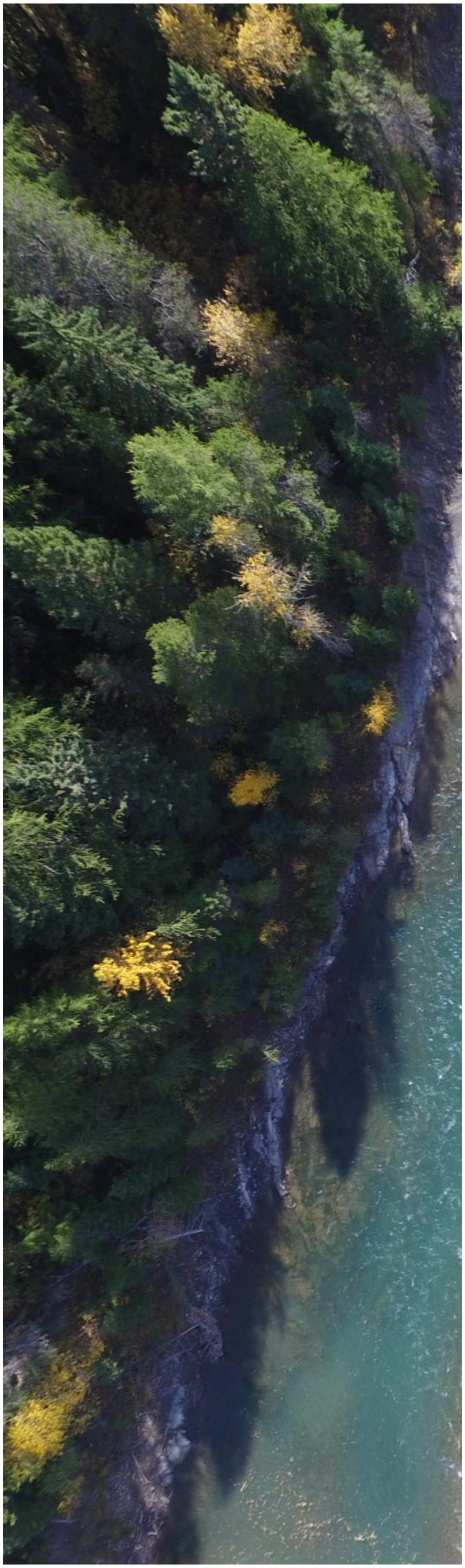

# Hydrologic Assessment of the Upper Columbia River Watershed

**Prepared For**

Columbia Wetlands Stewardship Partners

**Prepared By**

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# Summary of Findings

- This study provides an assessment of the available hydro-climatic data and a first order estimate of current and future conditions in the upper Columbia River Basin and its tributaries and wetlands.
- Nine sites in the study region have long-term climate records; all are located in valley-bottom locations. The highest station (Yoho Park) is located at just over 1,600 m, while elevations in the upper Columbia River watershed extend up to over 3,500 m.
- Seven active Water Survey of Canada (WSC) hydrometric stations exist in the study region, including six in the upper Columbia River watershed, and one in the upper Kootenay River watershed. Only one of these stations (Spillimacheen River) measures streamflow on the west side of the study area and no small tributaries in the Rocky Mountain Trench are currently monitored. This study identified hundreds of sub-basins within the study area, and an approximate estimate is that 1-2% of the streams are monitored.
- Collected water levels in wetlands along the Columbia River Valley from summer 2009 and 2010 are presented and correlated with regional WSC hydrometric data. Water levels in naturally Drained wetlands (those with surface water connections to the Columbia River floodplain) followed a seasonal pattern of increasing late spring/early summer, concurrent with snow melt, and were highly correlated to streamflow on the Columbia River. Conversely, naturally Isolated wetlands (those without surface water connections to the Columbia River floodplain) were not correlated with streamflow at any WSC stations in the region.
- Clustering was applied in order to identify sub-basin 'hydrological types' and how these types affect water levels in wetlands within the Columbia River valley. Cluster analysis using morphometric, climate, and land cover variables was applied to all WSC sub-basins, and a comprehensive collection of all sub-basins in the region with a drainage area greater than 5 $km^2$. In both cases, clustering identified two sub-basin types:
  - Cluster A; characterized by high elevations, cold air temperatures, high precipitation, and glaciers,
  - Cluster B; characterized by low elevations, less snowfall, and no glaciers. Further analysis was conducted to determine if Cluster B could be broken into additional sub-groups; however, it was determined that smaller-scale data are required to differentiate between sub-basin types.
- Long-term, active hydrometric records are currently only available for cluster A. While streamflow from cluster A sub-basins is likely the driving factor in Drained wetland water levels within the Rocky Mountain Trench, a lack of understanding of the hydrology of cluster B could be pertinent for a variety of other hydrological and ecological factors.
- Climate change projections for the region indicate increases in air temperature and precipitation, and a decrease in the snowfall fraction. This will likely affect streamflow in

both clusters, but cluster A will be particularly vulnerable since this will additionally accelerate glacier retreat.

- Further analysis is required to determine the vulnerability of wetlands in the study area. This analysis should include investigation into the source water for each wetland type as well as physically-based modelling.
- Future efforts to implement hydrometric gauging sites on small tributaries and collect relevant morphometric data would provide an understanding of the role of these tributaries in wetland function as well as how they can be differentiated from one another.
- Future efforts to complete physically based hydrological modelling of the study region could provide estimates of streamflow in un-gauged sub-basins and data poor regions and more fully describing the location and timing of major water inflows to the upper Columbia River watershed. Modelling efforts in the study region could additionally estimate of the impact of climate change and land use on water resources.

# 1 Background and Objectives

The purpose of this study is to provide information on the current and projected status of hydrologic conditions in the upper Columbia River watershed and Columbia Wetlands with the goal of informing priorities in the development of the Columbia Wetlands Strategic Plan. A 2019 report *Water Monitoring and Climate Change in the Upper Columbia Basin - Guidance Information for Planning Monitoring Programs* (Carver, 2019) outlined several objectives for further water and climate monitoring work. These objectives include identifying and addressing "gaps in monitoring locations by hydrologic region" while also focusing on elevation bands and other site characteristics including "region, period of record, and landscape, etc.". In addition, the report highlights the need to use available data to describe the condition and status of waterbodies within the region, with particular focus on smaller streams, lakes, and wetlands.

This report addresses several of the recommendations from this *Water Monitoring and Climate Change* report (Carver, 2019). The overall goal of this study is to provide an assessment of the hydrologic conditions of the upper Columbia River watershed. Specifically, we focus on the availability of long-term hydroclimatic records and how these records inform smaller-scale phenomena, including wetland function in the Rocky Mountain Trench. In order to provide this information, we have the following specific objectives:

1. Identify existing and past hydrometric and climate stations and provide a high-level overview of hydroclimatic conditions in regional sub-basins, specifically;
    a. Compile record length, timing, and the spatial extent of available data,
    b. Provide average streamflow and range of natural variability for available records,
    c. Identify long-term hydroclimatic trends (or a lack thereof).
    d. Quantify projected climatic changes under future climate scenarios.
2. Summarise water levels in wetlands from monitoring and link to major inflows, specifically;
    a. Present seasonal patterns in wetland water level at monitored locations,
    Link patterns to measured streamflow from available records in the upper Columbia River watershed to identify most correlated inflows.
3. Identify hydrological sub-basin types within the upper Columbia and upper Kootenay River watersheds and identify gaps in current monitoring, specifically;
    a. Summarise hydrometric, climate, morphometric, and land cover types for all current and former WSC sub-basins,
    b. Identify what parameters drive hydrological processes in the region, with particular focus on those that affect wetland hydrology (informed by 2.),
    c. Apply quantitative clustering to identify sub-basin types,
    d. Identify data gaps within each cluster, including long-term hydrometric records and active monitoring.
4. Provide recommendations for further work and/or monitoring efforts to improve understanding of the hydrology of the upper Columbia River watershed. And briefly provide information to inform the public about the hydrologic issues in the upper Columbia Watershed.

# 2 Study Area

## 2.1 Overview

This study considers the upper Columbia River watershed located in southeastern British Columbia. This area is delineated as all drainage area upstream of the Columbia River at Donald Water Survey of Canada hydrometric station as well as all drainage area on the Kootenay River upstream of Kootenay River at Canal Flats (discontinued) hydrometric station. The study area encompasses high elevation mountain ranges including the Rocky Mountains to the east and the Columbia and Purcell Mountains in the west, separated by a deep post-glacial valley known as the Rocky Mountain Trench. The Columbia River drains several major tributaries in the study area. The Blaeberry and Kicking Horse Rivers drain the northeast corner of the study area, originating in the Rocky Mountains. The Spillimacheen River and Bugaboo, Horsethief, and Toby Creeks are major tributaries along the west of the study area, originating in the Purcell Mountains. In addition, there are innumerable small creeks that originate on both sides of the high valley sidewalls of the Rocky Mountain Trench.

The region extends from under 800 m above sea level (a.s.l.) in the Rocky Mountain Trench, to over 3,500 m a.s.l. at the highest mountain peaks in the Rocky Mountains. The region predominantly consists of coniferous forests below 2,200 m a.s.l. and alpine grasslands and talus above. Several large glaciers and icefields are located within the study area, including the Wapta and Waputik Icefields, located in Yoho National Park, and the Conrad Glacier located in the Columbia Mountains. Within the Rocky Mountain Trench, the Columbia River flows slowly, creating a braided system of wetlands within the wide valley.

East of the Rocky Mountain Trench, much of the region is protected, falling within Kootenay and Yoho National Parks, as well as Assiniboine and Height of the Rockies Provincial Parks. West of the Rocky Mountain Trench, small mountainous regions are protected as Bugaboo and Purcell Wilderness Conservancy Provincial Parks. Outside of these protected areas, substantial other land use such as forestry and agriculture exist, particularly at lower elevations. In addition, recent major forest fires have burned large portions of forest in Kootenay National Park and Height of the Rockies Provincial Park.

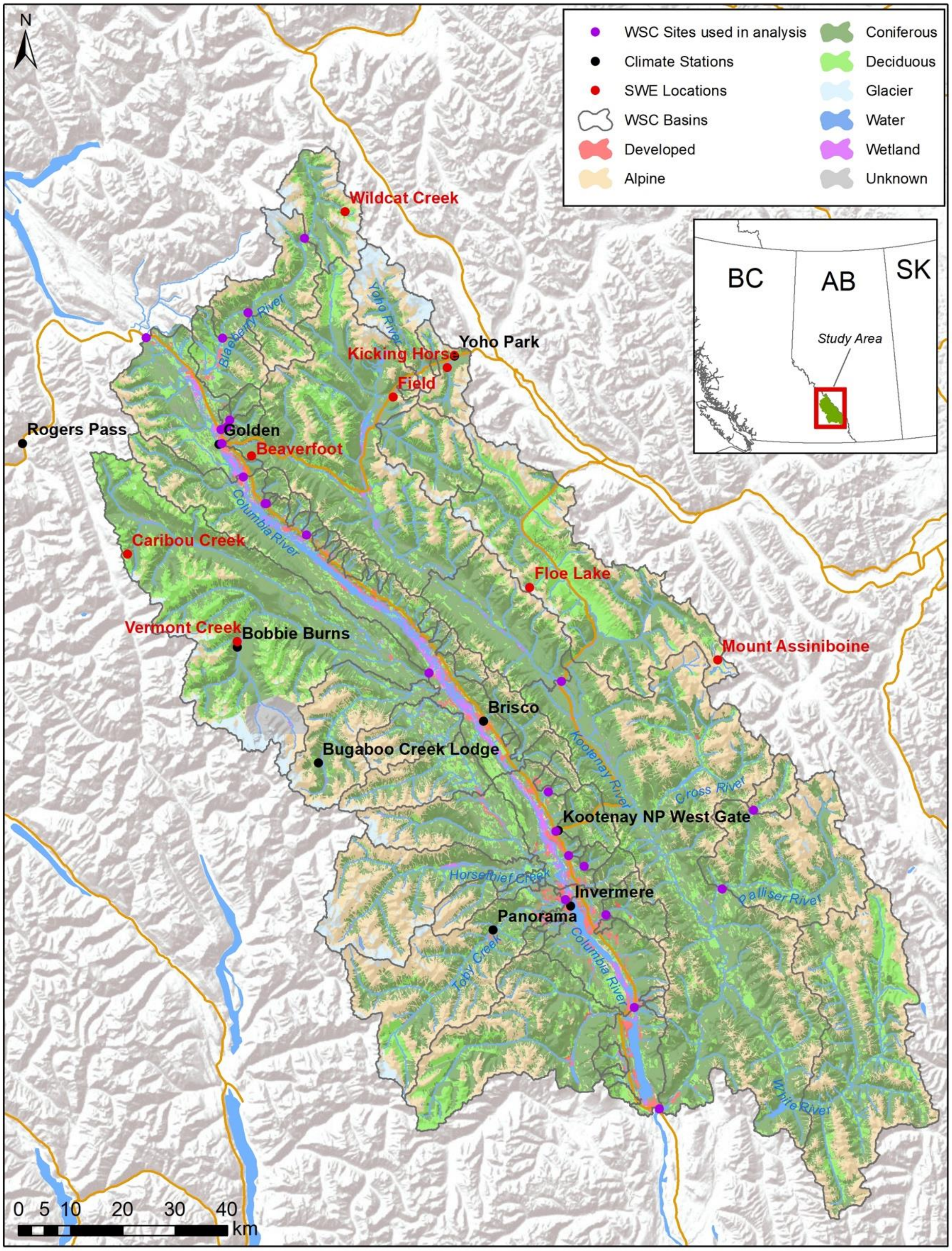


**Figure 1. Map of study area, including all 39 delineated WSC sub-basins (in grey) and all monitoring sites used in data.**

## 2.2 Geologic and Geomorphic Environment

Beginning 185 million years ago, flat-lying sedimentary and underlying metamorphic rock collided with the North American plate (Gadd and Wheeler, 1986). This southwest to northeast collision led to thrust-faulting and up-thrust of the underlying metamorphic rock and the creation of the Columbia Mountains. By 60 million years ago, these interactions had also led to the formation of the Rocky Mountains, where the shallower sedimentary rock was folded and faulted, but the underlying metamorphic rock remained buried and undisturbed. 55 million years before present day, the forces causing the plate collision had shifted to produce north-south slippage (termed transcurrent faulting) which separated the Columbia and Rocky Mountain Ranges and created the Rocky Mountain Trench; a deep and wide low-elevation area. These geologic formations have led to the Columbia Mountains being composed of dense, hard, and less erodible granite and gneiss rock while this layer is buried in the Rocky Mountains beneath more erodible limestone and shale.

The upper Columbia River watershed is a post-glacial environment, formed by heavy glaciation, glacial erosion, and till deposition during and since the last glacial maxima. The region was covered by the Cordilleran Ice Sheet at depths of up to 2 km. The ice sheet flowed south, reaching a maximum just south of the 49$^{th}$ parallel approximately 17,000 years ago (14,000 $^{14}C$ yr BP; Clague and James, 2002). Although the dynamics of ice sheet retreat are less well known in the Columbia Mountains (compared to the Coast and Cascade Mountains), it is estimated that the ice sheet began to thin markedly approximately 15,000 to 12,000 years ago (13,000 to 11,000 $^{14}C$ yr BP).

During the deglaciation of the region, ice receded north and meltwater outflows in the Rocky Mountain Trench were dammed in the south, creating a 210 km long, 100 m deep lake that extended from Skookumchuck to Donald, BC named Lake Invermere (Sawicki and Smith, 1992). Outflow from the lake flowed southwards until sometime prior to 10,000 years ago when glacial retreat north of Donald allowed the lake to drain north and established the present-day upper Columbia River. More recently, more modest alpine glacial advances have been documented in the region, reaching a glacial maximum between 1750 and 1850, known as the Little Ice Age (Luckman, 2000). Glaciers in the region have retreated substantially since then, losing between 5-15% of their ice cover between 1951 and 2001 (DeBeer and Sharp, 2009) and continued and accelerated glacier retreat is projected over the coming decades (Clarke et al., 2015).

While glacial retreat has and will continue to have important effects on streamflow magnitude and timing (Stahl and Moore, 2006), water temperatures, and vegetation (Moore et al., 2009), it has also played an important role in shaping the geomorphic environment of the region. Quaternary glaciation has deposited thick layers of till (unconsolidated rock, gravels, and silt) across the landscape, and has formed deep U-shaped valleys with steep sidewalls. Modern alpine glaciation has also shaped high elevation landscapes, carving steep glacial cirques and eroding rock outcrops. These factors have created a high erosion environment where frequent landslides, rock falls, and debris flows occur in steep headwater reaches (Holm et al., 2004). These events, along with the thick layer of glacial sediments (till), supply the Columbia River Valley with a high concentration of both fine and coarse sediment. Sediment carried by Columbia River and its tributaries are transported from steep headwater reaches and deposited along the low-gradient Rocky Mountain Trench. This sediment deposition, along with thick clay layers left behind from the ancient Lake Invermere, have created areas of poorly drained soils which have led to water ponding and the creation of a series of wetlands along the valley bottom.

# 3 Methods

## 3.1 Data

### 3.1.1 Regional Hydroclimatic Data Selection

We acquired air temperature and precipitation data from Environment Canada (EC, 2019), BC Hydro, BC Ministry of Forests, Lands, Natural Resource Operations and Rural Development (FLNRORD), and BC Ministry of Transportation and Infrastructure (MoTI) climate stations in the upper Columbia and Kootenay River watersheds. Environment Canada data were downloaded and compiled using the `weathercan` package in R (LaZerte and Albers, 2018; R Core Team, 2017), while all other sources were accessed from the Pacific Climate Impacts Consortium BC Station Data portal (PCIC, 2019). Climate stations selected for this analysis had to have at least 30 years of air temperature and precipitation observations at a daily timescale and observations since the year 2000. In cases where several disparate climate records were located in close proximity (i.e. within several kms) and similar elevation, those records were combined to form longer-term records.

We obtained snow water equivalent (mm water equivalent) observations for all available records in the region. These data included manual (monthly) snow survey measurements as well as automatic (daily/hourly) snow pillow records and were obtained from the British Columbia Snow Station Interactive Map (BC River Forecast Centre, 2019). Additional stations located within Alberta were obtained from Alberta Environment and Parks (AEP, 2018).

We obtained hydrometric records from Water Survey of Canada (WSC) for all sites in the upper Columbia River (above Donald, BC) and in the upper Kootenay River (above Canal Flats, BC) watersheds, which resulted in 70 hydrometric stations with streamflow observations (eight sites in the upper Kootenay River). From this dataset, we then selected all streamflow observations that occurred since 1960; which consisted of 39 hydrometric stations. Then we filtered for stations that had at least five years of complete summers, where a complete summer was defined as containing at least 180 days of observation per year between April and October. This method identified 24 WSC hydrometric stations which were used for further analysis.

For selected stations;

- Maximum annual flow was calculated for all years with more than 180 observations between April and October,
- Minimum annual flow was calculated for all years with more than 100 observations between November and March,
- Mean annual flow was calculated for all years with more than 300 observations.

We calculated hydrometric statistics Mean Annual Runoff and Average Maximum Annual Runoff by finding the average mean annual flow and maximum annual flow for each station for all available years and scaling by the reported drainage area. Finally, we identified seven hydrometric stations which contained daily data that overlapped with wetland water level data collected during the summers of 2009 and 2010.

### 3.1.2 Wetland Water Levels

Water level (m) was collected from 53 lakes/wetlands at approximately monthly intervals between May and August 2009 and 2010 (S. Bayley. *Pers. Comm*.). All available manual measurements were used in this analysis. The water bodies are located along the Columbia River floodplain between Lake Windermere and Golden, BC in the Rocky Mountain Trench, located in valley-bottom locations between 785-800m (a.s.l.). The wetlands were categorized as either naturally 'Drained' or 'Isolated" based on whether the ~~body~~ wetland basin had large surface water connections to the Columbia River that permitted water to flow into the wetlands on the rising water levels and flow out of the wetland when Columbia River water levels fell. The naturally isolated wetlands had restricted inflow/outflow channels that permitted surface water to remain in the wetland over the winter and early spring.

### 3.1.3 Spatial Data

We derived a shapefile of all Water Survey of Canada (WSC) sub-basins in the upper Columbia River and Kootenay River watersheds (including those without sufficient streamflow observations) by using a Digital Elevation Model (DEM) to delineate watershed boundaries from gauge locations, yielding 73 sub-basins. All spatial statistics were calculated from the spatial extent of these nested sub-basin boundaries. A second set of sub-basins was delineated for all sub-basins (and nested sub-basins) greater than 5 km$^2$ upstream of Donald, BC, which generated a total of 991 sub-basins. Generally speaking, WSC gauging stations do not represent smaller sub-basins.

We obtained annual climate variables Air Temperature (°C), Precipitation (mm), Snowfall (mm), Evaporation (mm), Continentality (°C), and Snowfall Fraction from ClimateBC raster files (Wang, 2012), which we then extracted for each WSC sub-basin in the study area. Historical climate normals were obtained from the 1981-2010 Climate Normals dataset. We also obtained six climate change scenarios for three future periods (2011-2040, 2041-2070, 2071-2100); consisting of three GCMs (CanESM2, CCSM4, and HadGEM2-ES) for two greenhouse gas concentration pathways (RCP 4.5, RCP 8.5). The Representative Concentration Pathway (RCP) 4.5 represents moderate greenhouse gas reductions, while RCP 8.5 represents business as usual greenhouse gas concentrations.

We extracted land cover percentages for each WSC sub-basin using a compiled vector dataset of land cover (see Appendix D: Spatial Datasets for full details on data sources and processing steps). We grouped similar land cover types to obtain the following broad groups: Forest, Alpine, Aquatic, Glacier, and Developed. We then calculated the total areal coverage of each land cover type in each sub-basin and divided by the total sub-basin area to obtain a percent coverage.

We derived morphometric statistics averaged over each WSC sub-basin using a DEM. From this DEM, we calculated Elevation (minimum, maximum, mean), slope, wetness, stream slope, and sinuosity from the DEM. Statistics were also re-derived for the comprehensive sub-basin set (i.e. all sub-basins greater than 5 km$^2$) and were used in further clustering routines, described below.

## 3.2 Analysis

### 3.2.1 Trend Analysis

Trend analysis allows us to determine if long-term changes are occurring in the study area. We calculated trends for annual flow statistics mean annual flow and maximum annual flow for all WSC hydrometric stations with significant, continuous long-term records. No climate station records contained sufficient continuous records to be used in this analysis. This consisted of Blaeberry River above Willowbank Creek, Columbia River at Donald, Columbia River at Nicholson, Kicking Horse River at Golden, Kootenay River at Kootenay Crossing, and Split Creek at the Mouth. Trends were computed using the Mann-Kendall test, and significant trends were noted as those with a $p$ value < 0.10.

### 3.2.2 Watershed Clustering

The purpose of sub-basin clustering was to identify sub-basin 'hydrological types' and how these types affect water levels in wetlands within the Columbia River watershed. Since wetland water levels are closely tied to streamflow, clustering should have the objective of grouping sub-basins based on their hydrologic characteristics. Furthermore, since the full parameter set is unlikely to fully (and equally) characterize the hydrologic conditions within each sub-basin, parameters were paired down and selected based on their ability to predict hydrological characteristics, process understanding, and to minimize parameter overlap and collinearity.

As a first step, we scaled and input all 17 (climate, land use, and morphometric) parameters into a linear regression model to predict mean annual runoff (mm) from the 24 WSC hydrometric stations identified as having good long-term streamflow records. We then calculated the relative importance of each parameter in predicting runoff within R (R Core Team, 2017) using the 'lmg' and 'genizi', and 'car' algorithms within the "relaimpo" package (Groemping, 2006). Average (relative) parameter importance was calculated for each parameter by averaging algorithm outputs for each routine. See Figure 11 for full list and relative importance if each parameter.

We clustered sub-basins using three approaches: k-means, agglomerative hierarchical clustering, and divisive hierarchical clustering, which we calculated using the "cluster" package in R (Maechler et al., 2017). We initially selected the specified number of clusters using two methods: within cluster sums of squares (using the 'elbow method' to visually identify the inflection point) and average silhouette (finding the first maximum value), calculated within the "cluster" package. We compared clustering groups for each method and calculated the modal cluster for each WSC sub-basin in the event all algorithms did not assign the site to the same cluster.

