Cr		Coffee Cr		Balfour Face	
Mean Annual flow	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑	↓	↑
Summer Low Flow	↓	↓	↓	↓	↓	⬇	↓	↓	↓	⬇	↓	⬇
2-Year peak flow	⬇	↓	⬇	↓	⬇	↓	⬇	↓	⬇	↓	↓	↑
100-year flood	↑	↓	⬆	↑	↑	↓	⬆	↑	↑	↑	⬆	↑
Day of Peak	↓	⬇	↓	↓	↓	⬇	↓	⬇	↓	⬇	⬇	↓

Currently, there are few studies undertaken in forested snowmelt regions to investigate the potential cumulative effects of climate change and landcover disturbance on watershed response (Giles-Hansen et al., 2019, Chernos et al. 2021). The projected changes to hydrological metrics observed in this study are generally consistent with the one existing study outcomes as well as other model and empirical-based studies that have investigated changes in runoff alone (Milly and Dunne, 2020). Differences in the response of hydrological metrics to climate change in the different watersheds likely relate to watershed elevation and how it factors into the transition from snowmelt to rainfall driven runoff. For example, in watersheds such as Cayuse Creek and Forty-nine Creek, that are likely to lose much of their snowpack, extreme floods (100-year flood) initially show an increase and then a decrease in magnitude relative to current conditions as the process generating extreme floods transitions from snowmelt to rainfall dominated.

Limitations

As with all models there is room for improvement and evolution. Model calibration indicates that processes of snow accumulation and melt are well represented as is timing of peak runoff during the main freshet period of the hydrograph across the Southern Selkirk region. Low flows, particularly during the winter months, are not as well represented in the model and the magnitude of peak flows is generally underestimated. While hydrological response given landcover disturbance for metrics relating to annual water yield, the 2-year peak flow, the 100-year flood are consistent with published studies (Winkler et al., 2015, Green and Alila, 2012, Schnorbus and Alila, 2004; Schnorbus and Alila 2013), the simulated response of summer low flows is more uncertain. Studies in watersheds based in the Thompson – Okanagan region have found that in smaller watersheds, summer low flows decrease following harvest (Winkler et al, 2015) but this outcome is not consistent across studies (Winkler et al, 2010) and in some cases, is found to increase while in other studies is observed to decrease following harvest. Watershed physical characteristics including watershed size, slope-aspect, and soil depth, climatic characteristics, such as precipitation and evaporation patterns, and the state of regenerating forests are likely important factors affecting the low flow response to landcover change. Further work is required, both in modeling and in empirical studies, to better understand the importance and interaction of these factors in driving streamflow during the late summer months, which could ultimately lead to better process-representation and model parameterization.

In addition, improvements could be made to better model watershed response to extreme rainfall events which are currently under-represented in this version of the model. This includes two major factors: process-representation and data inputs. Notably, the hydrological model does not explicitly account for the complicated dynamics of changing runoff and infiltration during rain-on-snow events. When rainfall occurs with snow on the ground, for simplicity, the model assumes these two processes happen in parallel; however, these two processes have additive effects, such as increases in snowmelt and reduced infiltration rates, both of which can lead to higher streamflow. In addition, extreme precipitation events are notoriously difficult to capture in weather station data, due to the relatively coarse network of available observations, concentrated spatial patterns, and due to higher sensor failure during extreme events (i.e. McMillan et al., 2011). These factors tend to lead to underestimated model forcing data, which combined with model process-weaknesses during these extreme events, tend to lead to model under-estimates of extreme high flows. Future work in improved model forcing data as well as better process-representation of these key extreme event periods is needed to reduce uncertainty and better constrain risk, particularly considering how these factors may change in response to climate change.

Finally, the process of hydrological recovery of a forest stand following harvest or disturbance (i.e. burn) is coarsely represented as three age classes: Disturbed, Young Forest, and Mature Forest. Further improvements could be made in terms of representing forest interception and shading in several stages of a juvenile forest (i.e., early, young, and advanced juvenile). In addition, this level of model parameterization does not explicitly consider disturbance severity, particularly for fire disturbance, nor does it account for variable rates of recovery between BEC zones/elevation bands, or due to the level of forest disturbance, such as in cases of severe forest fires removing most organic material. Improving this representation in the hydrological model is possible, but requires additional data, both in terms of historical disturbance severity and recovery, and in terms of model parameterizations, particularly in a finer level of resolution in understanding the changes in stand-level interception, snow accumulation, and melt in the years following disturbance.

The southern Selkirk hydrological model has been calibrated for watersheds ranging in size from 50 km^2 to 90 km^2. Application of this model to small watersheds less than about 5km^2 such as the watersheds on Balfour Face have much greater uncertainty associated with hydrological response predictions due to the greater influence of local forest cover, geology and soils related heterogeneities. Improved confidence in model outputs for small watersheds would require streamflow and field-based observations to verify model performance.

Conclusions

The development and application of a process-based hydrological model of watersheds of the southern Selkirks provides a more rigorous approach to estimate the potential for watershed hydrological response to forest harvesting compared to traditional methods of Equivalent Clear Cut area calculations. In addition, it provides a novel approach for investigating cumulative effects of a changing climate and forest disturbance on short and long-term watershed flow. The model has been successfully applied to watersheds of varying hydroclimatic characteristics and sizes across the study region and could be applied to other watersheds of varying size within the region.

Outcomes of the hydrological model for flow volume, flood magnitude and timing of peak flows are generally consistent with empirically based studies as well as other model-based studies. The strength of this tool to support forest management decisions in watershed lies in the ability of the model to replicate physical watershed processes and in doing so, provide estimates of the likelihood for hydrological change related to a solid process understanding of watershed function. Further work could include a refining model parameterization to incorporate more stages of forest regrowth, better process-representation and data inputs during peak flow periods, and further empirical and conceptual (modeling) work to better understand the key factors determining of late-summer streamflow.

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