MacHydro

# Characterizing the Vulnerability of the Columbia River Floodplain Wetlands to Climate Change

**Prepared For:**
Columbia Wetlands Stewardship Partners
P.O. Box 81
Brisco, BC
V0A 1B0

**Prepared By:**
MacDonald Hydrology Consultants Ltd.
4262 Hilltop Cres.
Cranbrook, BC V1C 6W3

MacHydro

# Characterizing the vulnerability of the Columbia River Floodplain Wetlands to Climate Change

*March 21, 2025*


| **Report Prepared By:** | **Report Reviewed By:** |
|---|---|
| Beth Millions, MSc., R.P.Bio.<br>Biologist<br>MacDonald Hydrology Consultants Ltd.<br>R.P.Bio Reg #4576 | Ryan MacDonald, Ph.D., P.Ag.<br>Senior Hydrologist<br>MacDonald Hydrology Consultants Ltd.<br>P.Ag. ID #2965 |



**Suggested Citation:**

Millions, E.L., MacDonald, R.J., Braaten, M., Chernos, M., and Plews, R., (2025). Characterizing the Vulnerability of the Columbia River Floodplain Wetlands to Climate Change. Prepared for the Columbia Wetlands Stewardship Partners. (March 2025).

# Contents



**List of Figures**

**List of Tables**

# 1 Executive Summary

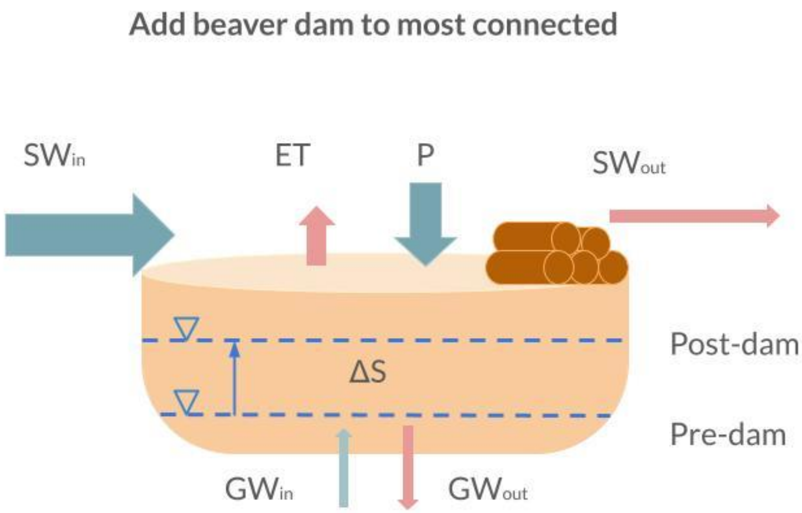
Wetlands provide several critical hydrological functions on the landscape, such as reducing flood risks and improving low flows through water storage, infiltration, and groundwater recharge, which can reduce drought risks. However, due to their dependency on the hydrologic cycle, wetlands are highly sensitive to changes in local hydrology caused by a changing climate and studies have found that north America could lose 10% of its wetland area because of climate change. Within the Upper Columbia River Valley there are approximately 26, 000 ha of wetlands, recognized as being of international importance under the RAMSAR Treaty. These wetlands have already experienced drying and loss of their wetted area, which is of great concern given their importance ecologically.

Snow accumulation and melt play an important role in shaping the Columbia River and the Columbia Wetlands given that the Columbia River is a nival (snowmelt driven) system. Climate change is predicted to cause an increase in air temperatures, leading to a reduction in snow accumulation and an advancement of melt. Due to the relative importance in snowmelt in the Columbia Wetland water supply, reductions in winter snowpack may result in a reduction in wetland recharge from stream water and groundwater sources.

Fortunately, the Columbia Wetlands are surrounded by levees and beaver dams at various elevations, which are often overtopped by floodwater. These levees dictate wetland connectivity to the Columbia River, and how fast water drains from storage. The dynamic of changes in water supply from the Columbia River and altered states of wetland connectivity pose a challenge for maintaining the diversity and ecological functioning of these systems.

This study examines the vulnerability of the Columbia Wetlands to climate change based on their location using a combination of field investigation and hydrological modelling, with special attention paid to select wetlands that have either experienced or have planned restoration efforts to improve water retention.

We found there is regional variation in wetland vulnerability, where the northern portion of the study is likely to be less affected by shifts in climate due to an increase in water supply and less atmospheric sensitivity. The southern portion of the study area is highly vulnerable, with an earlier onset of spring freshet accompanied by an insignificant increase in peak streamflow and substantial water loss under a warmer climate. All wetland groups are likely to be equally vulnerable; however, water retention will be critical to maintain wetland diversity. The Beaver Dam Analogues are an important adaptation measure, particularly in the southern portion of the study area. Without these structures, it is likely that water levels would continue to follow the patterns of the Columbia River. A longer streamflow recession period with hotter and drier summer conditions could lead to a substantial reduction in open water area, already being observed in other studies.




Our conceptual understanding of wetland hydroperiod and behavior of connected vs. disconnected groupings has evolved substantially using intense field sampling and hydrological modelling. We recommend applying this knowledge to prioritize restoration efforts, focusing on increasing the numbers of wetlands with retained summer and fall storage. This will improve ecological integrity through the development and maintenance of a diverse range of wetland types, creating redundancy across the floodplain.

# 2 Introduction

Wetlands are valuable semi-aquatic ecosystems that provide countless hydrological functions, including 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), and improving drought and flood resilience (Golder, et al., 2021; Phillips, 1996). However, as wetlands are highly responsive to changes in the surrounding surface-water and groundwater hydrology (Wang et al., 2016; Wang et al., 2018; Hathaway et al., 2022), they are largely considered to be sensitive to changes in climate (Lee et al., 2015). Changes in air temperatures and precipitation patterns from climate change are expected to have large effects on local hydrology, subsequently impacting wetlands. Xu et al., (2024) found that the projected impacts of climate change on wetlands across North America from 25° to 53° North could be a 10% reduction in area by the end of the century under a higher emission (SSP585) scenario. However, regional impacts vary, and not all wetlands will experience the same degree of drying, underlying the importance of forming a strong understanding of the local impacts of climate change on an area.

The Columbia Wetlands are a series of floodplain wetlands within the Upper Columbia River Basin, located in the Rocky Mountain Trench between the Rocky Mountains to the east and the Purcells to the west. They occur as far south as Invermere, British Columbia, and continue north to Golden, BC, and contain 26,000 ha of Ramsar Wetlands of International Importance. As this section of the Columbia River is the only undammed section of the Columbia River, the natural hydrology is governed largely by 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). The seasonal pulses have shaped the Columbia Wetlands, where the combination of high and low flows of the Columbia River has resulted in an aggradation of sediments forming and maintaining levees that then withhold water after flood waters have receding into the late summer and fall (Filgueira-Rivera et al., 2007).

Over the past several decades, many hydroclimatic changes have occurred in the region, including increased air temperatures and evapotranspiration, precipitation shifts, and changes in flow timing, duration, and magnitude (Stewart, 2004; Utzig 2021; Rood et al. 2016; Brahney et al. 2017). The increase in air temperatures has already begun 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, particularly at low to mid elevations (Stewart, 2009; 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) with overall reduced flows n the Columbia River (Rood et al. 2016; Brahney et al. 2017). These hydroclimatic shifts have already resulted in a discernable reduction in open water in the Columbia Wetlands (Hopkins et al., 2020) and a change in landcover, with wetlands drying out and shifting from marshes and open water towards woody shrub landcover (Rodrigues et al., 2023).

Snow plays a critical role in shaping the hydrograph of the Columbia River and the Columbia Wetlands, both due to the large flood pulse that results in the late spring due to melting snow and rain on snow events, but also due to groundwater recharge. Remmer et al., 2023 found that alpine snowmelt is a major contributor to river and groundwater contributions in the Columbia Wetlands, and that snow-fed groundwater is an important source of water for many wetlands later in the season. This is in keeping with previous research that has found that snowmelt dominated watersheds tend to have a higher percentage of snowmelt contributing to groundwater recharge (Earman et al., 2006; Ajami et al., 2012), and that snowmelt is better able to infiltrate deeper into soils than rainwater (Earman et al., 2006).

Increasing air temperature is predicted to alter snow accumulation, even at higher elevations in the region (Carver, 2017). This is due partly due to less precipitation falling as snow (Dierauer, et al., 2021), but also due to rain on snow events, which can reduce snow accumulations and even reduce the SWE due to snowmelt (Brandt et al., 2022) and instigate floods and debris flows (Surfleet and Tullos, 2013; Hatchett et al., 2020). Due to the relative importance in snowmelt in the Columbia Wetland water budgets, reductions in winter snowpack may result in a reduction in wetland recharge from stream and groundwater sources. This is likely to result in higher floodplain wetland vulnerability, leading to potential long-term challenges for the Columbia Wetland ecosystem.

Wetland vulnerability to climate change has been shown to be linked to their location and connection on the hydrologic landscape (Winter, 2000; Meng et al., 2020). Here we examine vulnerability to climate change using a combination of field investigation and hydrological modelling, extending to an area that encompasses a broad geographic range. Locally, recent work has shown that beaver dams play a critical role in determining wetland connections to the Columbia River (Leven, 2024) and efforts are underway to improve water storage in wetlands by repairing and enhancing beaver dams in floodplain wetlands (Leven et al., 2024). Combined, an understanding of vulnerability and local adaptations focused on increasing storage have a chance at improving the functioning of floodplain wetlands in this important region.

# 3 Study Area

The Columbia Wetland Complex extends from south of Invermere, BC, to Golden, BC in the Rocky Mountain Trench, approximately 180 km in length and 260 $km^2$ in area (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 24 $km^2$ of area, a little under 10% of the overall Columbia Wetland Complex (Figure 1). The wetlands exist along the Columbia River floodplain, which is restricted laterally in a 1.5 km wide valley between the Rocky Mountain Range and the Purcell Mountain Range, with an average slope of 11.5 cm/km (Makaske et al., 2009). As the regional climate and hydrologic model were developed using data from several gauging stations located throughout the watershed, a larger Regional Study Area is used to develop the hydrologic models, whereas a smaller Local Study Area that encompasses the area directly affecting the study wetlands (Figure 1). The regional models developed considered watersheds with long-term hydrometric records to calibrate and validate model performance (Table 1).

