MacHydro

Vulnerability Assessment of the Columbia Floodplain Wetlands

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1 Introduction

Wetlands are important ecosystems that provide necessary hydrological functions and ecosystem services while creating critical wildlife habitat; these include modulating peak flows and increasing low flows through water storage, infiltration, and groundwater recharge (Ferreira et al., 2023; Ferreira et al., 2020; Wu et al., 2023), filtering and removing pollutants (Hatvani et al., 2022) and sediment ((Lottig et al., 2013) from surface runoff, and providing critical habitat for migratory birds (Environment and Climate Change Canada, 2018; Darvill, 2020) and fish (Cooper et al., 2017). Further, the conservation and restoration of wetlands may be an effective tool in carbon sequestration and reducing the impacts of climate change (Taillardat et al., 2020). However, wetlands are largely considered to be sensitive to changes in climate (Lee et al., 2015) as they can be responsive to changes in the surrounding surface-water and groundwater hydrology (Wang et al., 2016; Wang et al., 2018; Hathaway et al., 2022).

The Columbia Wetlands are a series of floodplain wetlands within the Upper Columbia River Basin in Canada which exist in the only undammed portion of the river system. As these wetlands are largely influenced by the seasonal flood pulses that occur around June and are driven by snowmelt and rainfall (MacDonald Hydrology Consultants Ltd. 2020; Carli and Bayley 2015; Makaske et al., 2009) these wetlands may be greatly impacted by the potential impacts of climate change (Hopkinson et al., 2020; Utzig, 2021).

Over the past several decades several hydroclimatic changes have occurred, including increased air temperatures, precipitation shifts, and changes in flow timing, duration, and magnitude. An increase in air temperature has been observed (Utzig, 2021) causing a shift in precipitation type with more precipitation occurring as rain and instead of snow (Zhang et al. (2000), Schnorbus et al. (2014), and Vincent et al. (2015). This is in turn driving a decrease in snow accumulation and duration (Valeo et al., 2007; Whitfield, 2014), resulting in earlier onset and more rapid snowmelt during the spring freshet period and an earlier and longer low flow period in the summer and fall (DeBeer et al., 2021; Foster et al., 2016; Leppi et al., 2012).

These hydroclimatic changes have already begun to alter the landcover throughout the Columbia Wetlands, with wetlands drying out and shifting from marshes and open water towards woody shrub landcover (Rodrigues et al., 2023). These effects may have large impacts on the plants and animals that call the Columbia Valley home (Stewart, 2009 – double check; Bayley, 1995). Further analysis is required to examine which wetlands are the most vulnerable to the effects of climate changes and what can be done to build their resilience.

In the current study we examine the vulnerability of the Columbia Valley floodplain wetlands to climate change by examining a) the impacts of climate change on the Columbia River, and b) the effects of climate change on areas within the wetlands without the influence of the river. This allows us to interpret the effects of seasonal changes in environmental factors and better understand which wetlands are more at risk of change under future climate conditions.

2 Study Area

The Columbia Wetlands are a series of wetlands that extend from south of Invermere, BC, to Golden, BC in the Rocky Mountain Trench, approximately 180 km in length and 260 km^2 (Environment and Climate Change Canada, 2018). The wetlands examined in the current project fall within this reach, extending just north of Wilmer to Parsons, BC, spanning approximately 75 km and covering nearly 2400 Ha of area (Figure 1).

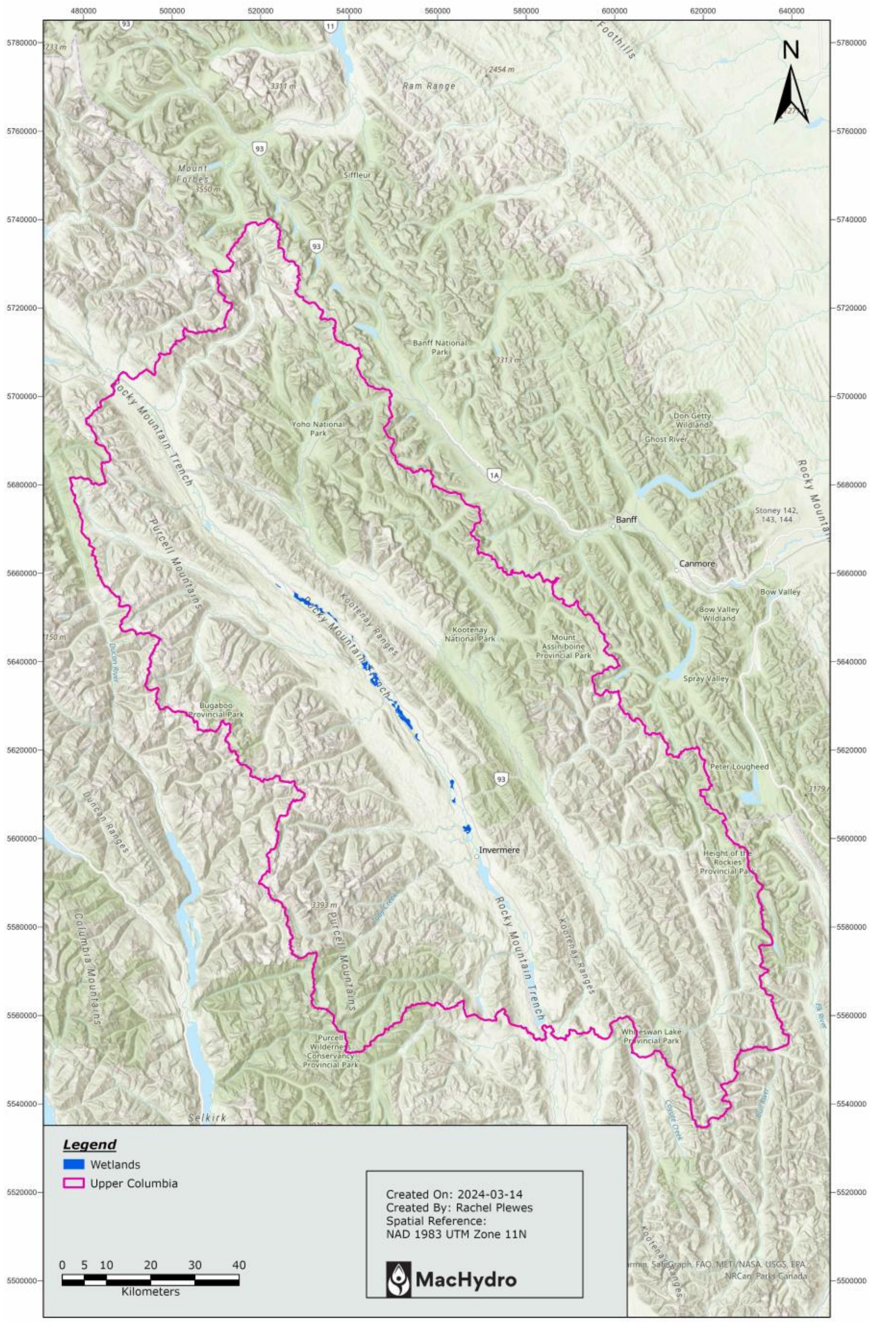


Figure 1. The floodplain wetlands examined in this study within the Upper Columbia River Watershed.

The regional climate and hydrological models were developed for the Upper Columbia region in the East Kootenay region of British Columbia. The study area for the models focused on the mountain ranges on each side of the Rocky Mountain Trench, including the headwaters of the Columbia River and Kootenay River (Figure 2). The regional model developed considered watersheds with long-term hydrometric records to calibrate and validate model performance (

Table 1).