# 4 Results

## 4.1 Climate Records

There were nine locations in the study region that contained long-term climate records (Table 1). With the exception of Golden, all long-term records were generated by combining records from several climate stations in close proximity. Of these sites, only stations in Brisco, Invermere, and

Golden contain records from the first half of the 20th century. Golden, Yoho Park, and Kootenay NP West Gate are the only Environment Canada stations where observations extend up to present day (2018 for the most recent verified data). Of these stations, Kootenay NP has not had quality checks on any data since 2007. Active FLNRORD sites include Whiskey (close to Bobbie Burns EC site), Brisco, and Toby (close to Invermere), while BC Hydro operates an active climate station at Rogers Pass.

**Table 1. Climate stations in the study region with long-term records. Records in very close proximity were combined to form a single long-term record and are grouped accordingly.**

| Station Name | Climate ID | Start Year | End Year | Latitude | Longitude | Elevation (m) | Network |
|---|---|---|---|---|---|---|---|
| *Yoho Park* | | | | | | | |
| YOHO NP WAPTA LAKE | 117900R | 1974 | 1993 | 51.45 | -116.33 | 1,646 | EC |
| YOHO PARK | 11790J1 | 1992 | 2018 | 51.44 | -116.34 | 1,602 | EC |
| *Bugaboo Creek Lodge* | | | | | | | |
| BUGABOO CREEK LODGE | 1171105 | 1972 | 2006 | 50.75 | -116.71 | 1,529 | EC |
| *Bobbie Burns* | | | | | | | |
| BOBBIE BURNS | 1170R01 | 1981 | 2001 | 50.95 | -116.93 | 1,370 | EC |
| WHISKEY | 1911 | 1976 | 2019 | 51.07 | -116.79 | 1,300 | FLNRO |
| *Rogers Pass* | | | | | | | |
| GLACIER NP ROGERS PASS | 1173191 | 1965 | 2014 | 51.30 | -117.52 | 1,330 | EC |
| Glacier np Roger's Pass | 2466 | 1982 | 2019 | 51.27 | -117.51 | 1,182 | BCH |
| *Panorama* | | | | | | | |
| Toby Creek Manual | 2801 | 1981 | 2001 | 50.46 | -116.24 | 1,130 | MoTI |
| Panorama Ski Area | 2802 | 1980 | 2003 | 50.46 | -116.24 | 1,190 | MoTI |
| Toby Creek | 2803 | 2002 | 2019 | 50.45 | -116.25 | 1,130 | MoTI |
| *Kootenay NP West Gate* | | | | | | | |
| KOOTENAY NP WEST GATE | 1154410 | 1968 | 2018 | 50.63 | -116.06 | 935 | EC |
| *Brisco* | | | | | | | |
| BRISCO | 1171020 | 1924 | 2004 | 50.82 | -116.26 | 823 | EC |
| BRISCO | 2282 | 2004 | 2019 | 50.82 | -116.24 | 930 | FLNRO |
| *Golden* | | | | | | | |
| GOLDEN A | 1173210 | 1902 | 2018 | 51.30 | -116.98 | 785 | EC |
| *Invermere* | | | | | | | |
| INVERMERE | 1153655 | 1912 | 1993 | 50.50 | -116.03 | 810 | EC |
| Invermere | 2791 | 1976 | 2002 | 50.52 | -116.03 | 820 | MoTI |
| TOBY | 1957 | 1989 | 2019 | 50.51 | -116.06 | 894 | FLNRO |
| ZZ INVERMERE R/S | 1954 | 1970 | 2000 | 50.50 | -116.00 | 810 | FLNRO |

All nine long-term climate station sites are located in valley-bottoms. Yoho Park, Bugaboo Creek, Bobbie Burns, and Rogers Pass are located above the Rocky Mountain Trench and are located in mountain passes, while other sites are located in the lowest elevations of the region. The highest station (Yoho Park) is located at just over 1,600 m, while elevations in the upper Columbia River watershed extend up to over 3,500 m. Most sites (Panorama, Kootenay, Brisco, Golden, Invermere) are located along a narrow north-south band within the Rocky Mountain Trench.

Overall, climate observations for the region are sparse and even at climate stations with long-term records substantial data gaps exist (Figure 2). For instance, while Brisco contains a very long climate record, observations are mostly limited to precipitation and air temperatures were only available over a period of several years in the 1980's and late 1990's onwards. A similar lack of precipitation data exists for the Panorama. Likewise, while Yoho Park has a long-term active record, there is substantial missing data; with only approximately half of months containing complete months of precipitation observations. Missing observations are also an issue with recent (i.e. since 2010) Golden, Invermere, and Kootenay NP climate stations. Likely a single, more robust climate record could be derived using observations from Panorama, Invermere, and Kootenay NP West Gate; however, this would require careful use of imputation to generate a single un-biased long-term record.

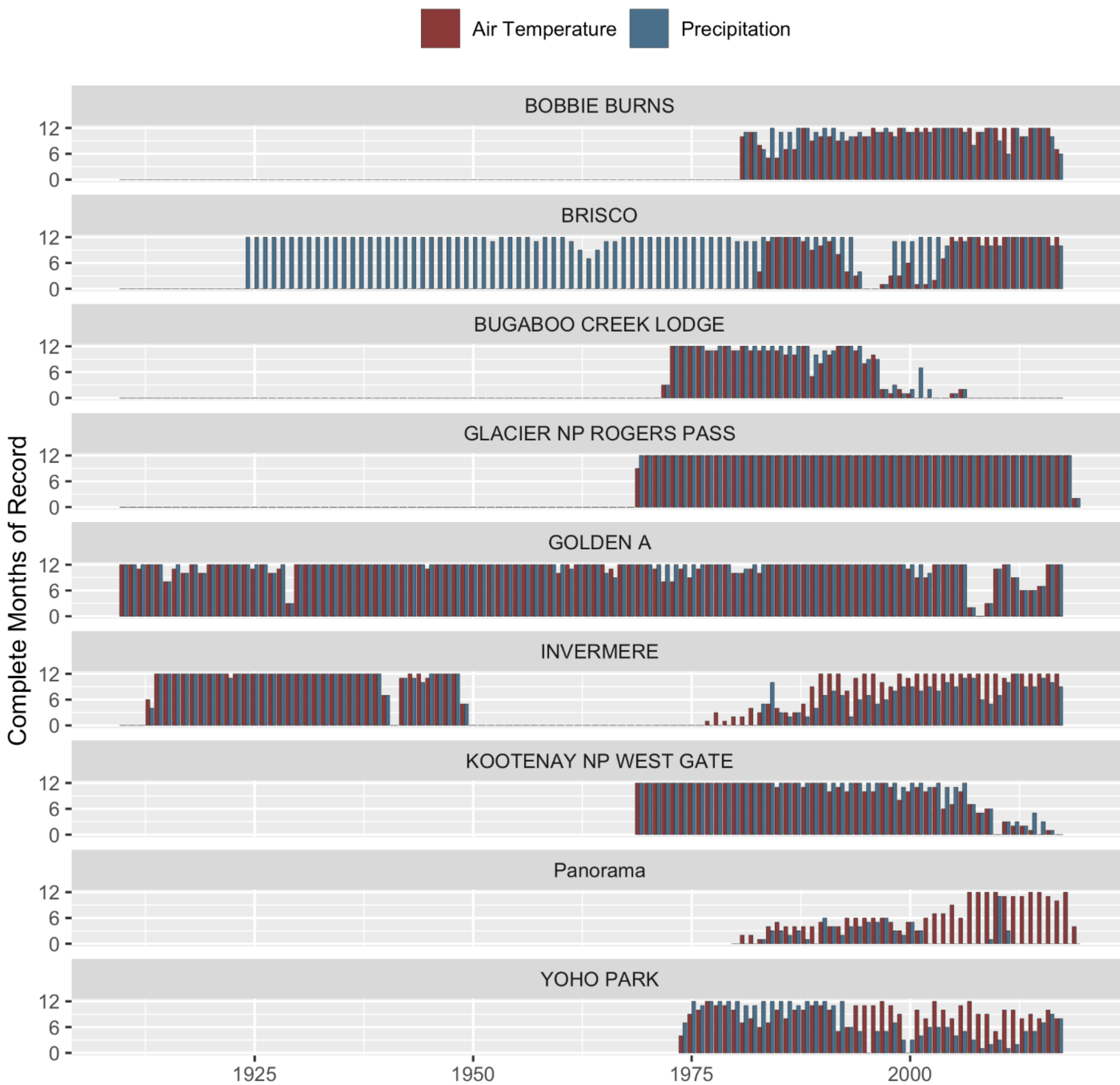


**Figure 2. Complete months of record for regional climate stations with long-term records.**

At the nine sites with long-term climate records, air temperatures exhibit a strong seasonal pattern (Figure 3). Air temperatures peak in July and August and are lowest in December. Air temperatures were generally higher at low elevation sites where summer daytime highs averaged 17°C at Golden and Invermere and 19°C at Panorama, while highest elevation sites were cooler; 15°C at Yoho Park and 14°C at Rogers Pass. Winter air temperatures were generally cool; most sites had average December daytime highs of negative 6-8°C while Rogers Pass and Yoho Park were negative 4-5°C. Average annual maximum air temperatures were greatest in the Rocky Mountain Trench at Golden and Invermere (12.5°C and12.3°C, respectively) and lowest at highest elevations (Rogers Pass = 8.6°C) and east of the Rocky Mountain Trench (Yoho Park and Kootenay West Gate = 10.6°C).

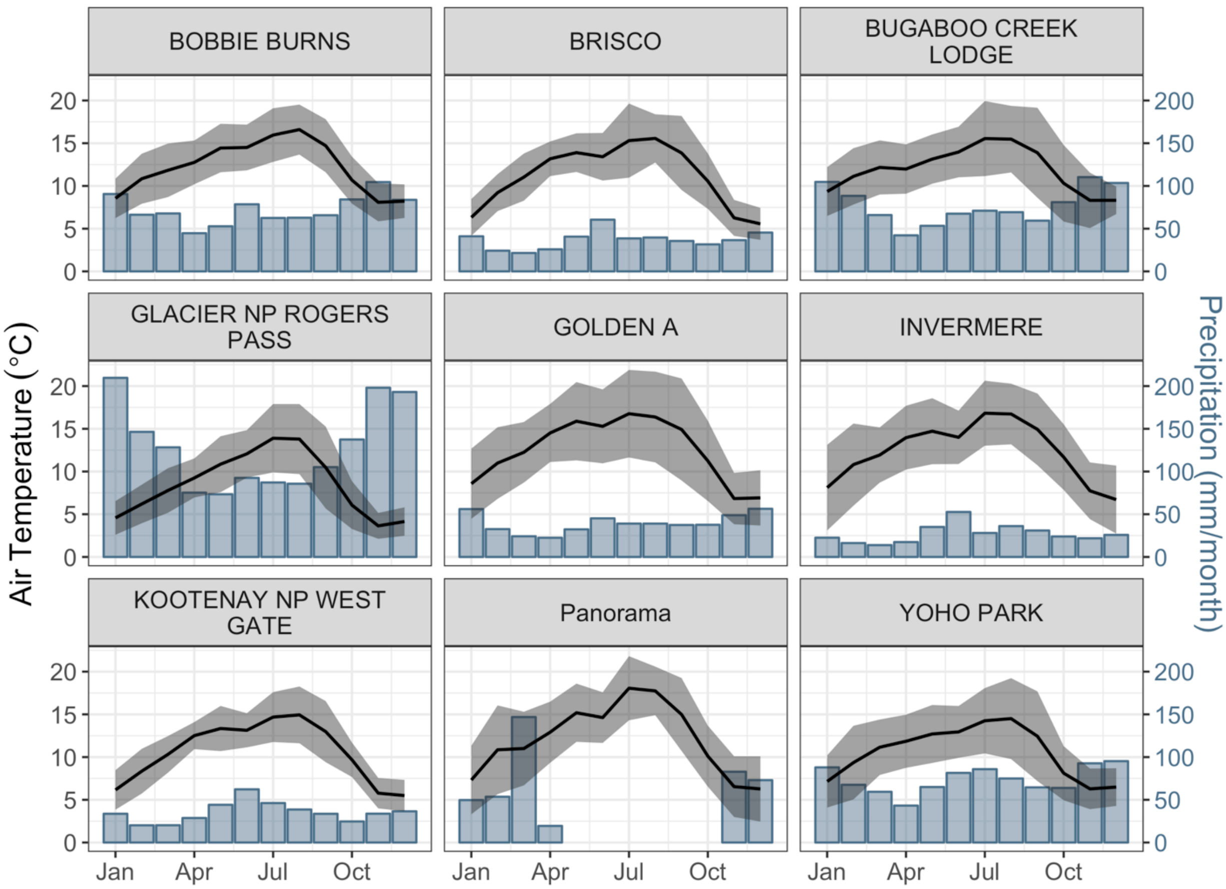


**Figure 3. Monthly average precipitation and maximum daily air temperature (shaded areas correspond to two standard deviations from mean), calculated from all available records for all regional climate stations with long-term records.**

Precipitation was variable between climate stations. Within the Rocky Mountain Trench, at lowest elevations, annual precipitation was low; annual precipitation was 325 mm/year at Invermere, 421 mm/year at Kootenay West Gate, 441 mm/year for Brisco, and 471 mm/year at Golden. Conversely, in the Rocky Mountains, Yoho Park averaged 991 mm/year of precipitation, while in the Columbia Mountains, Rogers Pass averaged 1531 mm/year. In the mountainous regions in the study area, precipitation was highest during the winter months; Rogers Pass exceeded an average of 200 mm/month in November, December, and January, while Yoho Park and Bugaboo Creek

Lodge both approached 100 mm/month during the winter. Conversely, in the Rocky Mountain Trench, Kootenay West Gate, Golden, and Brisco all averaged less than 50 mm/month during the winter months.

Snow water equivalent (SWE; mm) observations were available for eight locations in the study region (Figure 4). Continuous (automatic snow pillow) observations were available at Floe Lake since the mid-1990s, while two sites (Wildcat Creek and Caribou Creek) were recent installations and each contain four years of observations. Monthly snow survey records of over 60 years are available for Kicking Horse Creek and Field. These sites are located in close proximity in Yoho National Park, but at differing elevations. Since 1970, additional manual surveys have been collected at Beaverfoot, Vermont Creek, Mount Assiniboine, and Floe Lake. SWE data in the study region are available at elevations of 1,285 m to 2,230 m. While the SWE site network captures most middle elevation reaches in the study region, it does not capture the lowest elevations (<1,000 m) nor does it capture the high elevation reaches, which include several major icefields that extend over 3,000 m.

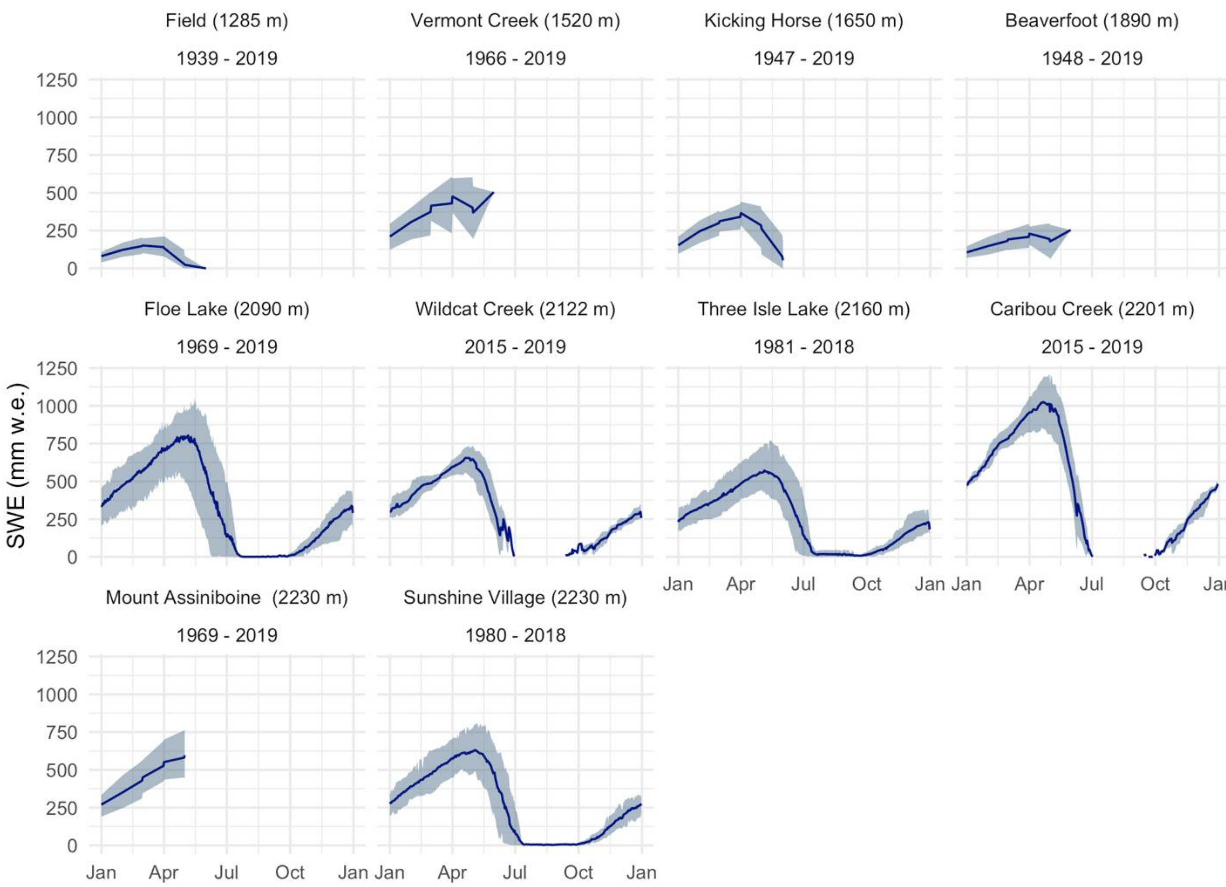


**Figure 4. Snow water equivalent (mm w.e.) records from 10 sites in the study region. Solid line is average daily (or monthly) value for the site while the shaded area is the 10-90% quantiles. Five sites contain continuous daily SWE measurements and six contain periodic manual measurements (Floe Lake contains both manual and automatic observations).**

Peak snow water equivalent ranged from approximately 200 mm at Field to over 1000 mm at Caribou Creek and Floe Lake. There was a strong elevation gradient in the region and SWE generally peaked in April at lowest elevation sites (Field, Beaverfoot) and May at higher elevation sites. Lower elevation sites were typically snow free by late May while sites above 2,000 m typically held snow until July. Spatially, SWE was higher west of the Rocky Mountain Trench (in the Purcell and Columbia Mountains).

## 4.2 Available Streamflow Records

Of the 24 WSC hydrometric stations identified as having significant streamflow records (Figure 5), only seven were active hydrometric stations (6 in the upper Columbia River watershed). These stations are: Kootenay River at Kootenay Crossing, Spillimacheen River Near Spillimacheen, Columbia River at Nicholson, Kicking Horse River at Golden, Split Creek at the Mouth, Blaeberry River Above Willowbank Creek, and Columbia River at Donald. Notably, only Spillimacheen River Near Spillimacheen is located on the western side of the Rocky Mountain Trench, while the Blaeberry, Kicking Horse, and Kootenay River systems all originate in the Rocky Mountains. All streamflow records are annual (i.e. contain winter observations).

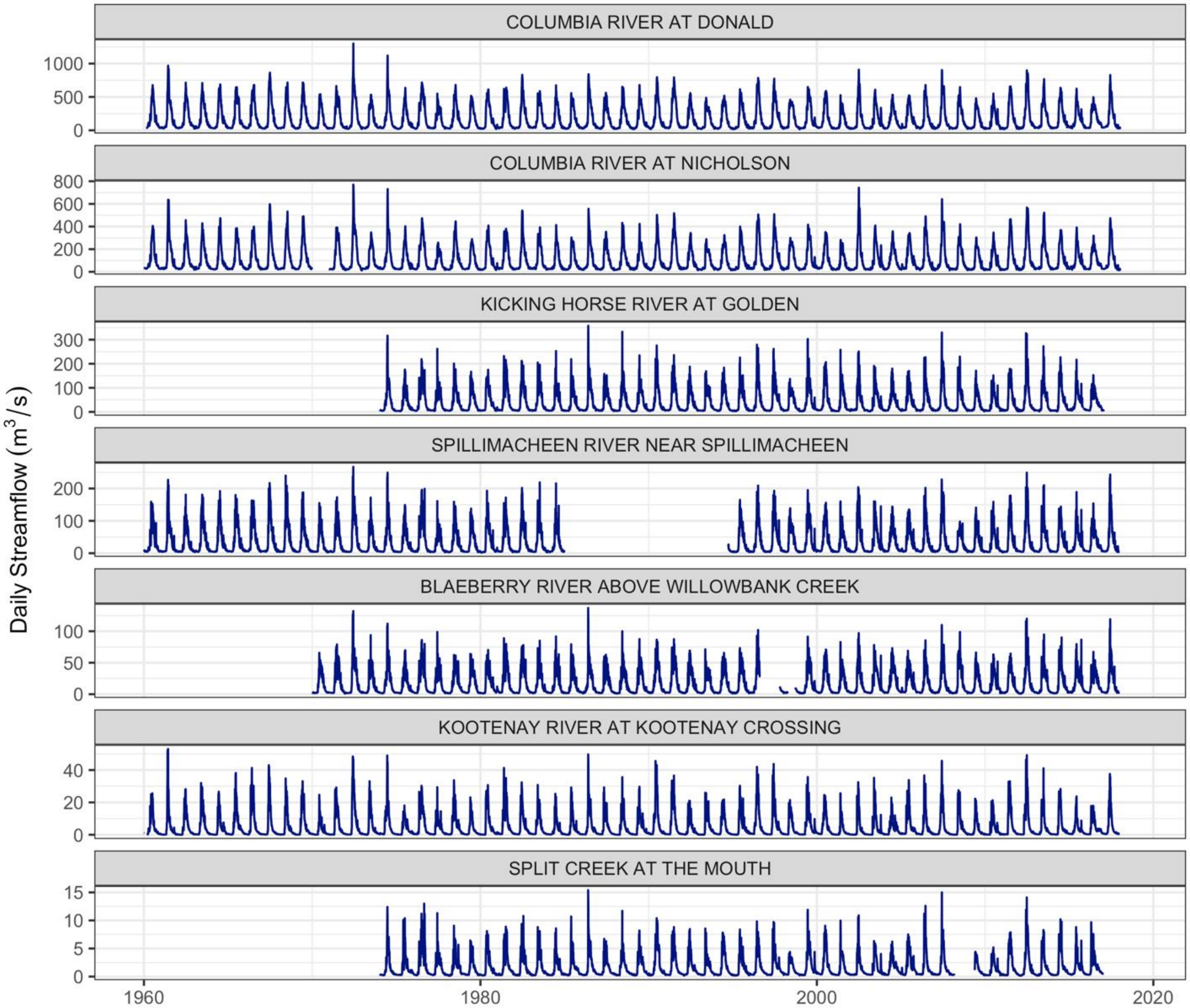


**Figure 5. Daily streamflow records for the 7 WSC hydrometric stations with continuous records considered in further analyses.**

It has been suggested that wetlands in the Rocky Mountain Trench respond to high flows on the Columbia River main stem; when streamflow exceeds 445 $m^3$/s at Columbia River at Nicholson overbank flooding is likely to occur at many of the wetlands in the valley (S. Bayley. Pers. Comm.). Peak flows on the Columbia River exceed this threshold 49 times over the available period of record (1902-2017), occurring in approximately 43% of years (Figure 6). Peak flows exceeded this threshold consistently during the 1910's and 1950's, but this has occurred less frequently during recent decades. Exceedances have typically occurred in temporally grouped patterns, with several consecutive years exceeding the threshold followed by several years of non-exceedance. We additionally note that peak streamflow in both 2009 and 2010, the two years with wetland water level observations, did not exceed the 445 $m^3$/s threshold for overland flooding.