*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 |

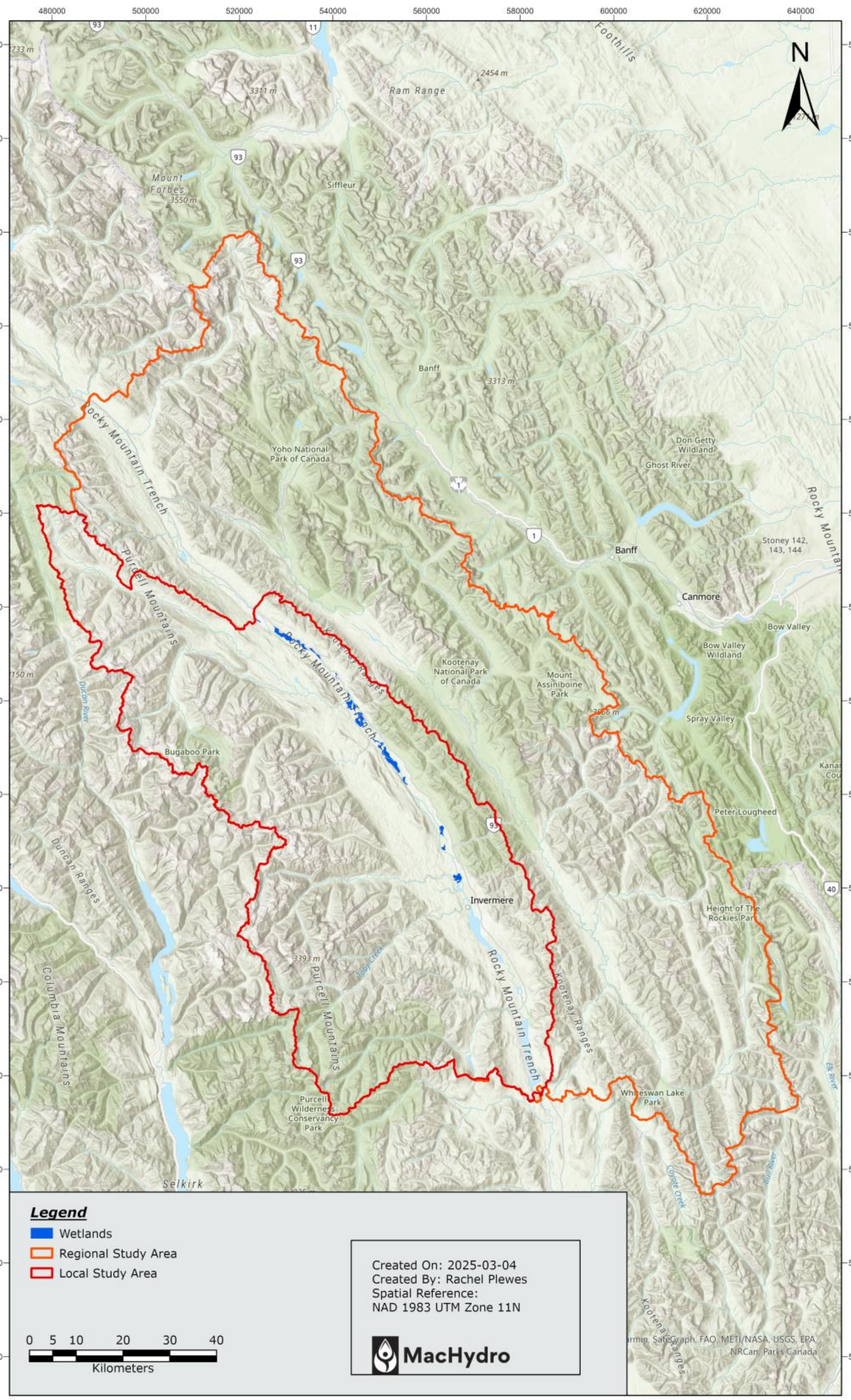



*Figure 1. The floodplain wetlands examined within the local (red) and regional (orange) study areas within the Upper Columbia River Watershed.*

## 3.1 Regional Study Area

The Regional Study Area consists of the drainage area upstream of the gauging station at Donald, BC, which drains an area of 15, 193 $km^2$. 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. The area extends from below 800 m.a.s.l. at Donald, BC to over 3500 m.a.s.l. at the highest peaks along the Continental Divide and in the Selkirk Mountains. 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 and icefields located at the highest elevations in both mountain ranges; these include the Wapta and Waputik Icefields, located in Yoho National Park, and the Conrad Glacier located in the Columbia Mountains.

The gauging station on the Columbia River at Nicholson, BC (a few km south of Golden, BC) is downstream of the wetlands used in the field study. There are several major tributaries that flow into the Regional Study Area; most of these flow into the Local Study Area and are covered in the following section, but downstream of these the Blaeberry and Kicking Horse Rivers drain the northeast corner of the regional study area from the Rocky Mountains.

Soils within the study area include various types with textures including silt, sand, sandy loams, loamy sands, and loams (BC Ministry of Environment, 1990). Soils are imperfectly, well and rapidly drained. Depositional modes include glacial tills (especially within the valley bottoms), glaciofluvial, fluvial, and colluvial processes (BC Ministry of Environment, 1990). The regions to the western portion of the study area in the headwaters are predominantly undifferentiated bedrock, while silt is notably more present in the river bottoms of tributaries and the Columbia River floodplain, as is loam, sandy loam, and loamy sand.

The study area is made up primarily of sedimentary rocks from the Proterozoic to Paleozoic Eras, including the following (taken from the BC Data Catalogue):

- Coarse clastic sedimentary rocks from the Neoproterozoic associated with the Horsethief Creek Group,
- Conglomerate coarse clastic sedimentary rocks from the Neoproterozoic associated with the Toby Formation,
- Quartzite, quartz, arenite sedimentary rocks found throughout the study area from the Mesoproterozoic that are associated with the Mount Nelson Formation, as well as slivers in the north from the Neoproterozoic to Lower Cambrian associated with the Cranbrook Formation
- Undivided sedimentary rocks from the Mesoproterozoic associated with the Dutch Creek Formation, from the Ordovician associated with the Mount Wilson, Skoki, Tipperary, Glenogle, Survey Peak and Lyell Formations, and; Upper Ordovician to Middle Silurian associated with the Beaverfoot and Mount Wilson Formations
- Dolomitic carbonate rocks from the Mesoproterozoic in the southern portion of the study area that are associated with the Kitchener Formation and from the Middle Silurian to Upper Ordovician that are associated with the Beaverfoot Formation in the north
- Limestone, marble, calcareous sedimentary rocks from the Middle to Upper Cambrian that are associated with the Lyell, Sullivan, Jubilee, or Chancellor Formations
- Mudstone, siltstone, shale fine clastic sedimentary rocks from the Cambrian to Ordovician associated with the McKay group.

## 3.2 Local Study Area

The Local Study Area is the drainage area upstream of the Columbia River at the same location as the outflow of the most downstream study wetland, consisting of a total of 6,152 $km^2$ with an elevation range between 782 m.a.s.l. and 3489 m.a.s.l. (Figure 2). The main tributaries to the Columbia River within the Local Study Area are the Spillimacheen River and Bugaboo, Horsethief, and Toby Creeks, all originating in the Purcell Mountains. In addition, there are also Dutch, Sinclair, and Windermere Creeks that flow into the Columbia River, all of which are 6$^{th}$ order streams.

Glaciers cover 2.7% of the Local Study Area and exist in the headwaters of many of the major tributaries, such as Conrad Glacier in Spillimacheen River watershed Malloy Glacier, Vowell Glacier, Crescent Glacier, and Bugaboo Glacier in the Bugaboo Watershed, and Jumbo and Toby Glaciers in the Toby Creek Watershed.

## 3.3 Restoration Wetlands

The four individual wetlands that have either undergone restoration efforts or are in the planning phase for restoration activities are wetlands 38, 71, 24, and 145. These wetlands are all located within the LSA Columbia River floodplains (Figure 2).

### 3.3.1 Wetland 38

Site 38 is dammed by a natural beaver dam in the levee which was destroyed in flood waters during 2020. Despite the damage, the wetland has been classified as a wetland with low connection to the Columbia River except in 2022, where it was partially connected, likely due to the large flood pulse that year. A beaver dam analogue (BDA) was built in the original beaver dam location on site 38 in the fall of 2021, and received repair work in 2022 and 2023. The restoration efforts have resulted in an increase in water levels of 0.6 m from prior to the installation of the BDA.

### 3.3.2 Wetland 71

Site 71 has a small levee gap which was dammed by beavers in 2023, improving water levels of a 0.22 $km^2$ wetted area. This increased water levels by 0.25 m, resulting in an estimated increase in retention of 27,500$m^3$. This allowed the wetland to retain a greater amount of water into the fall in 2023 than was evident in previous years, despite 2023 being a low water year. Prior to the beaver activities, site 71 bounced between wetland groupings of partially connected with big gaps (2020, 2022) and most connected (2021).

### 3.3.3 Wetland 24

Site 24 is a 0.46 $km^2$ wetland that is considered most connected in all years as its hydrograph is like that of the Columbia Wetlands. Water retention is limited, with only a small amount of water remaining into the fall, due to two large gaps. Restoration efforts are still in the development phase and are engaging with the landowner, the Nature Trust, on future actions to retain water at the site.

### 3.3.4 Wetland 145

Site 145 is a most connected wetland that loses most of its water by the fall. A 10.5 m long and 1.35 m tall BDA has been proposed to be built in a large hole in the level which would effectively increase water levels 1.35 m, increasing water storage by 175, 500$m^3$. Restoration efforts are still in the development phase.

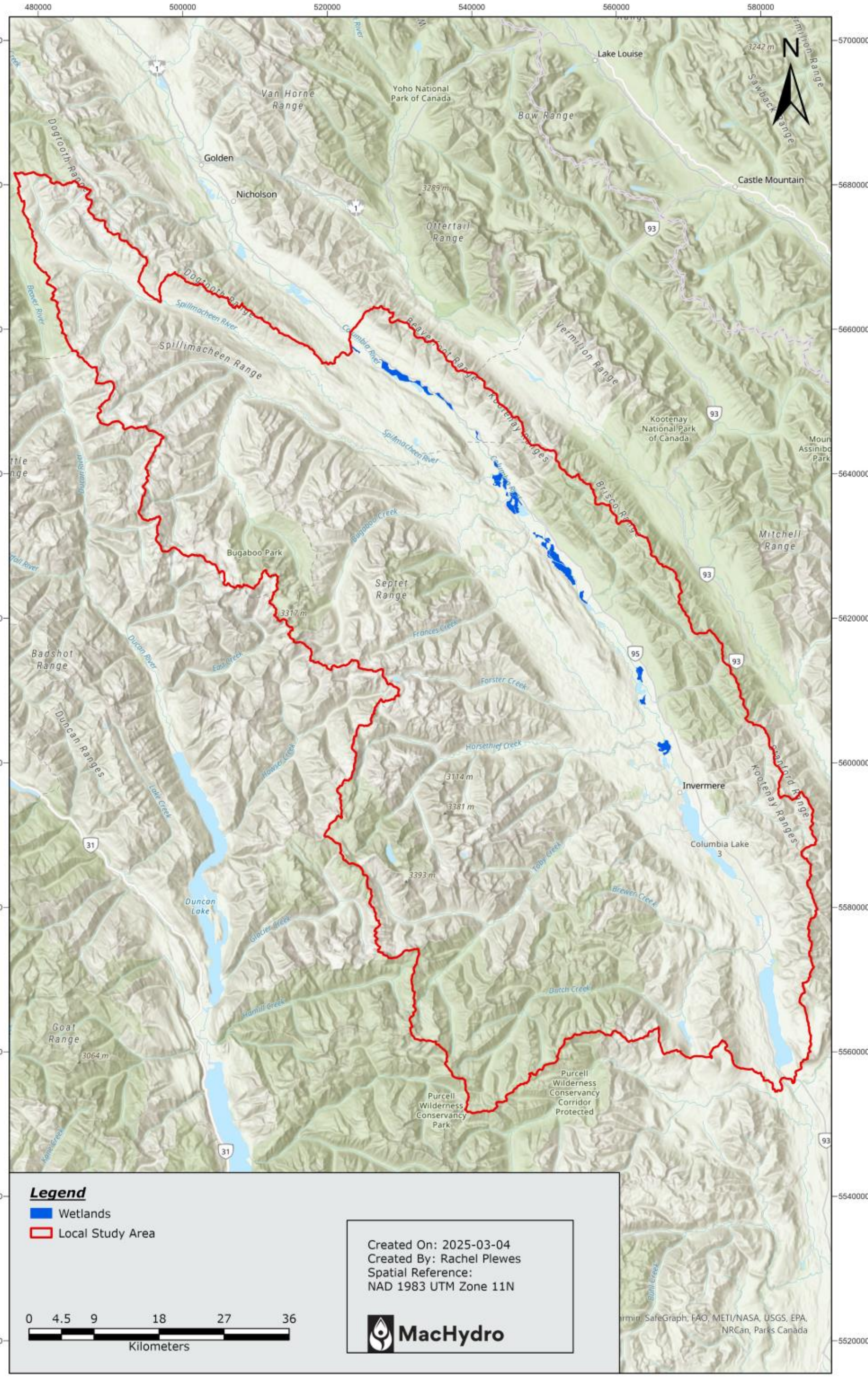



*Figure 2 the local study area of the floodplain wetlands in the Upper Columbia Wetlands.*