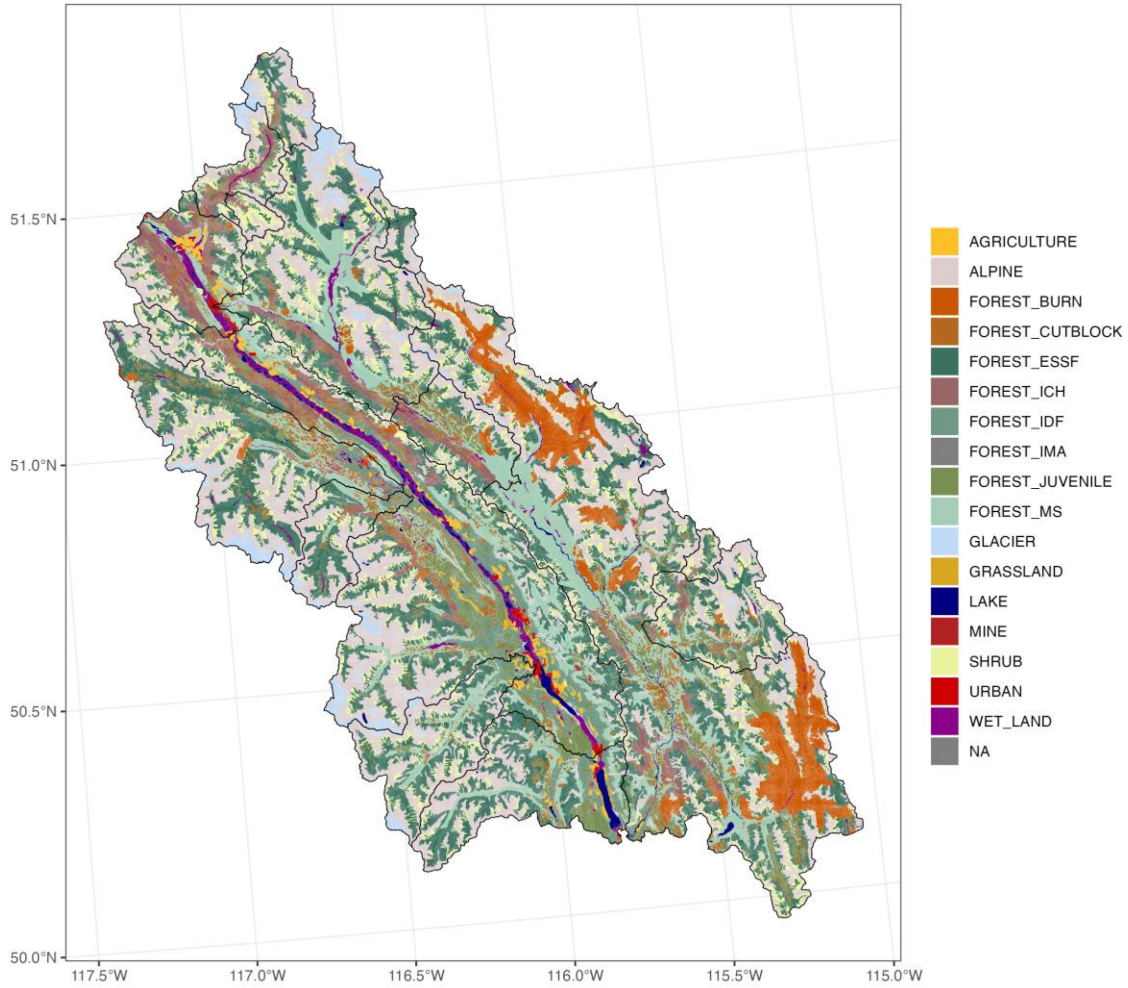


Figure 2. Map of the study area showing land cover current of the year 2022 and sub-basins considered in regional model calibration.

Table 1. Water Survey of Canada hydrometric stations used in this study.

Name	Station Number	Date Range	Drainage Area (km2)
COLUMBIA RIVER AT DONALD	08NB005	1944-2021	3048
COLUMBIA RIVER AT NICHOLSON	08NA002	1903-2022	6688
KOOTENAY RIVER AT CANAL FLATS	08NF002	1939-1995	5456
KICKING HORSE RIVER AT GOLDEN	08NA006	1911-2022	1848
SPILLIMACHEEN RIVER NEAR SPILLIMACHEEN	08NA011	1912-2022	1458
COLUMBIA RIVER NEAR FAIRMONT HOT SPRINGS	08NA045	1944-1996	897
TOBY CREEK NEAR ATHALMER	08NA012	1912-1984	681
PALLISER RIVER IN LOT SL49	08NF006	1973-1995	672
BLAEBERRY RIVER ABOVE WILLOWBANK CREEK	08NB012	1970-2022	590
KOOTENAY RIVER AT KOOTENAY CROSSING	08NF001	1939-2022	423
BUGABOO CREEK NEAR SPILLIMACHEEN	08NA001	1912-1956	378
BLAEBERRY RIVER BELOW ENSIGN CREEK	08NB015	1974-1996	234
KICKING HORSE RIVER BELOW SHERBROOKE CREEK	08NA053	1952-1996	119
SPLIT CREEK AT THE MOUTH	08NB016	1974-2022	80
ALBERT RIVER AT 1310 M CONTOUR	08NF005	1972-1999	69

The region is characterized by high relief, extending from below 800 m at Donald, BC to over 3300 m at the highest peaks along the Continental Divide and in the Selkirk Mountains (Figure 3). Land cover consists primarily of forests below 2200 m, with biogeoclimatic zones of Interior Cedar Hemlock (ICH) in wetter low elevation areas, Montane Spruce (MS) at mid-elevations, and Engelmann Spruce Subalpine Fir (ESSF) at higher elevations. The Columbia River valley bottom consists of large lakes and wetlands. Above treeline, large areas of Alpine characterize most mountain tops, with several glaciers located at the highest elevations in both mountain ranges.

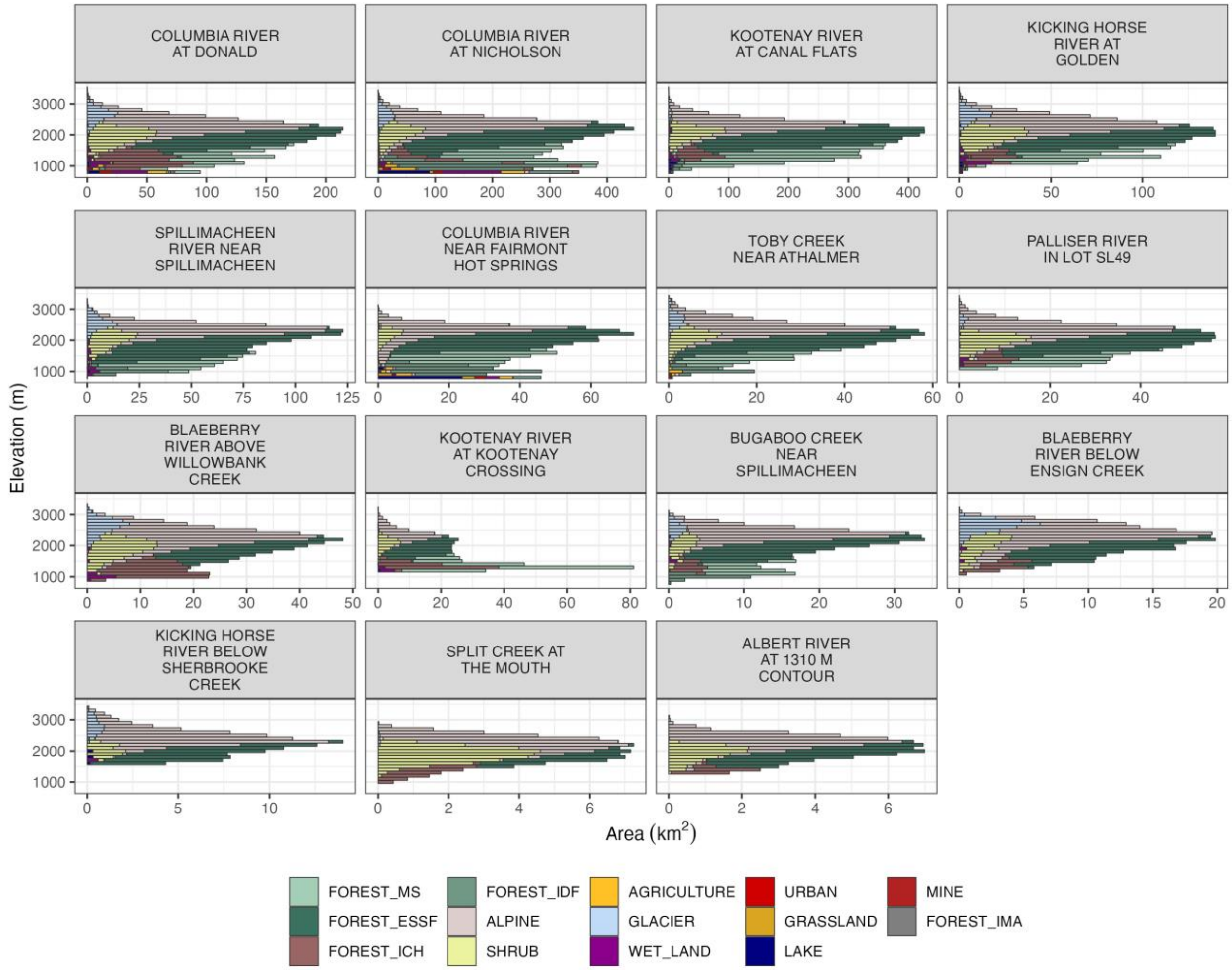


Figure 3. Hypsometry of watersheds considered in this study.

3 Methods

This assessment used a combination of empirical and modelling tools to evaluate wetland vulnerability under climate change. Relationships between streamflow and water levels were developed in addition to using a process-based hydrological model.

3.1.1 Streamflow-water level analysis

A regression analysis was employed to determine the relationship between observed water levels in wetlands and streamflow from the Columbia River. This linear relationship was then used to predict the response of each wetland cluster (Groups A, B, C, and D) to climate change scenarios (SSP2-4.5, SSP3-7.0, and SSP5-8.5) using simulated streamflow (methods described in the modeling section). The linear model was trained using three years of historical data from 2020 to 2023 at Environment Canada's hydrometric gauge Columbia River at Nicholson (08NA002), and water levels obtained from wetland numbers 49, 144, 38, and 110. These wetlands were chosen at random and meant to be representative of wetland groupings.

3.1.2 Model Formulation

The semi-distributed hydrological model used in this study is an adapted version of the HBV-EC model, emulated within the Raven Hydrological Modelling Framework version 3.8 (Craig et al., 2023). The model simulates streamflow and other hydro-climatic variables (i.e. snowmelt, evaporation, etc.) at a daily timestep. The model spatially distributes daily minimum and maximum air temperature, precipitation, and relative humidity from all weather stations across the study region. The model simulates major hydrological processes including canopy interception, snow accumulation and 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).

In the hydrological model, water inputs occur as precipitation, which is partitioned into rain or snow following the HBV linear transition based on air temperature. Precipitation interception 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). Glacier melt is estimated following the HBV routines (Craig et al., 2020). Potential evapotranspiration is estimated using the Priestley–Taylor equation over land and Hargreaves (1985) over water and varies between vegetation types. Once water infiltrates the 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.