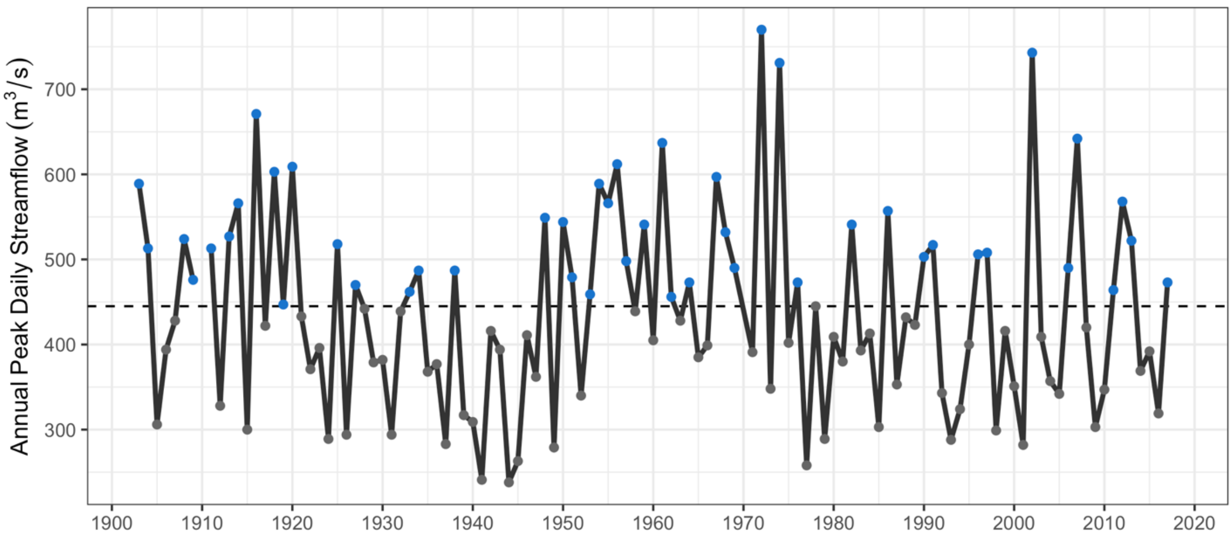


**Figure 6. Annual peak daily streamflow for Columbia River at Nicholson WSC hydrometric station. Dashed line corresponds to 445 m$^3$/s threshold for wetland overland flooding and years exceeding this value are highlighted in blue.**

In general, streamflow is well correlated between most sites (see Figure 7 for correlations against Columbia River at Donald and Appendix A: Correlation Matrix). In particular, streamflow along the Blaeberry, Kicking Horse, Spillimacheen, Kootenay, and Columbia Rivers have high correlations (>0.90), likely due to the fact that all these sub-basins contain high winter snowpack and melt at similar times. Conversely, correlations are low (-0.03 to 0.79) between these large sub-basins and smaller tributaries along the Rocky Mountain Trench, such as Pagliaro, Bower, Carbonate, Sinclair, and Hospital Creeks. This suggests that streamflow in the Columbia River is predominantly determined by large, high-elevation sub-basins. Smaller, lower-elevation tributaries have a different streamflow pattern and may not supply substantive water to the system as a whole but are critically important for irrigation or other uses.

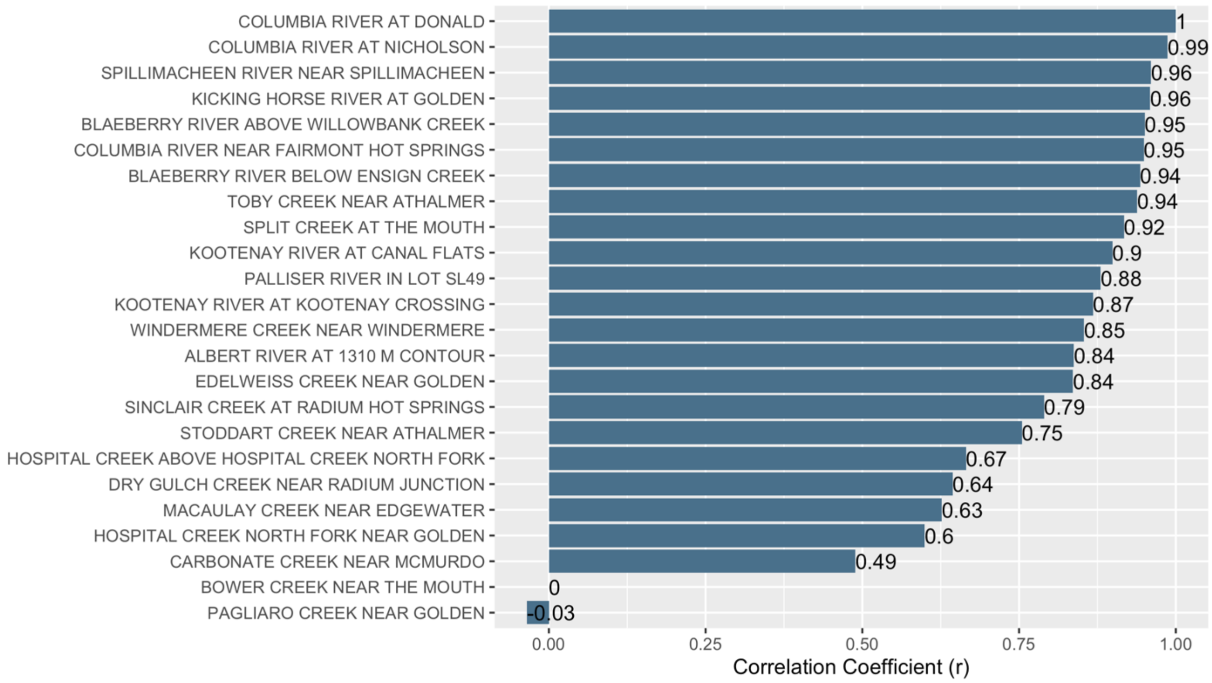


**Figure 7. Correlation coefficients for daily streamflow for all WSC hydrometric stations with significant records against Columbia River at Donald.**

Trend analysis from 1960-2018 revealed no strong trends in either mean annual flow, max annual flow, or the date of peak flow (Table 2). There was some hint of a decrease in maximum annual flow for Columbia at Donald (p = 0.08); however, the significance was marginal. We note that although no other sites have a significant decrease in maximum annual flow, the direction of the trend was negative in all cases except Blaeberry River above Willowbank Creek, where it was effectively zero. Additionally, there is some minor (non-significant) indication that the day of peak flow is decreasing for the two Columbia River stations. This finding mostly agrees with finding of an 11% decline in annual flows from 1999-2011 (Brahney et al., 2017a) and emphasizes the sensitivity of the period of record on trend analysis.

**Table 2. Mann-Kendall statistics for the six long-term, uninterrupted, hydrometric stations. Tau is the magnitude of the trend, while the p value represents its significance (bolded if p < 0.10).**

| Station Name | Mean Annual Flow | | Max Annual Flow | | Day of Peak Flow | |
|---|---|---|---|---|---|---|
| | *Tau* | *p* | *Tau* | *p* | *Tau* | *p* |
| BLAEBERRY RIVER ABOVE WILLOWBANK CREEK | 0.12 | 0.26 | 0.02 | 0.89 | 0.12 | 0.25 |
| COLUMBIA RIVER AT DONALD | -0.14 | 0.12 | **-0.16** | **0.08** | -0.12 | 0.18 |
| COLUMBIA RIVER AT NICHOLSON | -0.10 | 0.29 | -0.10 | 0.26 | -0.13 | 0.17 |
| KICKING HORSE RIVER AT GOLDEN | 0.01 | 0.92 | -0.05 | 0.64 | 0.06 | 0.59 |
| KOOTENAY RIVER AT KOOTENAY CROSSING | -0.12 | 0.20 | -0.08 | 0.36 | 0.03 | 0.73 |
| SPLIT CREEK AT THE MOUTH | 0.07 | 0.51 | -0.11 | 0.32 | -0.01 | 0.91 |

Examining seasonal streamflow, significant (p < 0.10) trends were detectable for summer average flows at Columbia River at Donald (p = 0.03) and Kootenay River at Kootenay Crossing (p = 0.04), where in both cases decreases of approximately 20% were observed during the period. This finding has been independently detected, specifically focusing in on August streamflow, and was attributed to decreasing glacial contributions to streamflow (Brahney et al., 2017b). No other seasonal streamflow records had significant trends, although Columbia River at Nicholson summer streamflow had a similar trend that did not reach the significance level (p = 0.13).

Given that streamflow between all these sites are very high correlated, the lack of consistently significant trends between sites suggests that while some sites are statistically significant, this analysis is sensitive to the length of record and results should be treated with caution. In addition, particularly for shorter records, trends could be due to multi-annual and decadal climate patters such as Pacific Decadal Oscillation (PDO) or El Niño Southern Oscillation (ENSO). Furthermore, these trends do not provide clarity on what should be expected in the future, nor how they will be affected by future climate and land cover.

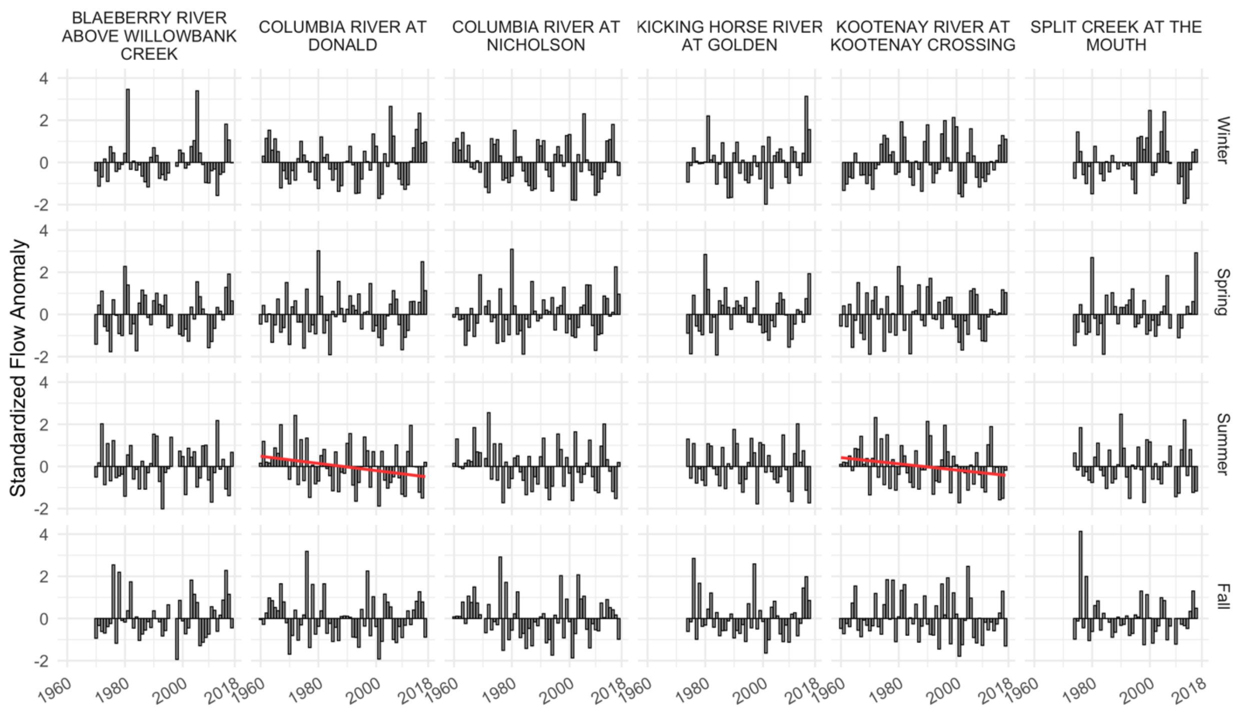


**Figure 8. Standardized Flow Anomalies (flow minus average site flow, divided by standard deviation) for all seven long-term hydrometric stations in the region. Stations with trends significant at p < 0.10 are demarcated by a red trend line.**

## 4.3 Wetland Water Levels

Water level in the wetlands displayed a seasonal pattern of increasing levels throughout the late-spring and early summer, with decreasing levels into August (Figure 9). This pattern is coincident with the snowmelt dominated pattern of streamflow in the upper Columbia River watershed. This pattern was more pronounced in the naturally drained wetlands, while the naturally isolated wetlands have a less pronounced peak. Naturally isolated wetlands have levees and smaller gaps in the levees which help retain water in the wetlands over winter, but also partially restrict inflows during the peak summer flows, unless water overtops the levees. Wetlands designated as drained have big natural gaps in their levees which permits water to enter and leave as the river water rises and falls. Variability does exist between wetlands of the same type (i.e. within Drained or Isolated categories), with water levels in most wetlands exhibiting a consistent seasonal pattern. Although wetlands are classified as a binary (Isolated or Drained), in reality this process likely falls on a continuum; while some wetlands may be completely disconnected from the Columbia River, most will have some degree of surface connectivity. This bears out in the water level records as well, where water levels for some Isolated wetlands exhibit stronger seasonal patterns, coincident with streamflow and Drained wetlands, than other Isolated water bodies.

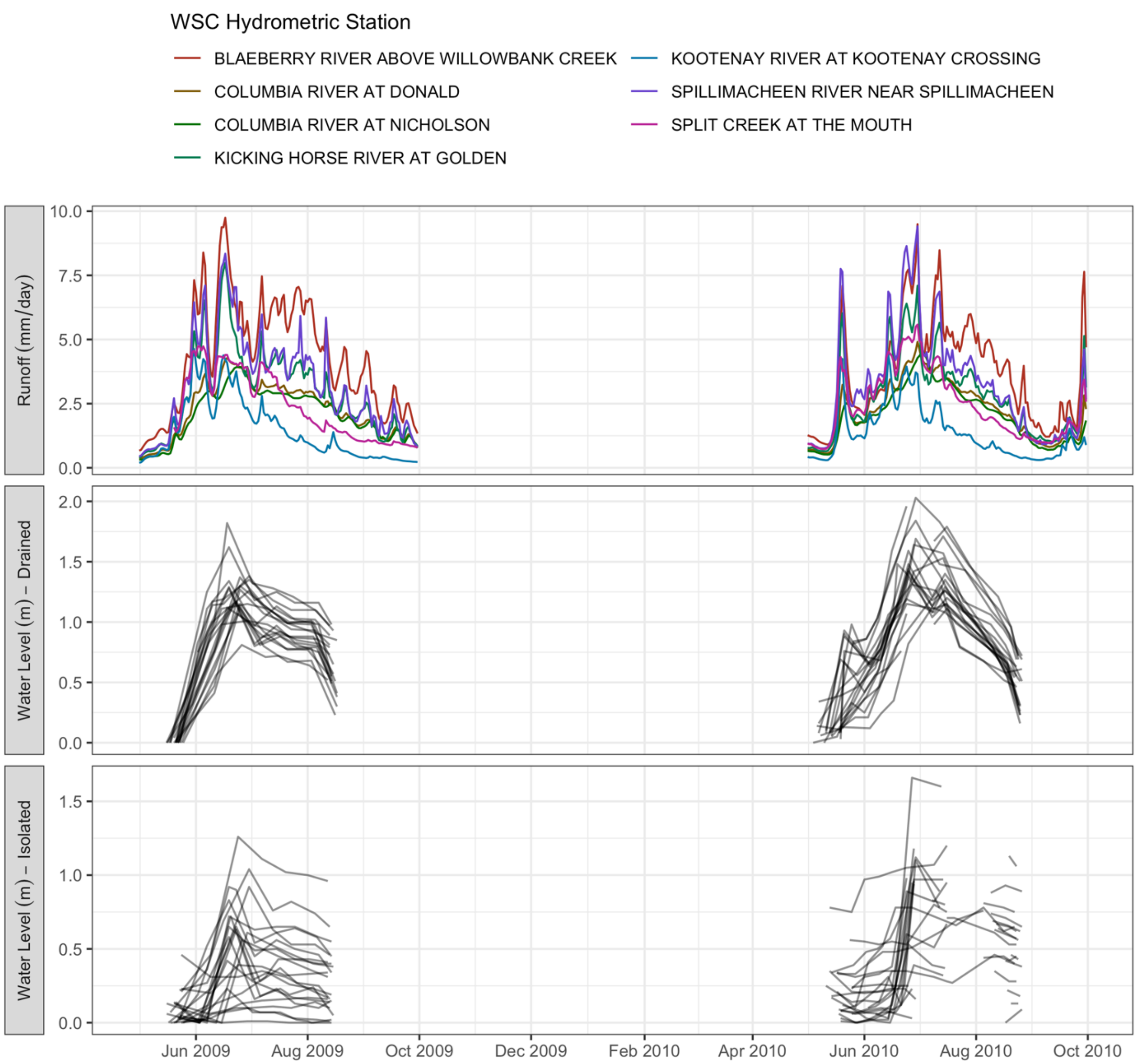


**Figure 9. Wetland water levels and runoff from 7 WSC hydrometric stations with available data during the 2009 and 2010 summers.**

We correlated each of the seven active WSC hydrometric records to all wetland water levels for all (combined) Drained and Isolated settings during the summers of 2009 and 2010 (Figure 10). We found that hydrometric gauges on the Columbia River were the most predictive for the Drained wetlands, where pearson correlation coefficients ($r^2$) reached 0.70 for Columbia River at Nicholson and 0.68 for Columbia River at Donald. Meanwhile, Kootenay River at Kootenay Crossing, which is located outside of the upper Columbia River watershed and therefore not connected to the wetlands, was a poor predictor of wetland water levels ($r^2$ = 0.13). Correlation coefficients ($r^2$) for hydrometric stations on the Spillimacheen River (0.35), Kicking Horse River (0.43), Split Creek (0.31), and Blaeberry River (0.51) were modest. Conversely, WSC streamflow records were poor predictors of water levels in Isolated wetlands, where $r^2$ values ranged from 0.09 at Columbia River at Nicholson and 0.06 at Blaeberry River Above Willowbank Creek, to 0.00 at Kootenay River at Kootenay Crossing. This suggests that in aggregate, water levels seem to follow the same temporal pattern as streamflow in Drained wetlands, while this signal is more muted in Isolated wetlands.

Given that the connectivity in wetlands likely falls on a continuum, rather than a binary Isolated/Drained paradigm, we re-ran the previous analysis by correlating each individual wetland, rather than the combined dataset for each group. At the individual wetland level, correlation coefficients were high for naturally drained wetlands ($r^2$ = 0.40-0.97), although sample sizes were modest (n = 9-23). The highest correlation for each Drained wetland was either Columbia River at Nicholson or Columbia River at Donald. Overall, these results suggest water levels in these naturally drained wetlands along the Columbia River valley respond primarily to streamflow in the Columbia River.

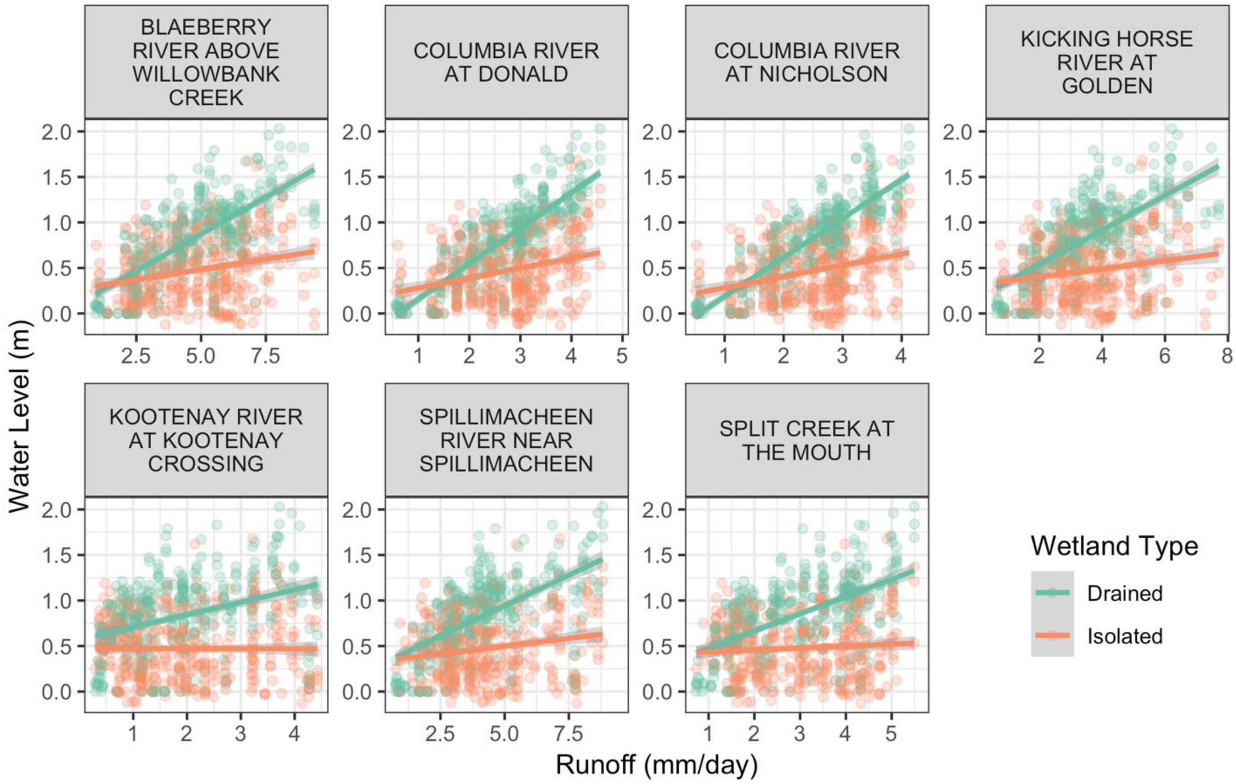


**Figure 10. Scatter plots of daily wetland water level and daily runoff at seven WSC hydrometric stations in the region during May-Aug 2009 and 2010. Solid line is the linear best-fit line of the correlation.**

Correlation coefficients in Isolated wetlands were comparatively lower than in Drained wetlands ($r^2$ = 0.66 – 0.03). Isolated wetland water levels were generally most correlated with the Blaeberry River and Columbia River hydrometric stations, although several sites were most correlated with Kootenay River at Kootenay Crossing or Spillimacheen River near Spillimacheen. Given that all wetlands (both Isolated and Drained) are located upstream of the Blaeberry River confluence and outside the Kootenay River watershed, it is unlikely that flow from these sub-basins are directly influencing wetland water levels. Instead, the relatively high correlations are likely because both water level in these wetlands and streamflow in these sub-basins are responding to the same hydro-meteorological conditions (i.e. snowmelt, precipitation, air temperature). Additionally, it is likely that there are groundwater interactions between the Columbia River and its tributaries and Isolated wetlands, which could also explain the relatively high correlations. Finally, the fact that the correlations from the Isolated wetlands are comparatively lower than those in Drained wetlands reinforces the idea that these wetlands are less hydrologically connected to the Columbia River, particularly when there is no overbank flooding of the levees. We recognize that both years of record had streamflow on the Columbia River below the threshold for overbank flooding of the levees.

## 4.4 Sub-Basin Cluster Analysis

### 4.4.1 Watershed Specific Data

The purpose of sub-basin clustering was to identify sub-basin 'hydrological types' and how these types affect water levels in wetlands within the Columbia River watershed. Since wetland water levels are closely tied to streamflow, clustering should have the objective of grouping sub-basins based on their hydrologic characteristics. Derived climate, land cover, and morphometric statistics were obtained for all current and historical WSC hydrometric station sub-basins in the upper Columbia and Kootenay River watersheds, for a total of 70 sub-basins. In addition, these statistics were also collected for the comprehensive list of all sub-basins greater than 5 km$^2$, for a total of 991 sub-basins. Histograms for both datasets are presented in Appendix B: WSC Sub-Basin Statistics Histograms, Figure 20 and Figure 21.

Air temperature indicators (Temperature, Evaporation, and Continentality) display similar (largely normal) distributions, with most sub-basins experiencing average annual air temperatures between -2$^o$C and 3$^o$C, annual evaporation between 300 mm and 600 mm, and Continentality (difference between hottest and coldest months) of 16-21$^o$C. Conversely, annual precipitation is much more variable, ranging from 400 mm to over 1800 mm, while the fraction of this precipitation that falls as snow ranged from 0.3 to 0.8 with most sub-basins greater than 0.5.