# 4 Methods

## 4.1 Field Methods

Stilling wells constructed out of PVC pipe were installed in a total of 38 wetlands throughout the Columbia Wetland Complex, though not all sites have data for all five years of data collection. Wetland sites were selected to represent different types of wetlands present in the valley based on local knowledge. Water-level loggers (Onset HOBO pressure transducers; Model U20–001–01, 4 m range with a 0.4 cm accuracy or 9 m range with 0.5 cm accuracy) were placed in each stilling well, along with two loggers in the Columbia (with one at Spillimacheen, BC, and the other at Brisco, BC). An additional logger was used to collect barometric pressure and placed in a central location within the study reach. As the deepest location within the wetland could not always be reached, the difference between the height of the logger in the stilling well and deepest location within the wetla nd was recorded. Loggers were deployed each year in late April or early May and collected data until October, and were set to collect water pressure (kpa) and temperature (◦C) at four-hour intervals. Water pressure was converted to water level (m) using the HOBOware Pro 3.7.26 barometric compensation tools.

### 4.1.1 Water level analysis

Water levels for each of the wetlands are used to develop a conceptual understanding of overall wetland hydroperiod. Correlation analysis was used to determine relatedness of wetland water level between wetland groupings, climate, and streamflow.

## 4.2 Hydrological Modelling

The study area was split into subbasins with outlets that coincide with Water Survey Canada hydrometric stations, extended north and south of the field study wetlands. Figure 3 shows the study area, subbasin delineation, and associated locations of floodplain wetlands in each subbasin. We expanded this analysis relative to the field study sites to evaluate the effect of climatic gradients along the Columbia River Valley.

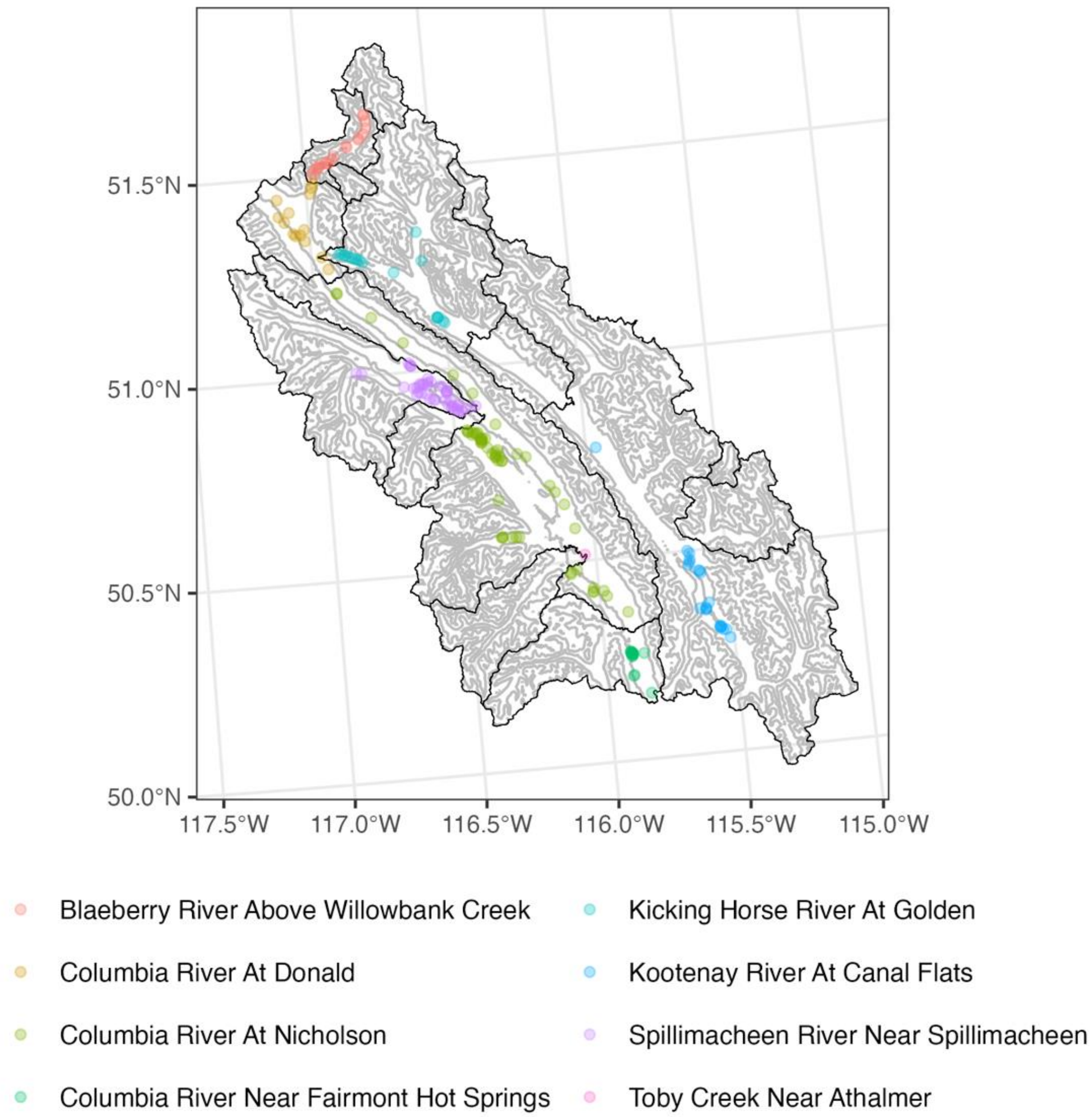



*Figure 3 Map of study area of hydrological model set up, elevation bands, and associated wetland locations in each subbasin.*

The Raven Hydrological Modelling Framework (v3.8; Craig et al., 2020) was used to predict and assess the state of wetlands in the Columbia River Valley. Raven is a mixed lumped/semi-distributed model that is typically used to simulate state variables and streamflow. Raven allows users to determine the degree of model complexity from lumped (single subbasin models) to semi-distributed (routing). Each watershed is assembled from several subbasins, which are assembled from contiguous or non-contiguous hydrological response units. These are defined as areas that are hydrologically unique responses to precipitation events. Each HRU can be defined by elevation, land use type, vegetation cover and terrain type, which is underlain by a soil profile. The model then solves the 1-dimensional water balance for each HRU where it can be later redistributed amongst surface water channels.

### 4.2.1 Model Setup

#### Meteorological Forcing Datasets

The model requires spatially distributed daily minimum and maximum air temperature to simulate state variables and fluxes. The forcing dataset used for the historical climate scenario (1980-2024) daily air temperature (maximum and minimum, °C), precipitation (mm/day) and relative humidity were collected from DayMet (Thornton et al., 2018). DayMet points were extracted at a regular grid pattern of approximately 1 degree resolution. While the meteorological forcing dataset used for future climate change (2021-2080) was obtained from Environment and Climate Change Canada (ECCC, 2021) statistically downscaled under Shared Socio-economic Pathways (SSPs). These data collected used the daily median projection from an equal-weighting ensemble forecast of 26 General Circulation Models (GCM) from the Coupled Model Inter-comparison Project Phase 6 (CMIP6) from 2021 – 2080. For this work, two SSP median ensembles were chosen: SSP 2-4.5 which represents a middle-of-the-road pathway of development, and SSP 5-8.5 which represents a scenario with intensified exploitation of fossil fuel resources.

The daily future meteorological variables from ECCC daily median project were first bias-corrected using the simulated future air temperature and precipitation and historical (simulated). Each future month and year were then matched with a proxy month from the historical 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 to correct the daily observed record for each climate scenario.

### 4.2.2 Conceptual Overview

The water balance problem is defined by the conservation equation whereby a conservative quantity entering a control volume during a defined period, minus the amount of the quantity leaving the volume during the period, equals the change in the amount of quantity stored in the volume during the period (Dingman, 2015).

Given the scope of the study, the hydrological model was set up as a semi-distributed model. Whereby each HRU water balance is quantified and then amalgamated as a single contribution to streamflow. To look at the specific implications of climate change on wetlands we assessed the 1-D water balance of wetlands located in the valley bottom (elevations less than 1400 m.a.s.l.) to conceptually understand how water storage may change from meteorological drivers. In this water balance, water enters the wetland through precipitation (P) and leaves from evaporation (PET).

$$dS = P - PET$$

#### Precipitation

Precipitation (rainfall and snowfall) were interpolated directly from the DayMet gauges using the inverse distance weighting interpolation method to generate a gridded product.

#### Potential Evapotranspiration

Potential Evapotranspiration (PET) was determined using the Priestley and Taylor (1972) relationship, whereby net radiation (calculated via model) derives daily PET, and a correction factor PET is driven by the vapor deficit.

$$PET = 1.26 \frac{1}{\rho_w \lambda_v} \left[ \frac{\Delta}{\Delta + \gamma} R_n \right] \quad (3)$$

Where $R_n$ is the net radiation. The default scaling factor of 1.26 is used to scale the radiation-driven PET for the vapor deficient driven PET. The saturated vapor pressure is determined by the air temperature:

$$e_s(T) = 0.6108 \; exp \; exp \left( \frac{17.23T}{T + 237.3} \right) \quad (4)$$

And the slope of this curve, $\Delta(T) = de_s/dT$,

$$\Delta = \frac{4.98}{T + 273.3} e_s T \quad (5)$$

Where the latent heat of vaporization of water, $\lambda_v$, is calculated by:

$$\lambda_v = 2.495 - 0.002361 * T \quad (6)$$

Where $T$ is the temperature and the psychometric constant is $\lambda_v$.