Small lakes were treated as lake storage with a linear rate of water release. Major lakes were treated as natural reservoirs where mass balance was calculated using storage curves derived from lake characteristics and flow attenuation coefficients. Treating a waterbody as a reservoir allows the model to simulate the mass balance of the lake and explicitly account for flow attenuation along the main channel. Both reservoirs and lakes freeze during below 0°C air temperatures, accumulate snow when frozen, and thaw once the overlying winter snowpack has melted away. In total, reservoirs were simulated at the outlet of two sub-basins to reflect Columbia Lake and Lake Windermere. Although Lake Windermere is not located at a sub-basin outlet, it was treated as such to also account for flow attenuation in the large wetland complex along the length of the Rocky Mountain Trench.

3.1.3 Spatial Discretization

The modelled study area was divided into sub-basins to provide model outputs at major points of interest, calibrate and verify model performance at hydrometric gauges, and to characterize hydroclimatic heterogeneity in the study area. Sub-basin delineation was based on outlets of WSC hydrometric monitoring locations in the region.

The study area was further discretized into 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 terra package (Hijmans, 2023), which incorporates the slope and aspect of each grid cell. Land cover was obtained from British Columbia's Baseline Thematic Mapping and forests were further delineated based on their Biogeoclimatic zone (Baldwin et al., 2019). Finally, forests were dynamically adjusted within the model runs for forest fires, which were obtained from the Canadian National Fire Database (Natural Resources Canada, 2023) and cutblocks from BC's Consolidated Cutblocks layer. Finally, forests were dynamically adjusted within the model runs for forest fires, which were obtained from the Canadian National Fire Database (Natural Resources Canada, 2023) and forest harvest. Forest was assumed to be "burn" (or "cutblock") for the 25 years following the fire, and "juvenile" for the following 25 years.

3.1.4 Model Forcing Data

To run the hydrological model configurations used in this study, daily air temperature (maximum and minimum, °C) and precipitation (mm/day) are required. These data, along with relative humidity, were collected from DayMet (Thornton et al., 2018) using the Single Pixel Extraction Tool to obtain observations from 1980-2022 at a 1/5th 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 within the hydrological model. Since HRUs are at much higher resolution, spatial interpolation between weather stations uses Inverse Distance Weighting.

Future climate change scenarios were generated from Coupled Model Intercomparison Project Phase 6(CMIP6) global climate models (GCMs), whose results were used in the latest Intergovernmental Panelon Climate Change (IPCC) Assessment Report (AR6). CMIP6 projections are based on the Shared Socio-economic Pathway (SSP) scenarios. Climate scenarios obtained from Environment and Climate Change Canada (ECCC, 2022) under three shares socioeconomic pathways (SSPs). SSP2-4.5 corresponds to a scenario middle of the road scenario, SSP3-7.0 corresponds to a "rocky road" with high challenges to mitigation and adaptation, while SSP5-8.5 represents a fossil-fueled development scenario with minimal greenhouse gas emission mitigation. These scenarios used the median projection from an equal-weighting ensemble forecast of 27 (24 for SSP3-7.0) GCMs from 2020-2100. Projections among climate models can vary because of differences intheir 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 (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(Figure 4) and annual (Figure 5) record for each climate scenario. It should be noted that the

2051-2080 climate change period extents past the expected life cycle of the Project and should therefore be considered as another stress test rather than expected conditions during mine operations and decommissioning

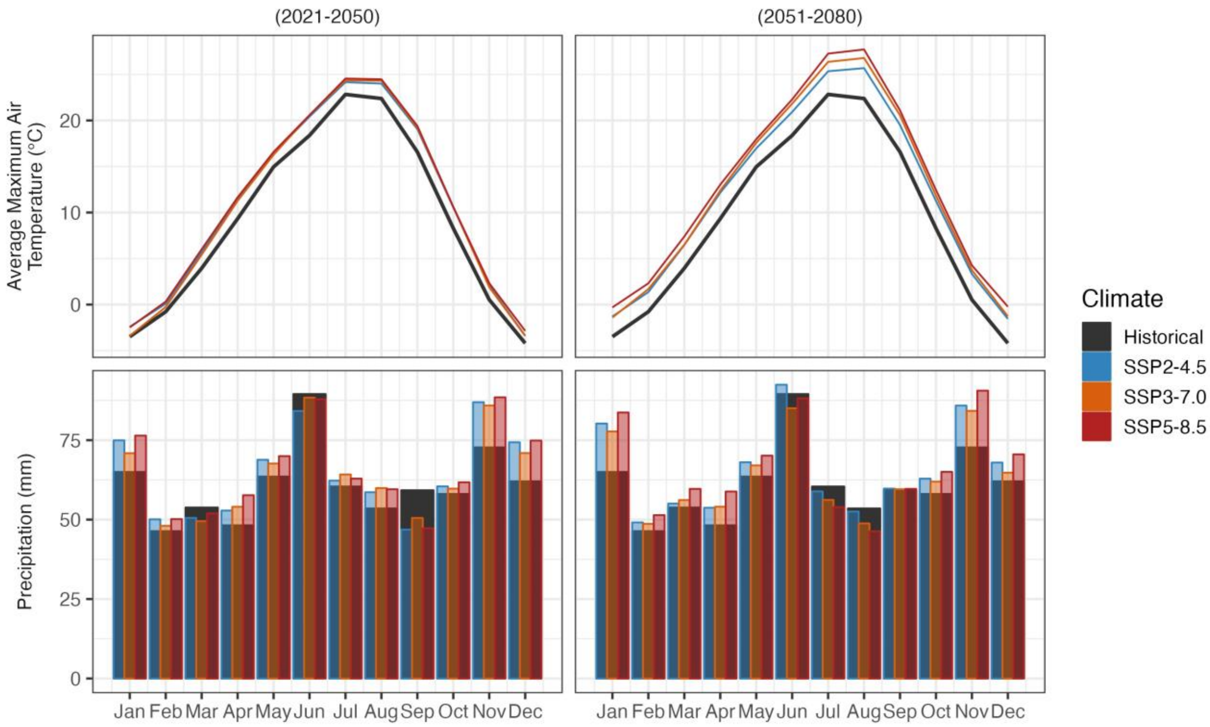


Figure 4. Monthly average maximum air temperature and total precipitation for Historical period (1991-2020) and two future periods under three future climate scenarios, including SSP2-4.5 (blue), SSP3-7.0 (orange), and SSP5-8.5 (red) climate scenarios.

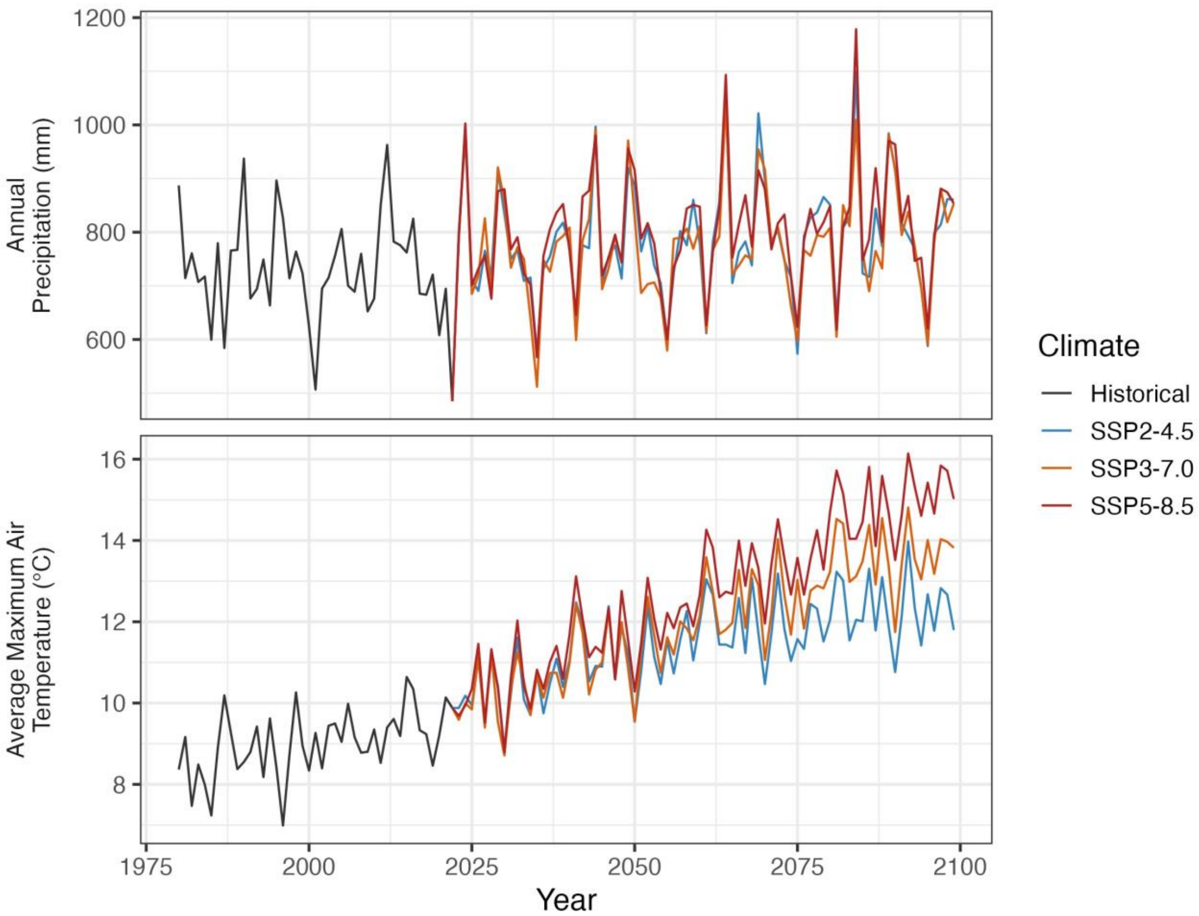


Figure 5. Annual precipitation (top) and maximum air temperature (bottom) for the Columbia Valley historically (black) and under the SSP2-4.5 (blue), SSP3-7.0 (orange), and SSP5-8.5 (red) climate scenarios.