Forest cover in the study region was high, with most sub-basins exceeding 50% forest cover, and a quarter of sub-basins with over 90% forest cover. Conversely, Alpine covered less than 75% of most sub-basins. The distribution is roughly bimodal; most sub-basins contain 15-40% alpine cover, while roughly a fifth of sub-basins contain less than 10% alpine coverage. Developed, Aquatic, and Glacier coverage all display similar distributions where the majority of sub-basins contain little to no coverage and a small fraction of sub-basins contain substantial coverage. In the case of glacier coverage, sub-basins contain up to 90% coverage, with most non-zero coverage sub-basins containing under 5% coverage.

Average elevation for sub-basins predominantly falls between 1,600 m and 2,200 m, while minimum elevation was generally between 800 m and 1,600 m. Conversely, there was substantial variability and a bimodal pattern in maximum sub-basin elevation. Just over half of sub-basins had maximum elevations between 2,300 m and 2,600 m, while approximately 30% of sub-basins were over 3,100 m, and a small fraction were below 2,000 m. Sinuosity (i.e. the degree of stream meandering) was generally low, with minimal variability; values ranged from 0.08 to 0.10. Similarly, stream slope was relatively steep, ranging from 10$^o$ to 20$^o$ with a mean value of 12$^o$.

In general, the shape of distributions for statistics in the WSC sub-basins closely resembled the comprehensive set of sub-basins. However, the variability was much greater in most cases for the comprehensive (> 5 km$^2$) set. This suggests that that while the WSC station coverage is generally representative of the regional sub-basin characteristics, it does not capture the extreme margins (i.e. very cold, very warm; very glaciated, etc.).

### 4.4.2 Parameter Selection

In predicting sub-basin runoff, Precipitation was the most important parameter in the full parameter dataset (Figure 11). This was followed by percent glacier coverage, forest coverage, and Snow Precipitation. Conversely, the minimum elevation of the sub-basin, percent of aquatic coverage, stream slope, wetness, and developed coverage were relatively unimportant parameters. In general, climate parameters were the most important, while land cover parameters were relatively unimportant, except for glacier and forest coverage.

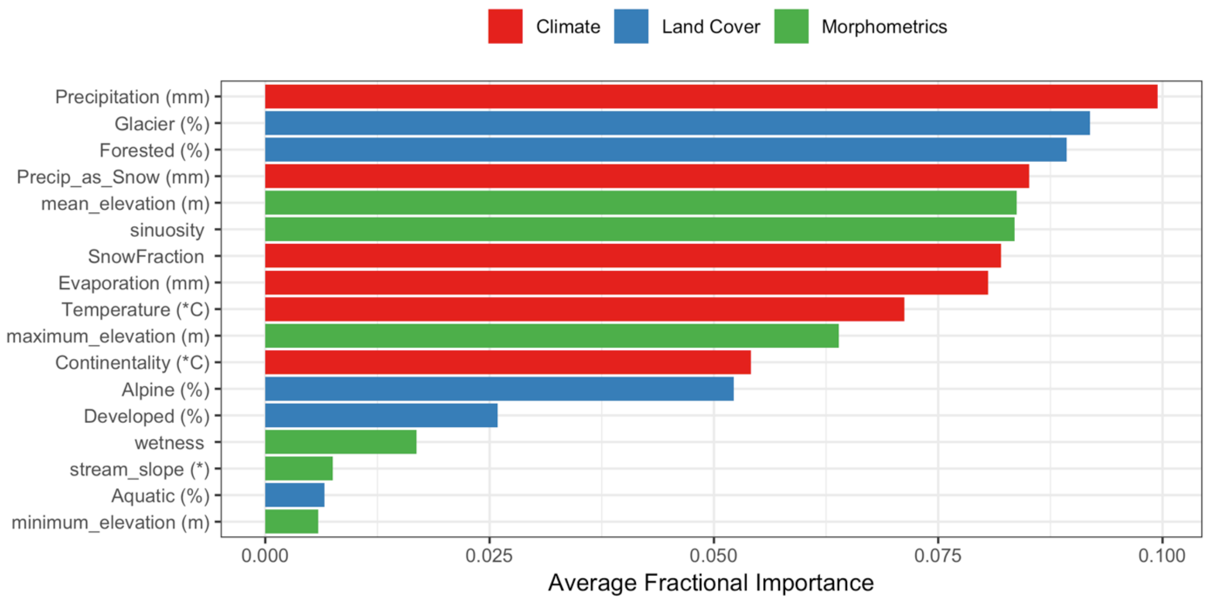


**Figure 11. Relative importance of all sub-basin parameters in predicting annual runoff.**

In addition to the relative importance in predicting runoff, we also attempted to remove parameters with significant overlap. For instance, although both Alpine and Forested coverage had high fractional importance values, they were highly (inversely) correlated (r = -0.97). Likewise, Evaporation, Temperature, and Continentality were strongly correlated (r = 0.97 – 0.99) as were Precipitation and Precipitation as Snow (r = 0.99). Given these factors, the final parameter set selected for clustering analysis contained:

- 3 climate variables: Precipitation, Snow Fraction, and Temperature,
- 2 land cover variables: glacier cover and forested cover,
- 3 morphometric variables: maximum elevation, mean elevation, sinuosity.

### 4.4.3 Clustering Analysis

Calculated optimal cluster numbers using the silhouette and weighted sum of squares (wss) methods generally suggested that two was the optimal group number for both the WSC and comprehensive sub-basins set (Figure 12).

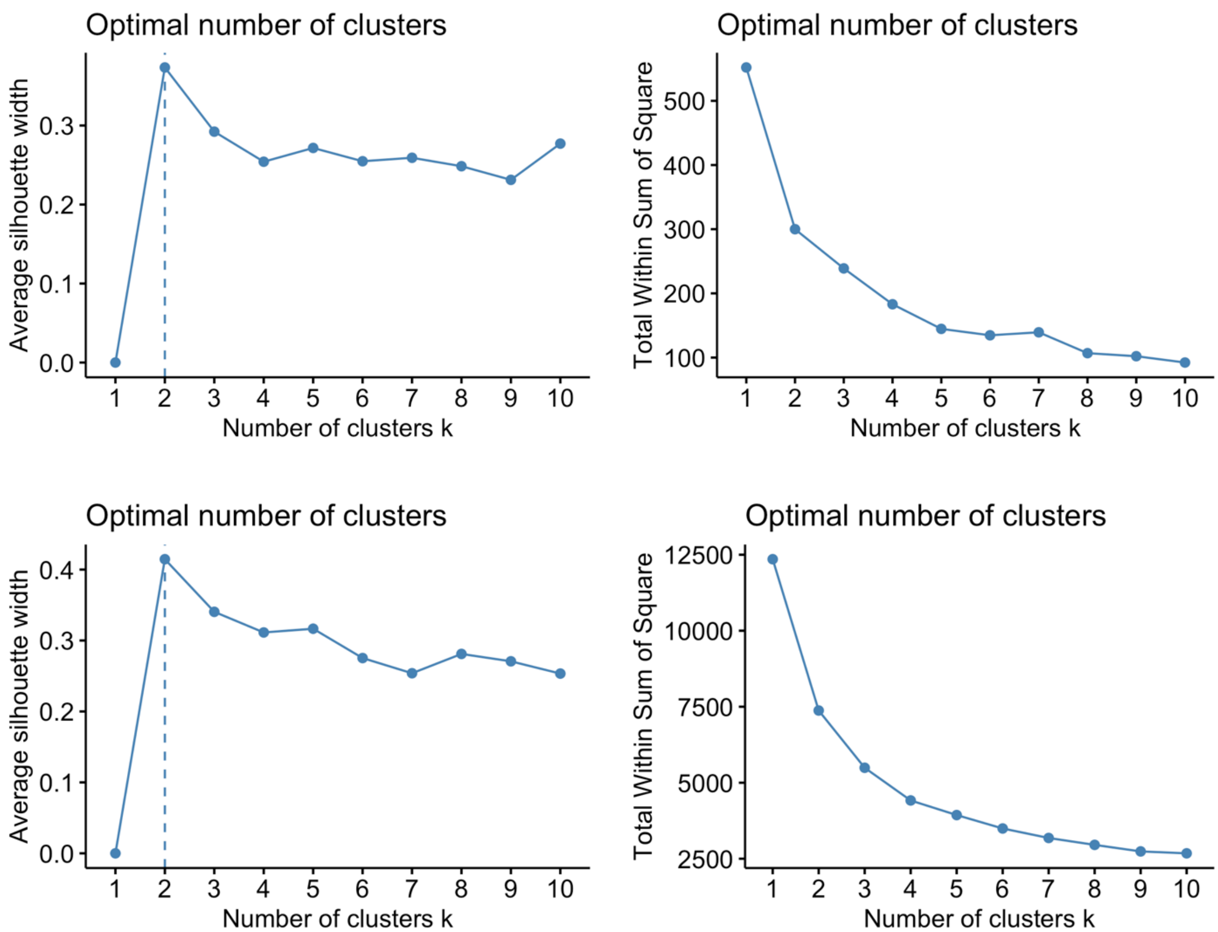


**Figure 12. Optimal clusters for WSC sub-basins dataset (top) and comprehensive (5 km$^2$) sub-basins dataset (bottom) using the silhouette (left) and wss (right) methods.**

The wss method is less precise, and while the inflection point was clearer at two groups, three groups does not appear to be qualitatively much less optimal, particularly in the comprehensive sub-basin set. However, given these findings, and a guiding principle of maintaining the most parsimonious clustering model, two groups was chosen for clustering analyses. Given this, future clustering could rely on a desired number of clusters based on external factors such as study design, conceptual understanding, or monitoring budget and logistics.

All three clustering methods showed almost complete agreement. The two groups are relatively distinct in climate, land cover, and morphometry (Figure 13). Cluster A was characterized by a wetter and colder climate: Precipitation ranging from 800-1250 mm, with over 50% of that falling as snow, and average annual air temperatures ranging from 1°C to -2°C. Conversely, in Cluster B, Precipitation was generally between 400-1000 mm, less than 60% falling as snow, and air temperatures above 0°C (up to 4°C). Cluster B consisted of high forested coverage (70-100%) and no glacier coverage, while Cluster A contained 40-70% forest coverage and glacier coverage. Cluster B consisted of lower maximum elevations, ranging from 1800-2700 m, average elevations under 2000 m, and lower sinuosity (<0.090), while Cluster A consisted of maximum elevations primarily over 3000 m (up to 3500 m), mean elevations ranging from 1800-2300 m, and higher sinuosity (0.085-0.10).

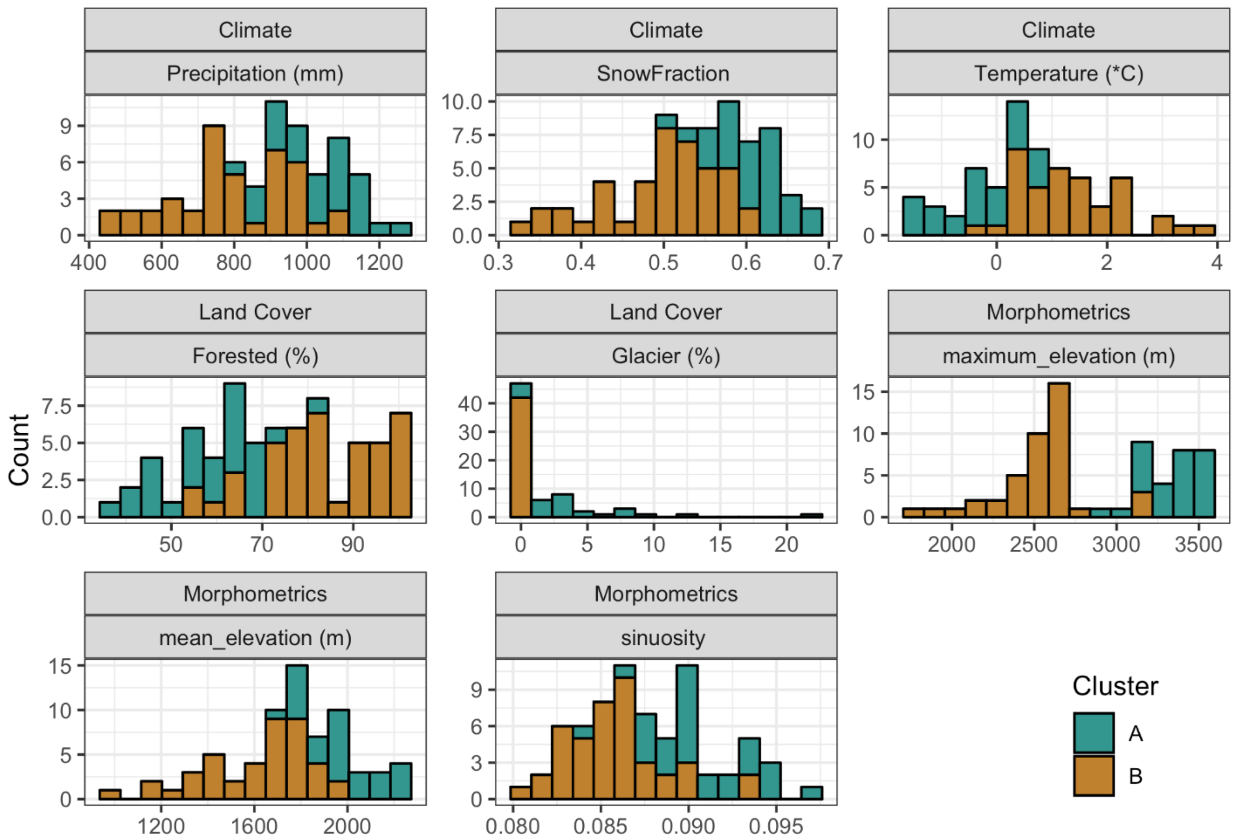


**Figure 13. Histogram of the eight parameters used in cluster analysis of WSC sub-basins, coloured by group.**

There were notable differences in the shape and timing of streamflow for each cluster (Figure 14). Hydrographs in Cluster A, noted to be cold, wet, glaciated, and full of high alpine regions, displayed a strongly snowmelt dominated pattern. Streamflow was low throughout the fall and winter months, before rising substantially in May. Streamflow tended to peak in early July for most sites and remained high until late-August at most hydrometric stations. This was most likely due to the presence of glacial melt supplementing late summer flows and later season snow depletion in the sub-basins. Conversely, in Cluster B streamflow tended to peak marginally earlier in the spring (May-June) and had a faster, more ephemeral peak flow, followed by a quicker return to low-flow conditions by late July. Peak streamflow values in Cluster A tended to be relatively large (5-500 $m^3/s$), while peak streamflow was much lower (0.05-50 $m^3/s$) in Cluster B. This pattern mainly reflects the discrepancy in drainage area, where cluster A contains much larger headwater sub-basins, but also reflects the Cluster A's higher precipitation and snowpack.

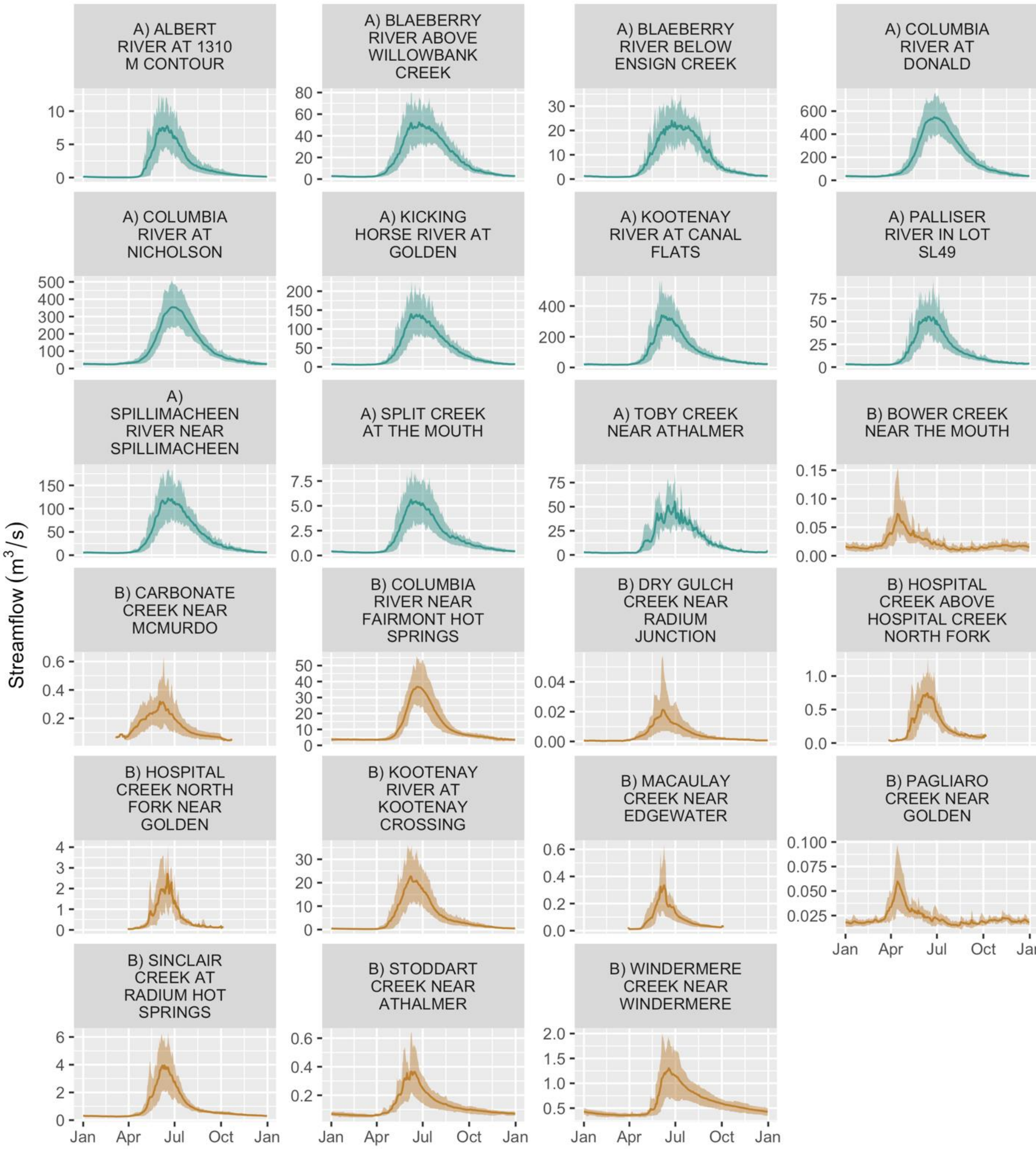


**Figure 14. Average streamflow of all WSC hydrometric stations with significant hydrometric records, colour coded by their cluster group (A in green, B in brown).**

Similar results were obtained for the comprehensive sub-basin set; sub-basins were demarcated primarily as high-elevation, cold, snowy, and glaciated areas, or warmer, forested, and dry. Given that all variables used in clustering were continuous, the number of clusters chosen is generally arbitrary. Although there are marked differences between the extreme sub-basins at either end of a cluster (i.e. the coldest, wettest sub-basin in Cluster A is very different than the driest, warmest sub-basin in Cluster B), the inverse is not true. In many respects the warmest, driest sub-basin in Cluster A is likely to be relatively similar to coldest, wettest sub-basin in Cluster B.

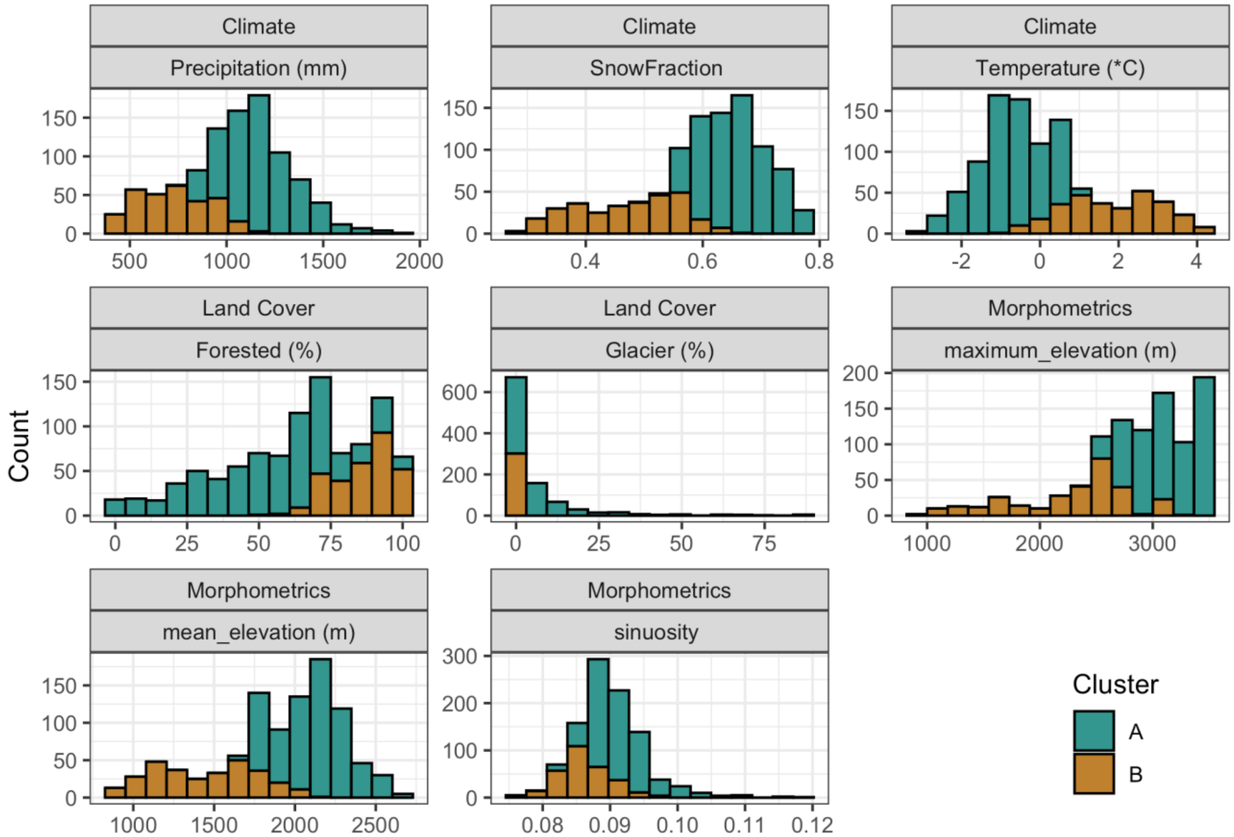


**Figure 15. Histogram of the eight parameters used in cluster analysis for the comprehensive sub-basin set, coloured by group.**

## 4.5 Climate change analysis

Under all climate change scenarios considered in this analysis, average annual air temperatures are projected to increase in all sub-basins, with average increases of 4°C by 2071-2100 relative to 1981-2010. While air temperatures are generally (~1°C) higher in Cluster B than in Cluster A, the pattern is consistent between the two clusters, indicating that future warming is expected throughout the region. Evaporation is projected to increase by approximately 200 mm/year in all sub-basins by 2071-2100, with similar responses in both sub-basin clusters.