#### Wetland Water Balance

The outputs of daily average precipitation, P (mm), and potential evapotranspiration, PET (mm), in wetlands in the region were summarized each year (mm/year) and averaged across a historical (1991-2020) and two future periods (2021-2050, 2051-2080). Spatial outputs of PET and precipitation were then used to evaluate vertical water balances. For each future period, the change in the surface water balance was estimated as the future value relative to the historical (1991-2020) period. The absolute change from the historical scenario in the period (1991-2020) and climate scenario (historical) was then used as a metric to understand how meteorological drivers influence wetlands spatially in the Columbia River Valley.

The cumulative monthly mean precipitation P (mm), and potential evapotranspiration, PET (mm), of each wetland were summarized by subbasin to assess how the water balance changes seasonally in the future. Lastly, we used simulated streamflow at a subbasin outlet on the northern (Columbia River at Donald) and southern (Columbia River Near Fairmont Hot Springs) regions to assess the implications of climate change on streamflow. The results from the seasonal and yearly water balances and streamflow on the Columbia River were then used to conceptually understand how connected, partially connected, and isolated wetlands may change under middle of the road (SSP2-4.5) and worst-case scenario climate (SSP5-8.5) in current (2021-2050) and future (2051-2080) periods.

# 5 Results

## 5.1 Temporal Evaluation of Water Levels

There is considerable temporal variation in wetland water level characteristics within each of the groupings (most connected, partially connected, and least connected). Wetland water levels are responding to streamflow in the Columbia River following the regional temporal patterns. 2020 and 2021 had a similar hydrograph pattern, while 2022, 2023, and 2024 had unique patterns. These pattern shifts between years were consistent among groups, suggesting a larger-scale synoptic condition is driving wetland hydroperiod. It is likely that wetland vulnerability is independent of wetland grouping and that all floodplain wetlands in the study area are equally susceptible to changes in climate. Overall, these results suggest it is important to understand how large-scale processes governing hydroperiod may change under future climates to understand wetland vulnerability.

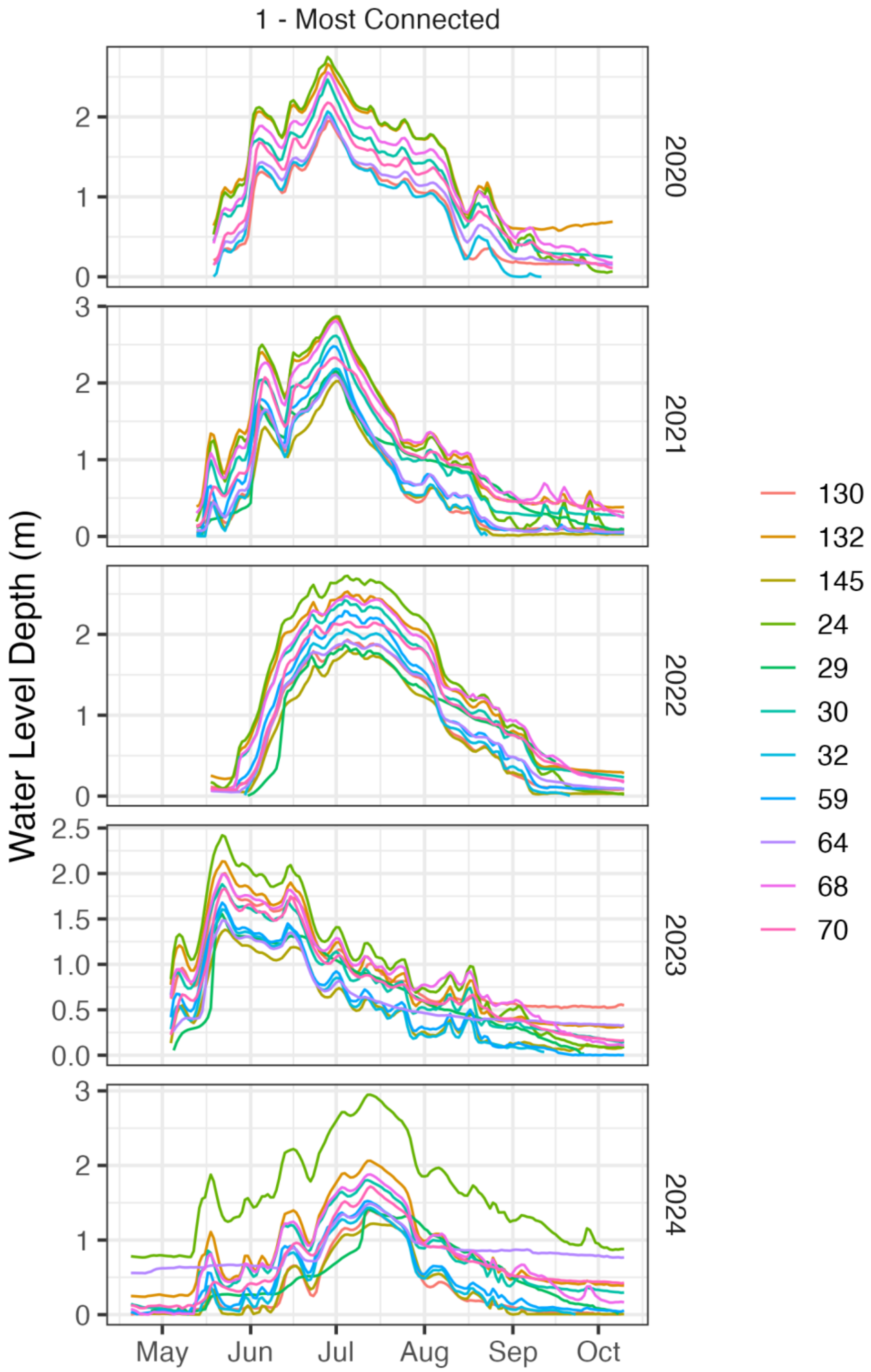



*Figure 4 Water levels for the most connected wetlands (130 (red), 132 (orange), 145 (brown), 24 (olive green), 29 (green), 30 (teal), 32 (light blue), 59 (blue), 64 (purple), 68 (pink), and 70 (fuchsia)) from 2020 (top) until 2024 (bottom).*

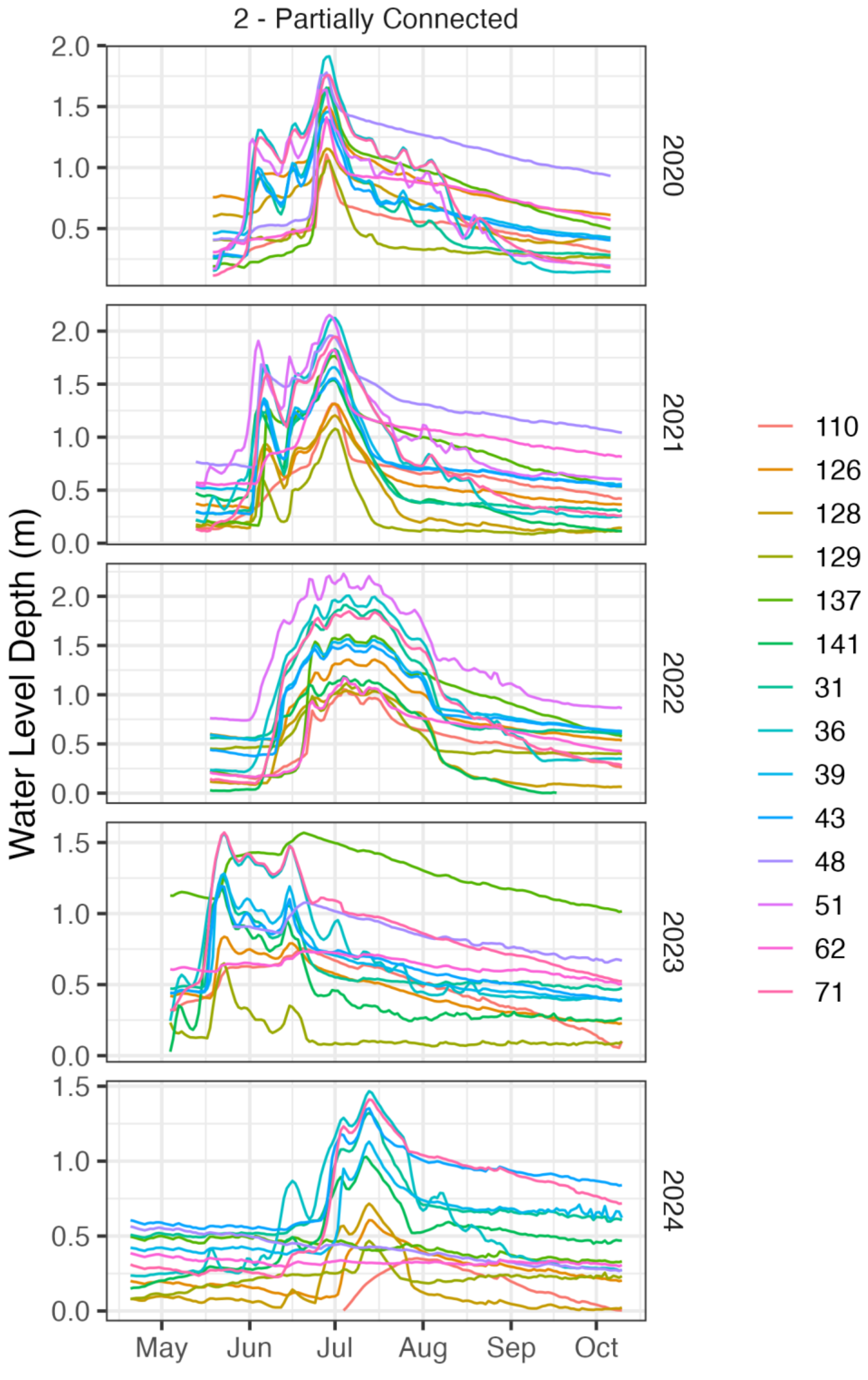



*Figure 5 Water levels for partially connected wetlands (110 (red), 126 (orange), 128 (brown), 129 (olive green), 137 (green), 141 (blue-green), 31 (teal), 36 (light blue), 39 (blue), 43 (dark blue), 48 (purple), 51 (light purple), 62 (pink), and 71 (fuchsia )) from 2020 (top) until 2024 (bottom).*