3.1.5 Model Calibration/Verification Data

Meteorologic and hydrometric observations were gathered from publicly available data sources to calibrate and verify the hydrological model (Table 2). This process is essential to ensure that the model is providing accurate results, to constrain uncertainty, and to ensure proper process-representation. Hydroclimatic data were available from several public data sources in or nearby the study area. Weather stations were available from Environment Canada (EC) with air temperature and precipitation observations. In addition, snow pillows and periodic (roughly monthly) snow surveys and were available across the study area and are collected and maintained in the Canadian historical Snow Water Equivalent dataset (CanSWE v5; Vionnet et al., 2021).

Table 2. Meteorologic stations used to calibrate and validate hydrologic processes including lapse rates and snowmelt across the study area. AE corresponds to Alberta Environment, BCE corresponds to British Columbia Environment, EC to Environment Canada.

Site	ID	Latitude	Longitude	Elevation (m)	Type	Source
MOUNT ASSINIBOINE	BCE-2C15	50.92	-115.61	2230	Snow Survey	BCE
SUNSHINE VILLAGE	ALE-05BB803	51.08	-115.78	2230	Snow Survey	AE
SUNSHINE VILLAGE PILLOW	ALE-05BB803P	51.08	-115.78	2230	Snow Pillow	AE
THREE ISLE LAKE	ALE-05BF824	50.63	-115.28	2160	Snow Survey	AE
THREE ISLE LAKE PILLOW	ALE-05BF824P	50.63	-115.28	2160	Snow Pillow	AE
WILDCAT CREEK	BCE-2A32P	51.70	-116.63	2122	Snow Pillow	BCE
FLOE LAKE	BCE-2C14	51.05	-116.13	2090	Snow Survey	BCE
FLOE LAKE-PILLOW	BCE-2C14P	51.06	-116.14	2090	Snow Pillow	BCE
BOW SUMMIT (NEW)	ALE-05BA813	51.71	-116.48	2031	Snow Survey	AE
YOHO NP OHARA LAKE	1347	51.36	-116.34	2025	Weather Station	EC
THUNDER CREEK	BCE-2C17	50.05	-115.23	2010	Snow Survey	BCE
MUD LAKE	ALE-05BF821	50.80	-115.32	1910	Snow Survey	AE
BEAVERFOOT	BCE-2A11	51.28	-116.88	1890	Snow Survey	BCE
MOUNT JOFFRE	BCE-2C16	50.53	-115.13	1750	Snow Survey	BCE
KICKING HORSE	BCE-2A07	51.44	-116.36	1650	Snow Survey	BCE
YOHO PARK	6844	51.44	-116.34	1602	Weather Station	EC
BOW RIVER	ALE-05BA801	51.42	-116.18	1580	Snow Survey	AE
BUGABOO CREEK LODGE	1353	50.75	-116.71	1529	Weather Station	EC
LAKE LOUISE	2409	51.43	-116.22	1524	Weather Station	EC
MARBLE CANYON	BCE-2C05	51.20	-116.13	1520	Snow Survey	BCE
VERMONT CREEK	BCE-2A19	50.96	-116.94	1520	Snow Survey	BCE
SINCLAIR PASS	BCE-2C01	50.66	-115.96	1370	Snow Survey	BCE
FIELD	BCE-2A03A	51.39	-116.51	1285	Snow Survey	BCE
YOHO NP EMERALD LAKE	27094	51.43	-116.54	1280	Weather Station	EC
YOHO NAT PARK BOULDER CR	1346	51.38	-116.53	1219	Weather Station	EC
KOOTENAY NP KTNY CRSG	1196	50.88	-116.05	1170	Weather Station	EC
KOOTENAY NP WEST GATE	1199	50.63	-116.06	935	Weather Station	EC
BRISCO	1352	50.82	-116.26	823	Weather Station	EC
INVERMERE	1189	50.50	-116.03	810	Weather Station	EC
GOLDEN A	1364	51.30	-116.98	785	Weather Station	EC

Streamflow (m^3/s) data were obtained from Water Survey of Canada (WSC) hydrometric stations in the study area with long-term records (

Table 1).

4 Results

4.1 Relationships between streamflow and wetland water levels

Relationships were relatively strong between streamflow in the Columbia River and wetland water levels on a daily average time step (Figure 6). Regression relationships were all significant at the 99% level and best for Group B ($r^2 = 0.925$). Interestingly, Group A showed the worst relationship ($r^2 = 0.505$). Group C ($r^2 = 0.882$) and Group D ($r^2 = 0.654$) showed relatively good relationships too.

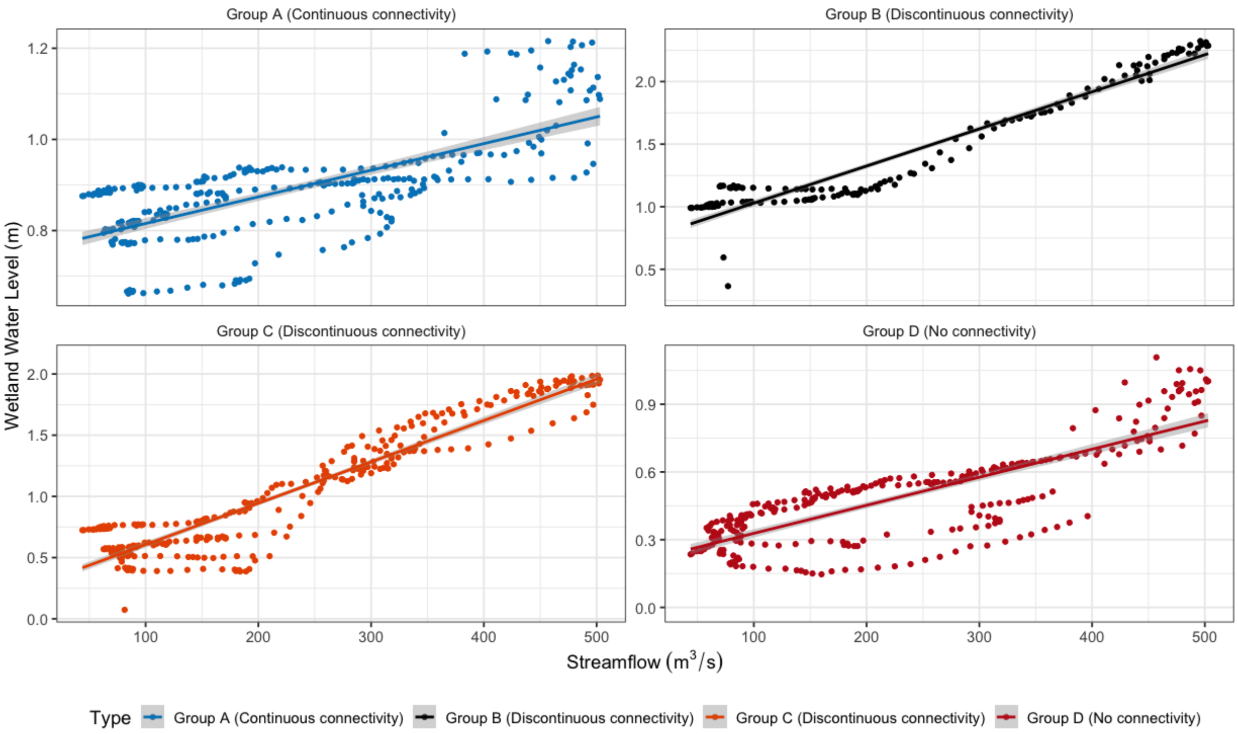


Figure 6 Relationships between Columbia River streamflow and wetland water levels for 2020-2023.

4.2 Hydrological Model Performance

4.2.1 Hydroclimatic Validation

Hydroclimatic variables including air temperature, precipitation, and snow water equivalent were evaluated at independent regional weather and snow pillow/survey stations (Table 3). Results demonstrate that the model had strong performance at distributing air temperatures (r^2 ranged from 0.96 to 0.99) and minimal bias. Monthly precipitation showed good performance ($r^2 = 0.56 – 0.85$) with a notable positive bias at Golden, Lake Louise, and Kootenay NP West Gate, and a negative bias at Yoho NP Emerald Lake and Yoho NP Ohara Lake. Snow Water Equivalent showed strong performance at snow pillows ($r^2 = 0.86 - 0.93$), and good performance at snow survey sites ($r^2 = 0.39 - 0.82$). Outliers included Beaverfoot, Field, Sinclair Pass, and Thunder Creek, where there is a considerable positive bias, and Floe Lake, where there is a moderate negative bias (Table 3).

Table 3.Meteorological validation statistics for all sites used in this study. R2 corresponds to the Pearson correlation coefficient, PBIAS to the percent bias, and N to the number of observations.