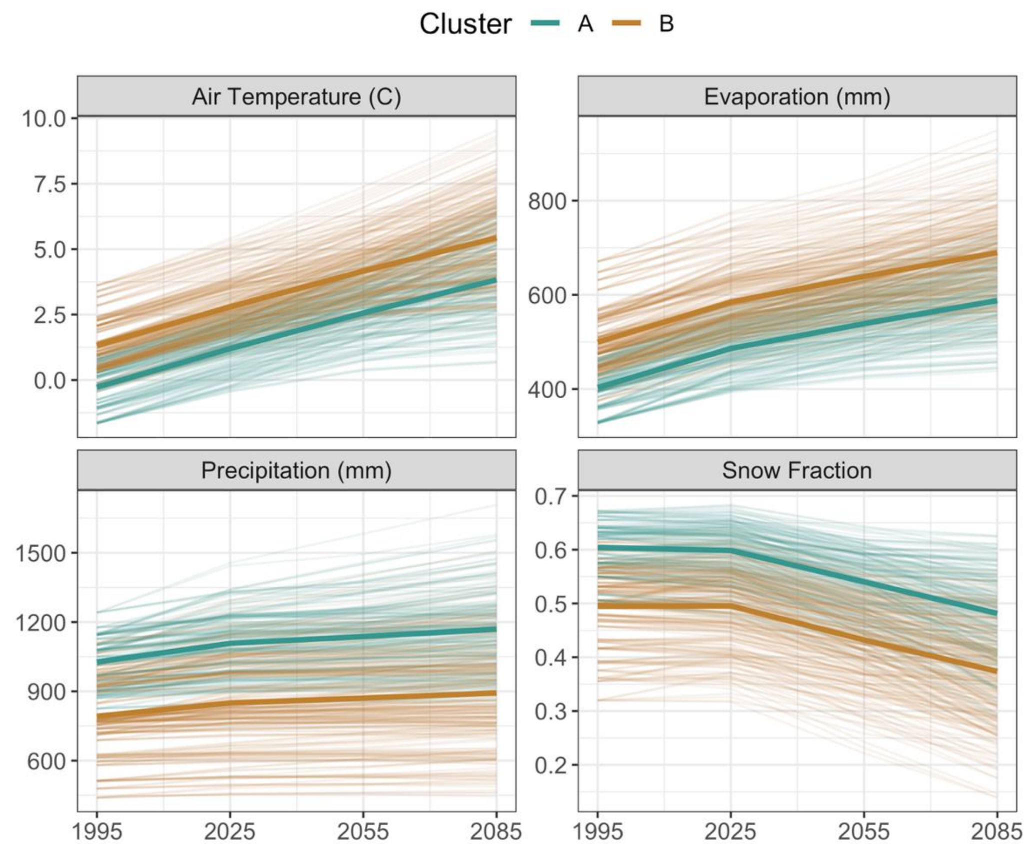


**Figure 16. Change in climatic variables in the study area for the historical period (1981-2010) and the mid-point of 3 future periods (2011-2040, 2041-2070, and 2071-2100), under two emissions pathways (RCP 4.5 and RCP 8.5) and three GCMs. Light lines correspond to individual sub-basins while thick lines correspond to cluster averages.**

Annual precipitation is projected to increase by an average of 150 mm/year in Cluster A, while only marginal increases (< 50 mm/year) are projected in Cluster B by the end of the century. Given that Cluster A is predominantly sub-basins with substantial high-elevation reaches, this suggests much higher increases in precipitation at high elevations rather than in valley-bottoms. The snow fraction (i.e. the fraction of precipitation that falls as snow) is projected to decrease in all sub-basins, particularly in the second half of the century. The snow fraction is projected average 0.35 in Cluster A, representing a decrease of 25% from 1981-2010. In Cluster B the average snow fraction is projected to reach below 0.50; a decrease of 20-25% from the historical period.

Given that precipitation is likely to increase in the coming decades, and snow fractions are likely to decrease, we should expect a change in the character of seasonal streamflow patterns, and subsequently Drained wetland water levels. Higher precipitation, but less falling at snow is likely to lead to earlier snow disappearance, accelerated glacier retreat; likely leading to higher spring peak flows and lower than currently observed flows during the late summer. In addition, while Isolated wetlands may not respond directly to streamflow in the Columbia River at lower streamflow levels, increased precipitation is likely to increase the frequency in which overbank flooding occurs. Although the precise drivers of water level in Isolated wetlands may not be well understood, they are almost assuredly affected to some degree by local precipitation and evaporation patterns. Increased evaporation is likely to lower Isolated wetland water levels during the late summer; however, the precise impact of this, and how it interacts with increased precipitation (primarily rainfall) or changes in groundwater contribution requires further study.

Overall, the entire upper Columbia River region is projected to become warmer and marginally wetter under the future climate scenarios used here. This will likely lead to higher evaporation rates and an overall decrease in the winter snowpack, particularly at lower elevations, as more of the annual precipitation falls as rain. These climatic changes will have important effects on the magnitude and timing of streamflow in the watershed. In particular, the seasonality of flows in both clusters will likely shift; with earlier onset of snowmelt leading to peak flows earlier in the summer and subsequently lower late-summer flows, further exacerbated by higher evaporation rates. More rainfall and periodic mid-winter snowmelt events in the region will likely also mean increased winter flows and more variable and erratic spikes in streamflow, which will be particularly notable in Cluster B which is already characterized by lower snowfall fractions. Finally, while substantial glacier retreat has already been documented in the region (DeBeer and Sharp, 2009), further retreat is very likely in the coming century (Clarke et al., 2015). This retreat will lead to less late-summer flows and will be particularly noteworthy in cluster A sub-basins, which contain substantial glacier coverage in their headwaters.

## 4.6 Data Gaps

Within the two clusters, the significant WSC hydrometric records are approximately evenly distributed, with Cluster A containing 11 sites and Cluster B containing 12 (Appendix C: Hydrometric Station Cluster Statistics). However, of the active WSC hydrometric stations, six are within Cluster A while only 1 (Kootenay River at Kootenay Crossing) was located within Cluster B, and this site did not even have complete agreement between clustering algorithms. This is additionally noteworthy since the Kootenay River is the third largest sub-basin in the cluster (425 $km^2$), and all smaller sub-basins are under 93 $km^2$. This highlights that streamflow in small sub-basins, which make up the majority of Cluster B, is not actively measured. Conversely, drainage area for actively measured sub-basins in Cluster A range from 79 to 9,682 $km^2$.

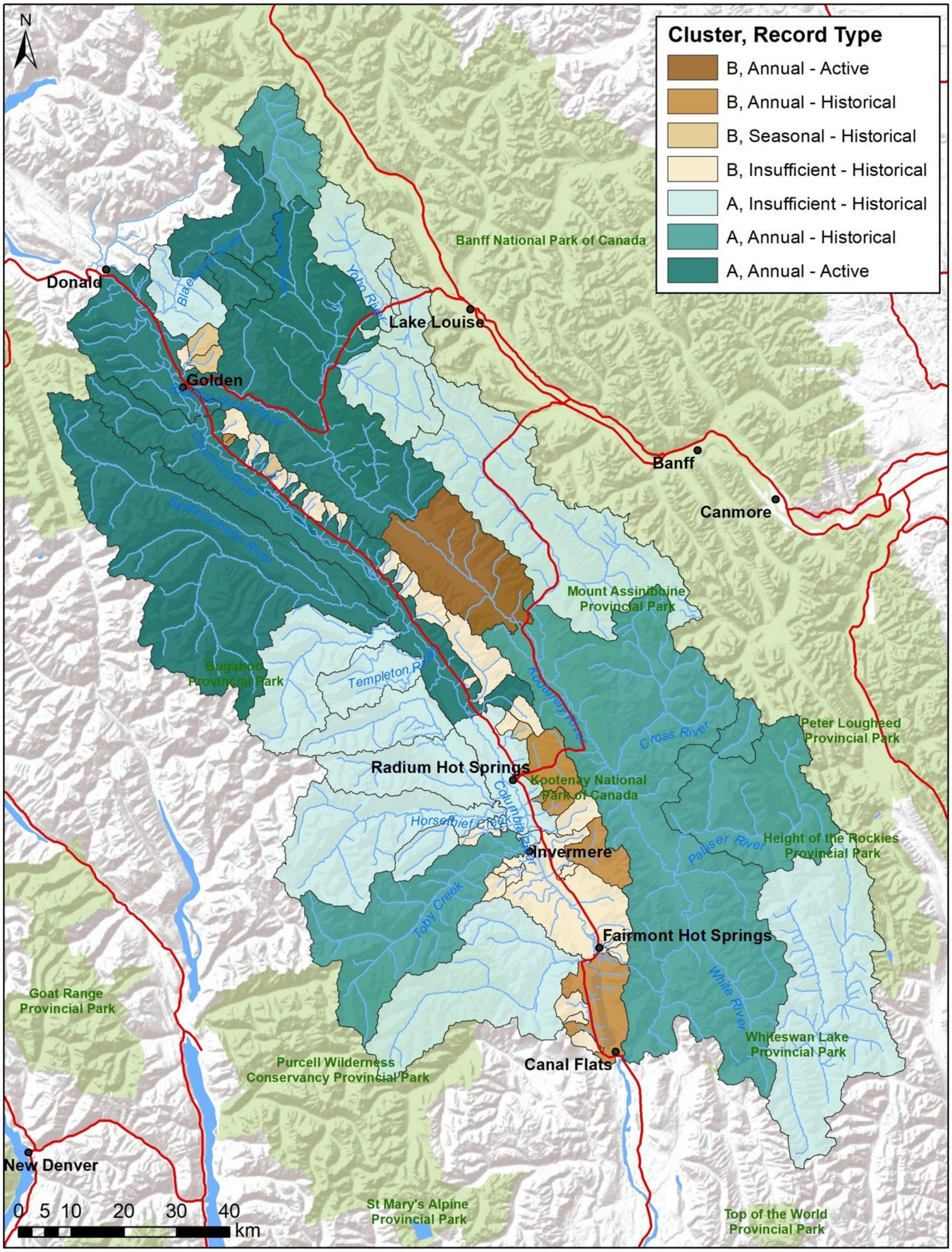


**Figure 17. Map of WSC sub-basins coloured by cluster and data availability, with darker colours indicating more hydrometric data available.**

The lack of long-term, active records in Cluster B emphasizes a relative bias in the types of Columbia River watershed tributaries that are measured. Specifically, there is a limited number of streamflow monitoring stations, and none active, that monitor the many small tributaries that drain the sidewalls of the Rocky Mountain Trench. While these streams contribute relatively little water to the watershed, they could potentially have important local environmental effects. In particular, while Isolated wetlands have low correlations with observed streamflow, this record is almost entirely composed of observations from Cluster A. As such, we cannot test the correlations between Cluster B sub-basins and nearby Isolated wetlands. It is unclear whether there are direct connections between these sub-basins and Isolated wetlands, or there is some degree of connectivity through groundwater, or even if flows and water levels are correlated due to sharing similar climate forcing. Future monitoring of these sub-basins may provide further clarity on these local-scale processes. In addition, the lack of monitoring in Cluster B sub-basins does highlight a lack of monitoring for small tributaries above the Rocky Mountain Trench and Columbia River Valley, and a general lack of understanding of the hydrological regime in Cluster B. These smaller systems provide important habitat for fish and wildlife, and are an important source of water for irrigation as well as domestic use.

Finally, comparison between the variables from the WSC and comprehensive (5 $km^2$) sub-basin datasets suggests that while the sites that have been sampled roughly emulate the conditions in the region, they do not capture the full range of natural variability. In particular, WSC sub-basins do not capture the most extreme regions; both in terms of high alpine, cold, glaciated sub-basins, and in the smallest, warmest tributaries in the Rocky Mountain Trench and Columbia River Valley.

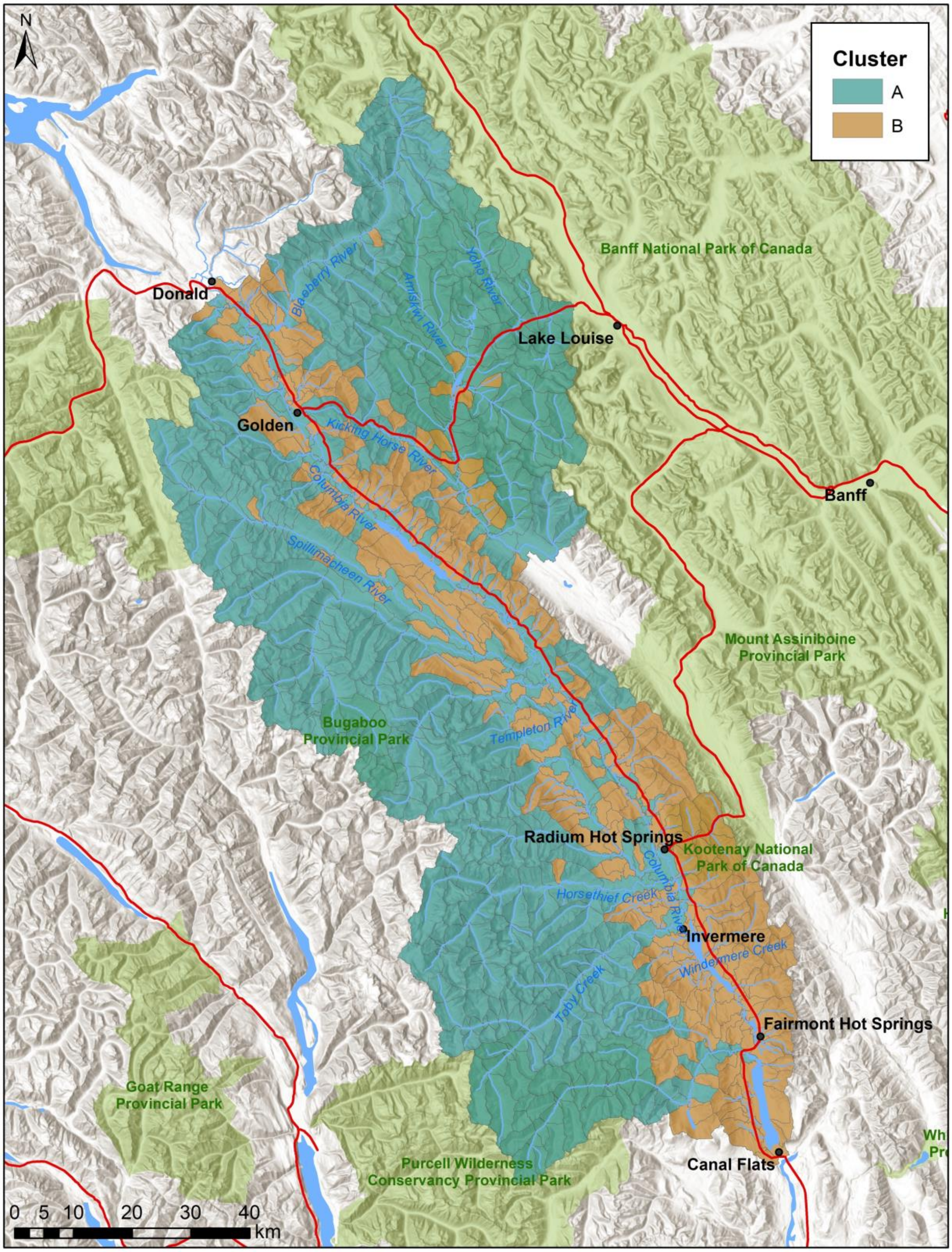


**Figure 18. Map of comprehensive (5 km$^2$) sub-basins, with Cluster A along high-elevation portions of the watershed, and Cluster B on sidewall tributaries in the Columbia Valley.**

# 5 Limitations and Recommendations

## 5.1 Limitations

While the analyses presented here provide a high-level overview of the hydrologic conditions, data availability, and sub-basin types in the upper Columbia River watershed, there are several limitations that should be noted. In some cases, more refined, small-scale analyses, additional data collection, or enhanced monitoring would improve the reliability of these analyses.

We note, critically, that this analysis was completed using Water Survey of Canada hydrometric gauge sites to determine which sub-basins to analyze. This selection is somewhat arbitrary and relies on the initial WSC gauge site selection being representative of differing streamflow regimes and the most important inflows for the study region. While this presents an important initial assessment of regional hydrology, future analyses could be refined by focusing on sub-basins that are more representative of a specific goal (i.e. further understand wetland function).

We note that our examination of wetland water levels is limited by a short record of only two summer seasons. There is potentially substantial inter-annual variability between wetland water levels and more years of monitoring would allow for a more refined understanding of their hydrological regime. This is particularly pertinent given that neither year had substantial overbank flooding. Furthermore, while in this analysis we have assumed that all wetlands function in a binary way (i.e. either Isolated or Drained), it is likely that there is more variability between wetlands than currently observed in this limited dataset. As such, we caution against wide-ranging assumptions based on this initial analysis.

We note that the parameter set ultimately used in clustering routines was limited by data availability. For instance, some hydrologic indicators, most notably annual runoff, peak flow, or some measure of streamflow variability, would have been useful parameters to cluster sub-basins. However, the lack of significant, representative, and overlapping streamflow records for two-thirds of the sub-basins meant that reliable statistics were unavailable. In addition, streamflow data for all but the seven active hydrometric stations were limited, with significant periods without data collection and non-overlapping periods of record between sites. This limits the ability to compare hydrologic values between sites (for instance comparing runoff between sub-basins) or to identify long-term trends.

While the parameter set used in the clustering routines was initially limited by data availability, it was also ultimately selected in order to best represent runoff from each sub-basin. This choice was made given that runoff was well correlated with some wetland water levels. However, this methodology remains flexible and could be adapted to accommodate a different goal (i.e. peak runoff, low flows, etc.). However, we note that this could potentially lead to different parameter sets and subsequently clustering outputs for the sub-basins.

Climate change projections supplied in this report are, by design, coarse and high level. These projections consider a large spatial scale; examining relatively large sub-basins that could contain over 2000 m of vertical relief, and temporal scale; considering averaged 30-year future periods. While these projections provide an overview of major processes in the water balance (precipitation, snowmelt, evaporation) for the region, these changes are not linked directly to future streamflow projections. In order to provide these more refined hydrological projections, we recommend applying a (quasi-)physically based hydrological model to consider future climate impacts on streamflow. Finally, these future conditions only consider how climate may affect future streamflow and does not consider other integral components such as future land use, landscape change, and water use. For example, future projections of forest disturbances, in particular increased forest harvest and natural disturbance (increased pest and fire regimes), as well as continued glacier retreat, could have profound effects on the timing and magnitude of streamflow. These changes could be additionally examined through hydrological modelling and the effect of each factor could be estimated individually as well as cumulatively.

## 5.2 Recommendations and future work

In order to refine the high-level assessment completed here, we recommend the following actions to improve hydrologic understanding in the upper Columbia River watershed:

- Identify regions, sub-basins, or sub-basin types of concern. Watersheds are currently delineated based on historical, sometimes dated, WSC stations and by arbitrary 5 $km^2$ basin sizes. This analysis could focus strategically on specific points of concern to provide more refined or small-scale results.
- Determine if streamflow records for Cluster B are important data for hydrological understanding in the region, and if so, identify sub-basins where monitoring, including a hydrometric station, could be installed. This could be supported by existing or additional clustering work. While we have found that two clusters provided the most optimal and parsimonious model, future clustering could be informed by a desired number of clusters based on external factors such as study design, conceptual understanding, or monitoring budget and logistics.
- Quantify water use (irrigation, municipal, other industrial uses) in the watershed, and determine what percentage of current and future streamflow is allocated and whether this allocation is sustainable.
- Quantify the hydrologic regime of smaller watersheds using a physically based hydrological model and examine the cumulative effects of land cover and climate change on the hydrology of region. Examine whether changes in average or extreme flows are expected and how this will impact human and ecological communities, especially the future survival of the wetlands

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## Appendix A: Correlation Matrix

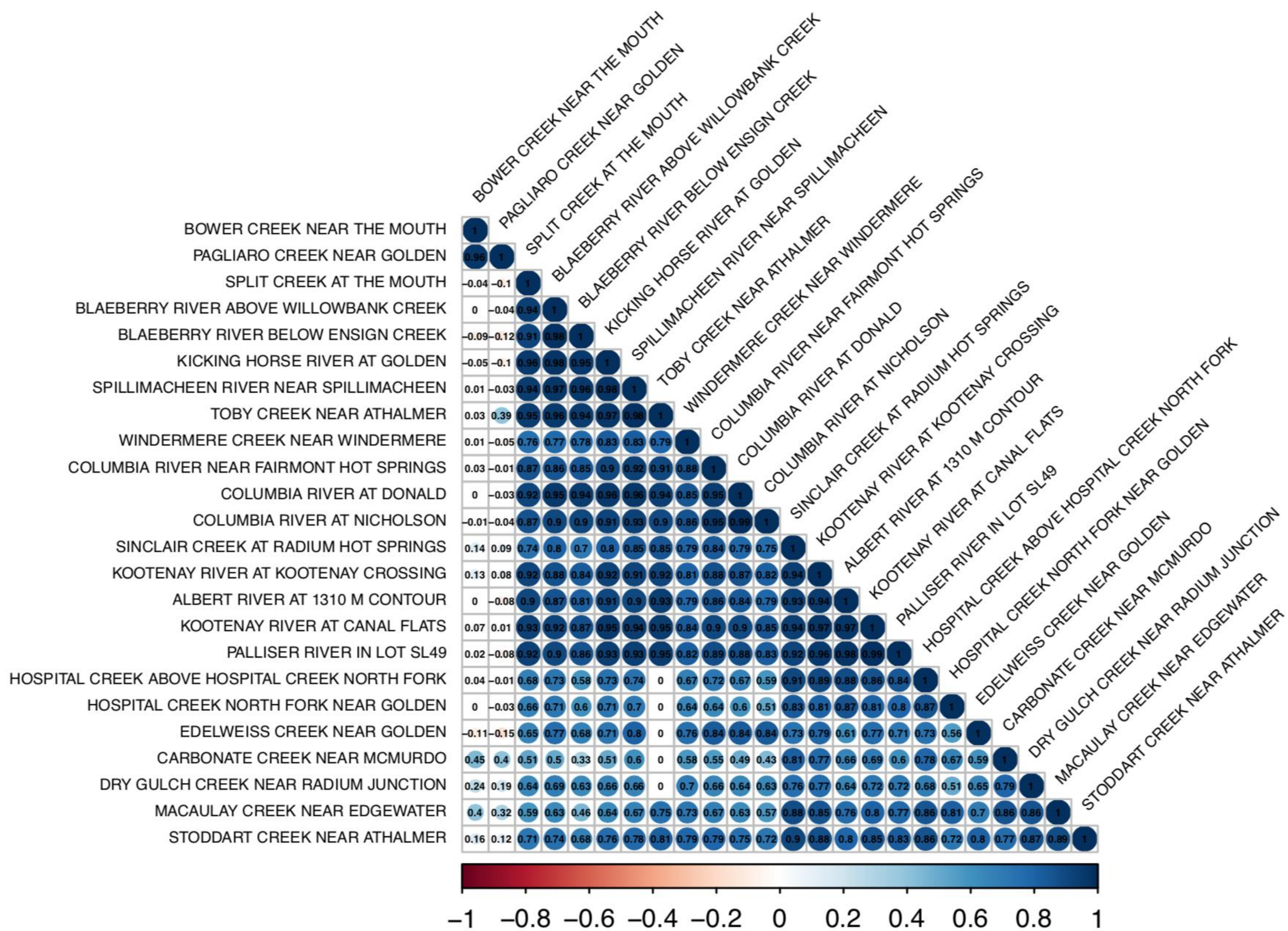


**Figure 19. Correlation matrix for daily streamflow between all WSC hydrometric stations with significant records.**

# Appendix B: WSC Sub-Basin Statistics Histograms

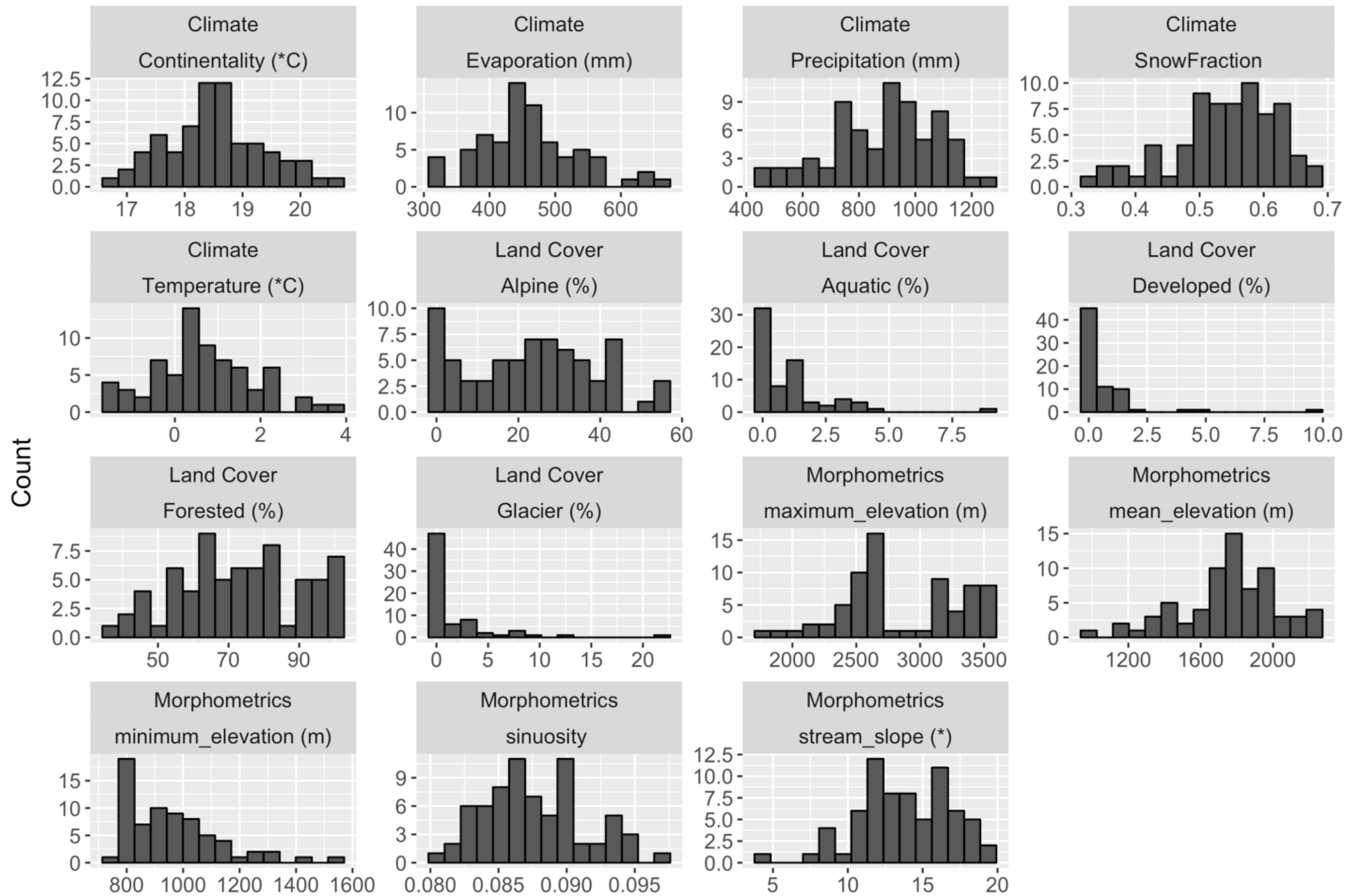


**Figure 20. Histograms of climate, land cover, and morphometric statistics for all WSC hydrometric stations identified in the upper Columbia and upper Kootenay River watersheds.**