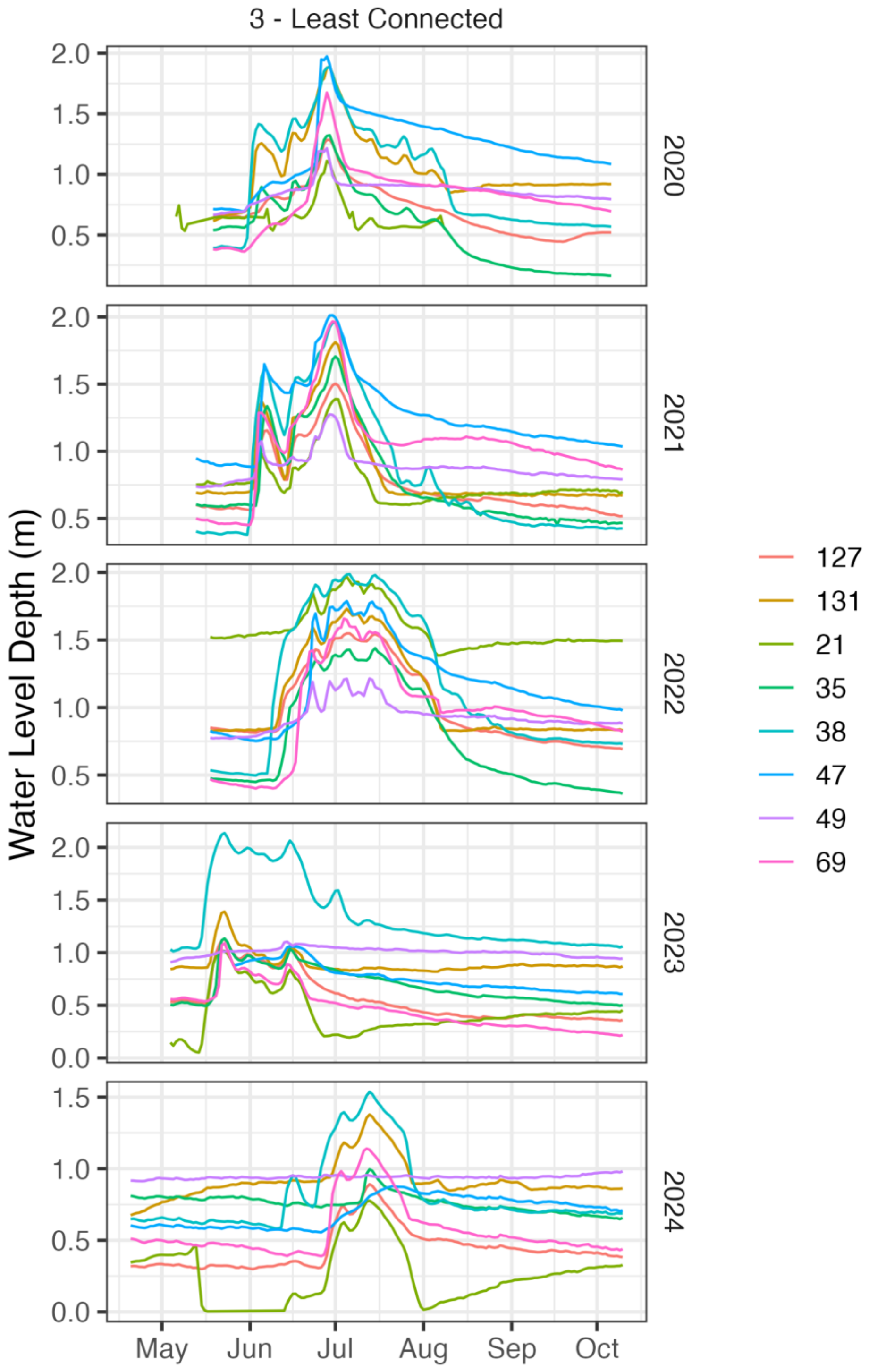



*Figure 6 Water levels for the least connected wetlands (127 (red), 131 (orange), 21 (olive green), 35 (green), 38 (light blue), 47 (blue), 49 (purple), 69 (pink)) from 2020 (top) until 2024 (bottom).*

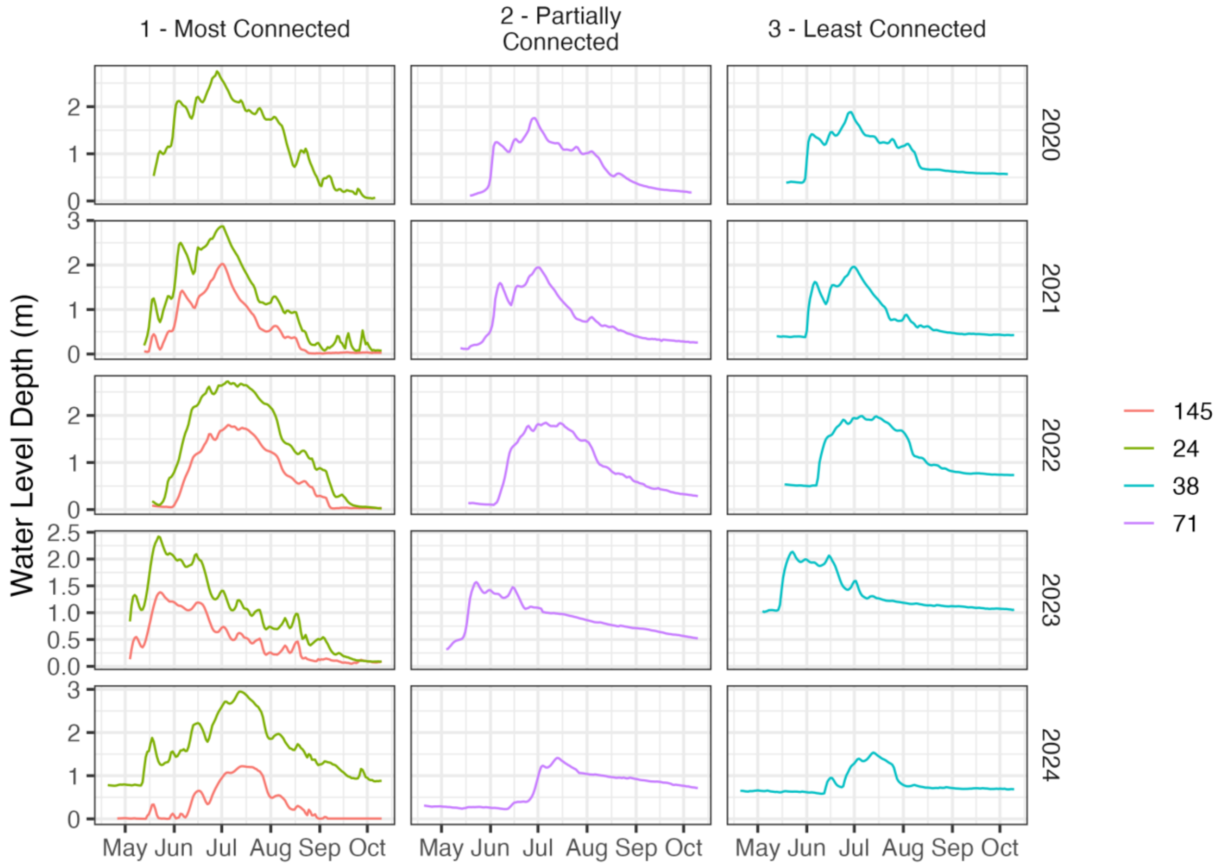



*Figure 7 Water levels for the four restoration wetlands (145 (red), 24 (green), 38 (blue), and 71 (purple)) from 2020 (top) to 2024 (bottom).*

The four restoration wetlands fall into all three wetland groupings, with 24 and 145 illustrating a strong connection to the Columbia River, where they rise and fall in a similar pattern to the river and lose most of their water by the fall. Both wetlands have large holes in their levees that allow water to drain, creating this connection with the Columbia River. The two wetlands that have been restored show changes in their hydrographs because of the beaver dams. A beaver dam analogue (BDA) was installed in the fall of 2021 in 38. In the years preceding the restoration works the water level drops significantly in the fall; following the construction of the BDA, water levels do not drop as quickly but hold steady at a higher level from 2022 to 2024. These effects are even more evident in 71, where a natural beaver dam was constructed in the spring of 2023. The shape of the hydrograph changes in these years and is even more dissimilar to the flows of the Columbia River, now showing strong retention of water levels following the freshet pulse. Considering that 2023 and 2024 were low flow years, this illustrates how beaver dams and BDAs can influence wetland connectivity and shows the benefit of beaver dams at improving wetland water storage and helping combat the effects of climate change on the Columbia Wetlands.

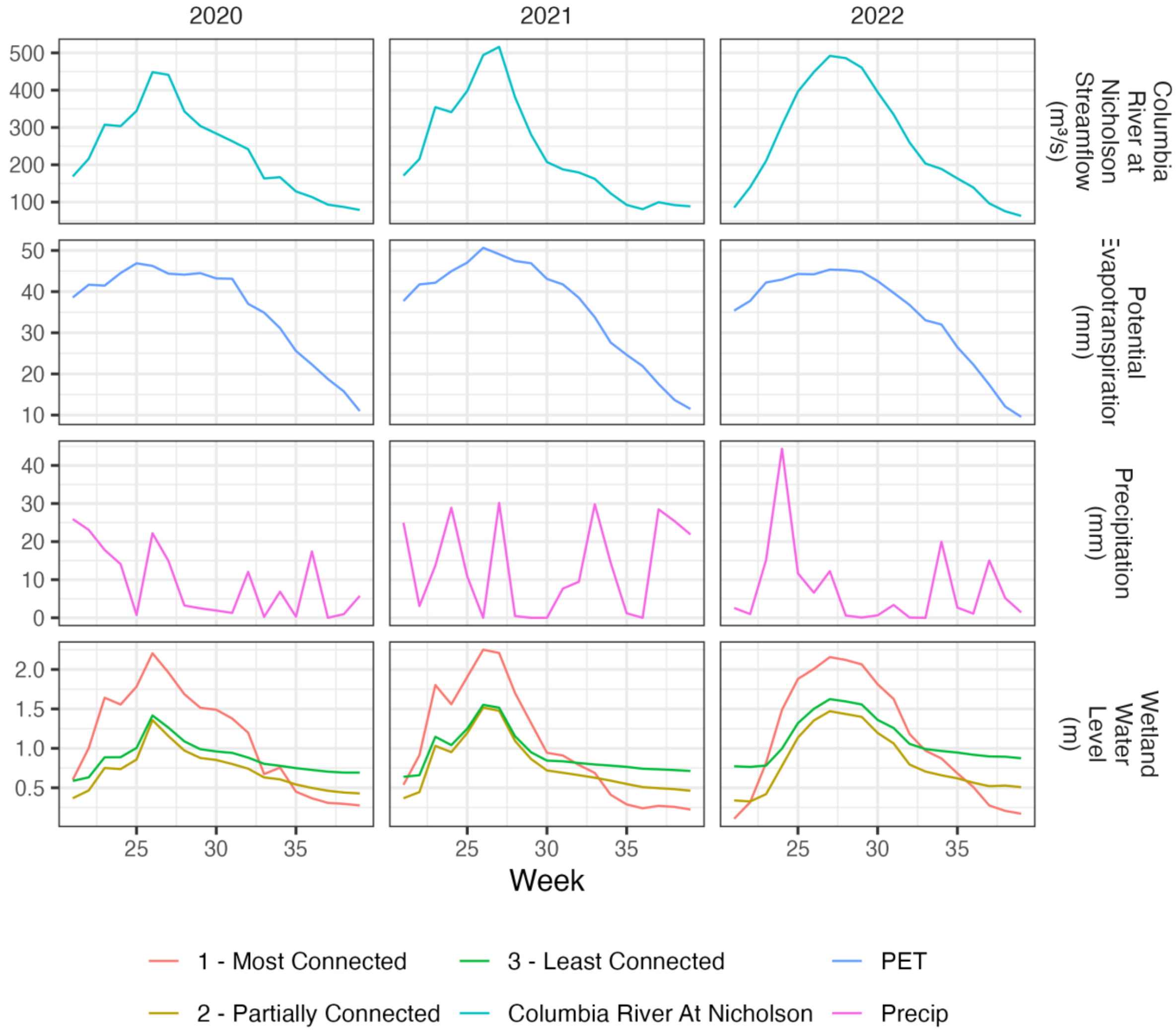



*Figure 8 Mean weekly water levels, PET, precipitation, and streamflow for 2020, 2021, and 2022 from all wetlands in each grouping.*

A visual assessment of mean weekly water level, PET, precipitation, and streamflow suggests all groupings primarily follow the temporal pattern of the Columbia River (Figure 8). The most connected wetlands have a faster hydrograph recession in all three years, indicating storage ability is lacking. Precipitation likely adds some amount of water to wetlands; however, it is a minor contributor. PET is a negative flux away from wetland storage and is a driver of loss. However, again relative to the contributions to the Columbia River, it is likely minor. These results suggest the Columbia River hydrologic condition is the dominant driver of wetland function with a secondary driver being connectivity, and the ability to store water post-freshet. The results also suggest that overall vulnerability to climate change is driven by changes in the Columbia River watershed. Although BDA and natural dam construction has the potential to improve water retention, inter-annual variation in wetland water levels across groups suggests BDA's and natural dams cannot alone mitigate larger-scale dynamics affecting vulnerability.