Site	Daily Maximum Air Temperature			Monthly Precipitation			Snow Water Equivalent		
	R2	**PBIAS**	**N**	**R2**	**PBIAS**	**N**	**R2**	**PBIAS**	**N**
GOLDEN A	0.98	8%	11517	0.73	41%	382	—	—	—
KOOTENAY NP WEST GATE	0.98	2%	10269	0.85	18%	360	—	—	—
YOHO PARK	0.98	4%	9578	0.56	−6%	195	—	—	—
LAKE LOUISE	0.98	−3%	6342	0.75	32%	173	—	—	—
YOHO NP OHARA LAKE	0.97	−1%	5473	0.66	−12%	218	—	—	—
YOHO NP EMERALD LAKE	0.96	−1%	5006	0.65	−19%	196	—	—	—
KOOTENAY NP KTNY CRSG	0.99	1%	4530	0.85	5%	151	—	—	—
BRISCO	0.98	8%	3632	0.82	10%	128	—	—	—
BUGABOO CREEK LODGE	0.98	−5%	3205	0.85	2%	107	—	—	—
YOHO NAT PARK BOULDER CR	0.99	3%	1367	0.82	12%	44	—	—	—
BEAVERFOOT	—	—	—	—	—	—	0.40	253%	203
BOW RIVER	—	—	—	—	—	—	0.54	43%	125
BOW SUMMIT NEW	—	—	—	—	—	—	0.39	41%	204
FIELD	—	—	—	—	—	—	0.42	79%	165
FLOE LAKE	—	—	—	—	—	—	0.67	−28%	175
FLOE LAKE-PILLOW	—	—	—	—	—	—	0.93	−23%	9125
INVERMERE	—	—	—	0.81	42%	16	—	—	—
KICKING HORSE	—	—	—	—	—	—	0.63	21%	239
MARBLE CANYON	—	—	—	—	—	—	0.82	−11%	165
MOUNT ASSINIBOINE	—	—	—	—	—	—	0.69	−3%	191
MOUNT JOFFRE	—	—	—	—	—	—	0.62	−20%	190
MUD LAKE	—	—	—	—	—	—	0.72	7%	276
SINCLAIR PASS	—	—	—	—	—	—	0.68	138%	164
SUNSHINE VILLAGE	—	—	—	—	—	—	0.77	−4%	280
SUNSHINE VILLAGE PILLOW	—	—	—	—	—	—	0.91	2%	9901
THREE ISLE LAKE	—	—	—	—	—	—	0.82	−21%	256
THREE ISLE LAKE PILLOW	—	—	—	—	—	—	0.86	−6%	10100
THUNDER CREEK	—	—	—	—	—	—	0.69	81%	192
VERMONT CREEK	—	—	—	—	—	—	0.50	38%	202
WILDCAT CREEK	—	—	—	—	—	—	0.81	−13%	2130

4.2.2 Streamflow Verification

The hydrological model was calibrated and validated using daily streamflow observations from the Water Survey of Canada hydrometric gauges in the region. Average daily conditions were very well represented at most hydrometric gauges (Figure 7), with the timing of freshet and low flow well reproduced at all sites. Along the mainstem and major tributaries, daily performance statistics are very strong (e.g. KGE = 0.92 for Columbia River at Donald; Table 4).

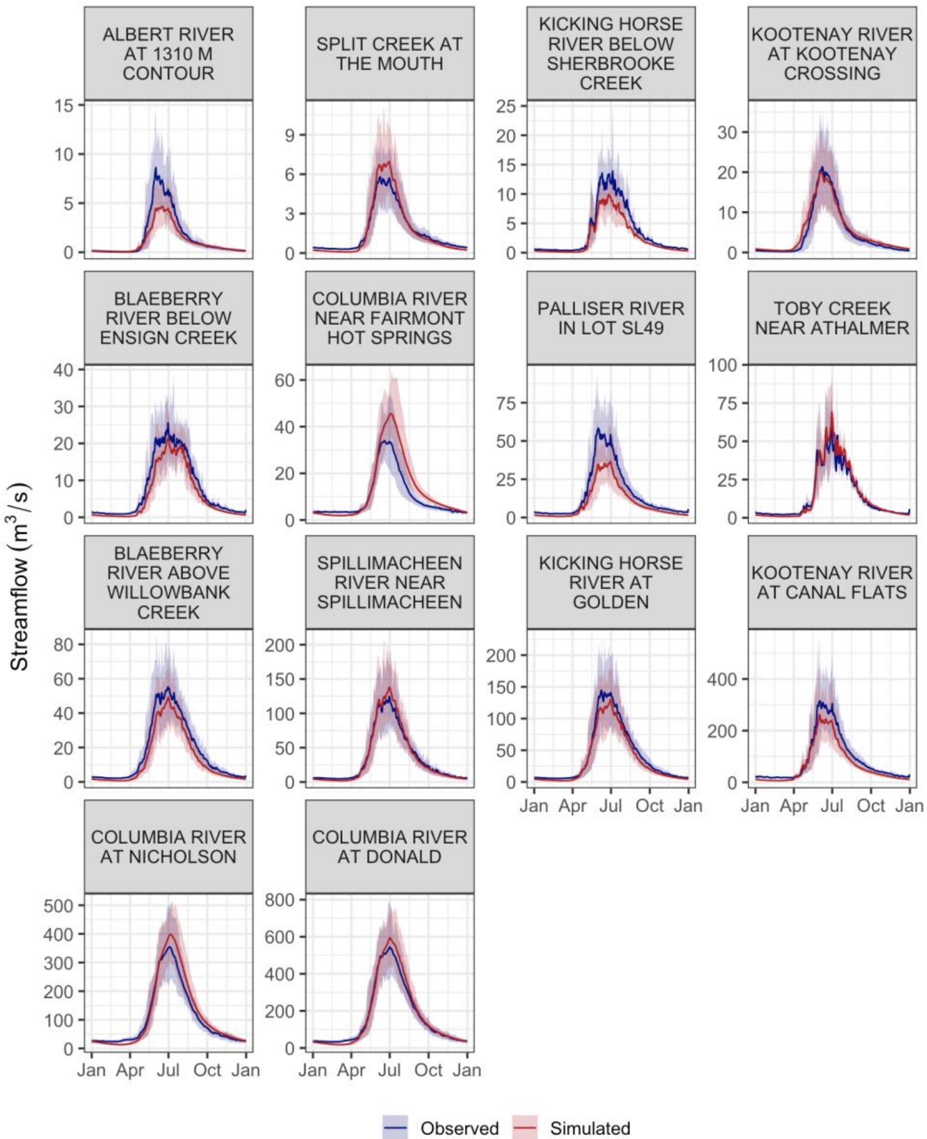


Figure 7. Observed and simulated streamflow at all sites used in model calibration. Solid lines correspond to average flows while shaded areas correspond to 10-90% quantiles.

Overall, performance statistics demonstrate very good model accuracy and low bias at most sites (<20% ;Table 4). Columbia River at Donald has a NSE of 0.94 over the full period, while in the Kootenay River, performance is almost as strong (NSE 0.88). Performance is comparable in major tributaries Kicking Horse River, Spillimacheen River, and Blaeberry River (NSE = 0.86 - 0.89). The model overestimates streamflow in the Columbia River's southern headwaters; Columbia River near Fairmont Hot Springs has a positive bias of 28%, likely due to overestimates of winter precipitation/snowpack in the catchment. Conversely, the model underestimated summer freshet in the Palliser River and Albert Creek as well as upper headwaters of the Kicking Horse and Blaeberry River. This dynamic suggests the model may geographically overestimate precipitation in southwestern areas on the lee side of the Selkirk and Purcell Mountain ranges, and may correspondingly underestimate precipitation on the east side of watershed in the Rocky Mountains.

Table 4. Hydrological model performance statistics for all hydrometric gauges in the regional model. Statistics include the Nash-Sutcliffe Efficiency (NSE), log-NSE, Kling Gupta Efficiency (KGE), Percent Bias (PBIAS), and number of daily observations (N) and are calculated over the 1981-2022 period.

Site	NSE	logNSE	KGE	R2	PBIAS	N
COLUMBIA RIVER AT NICHOLSON	0.90	0.86	0.88	0.93	8%	15342
KOOTENAY RIVER AT KOOTENAY CROSSING	0.89	0.88	0.79	0.90	10%	15342
KICKING HORSE RIVER AT GOLDEN	0.90	0.84	0.82	0.92	−15%	15324
COLUMBIA RIVER AT DONALD	0.94	0.89	0.92	0.96	3%	14977
SPLIT CREEK AT THE MOUTH	0.80	0.88	0.76	0.88	2%	14822
BLAEBERRY RIVER ABOVE WILLOWBANK CREEK	0.87	0.82	0.73	0.92	−23%	14738
SPILLIMACHEEN RIVER NEAR SPILLIMACHEEN	0.89	0.88	0.86	0.91	0%	11787
ALBERT RIVER AT 1310 M CONTOUR	0.75	0.89	0.65	0.90	−29%	6667
COLUMBIA RIVER NEAR FAIRMONT HOT SPRINGS	0.67	0.77	0.70	0.89	28%	5720
BLAEBERRY RIVER BELOW ENSIGN CREEK	0.86	0.84	0.71	0.91	−24%	5573
KOOTENAY RIVER AT CANAL FLATS	0.88	0.71	0.75	0.94	−22%	5229
PALLISER RIVER IN LOT SL49	0.75	0.72	0.62	0.92	−36%	5216
KICKING HORSE RIVER BELOW SHERBROOKE CREEK	0.81	0.88	0.68	0.91	−30%	1716
TOBY CREEK NEAR ATHALMER	0.92	0.90	0.90	0.94	3%	1463

Since the hydrological model will be used to derive hydrologic indicators related to peak and low flow conditions, peak annual and 7-day summer low flows are compared against observations as a secondary step in model validation. Results are provided in Table 5. Overall, results demonstrate that peak daily flows are difficult to simulate and exhibit a high degree of variability at most sites. Performance is strongest on mainstems; both the Kootenay River and Columbia River have biases of under 10% in peak flows. Minimum 7-Day Summer Flows exhibit less variability, and comparatively good performance (r^2 = 0.15-0.68), though most sites on the mainstem have a positive bias.