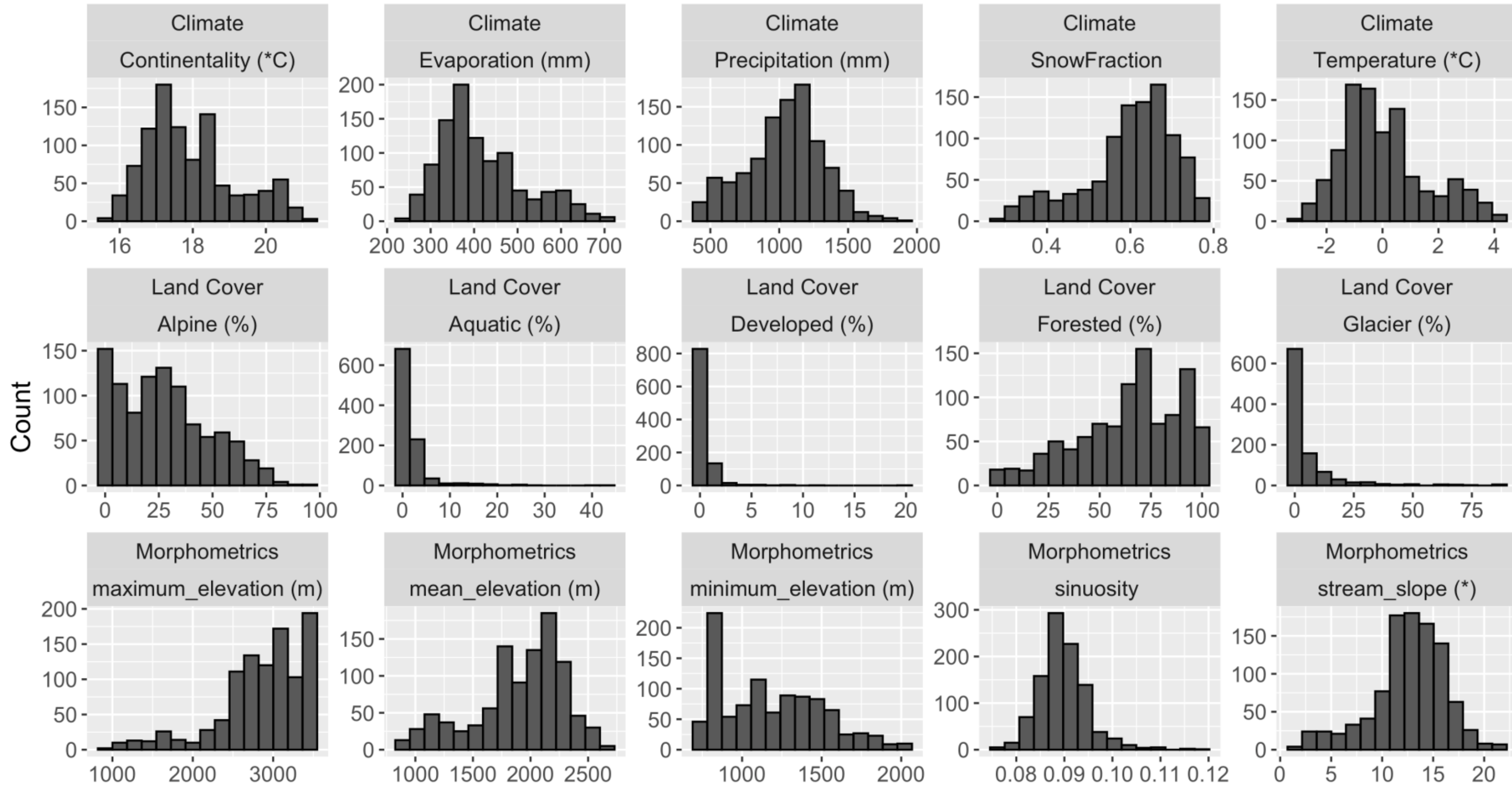


**Figure 21. Histograms of climate, land cover, and morphometric statistics for all 991 sub-basins greater than 5 km$^2$ identified in the upper Columbia River watershed.**

# Appendix C: Hydrometric Station Cluster Statistics

**Table 3. Historical and current WSC hydrometric stations in the upper Columbia River and Kootenay River watersheds, sorted by cluster. *Italicized* stations contain active records.**

| Station Name | Station Number | Drainage Area (km²) | Year From | Year To | Complete Summers | Complete Years | Record Type |
|---|---|---|---|---|---|---|---|
| ***Cluster A*** | | | | | | | |
| *COLUMBIA RIVER AT DONALD* | *08NB005* | *9,682* | *1944* | *2019* | *58* | *58* | *Annual - Active* |
| *COLUMBIA RIVER AT NICHOLSON* | *08NA002* | *6,652* | *1903* | *2019* | *57* | *57* | *Annual - Active* |
| KOOTENAY RIVER AT CANAL FLATS | 08NF002 | 5,387 | 1939 | 1995 | 31 | 31 | Annual - Historical |
| COLUMBIA RIVER NEAR EDGEWATER | 08NA052 | 3,554 | 1948 | 1956 | 0 | 0 | Insufficient - Historical |
| COLUMBIA RIVER NEAR ATHALMER | - | 2,029 | - | - | 0 | 0 | Insufficient - Historical |
| *KICKING HORSE RIVER AT GOLDEN* | *08NA006* | *1,842* | *1911* | *2019* | *43* | *43* | *Annual - Active* |
| *SPILLIMACHEEN RIVER NEAR SPILLIMACHEEN* | *08NA011* | *1,456* | *1912* | *2019* | *48* | *48* | *Annual - Active* |
| WHITE RIVER NEAR CANAL FLATS | 08NF003 | 1,009 | 1940 | 1948 | 0 | 0 | Insufficient - Historical |
| VERMILION RIVER NEAR RADIUM HOT SPRINGS | 08NF004 | 986 | 1946 | 1956 | 0 | 0 | Insufficient - Historical |
| BLAEBERRY RIVER NEAR GOLDEN | 08NB001 | 738 | 1911 | 1969 | 0 | 0 | Insufficient - Historical |
| DUTCH CREEK NEAR FAIRMONT HOT SPRINGS | 08NA014 | 675 | 1912 | 1937 | 0 | 0 | Insufficient - Historical |
| TOBY CREEK NEAR ATHALMER | 08NA012 | 668 | 1912 | 1984 | 6 | 6 | Annual - Historical |
| PALLISER RIVER IN LOT SL49 | 08NF006 | 667 | 1971 | 1995 | 22 | 22 | Annual - Historical |
| HORSETHIEF CREEK NEAR WILMER | 08NA005 | 601 | 1912 | 1954 | 0 | 0 | Insufficient - Historical |
| *BLAEBERRY RIVER ABOVE WILLOWBANK CREEK* | *08NB012* | *586* | *1970* | *2019* | *45* | *45* | *Annual - Active* |
| FORSTER CREEK NEAR WILMER | 08NA009 | 515 | 1912 | 1922 | 0 | 0 | Insufficient - Historical |
| BUGABOO CREEK NEAR SPILLIMACHEEN | 08NA001 | 375 | 1912 | 1956 | 0 | 0 | Insufficient - Historical |
| KICKING HORSE RIVER NEAR FIELD | 08NA007 | 337 | 1912 | 1921 | 0 | 0 | Insufficient - Historical |
| OTTERTAIL RIVER NEAR FIELD | 08NA010 | 234 | 1912 | 1913 | 0 | 0 | Insufficient - Historical |
| BLAEBERRY RIVER BELOW ENSIGN CREEK | 08NB015 | 232 | 1973 | 1998 | 22 | 22 | Annual - Historical |
| FRANCES CREEK NEAR WILMER | 08NA051 | 226 | 1946 | 1954 | 0 | 0 | Insufficient - Historical |

| Station Name | Station Number | Drainage Area (km²) | Year From | Year To | Complete Summers | Complete Years | Record Type |
|---|---|---|---|---|---|---|---|
| TEMPLETON RIVER NEAR BRISCO | 08NA049 | 162 | 1946 | 1951 | 0 | 0 | Insufficient - Historical |
| KICKING HORSE RIVER AT NO. 2 TUNNEL | 08NA008 | 121 | 1912 | 1921 | 0 | 0 | Insufficient - Historical |
| KICKING HORSE RIVER BELOW SHERBROOKE CREEK | 08NA053 | 117 | 1952 | 1998 | 0 | 0 | Insufficient - Historical |
| BRUCE CREEK NEAR WILMER | 08NA060 | 80 | 1921 | 1977 | 0 | 0 | Insufficient - Historical |
| *SPLIT CREEK AT THE MOUTH* | *08NB016* | *79* | *1973* | *2019* | *41* | *41* | *Annual - Active* |
| ALBERT RIVER AT 1310 M CONTOUR | 08NF005 | 68 | 1972 | 1999 | 26 | 26 | Annual - Historical |
| FIELD SPRING (NO. 1) NEAR FIELD | 08NA015 | 6 | 1914 | 1915 | 0 | 0 | Insufficient - Historical |
| ***Cluster B*** | | | | | | | |
| COLUMBIA RIVER AT ATHALMER | 08NA004 | 1,352 | 1912 | 1984 | 0 | 0 | Insufficient - Historical |
| COLUMBIA RIVER NEAR FAIRMONT HOT SPRINGS | 08NA045 | 881 | 1937 | 1998 | 36 | 36 | Annual - Historical |
| *KOOTENAY RIVER AT KOOTENAY CROSSING* | *08NF001* | *425* | *1939* | *2019* | *58* | *58* | *Annual - Active* |
| SINCLAIR CREEK AT RADIUM HOT SPRINGS | 08NA018 | 93 | 1914 | 1978 | 18 | 17 | Annual - Historical |
| LUXOR CREEK NEAR BRISCO | 08NA021 | 92 | 1911 | 1929 | 0 | 0 | Insufficient - Historical |
| WINDERMERE CREEK NEAR WINDERMERE | 08NA024 | 84 | 1914 | 1979 | 20 | 20 | Annual - Historical |
| HOSPITAL CREEK NEAR GOLDEN | 08NB002 | 55 | 1914 | 1964 | 0 | 0 | Insufficient - Historical |
| SHUSWAP CREEK NEAR ATHALMER | 08NA019 | 40 | 1914 | 1927 | 0 | 0 | Insufficient - Historical |
| GOLDIE CREEK NEAR INVERMERE | 08NA026 | 32 | 1920 | 1966 | 0 | 0 | Insufficient - Historical |
| FRALING CREEK NEAR SPILLIMACHEEN | 08NA023 | 32 | 1912 | 1943 | 0 | 0 | Insufficient - Historical |
| HOSPITAL CREEK NORTH FORK NEAR GOLDEN | 08NB009 | 26 | 1965 | 1976 | 7 | 0 | Seasonal - Historical |
| MARION CREEK NEAR CANAL FLATS | 08NA062 | 25 | 1967 | 1971 | 0 | 0 | Insufficient - Historical |
| KINDERSLEY CREEK NEAR BRISCO | 08NA022 | 24 | 1911 | 1929 | 0 | 0 | Insufficient - Historical |
| HORSE CREEK NEAR GOLDEN | 08NA041 | 22 | 1912 | 1931 | 0 | 0 | Insufficient - Historical |
| STODDART CREEK NEAR ATHALMER | 08NA020 | 21 | 1913 | 1982 | 12 | 10 | Annual - Historical |
| HOSPITAL CREEK ABOVE HOSPITAL CREEK NORTH FORK | 08NB010 | 21 | 1965 | 1976 | 8 | 0 | Seasonal - Historical |
| HOGRANCH CREEK AT PARSON | 08NA038 | 20 | 1912 | 1930 | 0 | 0 | Insufficient - Historical |
| WILMER CREEK NEAR WILMER | 08NA057 | 19 | 1964 | 1969 | 0 | 0 | Insufficient - Historical |

| Station Name | Station Number | Drainage Area (km$^2$) | Year From | Year To | Complete Summers | Complete Years | Record Type |
|---|---|---|---|---|---|---|---|
| GOLDIE CREEK (SOUTH FORK) NEAR INVERMERE | 08NA055 | 17 | 1961 | 1970 | 0 | 0 | Insufficient - Historical |
| BIRCHLANDS CREEK NEAR GOLDEN | 08NA029 | 17 | 1930 | 1931 | 0 | 0 | Insufficient - Historical |
| COLUMBIA LAKE AT CANAL FLATS | NA | 14 | NA | NA | 0 | 0 | Insufficient - Historical |
| CEDARED CREEK NEAR SPILLIMACHEEN | 08NA047 | 13 | 1913 | 1947 | 0 | 0 | Insufficient - Historical |
| HATCH CREEK NEAR SPILLIMACHEEN | 08NA048 | 12 | 1925 | 1950 | 0 | 0 | Insufficient - Historical |
| SIXTY TWO MILE CREEK NEAR EDGEWATER | 08NA050 | 11 | 1947 | 1950 | 0 | 0 | Insufficient - Historical |
| CARBONATE CREEK NEAR MCMURDO | 08NA037 | 10 | 1912 | 1998 | 16 | 0 | Seasonal - Historical |
| HOTSPRING CREEK NEAR FAIRMONT HOT SPRINGS | 08NA058 | 10 | 1913 | 1969 | 0 | 0 | Insufficient - Historical |
| WARM SPRINGS CREEK NEAR FAIRMONT | 08NA031 | 10 | 1924 | 1926 | 0 | 0 | Insufficient - Historical |
| MACAULAY CREEK NEAR EDGEWATER | 08NA039 | 10 | 1913 | 1980 | 6 | 0 | Seasonal - Historical |
| UNNAMED CREEK NEAR MCMURDO | 08NA061 | 9 | 1963 | 1964 | 0 | 0 | Insufficient - Historical |
| SOLES CREEK NEAR GALENA | 08NA046 | 9 | 1945 | 1948 | 0 | 0 | Insufficient - Historical |
| COOLSPRING CREEK NEAR FAIRMONT HOT SPRINGS | 08NA030 | 8 | 1924 | 1964 | 0 | 0 | Insufficient - Historical |
| BEARD CREEK NEAR PARSON | 08NA036 | 6 | 1912 | 1968 | 0 | 0 | Insufficient - Historical |
| EAST SPRING CREEK NEAR WINDERMERE | 08NA043 | 6 | 1940 | 1941 | 0 | 0 | Insufficient - Historical |
| MARION CREEK (WEST FORK) NEAR CANAL FLATS | 08NA063 | 6 | 1967 | 1971 | 0 | 0 | Insufficient - Historical |
| QUINN CREEK NEAR CASTLEDALE | 08NA028 | 6 | 1930 | 1931 | 0 | 0 | Insufficient - Historical |
| MALLARD CREEK NEAR PARSON | 08NA025 | 5 | 1913 | 1931 | 0 | 0 | Insufficient - Historical |
| JOHNSON DRAW CREEK NEAR MCMURDO | NA | 5 | NA | NA | 0 | 0 | Insufficient - Historical |
| PAGLIARO CREEK NEAR GOLDEN | 08NA068 | 5 | 1972 | 1978 | 6 | 6 | Annual - Historical |
| DRY GULCH CREEK NEAR RADIUM JUNCTION | 08NA056 | 4 | 1963 | 1974 | 10 | 9 | Annual - Historical |
| SUNLIGHT CREEK NEAR INVERMERE | 08NA054 | 4 | 1912 | 1961 | 0 | 0 | Insufficient - Historical |
| MCCREADY CREEK NEAR BRISCO | 08NA042 | 4 | 1931 | 1931 | 0 | 0 | Insufficient - Historical |
| BOWER CREEK NEAR THE MOUTH | 08NA067 | 2 | 1972 | 1982 | 10 | 10 | Annual - Historical |

# Appendix D: Spatial Datasets

Footprint types include agriculture, built-up, mines, railways, recreation areas, roads, trails, and transmission infrastructure (Table 4). Buffers were applied to linear footprint types – 7.5 m buffer on paved roads, 2.5 m buffer on non-paved roads, 12.5 m on railways and transmission lines, 2.5 m buffer around built-up dams, and 10 m buffer around trails.

**Table 4. Landcover feature type and associated hierarchy.**

| Feature Type | Hierarchy |
|---|---|
| Mining (includes aggregates) | 1 |
| Built Up Areas (includes urban, rural, airstrips, waste disposal) | 2 |
| Roads | 3 |
| Railway | 4 |
| Transmission Lines | 5 |
| Rec Sites | 6 |
| Trails/Cutlines | 7 |
| Agriculture | 8 |
| Landscape features | 9 |

A more detailed table of the various footprint features and their data sources is included in Table 5 below.

**Table 5. Data sources for various footprint feature types. NB: Some features are listed multiple times, as they have multiple sources of data.**

| Group | Source File Description | Feature Type | Source Link | Query: |
|---|---|---|---|---|
| **Agriculture** | Agriculture Land Use | Polygon | https://catalogue.data.gov.bc.ca/dataset/baseline-thematic-mapping-present-land-use-version-1-spatial-layer | PLU_LABEL = 'Agriculture' |
| **Agriculture** | AAFC Crop Data | Raster | http://www.agr.gc.ca/atlas/data_donnees/agr/annualCropInventory/tif/ | gridcode >= 120 AND gridcode < 200 |
| **Built UP** | Canvec Airstrips | Polygon | http://ftp.maps.canada.ca/pub/nrcan_rncan/vector/canvec/fgdb/Transport/ | n/a |
| **Built UP** | Canvec Dams | Polygon | http://ftp.maps.canada.ca/pub/nrcan_rncan/vector/canvec/fgdb/ManMade/ | n/a |
| **Built UP** | DataBC Dams | Line | https://catalogue.data.gov.bc.ca/dataset/b-c-dams | n/a |
| **Built UP** | Canvec Waste Facilities | Polygon | http://ftp.maps.canada.ca/pub/nrcan_rncan/vector/canvec/fgdb/ManMade/ | n/a |

| | | | | |
|---|---|---|---|---|
| **Built UP** | Urban Land Use | Polygon | https://catalogue.data.gov.bc.ca/dataset/baseline-thematic-mapping-present-land-use-version-1-spatial-layer | PLU_LABEL = 'Urban' |
| **Built UP** | Urban from Parcel Fabric | Polygon | https://catalogue.data.gov.bc.ca/dataset/parcelmap-bc-parcel-fabric | (PARCEL_CLASS = 'Subdivision' AND OWNER_TYPE = 'Private') AND FEATURE_AREA_SQM <30000 |
| **Dams** | Hydro Dams | Line | https://catalogue.data.gov.bc.ca/dataset/b-c-dams | n/a |
| **Mining** | Canvec Aggregates | Polygon | http://ftp.maps.canada.ca/pub/nrcan_rncan/vector/canvec/fgdb/Res_MGT/ | n/a |
| **Mining** | Canvec Ore | Polygon | http://ftp.maps.canada.ca/pub/nrcan_rncan/vector/canvec/fgdb/Res_MGT/ | n/a |
| **Mining** | Forest Tenure SUP's | Polygon | https://catalogue.data.gov.bc.ca/dataset/forest-tenure-special-use-permit-polygon | SP_USE_DSC = 'Gravel Pit, Rock Quarry' |
| **Railway** | GBA Railway Tracks | Line | https://catalogue.data.gov.bc.ca/dataset/railway-track-line | n/a |
| **Rec Sites** | TANTALIS Rec Sites | Polygon | https://catalogue.data.gov.bc.ca/dataset/tantalis-crown-land-licenses | TNRSTG = 'TENURE' AND "TNRSBTP" = 'LICENCE OF OCCUPATION' AND "TNRPRPS" = 'COMMERCIAL RECREATION' AND "TNRSBPRPS" IN ( 'ECO TOURIST LODGE/RESORT', 'FISH CAMPS', 'HUNT CAMPS', 'HUNTING/FISHING CAMP', 'PRIVATE CAMPS', 'TIDAL SPORTS FISHING CAMPS') |
| **Roads** | Digital Road Atlas Roads | Line | ftp://ftp.geobc.gov.bc.ca/sections/outgoing/bmgs/DRA_Public/ | TRANSPORT_LINE_TYPE_CODE <> 'T' AND TRANSPORT_LINE_TYPE_CODE <> 'TR' AND TRANSPORT_LINE_TYPE_CODE <> 'TS' AND TRANSPORT_LINE_TYPE_CODE <> 'TD' AND TRANSPORT_LINE_TYPE_CODE <> 'RPM' |
| **Roads** | Forest Road Section Lines | Line | https://catalogue.data.gov.bc.ca/dataset/forest-tenure-road-section-lines | n/a |
| **Trails** | Digital Road Atlas Trails | | ftp://ftp.geobc.gov.bc.ca/sections/outgoing/bmgs/DRA_Public/ | TRANSPORT_LINE_TYPE_CODE = 'T' OR TRANSPORT_LINE_TYPE_CODE = 'TR' OR TRANSPORT_LINE_TYPE_CODE = 'TS' OR TRANSPORT_LINE_TYPE_CODE = 'TD' OR TRANSPORT_LINE_TYPE_CODE = 'RPM' |

| | | | | |
|---|---|---|---|---|
| **Trails** | Forest Tenure Rec Lines | Line | https://catalogue.data.gov.bc.ca/dataset/recreation-line | n/a |
| **Trails** | Canvec Trails | Line | http://ftp.maps.canada.ca/pub/nrcan_rncan/vector/canvec/fgdb/Transport/ | |
| **Transmission Lines** | TANTALIS power lines | Polygon | https://catalogue.data.gov.bc.ca/dataset/tantalis-crown-land-rights-of-way | FTRCD ='FA91400110' OR "FTRCD" = 'FA91400140' |
| **Transmission Lines** | Canvec Power Stations | Polygon | http://ftp.maps.canada.ca/pub/nrcan_rncan/vector/canvec/fgdb/Res_MGT/ | n/a |
| **Transmission Lines** | GBA Transmission Lines | Line | https://catalogue.data.gov.bc.ca/dataset/bc-transmission-lines | n/a |

Landscape types include, alpine areas; deciduous, coniferous, and mixedwood forests; exposed areas; snow, ice, or glaciers; lentic and lotic waters; wetlands; rocky areas; and shrubs or herbs. Data for landscape types was mainly derived from the provincial Vegetation Resources Inventory (VRI), while data for water features was derived from the Fresh Water Atlas (FWA). The FWA dataset takes priority over the VRI data when merging into one contiguous landscape layer. Complementary to the landcover dataset, are historical and current fire data, cutblock data, and pest data. Historic and current wildfire polygons were merged into one single layer, identifying each polygon by the most recent fire year and ensuring no overlap between polygons. For the cutblock data, a "Year Logged" identifier was added to each polygon, and the most recent year was kept in instances of overlapping polygons. Finally, reserve areas were eliminated from the overall cutblock area. For pest data, only insect pest types and the severe and very severe classes were kept. Pest polygons were identified by pest age, and more recent polygons were kept in areas of overlap.