## 5.2 Projected Changes in Large-Scale Hydroperiod Drivers

Figure 9 shows the simulated precipitation for each wetland over the historical and future time periods. This figure shows that precipitation in the wetlands located in the north of the study area, specifically the Blaeberry River, northern portion of Upper Columbia River (Columbia River at Donald) mainstem, and Kicking Horse River is projected to increase under SSP2-4.5 and SSP5-8.5 climate change scenarios in the near-term and long-term future periods. These trends are amplified near the end of the century under both climate forcing scenarios where they increase by over 150 mm. The wetlands in central and southern Columbia River Valley are projected to increase in precipitation, albeit lesser than the north with only 10-50 mm increase under both scenarios and in near-term and long-term future periods.

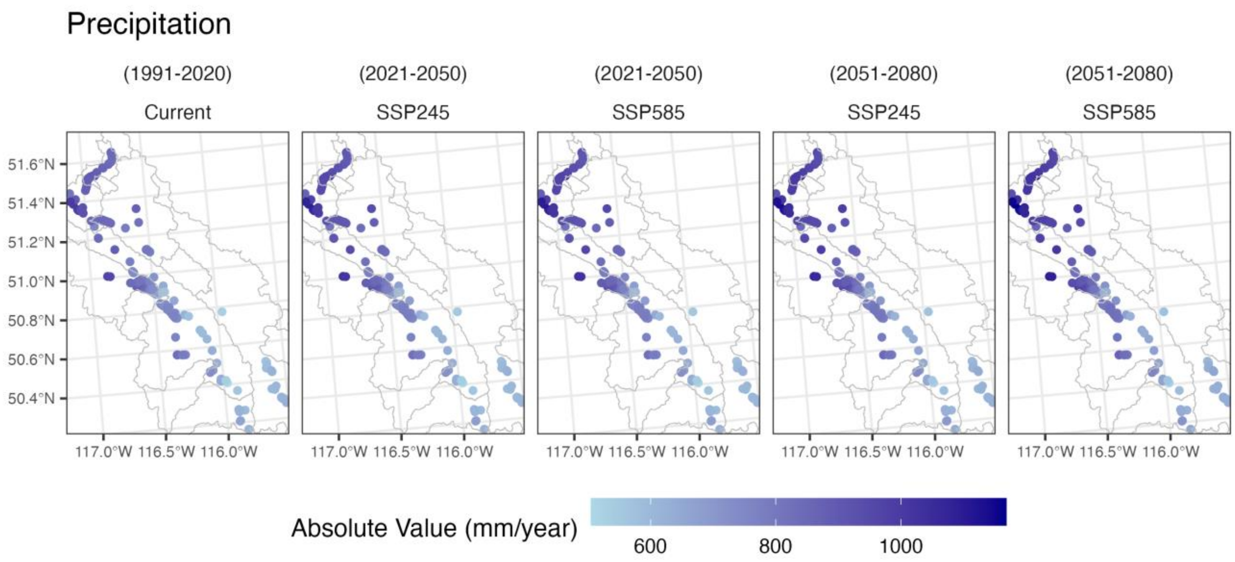



*Figure 9 Simulated precipitation (mm/year) under current (1991-2020) and future periods (2021-2050 and 2051-2081) under climate change scenarios (SSP2-4.5 and SSP5-8.5).*

Figure 10 shows simulated potential evapotranspiration (PET) for historical and future periods. These results show that evaporation rates are projected to increase in the wetlands adjacent to the Upper Columbia River at Donald and Blaeberry River. Over the next 30 years, 2021-2051 PET is predicted to increase to 50 mm of loss a year under SSP2-4.5 and 100 mm loss under SSP5-8.5. The centrally and southern located wetlands near Columbia River at Nicholson and Spillimicheen River are predicted to increase marginally by 50 mm/year. In 2051-2080 these trends persist but become more drastic with the northern wetlands losing up to 150 mm/year while the wetlands adjacent to Spillimicheen River and Columbia River by Donald are expected to lose up to 100 mm/year. The southern wetlands have the highest PET and are projected to further increase by another 50 mm/year under these climate scenarios.

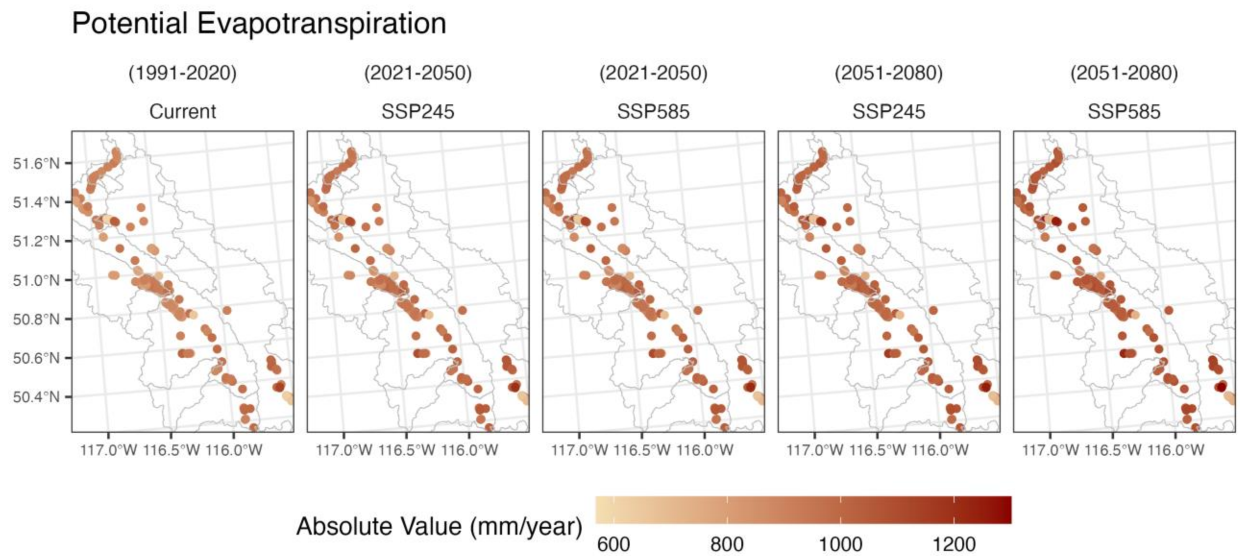



*Figure 10 Simulated potential evapotranspiration (mm/year) current (1991-2020) and future periods (2021-2050 and 2051-2081) under climate change scenarios (SSP2-4.5 and SSP5-8.5).*

Figure 11 shows simulated P-PET for each wetland over the historical and future periods. All wetlands have a negative water balance, with higher PET than precipitation, demonstrating the importance of water from the Columbia River and from nearby groundwater sources. The northern wetlands are expected to remain reasonably stable in the next 30 years under both climate change scenarios (SSP2-4.5 and SSP5-8.5). The southern wetlands are likely to see dramatic shifts towards negative water balance, highlighting their susceptibility to climate change.

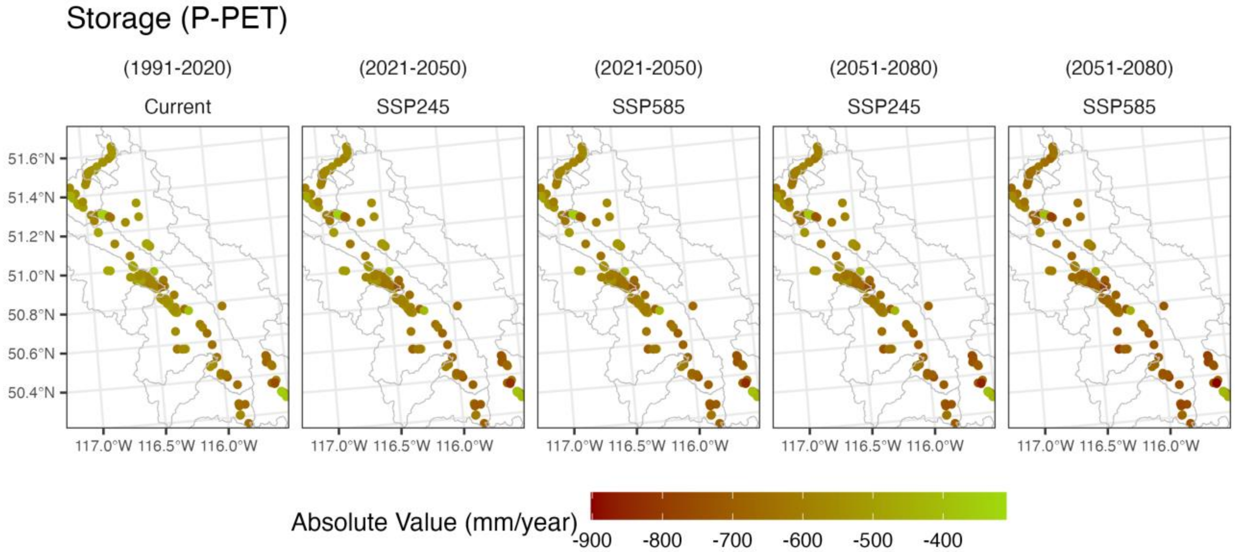



*Figure 11 Absolute change of P-PET (mm/year) under future periods (2021-2050 and 2051-2081) under climate change scenarios (SSP2-4.5 and SSP5-8.5) relative to the historical period (1991-2020).*

Figure 12 showcases the annual mean cumulative precipitation and PET for floodplain wetlands in the northern catchments of the Columbia River Valley. For the wetlands located in the northern basins such as Blaeberry River above Willowbank Creek, Columbia River at Donald, Spillimacheen River Near Spilliamacheen and Kicking Horse River at Golden, precipitation is likely to increase in the winter months (December and January). The future period of 2041-2080 under both scenarios showcase the largest influx of precipitation under the worst-case climate scenario (SSP5-8.5) increases historically from 875 mm/year to 1003 mm/year.