Table 5. Hydrological model performance statistics for hydrometric indicators at hydrometric gauges in the regional model with at least 20 years of data. Statistics include the Pearson Correlation Coefficient (R2), Percent Bias (PBIAS), and number of daily observations (N) and are calculated over the full 1981-2022 period

Site	Minimum Summer 7-Day Flow			Peak Annual Flow		
	N	PBIAS	R2	N	PBIAS	R2
ALBERT RIVER AT 1310 M CONTOUR	18	21%	0.30	19	−41%	0.38
BLAEBERRY RIVER ABOVE WILLOWBANK CREEK	41	−32%	0.15	42	−17%	0.22
BLAEBERRY RIVER BELOW ENSIGN CREEK	15	−19%	0.37	16	−7%	0.09
COLUMBIA RIVER AT DONALD	41	13%	0.47	42	7%	0.46
COLUMBIA RIVER AT NICHOLSON	42	32%	0.43	42	4%	0.53
COLUMBIA RIVER NEAR FAIRMONT HOT SPRINGS	16	53%	0.44	16	24%	0.82
KICKING HORSE RIVER AT GOLDEN	42	−20%	0.38	42	−16%	0.34
KOOTENAY RIVER AT CANAL FLATS	14	−25%	0.47	15	−9%	0.13
KOOTENAY RIVER AT KOOTENAY CROSSING	42	44%	0.68	42	−5%	0.46
PALLISER RIVER IN LOT SL49	14	−25%	0.36	15	−27%	0.14
SPILLIMACHEEN RIVER NEAR SPILLIMACHEEN	32	0%	0.16	34	14%	0.13
SPLIT CREEK AT THE MOUTH	41	−6%	0.55	42	15%	0.17

4.3 Potential climate change effects

4.3.1 Changes in the Columbia River at Nicholson

Streamflow in the Columbia River is a dominant driver of wetland hydrology and changes in the Columbia River will ultimately result in changes in wetland function. Results over multiple climate scenarios show several changes in hydrologic condition (Figure 8). Historically, streamflow follows a strongly seasonal pattern coinciding with spring snowmelt beginning in April and May resulting in peak flows in early July followed by low flows throughout the summer months. Under the climate change scenarios, peak flows shift to occur nearly two weeks earlier in the season. This shift coincides with earlier spring snowmelt and a less reliable winter snowpack, particularly at lower elevations.

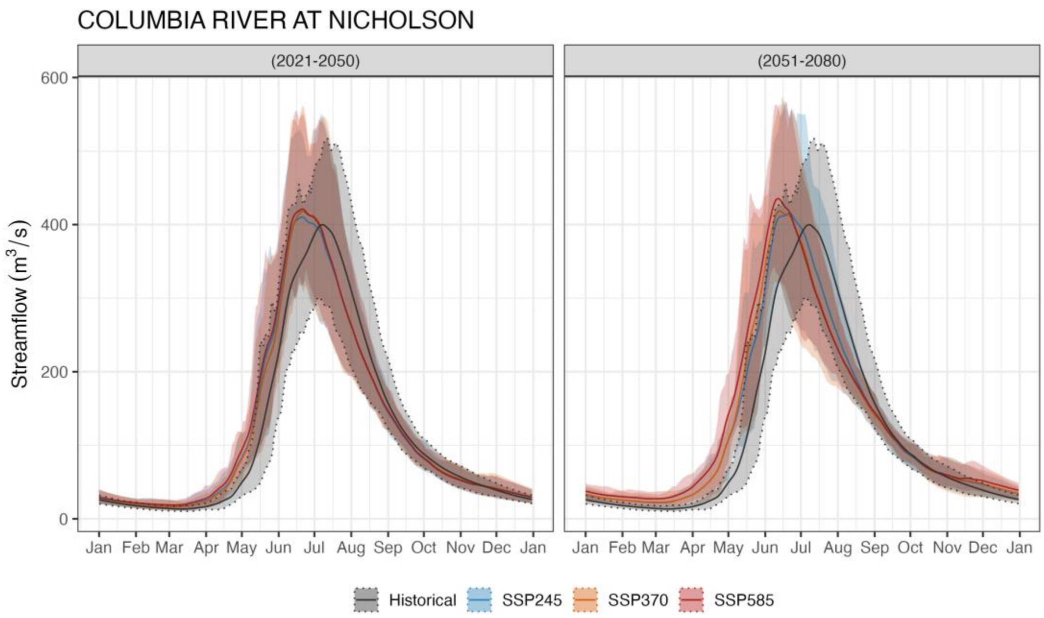


Figure 8. Average daily simulated streamflow and 10-90% quantiles (shaded area) for the Columbia River at Nicholson historically (black and for the SSP245 (blue), SSP370 (orange) and SSP585 (red) climate scenarios in two future time periods.

Mean annual flow and peak flow are both likely to increase under the climate change scenarios, while summer flows (Jul-Sep) and summer drought conditions (10-Year Summer Low Flow) are likely to decrease in the future (Table 6). The current model illustrates flow conditions could improve later in the century except for mean July to September flows, which are likely to decrease further. Lower streamflow during the low flow periods coinciding with earlier peak flow timing are likely to result in a longer period of open water and earlier wetland recession relative to historical conditions.

Table 6 Hydrologic indicator summary table for the Columbia River at Nicholson for three climate scenarios under two future periods as they deviate from historical norms.

COLUMBIA RIVER AT NICHOLSON

Climate	Mean Annual Flow	Mean Jul-Sep Flow	2-Year Peak Flow	20-Year Peak Flow	10-Year Summer Low Flow	Peak Flow Timing
2021-2050						
SSP245	5%	−10%	4%	−2%	−4%	-11.3 days
SSP370	4%	−9%	5%	5%	−1%	-9.7 days
SSP585	7%	−9%	6%	1%	−1%	-11.9 days
2051-2080						
SSP245	9%	−13%	6%	6%	2%	-15.1 days
SSP370	8%	−17%	6%	3%	6%	-18.3 days
SSP585	14%	−17%	7%	5%	9%	-21.2 days

4.3.2 Changes wetland conditions

Future simulations suggest Group A and Group B wetland water levels are likely to decrease in terms of peak and decrease over the summer period with a shift in seasonality (Figure 9). This shift in seasonality would result in a longer period of open water and hence period for evapotranspiration, resulting in earlier drying. It is important to note wetland water levels are under- and over-estimated during the summer period for Group A and Group B, respectively. This is likely due to the inability of this approach to represent impoundments. Regardless, trends towards a shift in seasonality are likely. Group C and Group D also show over- and under-estimates in summer, respectively. These groups are likely to see similar shifts in seasonality as well, with reduced peaks. Interestingly, observed water levels in Groups B and C resemble the climate change projections in terms of timing of peak, suggesting shifts have potentially occurred relative to previous decades.