A more detailed table of the data sources for landscape features, cutblocks, fires, and pest is included in Table 6 below.

**Table 6. Data sources for various landscape feature types. NB: Some features are listed multiple times, as they have multiple sources of data.**

| Group | Source File Description | Feature Type | Source Link | Query: |
|---|---|---|---|---|
| **Cutblocks** | Reserves from Results | Polygon | https://catalogue.data.gov.bc.ca/dataset/results-forest-cover-reserve | RES_CD <> 'D' AND "RES_CD" <> 'O' |
| **Cutblocks** | Consolidated Cutblocks | Polygon | https://catalogue.data.gov.bc.ca/dataset/harvested-areas-of-bc-consolidated-cutblocks- | n/a |

| | | | | |
|---|---|---|---|---|
| **Cutblocks** | Results Openings | Polygon | https://catalogue.data.gov.bc.ca/dataset/results-openings-svw | n/a |
| **Cutblocks** | Forest Tenure Cutblocks | Polygon | https://catalogue.data.gov.bc.ca/dataset/forest-tenure-cutblock-polygons-fta-4-0 | ("FEAT_CLASS" <> 616 and "FEAT_CLASS" <> 863) AND ("LIFE_ST_CD" <> 'PENDING') AND ("DSTRBNCSTR" <> ' ') |
| **Hydrology** | FWA Streams | Line | https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-stream-network | n/a |
| **Hydrology** | FWA Lakes | Polygon | https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-lakes | n/a |
| **Hydrology** | FWA Large Rivers | Polygon | https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-rivers | n/a |
| **Hydrology** | FWA Wetlands | Polygon | https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-wetlands | n/a |
| **Hydrology** | FWA Manmade Lakes | Polygon | https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-manmade-waterbodies | n/a |
| **Hydrology** | FWA Glaciers | Polygon | https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-glaciers | n/a |
| **Hydrology** | FWA Islands | Polygon | https://catalogue.data.gov.bc.ca/dataset/freshwater-atlas-islands | n/a |
| **Pest Infestations** | Pest Infestations | Polygon | https://catalogue.data.gov.bc.ca/dataset/pest-infestation-polygons | PSTSPCSCD LIKE 'I%' AND PSTSVRTCD in ( 'S' , 'V' ) |
| **Veg Cover** | VRI | Polygon | https://catalogue.data.gov.bc.ca/dataset/vri-forest-vegetation-composite-polygons-and-rank-1-layer | n/a |
| **Wildfires** | Historical Fires | Polygon | https://catalogue.data.gov.bc.ca/dataset/fire-perimeters-historical | n/a |
| **Wildfires** | Current Fires 2018 | Polygon | https://catalogue.data.gov.bc.ca/dataset/fire-perimeters-current | n/a |
| **Pest** | Pest Infestation Polygons | Polygon | https://catalogue.data.gov.bc.ca/dataset/pest-infestation-polygons | n/a |

Finally, summary statistics were run on the different landcover features and provide the outputs below in Table 7.

**Table 7. Summary statistics for feature types (FWA= Fresh Water Atlas, VRI = Vegetation Resource Inventory). The total study area is 9,675 km$^2$.**

| Feature Type | Total Area (ha) | % of total |
|---|---|---|
| Coniferous Forest | 496,810 | 51.35 |
| Alpine | 171,544 | 17.73 |
| Shrub/Herb | 126,360 | 13.06 |
| Rock | 40,279 | 4.16 |
| FWA Glaciers | 28,844 | 2.98 |

| | | |
|---|---|---|
| Mixedwood Forest | 20,722 | 2.14 |
| FWA Lakes | 10,818 | 1.12 |
| FWA Wetlands | 10,931 | 1.13 |
| Agriculture | 10,595 | 1.09 |
| Exposed | 7,830 | 0.81 |
| Roads | 5,875 | 0.61 |
| Unknown | 7,675 | 0.79 |
| FWA Rivers | 5,109 | 0.53 |
| Built-up | 6,983 | 0.72 |
| Deciduous Forest | 5,744 | 0.59 |
| Snow/Ice | 2,407 | 0.25 |
| VRI Wetland | 2,994 | 0.31 |
| VRI Developed | 1,815 | 0.19 |
| VRI Glacier | 1,258 | 0.13 |
| Trails | 763 | 0.08 |
| Transmission | 912 | 0.09 |
| Railway | 507 | 0.05 |
| Mines | 239 | 0.02 |
| VRI Lake | 280 | 0.03 |
| VRI River | 248 | 0.03 |
| Recreation | 2 | 0.00 |

Surficial geology and soils data were also collected as part of this project. Data sources include the Geological Survey of Canada, Soil Landscapes of Canada, and the BC government. See Table 8 below for detailed data sources, and Figure 22 through Figure 32 for layers.

**Table 8. Detailed data sources used in this study.**

| Group | Source File Description | Feature Type | Source Link | Query: |
|---|---|---|---|---|
| *Surficial Geology* | Surficial geology of Canada | Polygon | https://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=295462 | Feature = 'GEOPOLY' |
| *Soils Group* | Soil Landscapes of Canada | Polygon | http://sis.agr.gc.ca/cansis/nsdb/slc/v3.2/index.html | Feature = "G_GROUP2" |
| *Soils Parent Material* | British Columbia Soil Mapping Spatial Data | Polygon | http://www.env.gov.bc.ca/esd/distdata/ecosystems/Soil_Data/SOIL_DATA_FGDB/ | Feature = "PM1_1" |