Floodplain wetlands of these northern areas are expected to lose water to PET earlier in the year during February. Moreover, PET is expected to increase substantially during the growing season. Although both scenarios are predicted to have PET increases, SSP5-8.5 is expected to increase the most by 11 to 15% annually. As a result, the PET increases just enough to exceed the precipitation. This suggests that over the next several decades the northern region is likely to be more resilient to changes in climate; however, a tipping point may be reached in later decades where a depletion in storage is likely.

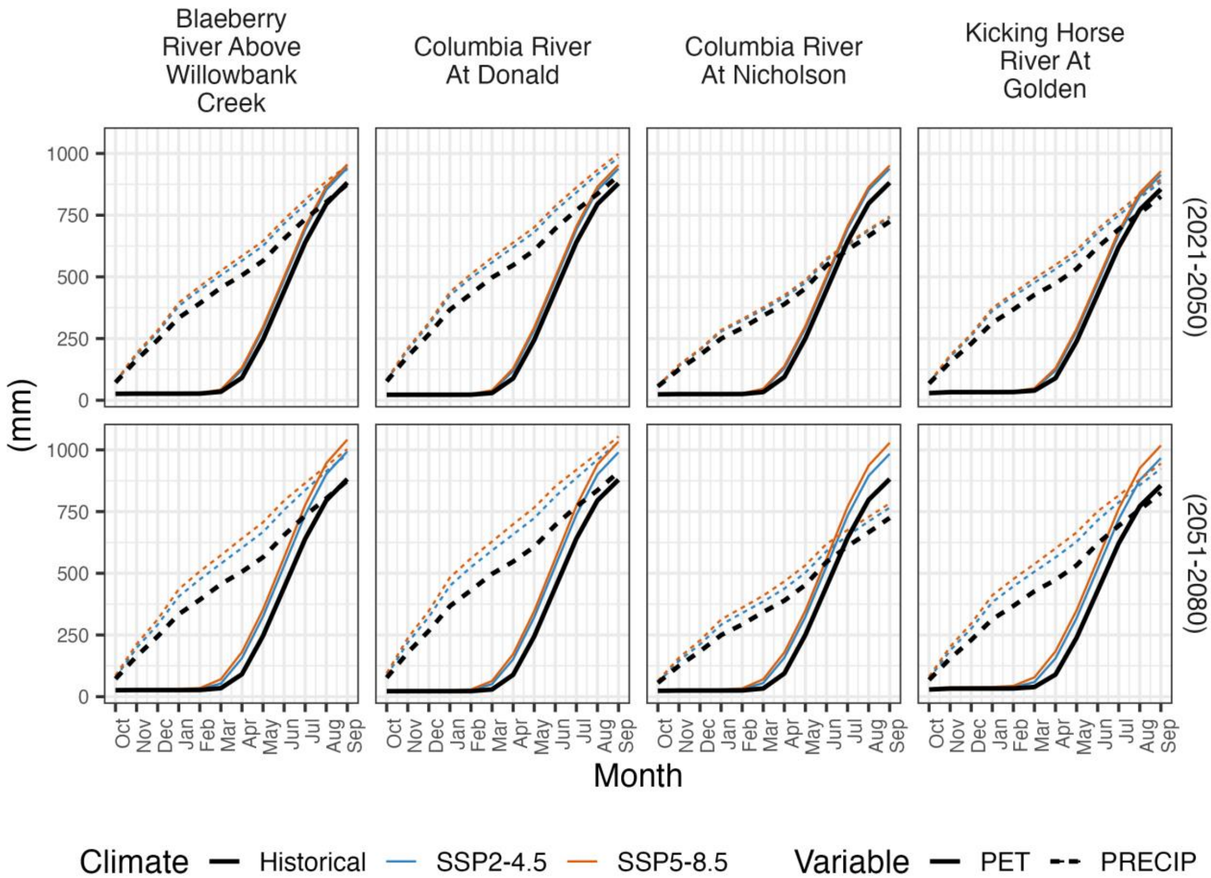



*Figure 12 Monthly mean cumulative potential evapotranspiration (PET) and precipitation (PRECIP) for historical (1991-2020) and future periods (2021-2050 and 2051-2081) under climate change scenarios (SSP2-4.5 and SSP5-8.5).*

Figure 13 showcases the annual mean cumulative precipitation and PET for floodplain wetlands located in the more southern catchments of the Columbia River Valley. Southern wetlands have a similar general trend to the northern sites with precipitation increasing during the winter months but to a lesser extent (4 to 5% increase). Meanwhile PET in these wetlands such as Toby Creek Near Athlmer are expected to decrease or stay the same in the current period under climate scenarios. Columbia River at Nicholson and Kootenay River at Canal Flats are projected to increase only 6% by 55 mm/year in the next period, while in 2050-2081 these values are expected to increase up to 14.3% to from 882 mm to 1029 mm. PET is expected to increase on average and will very likely continue to exceed precipitation resulting in a water deficit making the pulse of inflow from the Columbia River critically important.

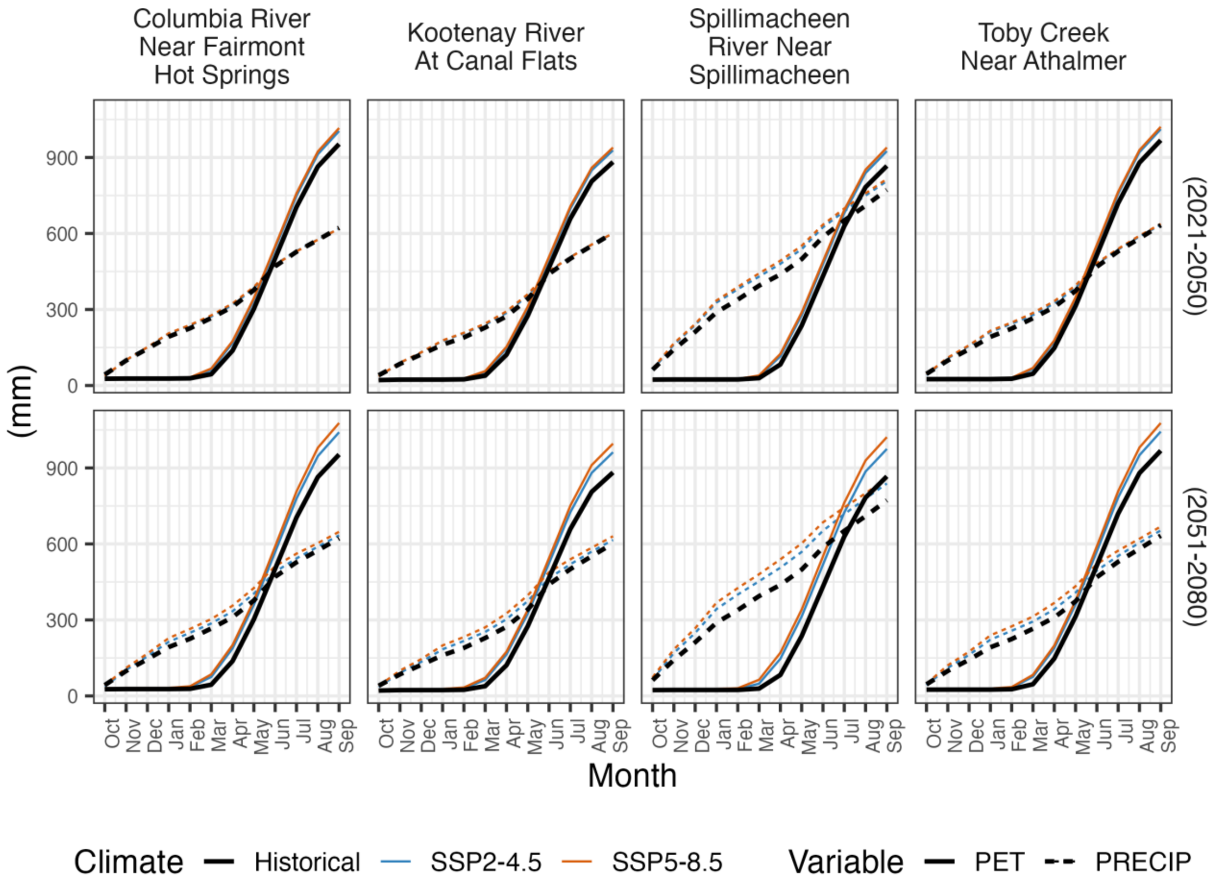



*Figure 13 Monthly mean cumulative potential evapotranspiration (PET) and precipitation (PRECIP) for historical (1991-2020) and future periods (2021-2050 and 2051-2081) under climate change scenarios (SSP2-4.5 and SSP5-8.5).*

Figure 14 showcases the simulated streamflow for the most northern subbasin Columbia River at Donald. The hydrological regime is expected to shift earlier under both future periods, as snow melt occurs earlier causing freshet to occur in late May and early June in both periods with SSP5-8.5 having the most extreme shift in 2051-2080. In the current period, evapotranspiration is supposed to stay consistent as the baseflow and recession of the hydrograph maintain values like historical streamflow. However, in future period of 2051-2080 the streamflow is expected to become depleted more quickly in the summer months while consistent precipitation increases winter and fall result in higher baseflow. The freshet pulse is expected to be larger into the future; however, a longer open water period will likely result in increased vulnerability to higher PET.

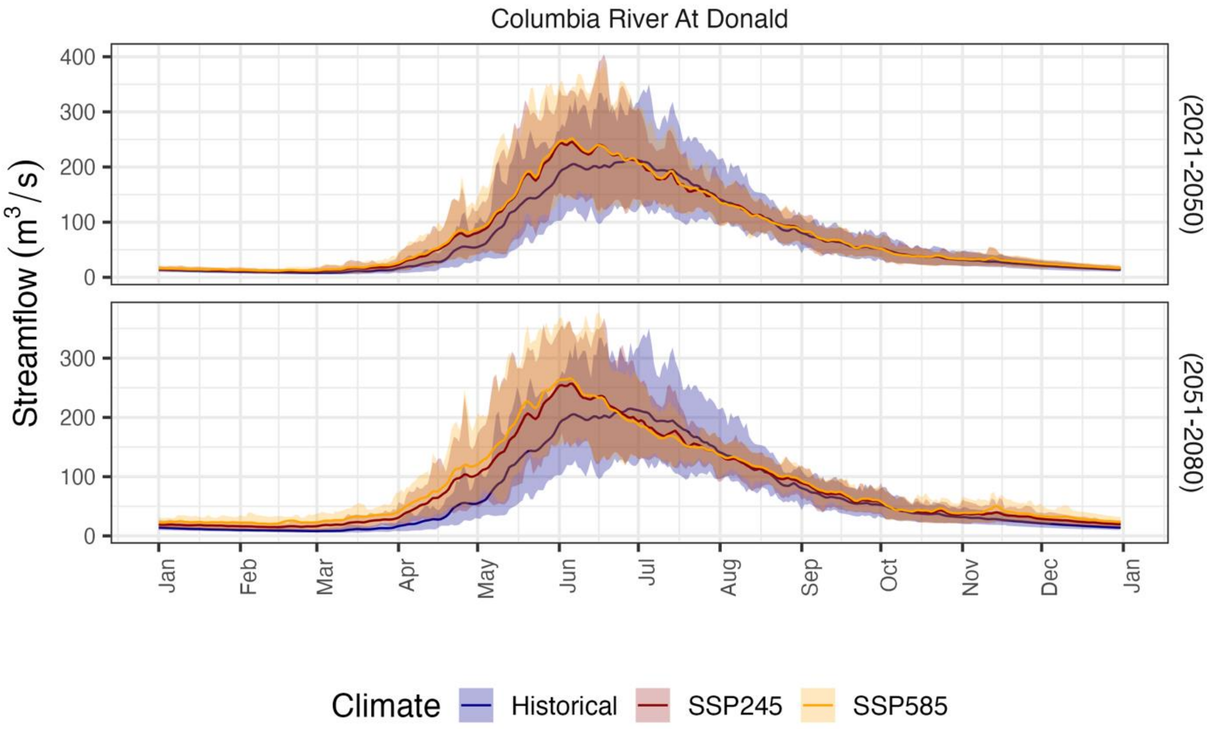



*Figure 14 Average daily streamflow for future periods comparing historic streamflow to climate change scenarios (SSP24 and SSP585) for north location on the Columbia River.*

Figure 15 showcases the simulated streamflow at Columbia River Near Fairmont Hot Springs, the most southern subbasin in the study area. Peak streamflow is expected to increase very marginally and shift earlier in the year. Streamflow is expected to decrease dramatically throughout the summer and fall periods. A similar freshet to current conditions that occurs earlier and recedes rapidly is very likely to result in substantial changes in wetland water levels and increase vulnerability to climate change.