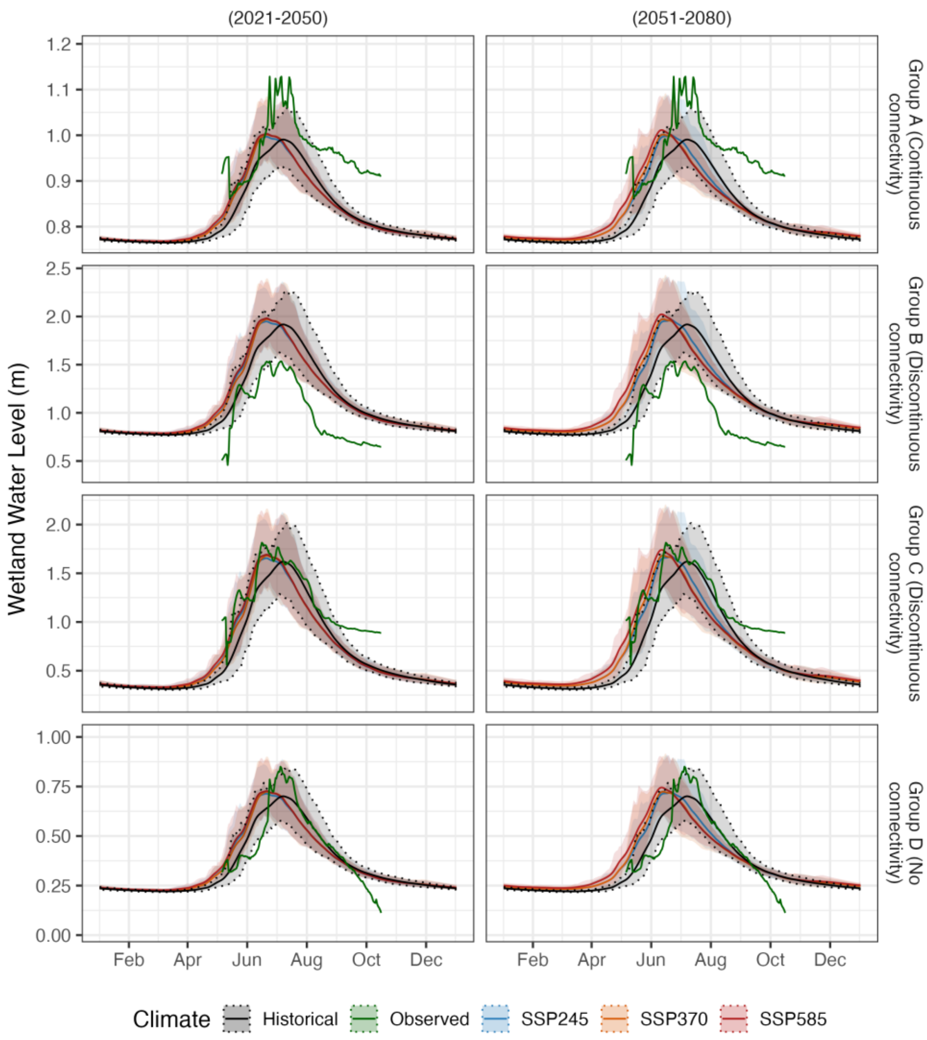


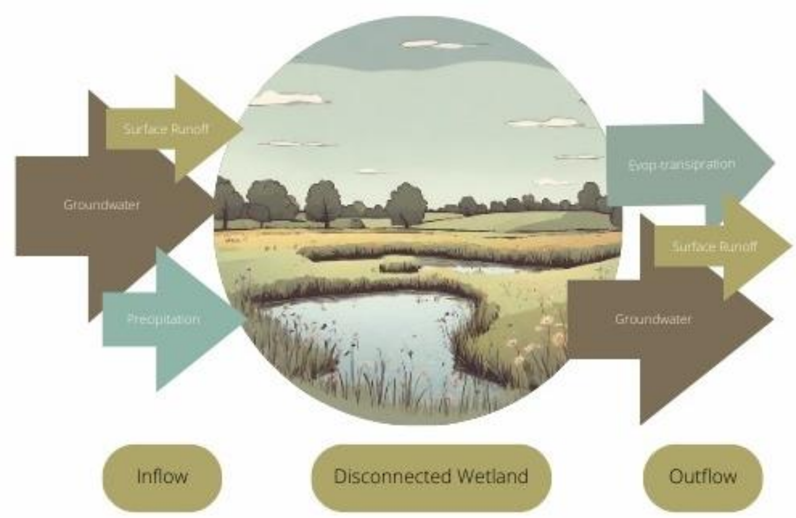
Figure 9. Average daily simulated wetland levels and 10-90% quantiles (shaded area) for each wetland group historically (black) and for the SSP245 (blue), SSP370 (orange) and SSP585 (red) climate scenarios in two future time periods. Observed 2020-2023 levels are shown in green.

5 Discussion and Recommendations

5.1 Wetland Vulnerability

The results of this study suggest that the floodplain wetlands within the Upper Columbia Valley are vulnerable to climate change. Peak flows on the Columbia River are expected to increase, while low flows are expected to decrease. Climate change scenarios suggest that the region will experience increased air temperatures and small increases in precipitation, though not enough to offset the drying effect of the increased air temperatures. As the floodplain wetlands are intrinsically tied to the Columbia River and receive minimal inputs after the freshet period, this will result in a longer drying period for the Columbia wetlands where they will experience a greater seasonal water deficit from the historic norm, as water inputs will cease earlier in the season and evaporation will be higher. Wetlands are expected to enter into a seasonal water deficit earlier in the season as a result of the seasonal shift in peak flows, so it will become increasingly important for wetlands to have an ability to store water during the dryer summer months.

Given that there are limited inputs to the water budget in the later season, one of the most important drivers in climate resilience for the floodplain wetlands will be increasing water storage. The more disconnected a floodplain wetland is, the more important the capacity of the wetland to store water during the dry, hot summer months when there are no streamflow inputs (Figure 10). This will be dependent on the peak flows occurring at a great enough magnitude and for a long enough duration to fill the wetland, as well as requiring that the wetland's levees provide adequate water storage capacity. This is critical during drought years, especially if drought conditions last for several years (Middleton, 2012) as seedbanks may not withstand severe, multi-season droughts (Brock and Rogers 1998; Brock et al., 2003) and could affect the geographic distribution of species (Lake 2008). This suggests a fundamental ecosystem shift could occur under future climates.



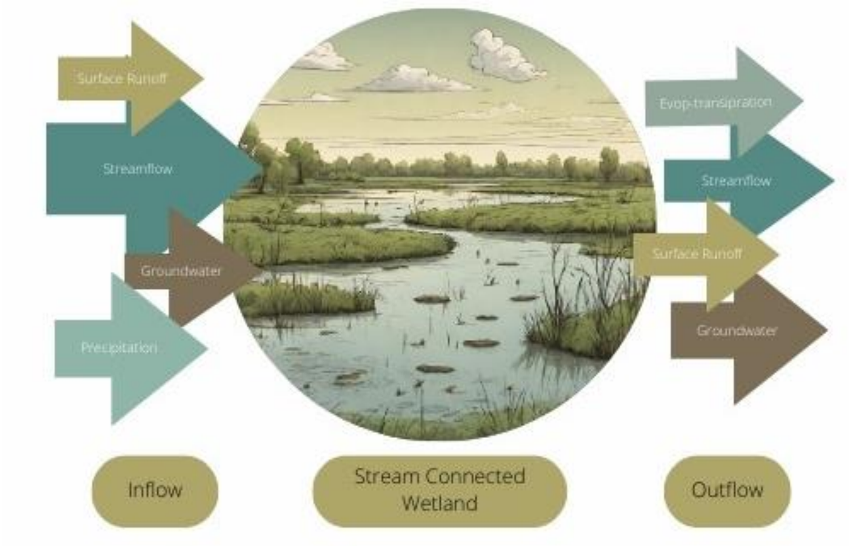


Figure 10. Conceptual model illustrating water balance differences between connected and disconnected streams.

5.2 Recommendations

Due to the importance of peak flows to the water balance of floodplain wetlands in the Upper Columbia Valley, our recommendations are to:

- Increase water storage capacity (block outflow using beaver dam analogues) to improve water retention during the later season when inflows are minimal.
- Survey the height of levees that show good seasonal storage and use these elevations in restoration efforts.
- As wetlands in the south are facing the greatest threats, focusing efforts on the southern region should take precedence.

6 Closing

The Upper Columbia River floodplain wetlands are experiencing climatic pressures and many are vulnerable to the effects of ongoing climate change. The Columbia River supplies the majority of the water to the water balance of each wetland, with minimal inputs occurring in the form of precipitation later in the season. Under climate change projections, there will be an earlier onset of freshet resulting in the drying period beginning earlier in the year and lasting longer, creating a greater seasonal water deficit. Increasing water storage potential may improve climate change resilience in floodplain wetlands in the Upper Columbia Valley.

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7 References

Baldwin, K.; Allen, L.; Basquill, S.; Chapman, K.; Downing, D.; Flynn, N.; MacKenzie, W.; Major, M.; Meades, W.; Meidinger, D.; Morneau, C.; Saucier, J-P.; Thorpe, J.; Uhlig, P. 2019. Vegetation Zones of Canada: a Biogeoclimatic Perspective. [Map] Scale 1:5,000,000. Natural Resources Canada, Canadian Forest Service. Great Lake Forestry Center, Sault Ste. Marie, ON, Canada.

Bayley, P.B. (1995). Understanding large river: floodplain ecosystems. BioScience, 45(3), 153-158, https://doi.org/10.2307/1 560 312554.

Bergström, S. (1995). The HBV model. Computer models of watershed hydrology., 443-476.

Brock, M.A., Nielsen, D.N., Shiel, R.J., Green, J.D., and Langley, J.D. (2003) Drought and aquatic community resilience: the role of eggs and seeds in sediments of temporary wetlands. Freshwater Biology, 48:1207–1218.

Carli, C.M., and Bayley, S.E. 2015. River Connectivity and Road Crossing Effects on Floodplain Vegetation of the Upper Columbia River, Canada. Ecoscience, 22 (2-4), 97–107, https://doi.org/10.1080/11956860.2015.1121705.

Chernos, M., MacDonald, R. J., Nemeth, M. W., & Craig, J. R. (2020). Current and future projections of glacier contribution to streamflow in the upper Athabasca River Basin. Canadian Water Resources Journal/Revue canadienne des ressources hydriques, 45(4), 324-344.

Cooper, D. J., Kaczynski, K. M., Sueltenfuss, J., Gaucherand, S., and Hazen, C. (2017). Mountain wetland restoration: the role of hydrologic regime and plant introductions after 15 years in the Colorado Rocky Mountains, USA. Ecological Engineering, 101, 46-59, https://doi.org/10.1016/j.ecoleng.2017.01.017.

Craig, J.R., and the Raven Development Team, Raven user’s and developer’s manual (Version 3.7), URL: http://raven.uwaterloo.ca/ (Accessed March 2023).

DeBeer, C.M., Wheater, H.S., Pomeroy, J.W., Barr, A.G., Baltzer, J.L., Johnstone, J.F., ... and Pietroniro, A. (2012). Summary and synthesis of Changing Cold Regions Network (CCRN) research in the interior of western Canada–Part 2: Future change in cryosphere, vegetation, and hydrology. Hydrology and Earth System Sciences, 25(4), 1849-1882, https://doi.org/10.5194/hess-25-1849-2021, 2021.

Darvill, R. and Westphal, A. (2020). Columbia Wetlands Marsh Bird Monitoring Project (CWMBMP) Final Report (p. 48). Goldeneye Ecological Services, Prepared for Fish and Wildlife Compensation Program.

Environment and Climate Change Canada (ECCC). (2021). CMIP5 statistically downscaled climate scenarios, https://climate-scenarios.canada.ca/?page=statistical-downscaling

Erwin, K.L. (2009). Wetlands and global climate change: the role of wetland restoration in a changing world. Wetlands Ecology and Management, 17, 71–84.

Eum, H. I., & Gupta, A. (2019). Hybrid climate datasets from a climate data evaluation system and their impacts on hydrologic simulations for the Athabasca River basin in Canada. Hydrology and Earth System Sciences, 23(12), 5151-5173.