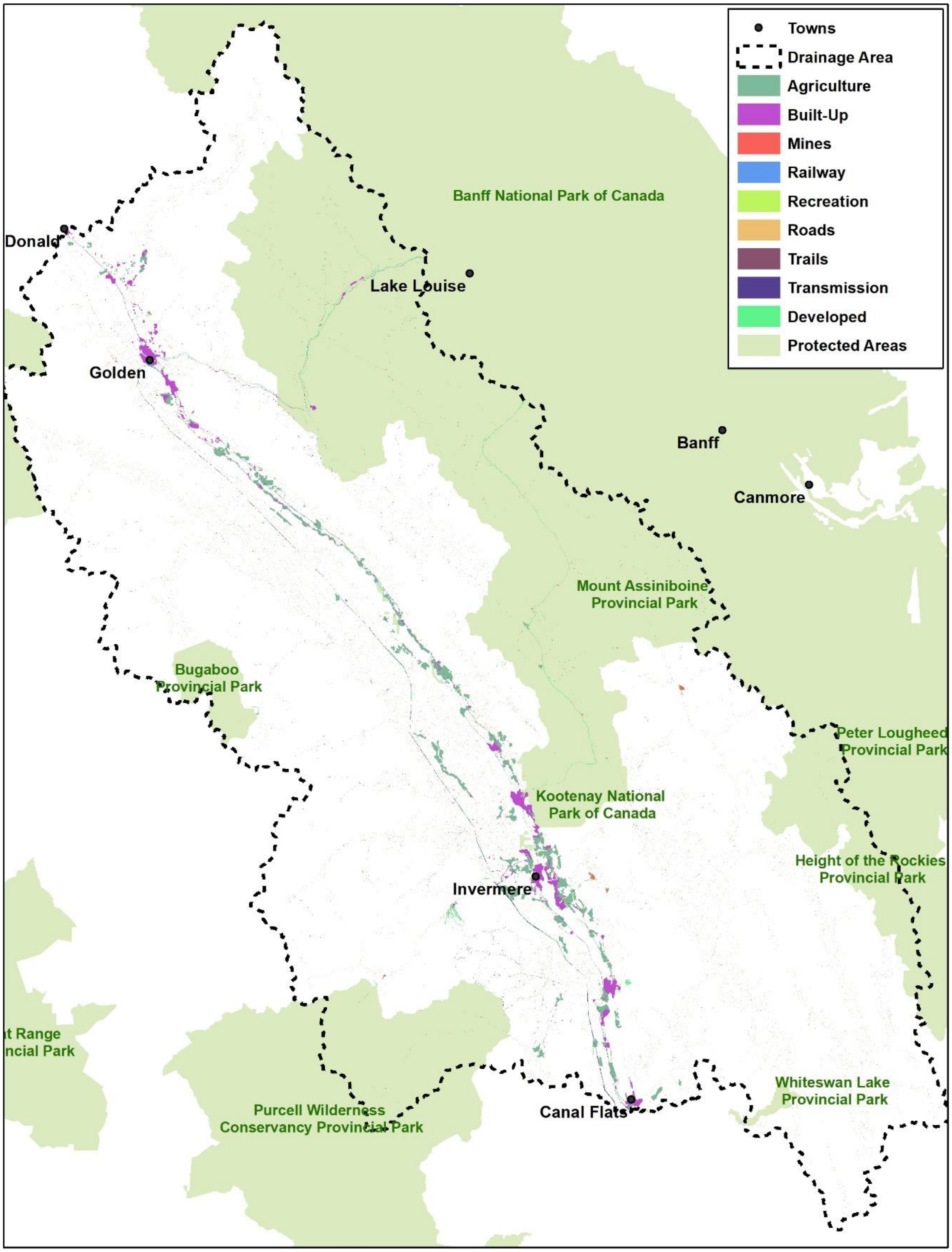


**Figure 22. Footprint types in the Columbia drainage at Donald.**

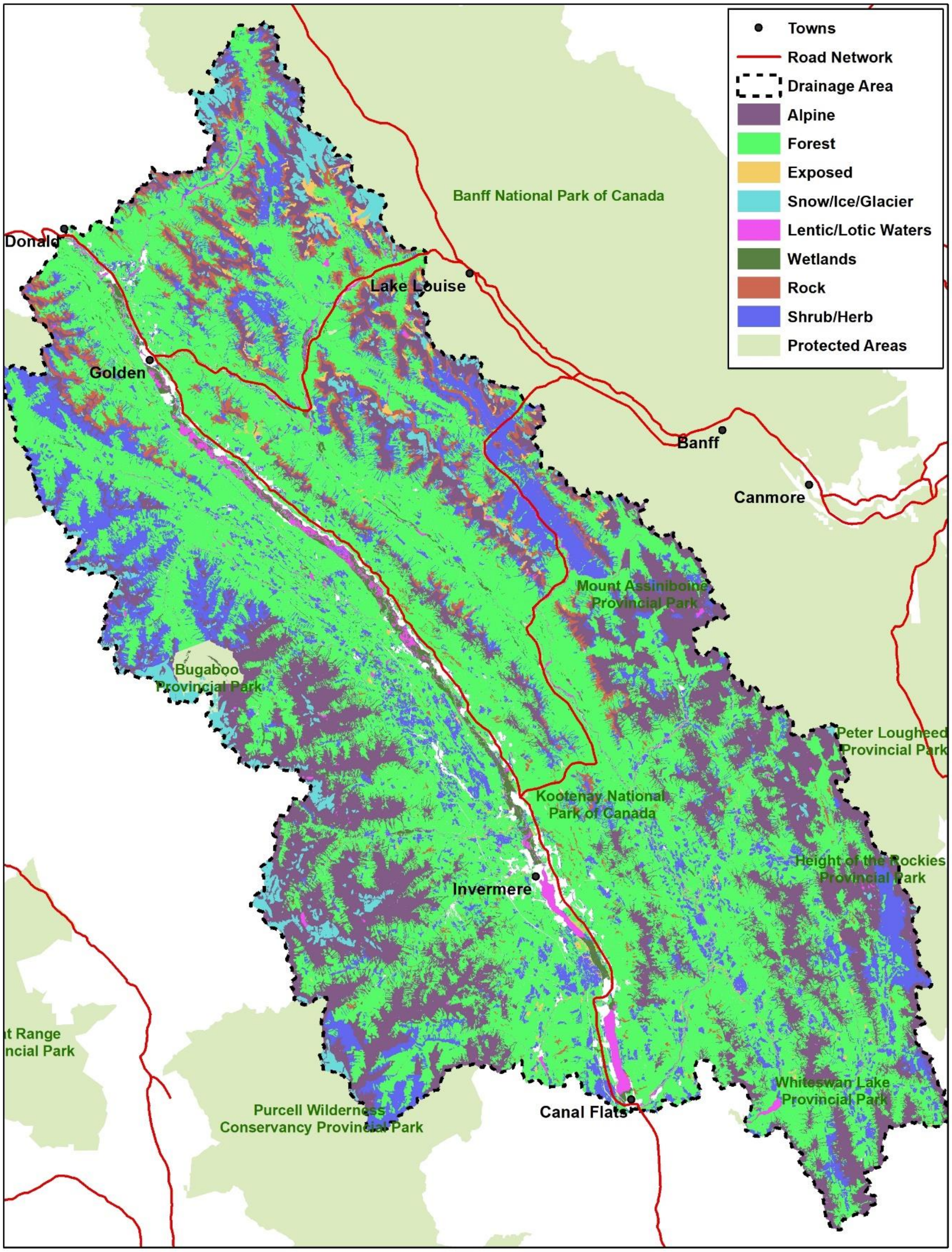


**Figure 23. Natural landscape types in the Columbia drainage at Donald.**

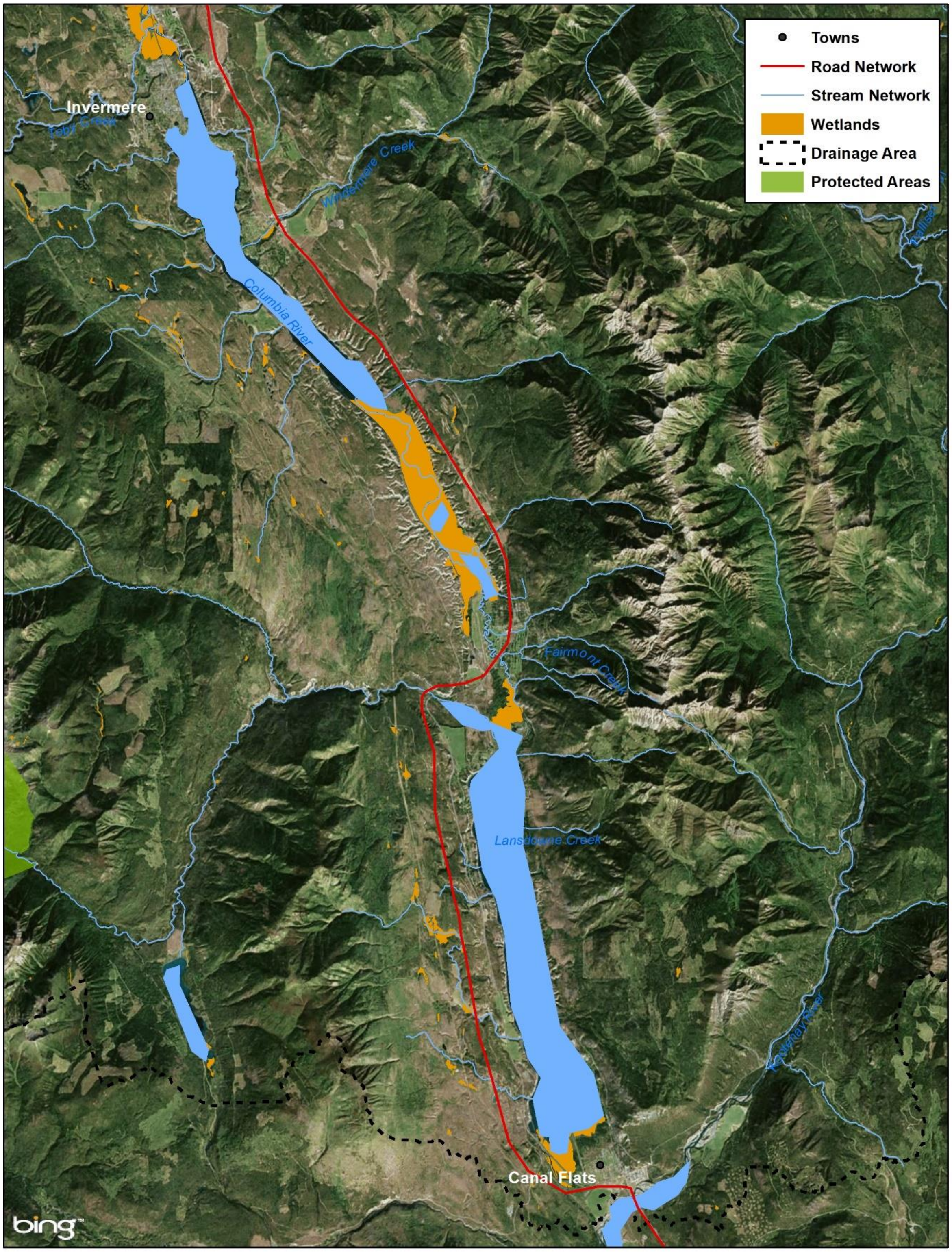


**Figure 24. Wetland coverage from Canal Flats to Invermere.**

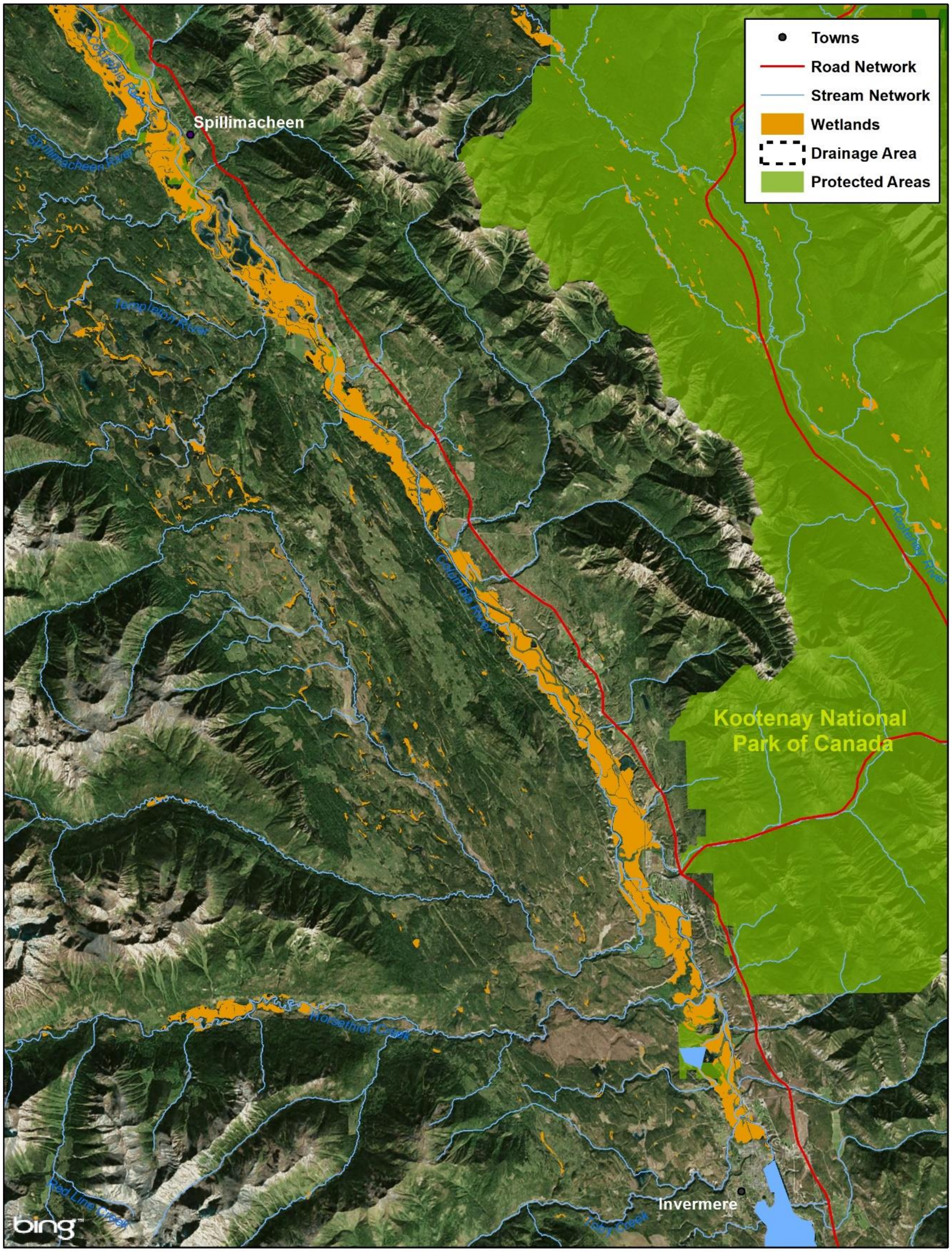


**Figure 25. Wetland coverage from Invermere to Spillimacheen.**

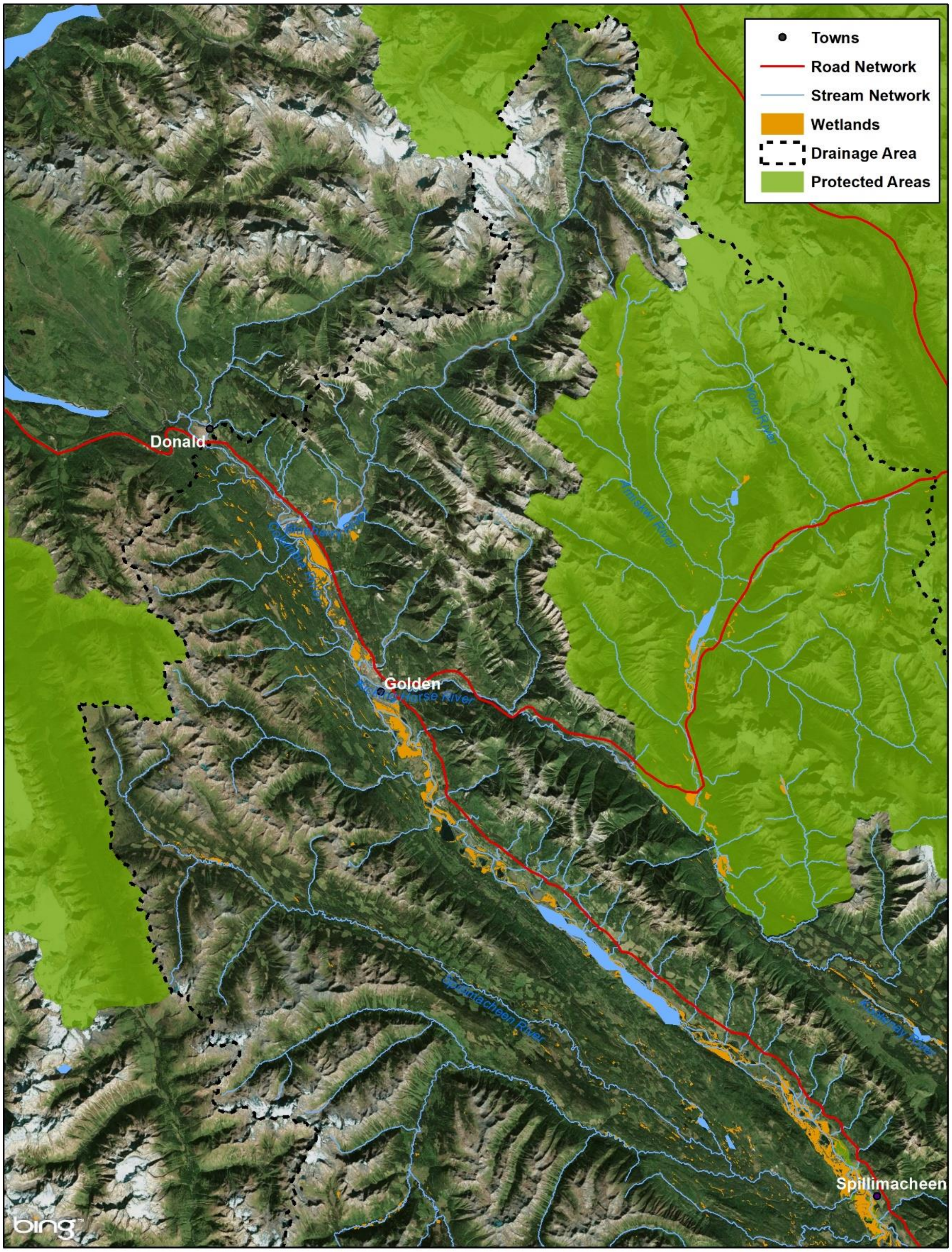


**Figure 26. Wetland coverage from Spillimacheen to Donald.**

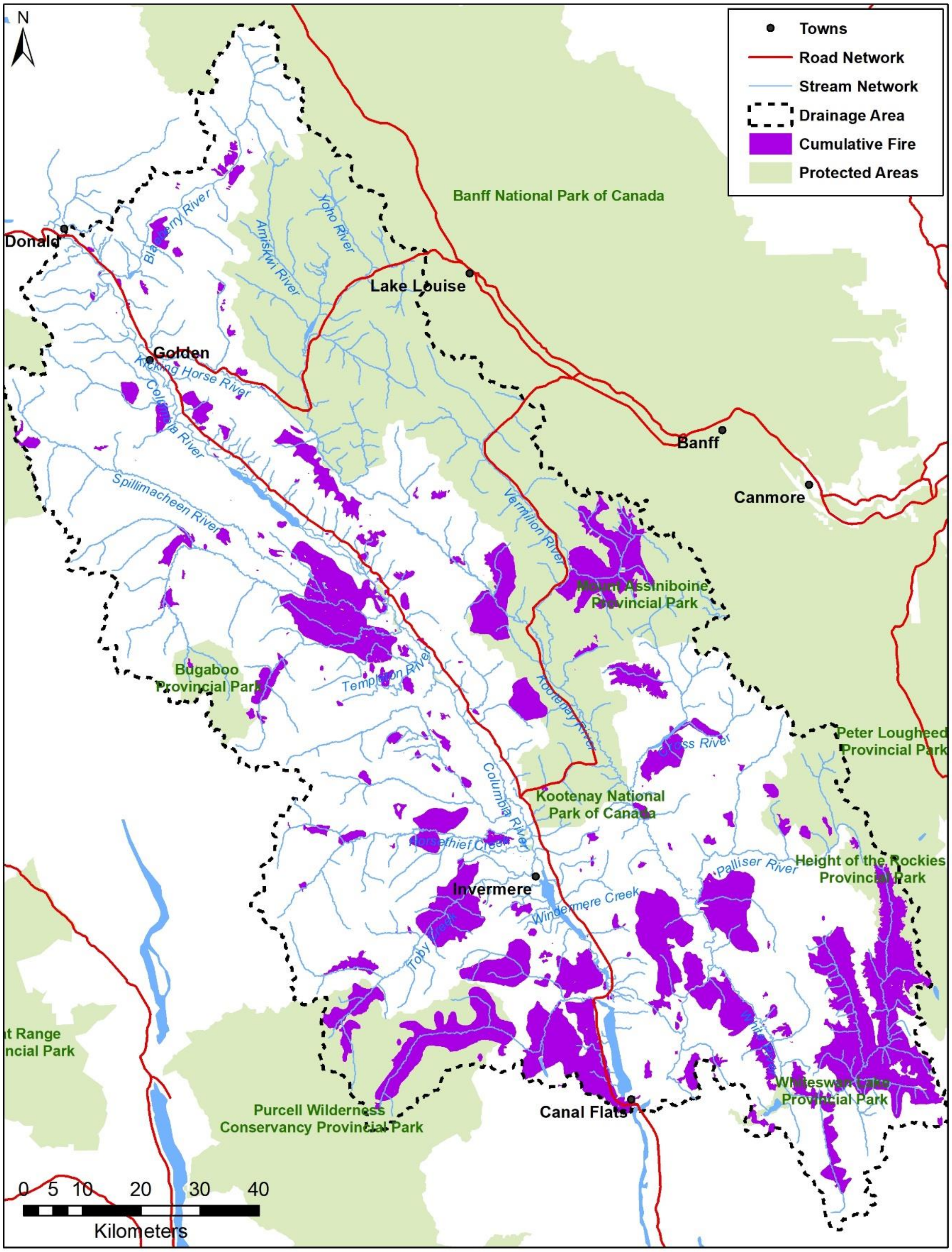


**Figure 27. Cumulative fire footprint in the Columbia drainage at Donald.**

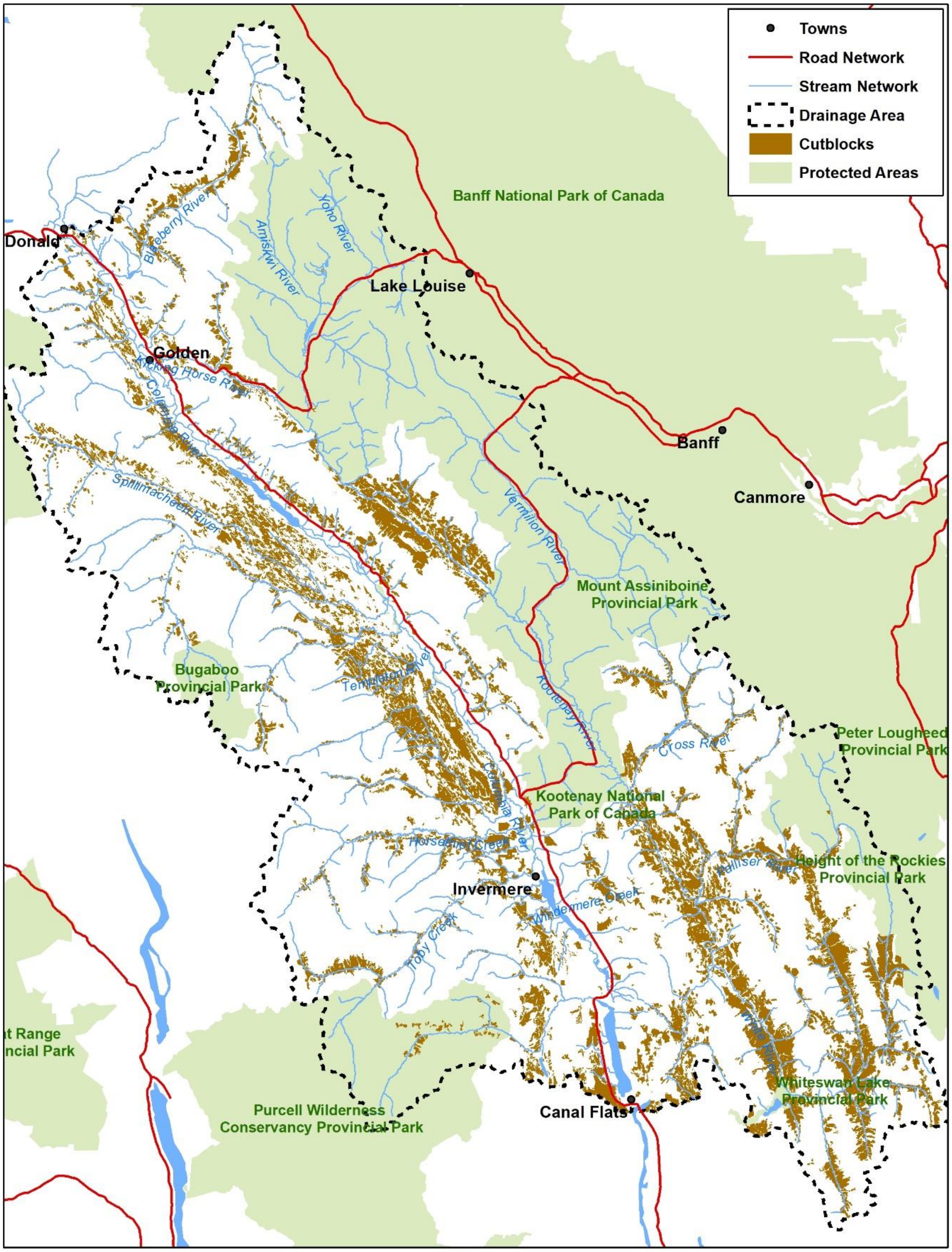


**Figure 28. Cutblock footprint in the Columbia drainage at Donald.**

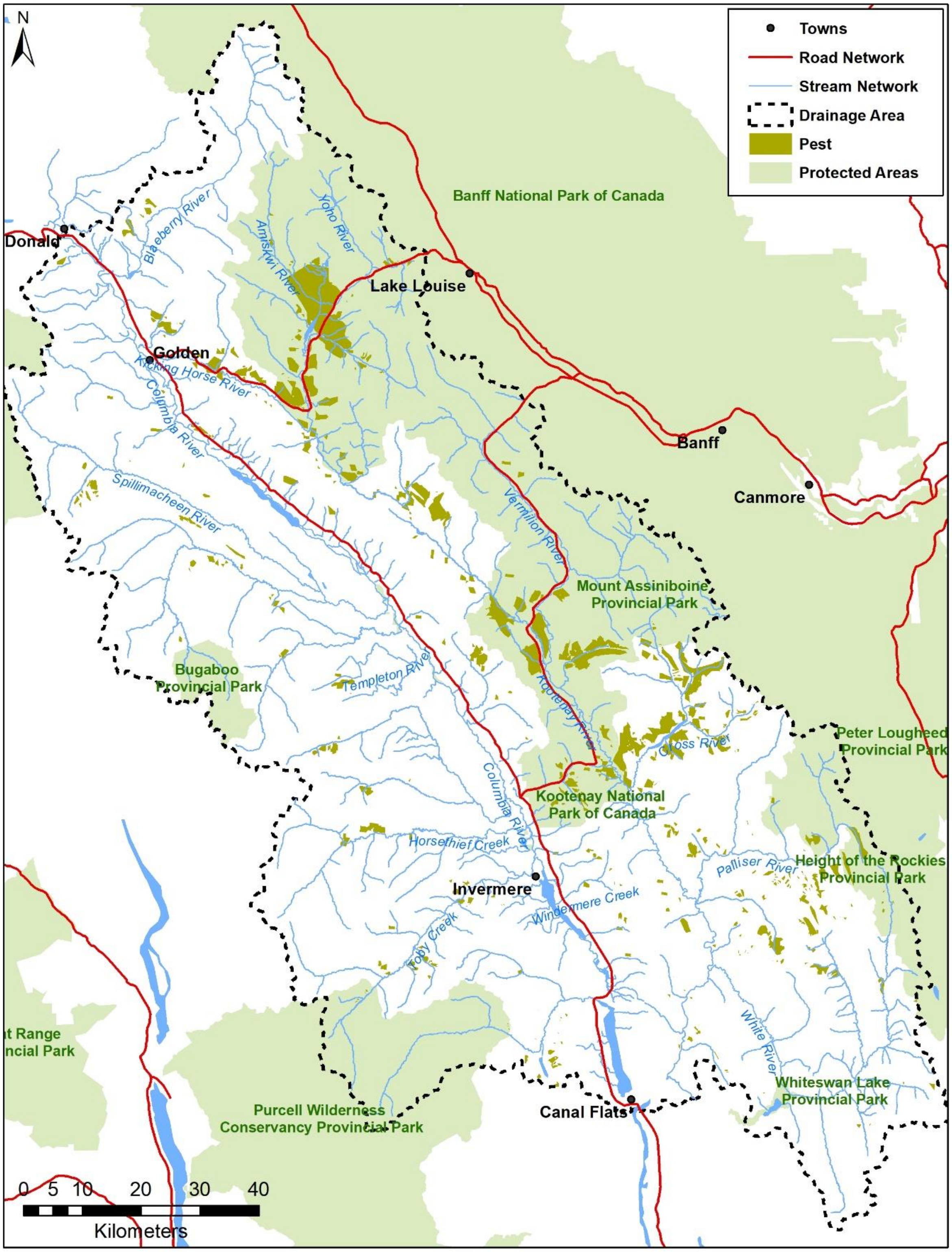


**Figure 29. Severe and very severe insect pest outbreaks in the Columbia drainage at Donald.**

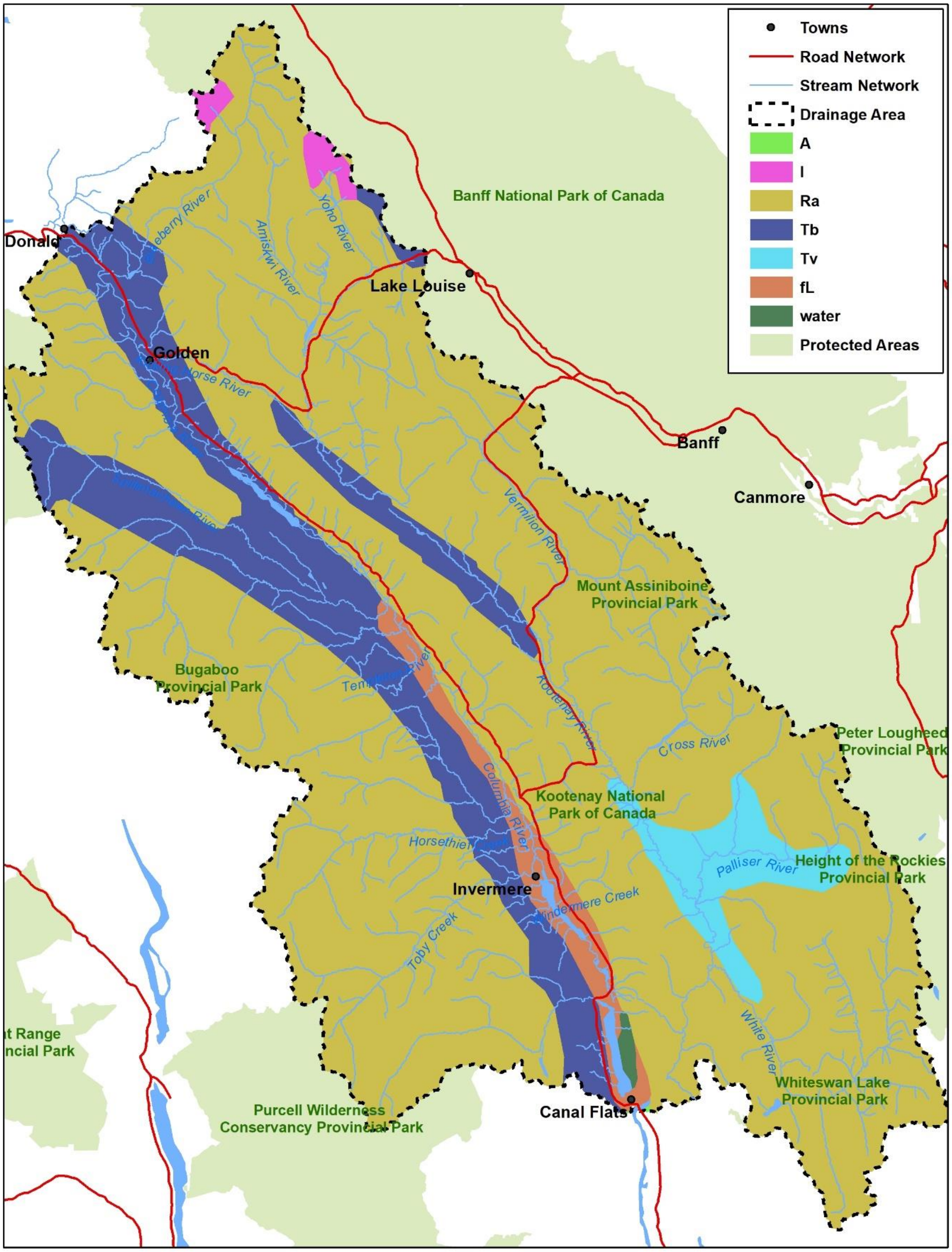


**Figure 30. Surficial geology types in the Columbia drainage at Donald.**

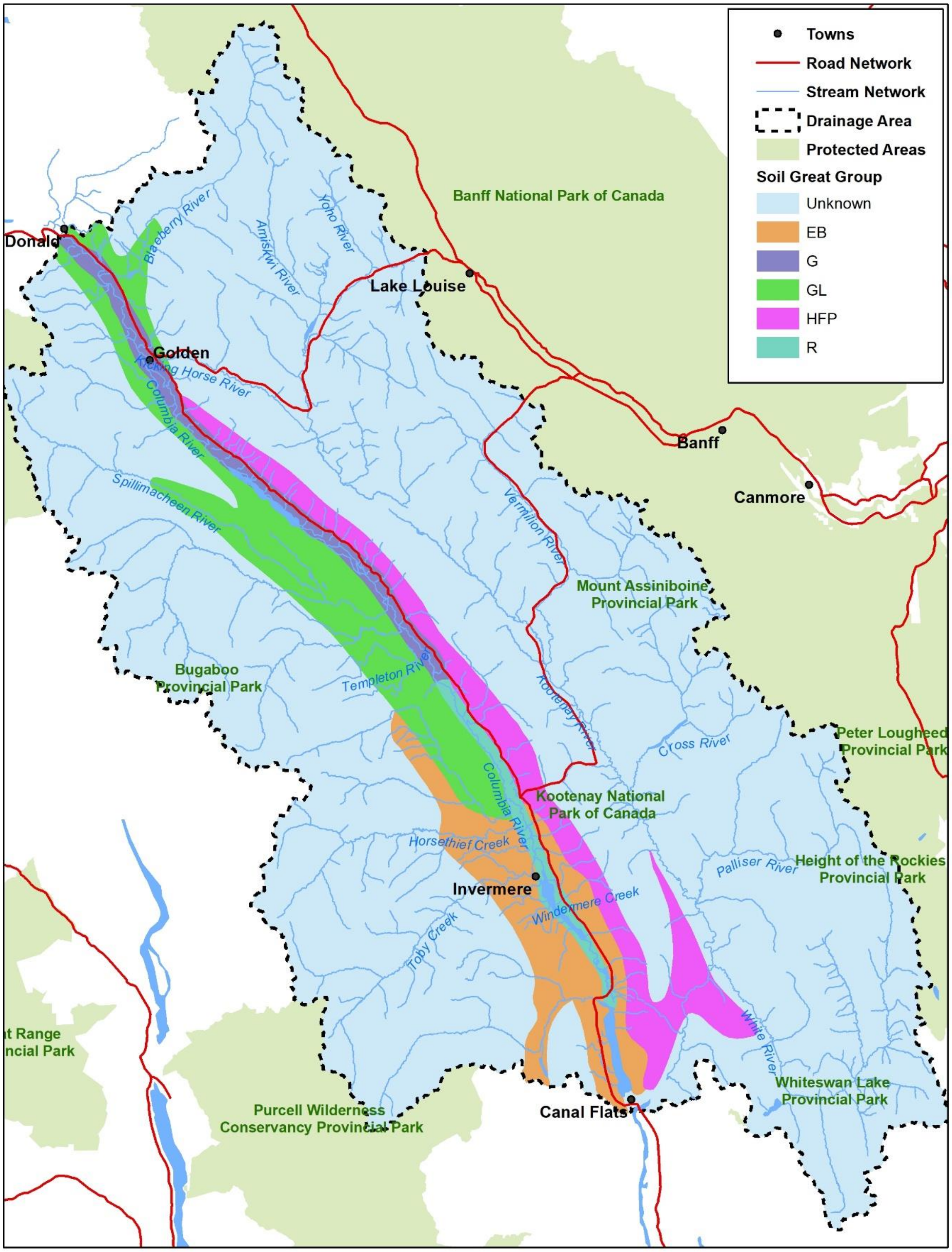


**Figure 31. Soil great group types in the Columbia drainage at Donald.**

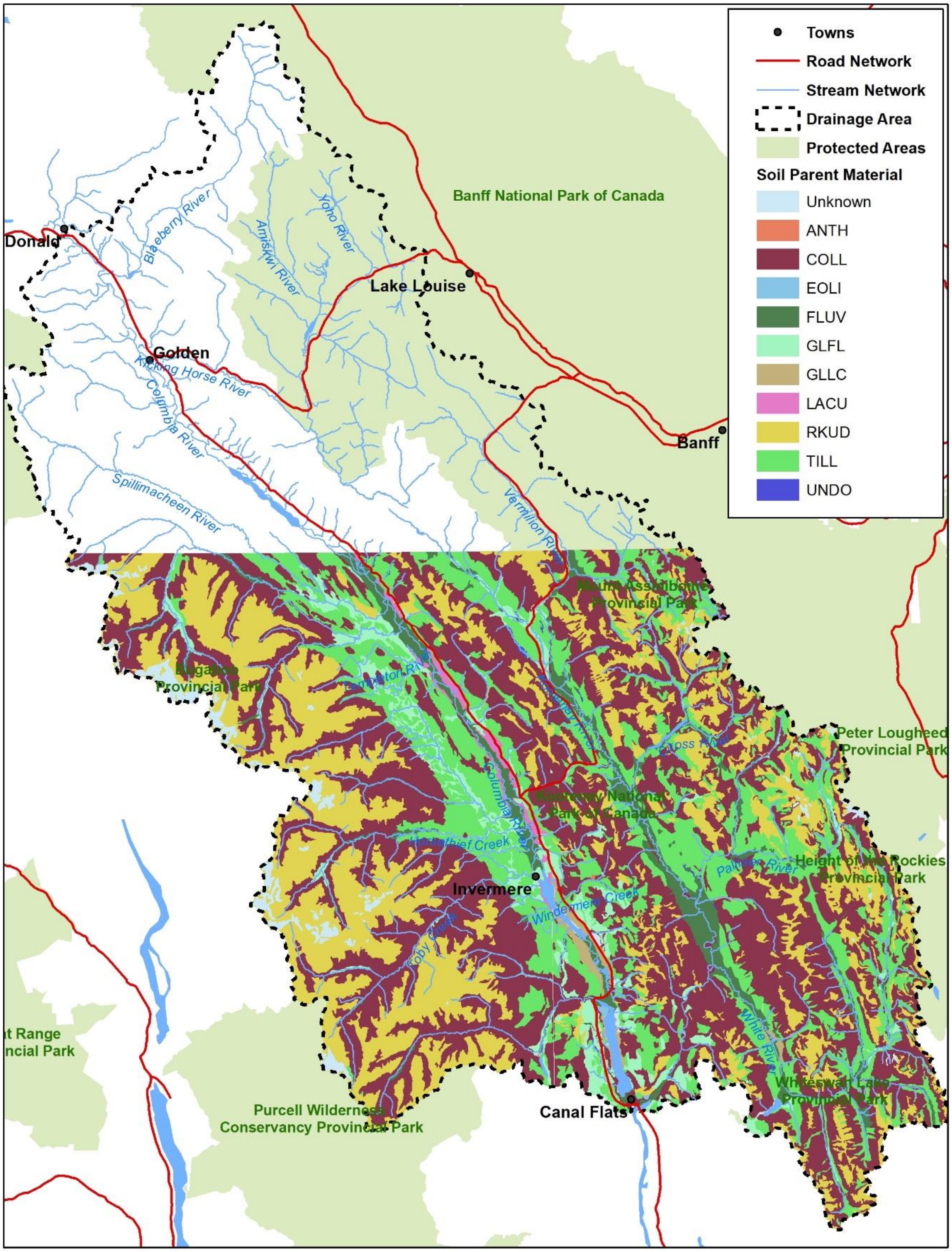


**Figure 32. Soil parent material type in the Columbia drainage at Donald. NB: this dataset only provides partial coverage of the study area.**