Ferreira, C., Mourato, S., Ksanin-Grubin, M., Ferreira, A.J.D., Destouni, G., and Kalantari, Z. (2020). Effectiveness of nature-based solutions in mitigating flood hazard in a mediterranean peri-urban catchment Water, 12, p. 2893

Ferreira, C., Kašanin-Grubin, M., Kapović Solomun, M., Sushkova, S., Minkina, T., Zhao, W., Kalantari, Z. (2023). Wetlands as nature-based solutions for water management in different environments. Current Opinion in Environmental Science & Health, 33, 100476.

Fernandes, R.A. and Sun, L. 2021. LEAF-Toolbox-Canada Repository. Government of Canada. available at https://github.com/rfernand387/LEAF-Toolbox-Canada.

Foster, L.M., Bearup, L.A., Molotch, N.P., Brooks, P.D., and Maxwell, R.M. (2016). Energy budget increases reduce mean streamflow more than snow–rain transitions: Using integrated modeling to isolate climate change impacts on Rocky Mountain hydrology. Environmental Research Letters, 11(4), 044015, https://doi.org/10.1088/1748-9326/11/4/044015.

Hathaway, J.M., Westbrook, C.J., Rooney, R.C., Petrone, R.M., and Langs, L.E. 2022. Quantifying relative contributions of source waters from a subalpine wetland to downstream water bodies. Hydrological Processes, 36(9), e14679, https://doi.org/10.1002/hyp.14679.

Hatvani, I.G. , Dokulil, M.T., and Clment A. (2022). The role of wetlands in mitigating impacts from diffuse agricultural loads. Encyclopedia of Inland Waters, 285-299.

Hedstrom, N. R., & Pomeroy, J. W. (1998). Measurements and modelling of snow interception in the boreal forest. Hydrological Processes, 12(10-11), 1611-1625.

Hermosilla, T., M.A. Wulder, J.C. White, N.C. Coops, G.W. Hobart, L.B. Campbell, (2016). Mass data processing of time series Landsat imagery: pixels to data products for forest monitoring. International Journal of Digital Earth 9(11), 1035-1054

Hijmans, R.J. (2023). terra: Spatial Data Analysis. R package version 1.7-18. https://CRAN.R-project.org/package=terra

Hopkinson, C., B. Fuoco, T. Grant, S. E. Bayley, B. Brisco, and R. MacDonald. (2020). Wetland Hydroperiod Change along the Upper Columbia River Floodplain, Canada, 1984 to 2019. Remote Sensing, 12(24), 4084. https://doi.org/10.3390/rs12244084.

Jost, G., Moore, R. D., Menounos, B., & Wheate, R. (2012). Quantifying the contribution of glacier runoff to streamflow in the upper Columbia River Basin, Canada. Hydrology and Earth System Sciences, 16(3), 849-860.

Lake, P.S. (2008) Drought the “creeping disaster”: effects on aquatic ecosystems. Land and Water Australia, Canberra, Australia.*http://lwa.gov.au/files/products/innovation/pn20677/pn20677.pdf*

Latifovic, R. (2023). 2020 Land Cover of Canada. Natural Resources Canada. Accessed 2023-09-01 from https://open.canada.ca/data/en/dataset/ee1580ab-a23d-4f86-a09b-79763677eb47

Lee S.-Y., Ryan M.E., Hamlet A.F., Palen W.J., Lawler J.J., and Halabisky, M. (2015) Projecting the Hydrologic Impacts of Climate Change on Montane Wetlands. PLoS ONE, 10(9), e0136385, https://doi:10.1371/journal.pone.0136385

Leppi, J.C., DeLuca, T.H., Harrar, S.W., and Running, S.W. (2012). Impacts of climate change on August stream discharge in the Central-Rocky Mountains. Climatic Change, 112, 997-1014, https://doi.org/10.1007/s10584-011-0235-1.

Lottig, N. R., Buffam, I., and Stanley, E. H. (2013). Comparisons of wetland and drainage lake influences on stream dissolved carbon concentrations and yields in a north temperate lake-rich region. Aquatic sciences, 75(4), 619-630, https://doi.org/10.1007/s00027-013-0305-8.

MacDonald, R., Leven, C., Bayley, S., Millions, B., Rooney, R., Goodbrand, A., and Des Rosiers-Ste.Marie, C. (2023). Columbia Wetlands: hydrology, beaver and climate change. Final Report. March 31, 2023.

MacDonald Hydrology Consultants Ltd. (2020). Hydrological Assessment of the Upper Columbia River Watershed. 64 pp. Submitted February 2020 to Columbia Wetlands Stewardship Partners.

Makaske, B., D. G. Smith, H. J. A. Berendsen, A. G. de Boe, M. F. van Nielen-Kiezebrink, and T. Locking. (2009). Hydraulic and Sedimentary Processes Causing Anatomosing Morphology of the Upper Columbia River, British Columbia, Canada. Geomorphology, 111(3–4), 194–205, https://doi.org/10.1016/j.geomorph.2009.04.019 .

Natural Resources Canada (2023). Canadian National Fire Database. Accessed 2023-09-01 from https://cwfis.cfs.nrcan.gc.ca/datamart/metadata/nfdbpoly

Rodrigues, I.S., Hopkinson, C., Chasmer, L., MacDonald, R., Bayley, S., and Brisco, B. (2023). Multi-decadal Floodplain Classification and Trend Analysis in the Upper Columbia River Valley, British Columbia, Hydrol. Earth Syst. Sci. Discuss. [preprint], https://doi.org/10.5194/hess-2023-211, in review.

Schnorbus, M., Werner, A., and Bennett, K. Impacts of climate change in three hydrologic regimes in British Columbia, Canada. Hydrological Processes, 28(3), 1170-89, https://doi.org/10.1002/hyp.9661.

Soil Landscapes of Canada Working Group, (2010). Soil Landscapes of Canada version 3.2. Agriculture and Agri-Food Canada. (digital map and database at 1:1 million scale).

Middleton, B.A., and Kleinebecker, T. (2012). The Effects of Climate-Change-Induced Drought and Freshwater Wetlands. Global Change and the Function and Distribution of Wetlands, 117–147. doi:10.1007/978-94-007-4494-3_4

Millennium Ecosystem Assessment. Ecosystems and human well-being: wetlands and water synthesis. In: Sarukhán J, Whyte A, Millennium Ecosystem Assessment Board of Review Editors. Washington, DC: World Resources Institute; 2005. pp 1–68.

Stewart, I.T. (2009). Changes in snowpack and snowmelt runoff for key mountain regions. Hydrological Processes: An International Journal, 23(1), 78-94, https://doi.org/10.1002/hyp.7128.

Taillardat, P., Thompson, B.S., Garneau, M., Trottier, K., Friess, D.A. (2020). Climate change mitigation potential of wetlands and the cost-effectiveness of their restoration. Interface Focus 10: 20190129. http://dx.doi.org/10.1098/rsfs.2019.0129

Utzig, G. (2021). The Columbia Wetlands and Climate Disruption. Nature Investigations Ltd. Nelson, BC. https://kootenayconservation.ca/wp-content/uploads/2021/06/Kootenay-Connect-Y2-Final-Report-09June2021.pdf

Valeo, C., Xiang, Z., Bouchart, F.C., Yeung, P., and Ryan, M.C., Climate change impacts in the Elbow River watershed. Canadian Water Resources Journal, 32(4), 285-302, https://doi.org/10.4296/cwrj3204285.

Vionnet, V., Mortimer, C., Brady, M., Arnal, L., & Brown, R. (2021) Canadian historical Snow Water Equivalent dataset (CanSWE, 1928–2022 v5), Earth Syst. Sci. Data, 13, 4603–4619, *https://doi.org/10.5194/essd-13-4603-2021*.

Vincent, L.A., Zhang, X., Brown, R.D., Feng, Y., Mekis, E., Milewska, E.J., Wan, H., and Wang, X.L. (2015). Observed trends in Canada's climate and influence of low-frequency variability modes. Journal of Climate, 28(11), 4545-4560, *https://doi.org/10.1175/JCLI-D-14-00697.1*.

Wang, X., Shaw, E. L., Westbrook, C. J., and Bedard-Haughn, A. (2018). Beaver dams induce hyporheic and biogeochemical changes in riparian areas in a mountain peatland. Wetlands, 38, 1017-1032, *https://doi.org/10.1007/s13157-018-1059-9*

Wang, X., Helgason, B., Westbrook, C., and Bedard-Haughn, A. (2016). Effect of mineral sediments on carbon mineralization, organic matter composition and microbial community dynamics in a mountain peatland. Soil Biology and Biochemistry, 103, 16-27, *https://doi.org/10.1016/j.soilbio.2016.07.025*

Whitfield, P. H. (2014). Climate station analysis and fitness for purpose assessment of 3053600 Kananaskis, Alberta. Atmosphere-Ocean, 52(5), 363-383, *https://doi.org/10.1080/07055900.2014.946388*.

Wu, Y., Sun, J., Blanchette, M., Rousseau, A. N., Xu, Y. J., Hu, B., and Zhang, G. (2023). Wetland mitigation functions on hydrological droughts: from drought characteristics to propagation of meteorological droughts to hydrological droughts. Journal of Hydrology, 617, Part B, 128971.

Zhang, X., Vincent, L. A., Hogg, W. D., and Niitsoo, A. (2000). Temperature and precipitation trends in Canada during the 20th century. Atmosphere-ocean, 38(3), 395-429, *https://doi.org/10.1080/07055900.2000.9649654*.