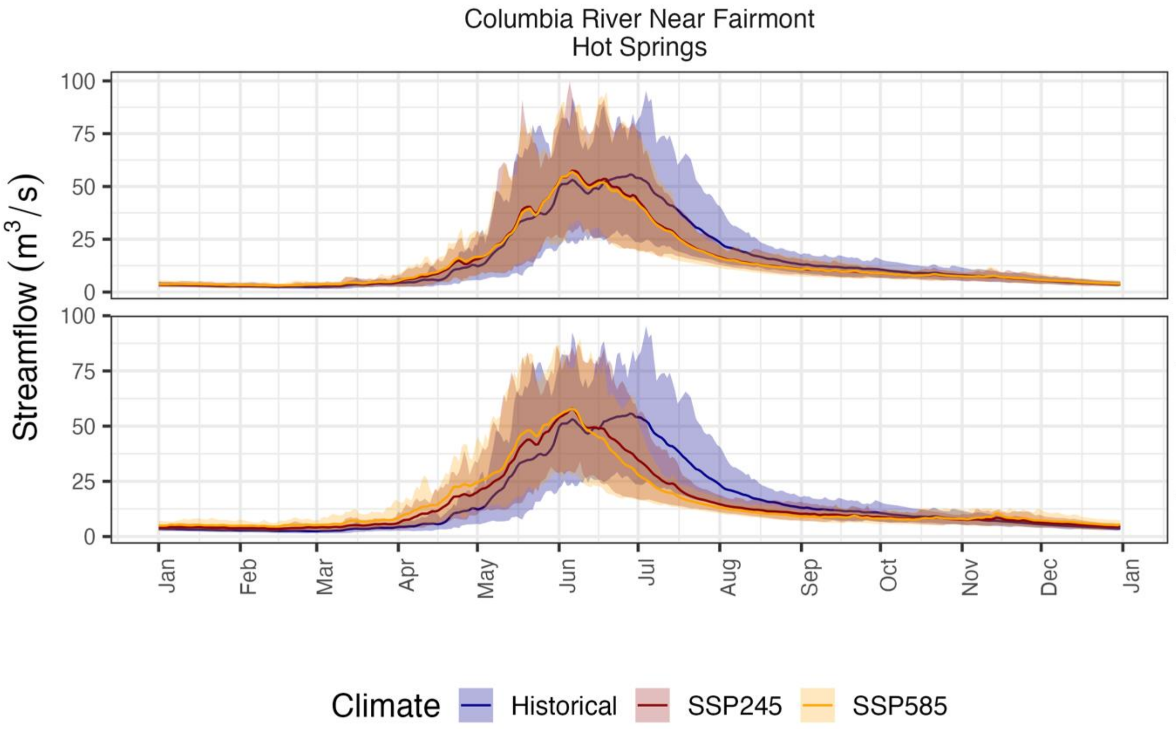



*Figure 15 Average daily streamflow for future periods comparing historical streamflow to climate change scenarios (SSP24 and SSP585) for southern location on the Columbia River.*

# 6 Discussion

## 6.1 Wetland Water Budgets Response to Climate Change

Wetland groupings from Leven (2024) were used in this work, though an analysis of wetland characteristics and groupings should be completed for the 2023 and 2024 data, as some significant group changes are evident in the data. Due to the compounding impact of multiple drought years, some wetland hydrographs in 2024 did not show typical features, such as a variation in level due to a flood pulse or seasonal variations in flow. It is evident that wetland group recruitment varies year to year in response to flows, as various flow qualities can dictate groupings year to year, including peak flow volume, duration, and timing. In general, high-water years will result in a greater number of wetlands being connected to the river, and vice versa. In general, the most connected wetlands would remain most connected in all wetland years, and the most isolated wetlands would remain isolated all year, whereas those of moderate connectivity may fluctuate in their groupings based on the Columbia River flows and alterations to their physical surroundings, such as the introduction or loss of a beaver dam.

Wetland water budgets are largely driven by the position in the hydrological landscape and their connection to the Columba River, which is heavily impacted by changes in climate. In the northern region of the study area, precipitation and PET increase, but the effects are offsetting so the reduction in storage potential is minimal. However, some reductions are still likely to occur due to the shift in more winter precipitation occurring during the winter as rain. As peak flows also increase, there is a shift for wetlands to show more connection to the Columbia River, particularly with wetlands that are already showing a tendency to be fully or partially connected to the river. In the southern regions of the Upper Columbia, precipitation, which is already lower than in the north, decreases further, and PET increases, causing an even greater reduction in storage.

More connected wetlands will fluctuate more depending on the changes in hydrology that the Columbia River experiences. More northern wetlands will experience very little overall change to the streamwater leaving the wetlands, despite an increase in stream water in, as the changes in precipitation and PET will be offset, resulting in only a marginal decrease in the existing water storage (Figure 16). In the southern region of the study area, precipitation decreases while PET increases because of climate change. The spring pulse also gets flashier with less water later in the season, depleting connected wetlands and reducing storage (Figure 16). For wetlands that already go dry before the end of the season, drying may occur earlier in the year.

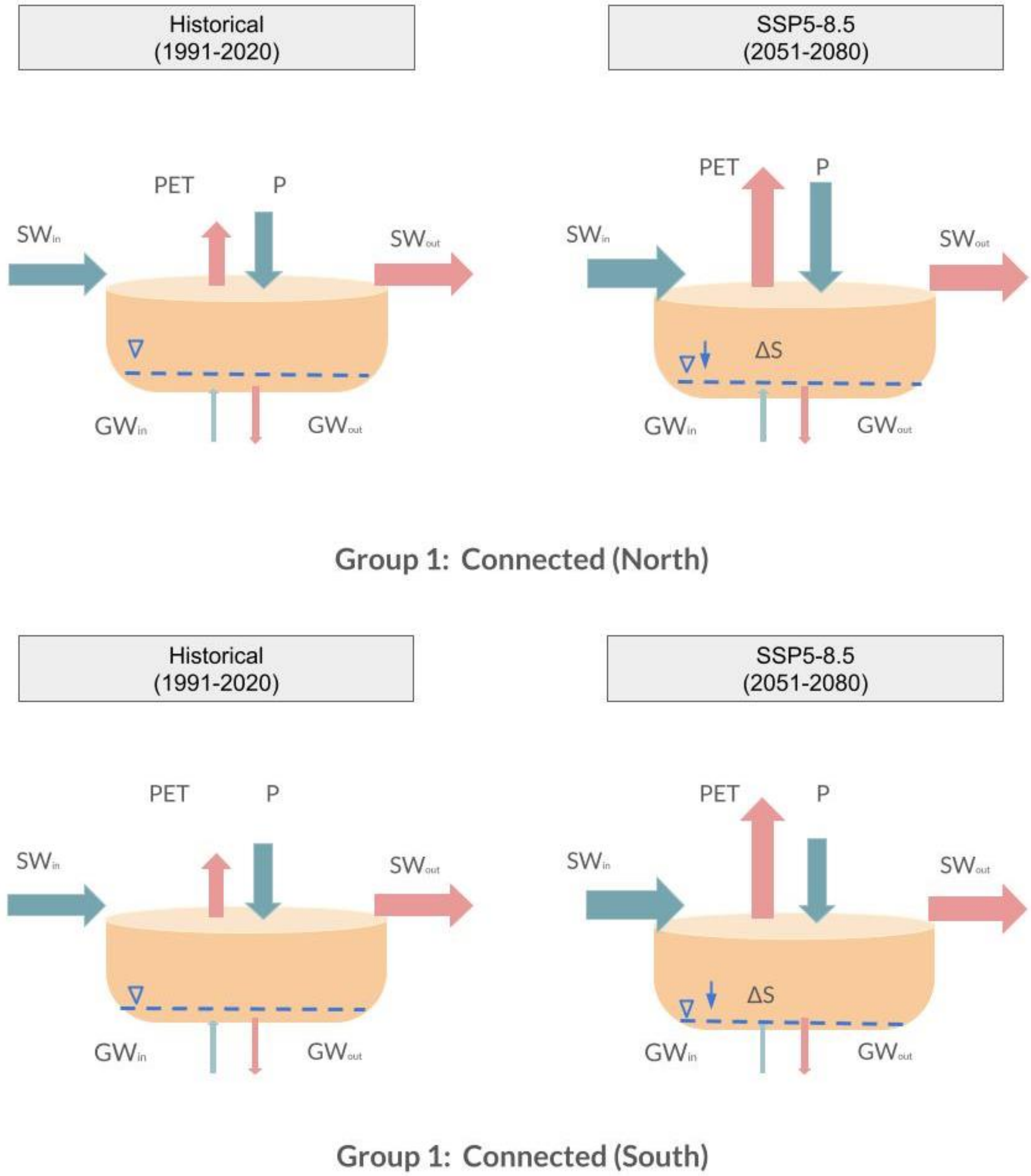



*Figure 16 Conceptual model showing connected wetland water balances for wetlands in the North (top) and South (bottom).*

Partially connected wetlands show similar trends to connected wetlands, and with streamflow peaks increasing these wetlands may shift to being more connected to the Columbia River. Due to the offsetting effect of increases in precipitation and PET in the north, changes in storage will again be minimal in the north, whereas further south wetlands will see increasingly less precipitation and greater PET, resulting in reductions in storage (Figure 17).

However, it should be noted that these water budgets characterize general trends, but drought years might have different results where wetland specific factors need to be considered. For example, 2023 and 2024 were back-to-back low water years with small pulses in the Columbia River. Wetlands 62 and 137 are both partially connected wetlands that showed no connection to the Columbia River in 2024, and instead experienced a slow, steady reduction in water levels throughout the season. Efforts should be made to investigate the causes of these abrupt changes in the hydrograph and characterize what characteristics of partially connected wetlands make them either better able to store floodwaters or prone to drying out.

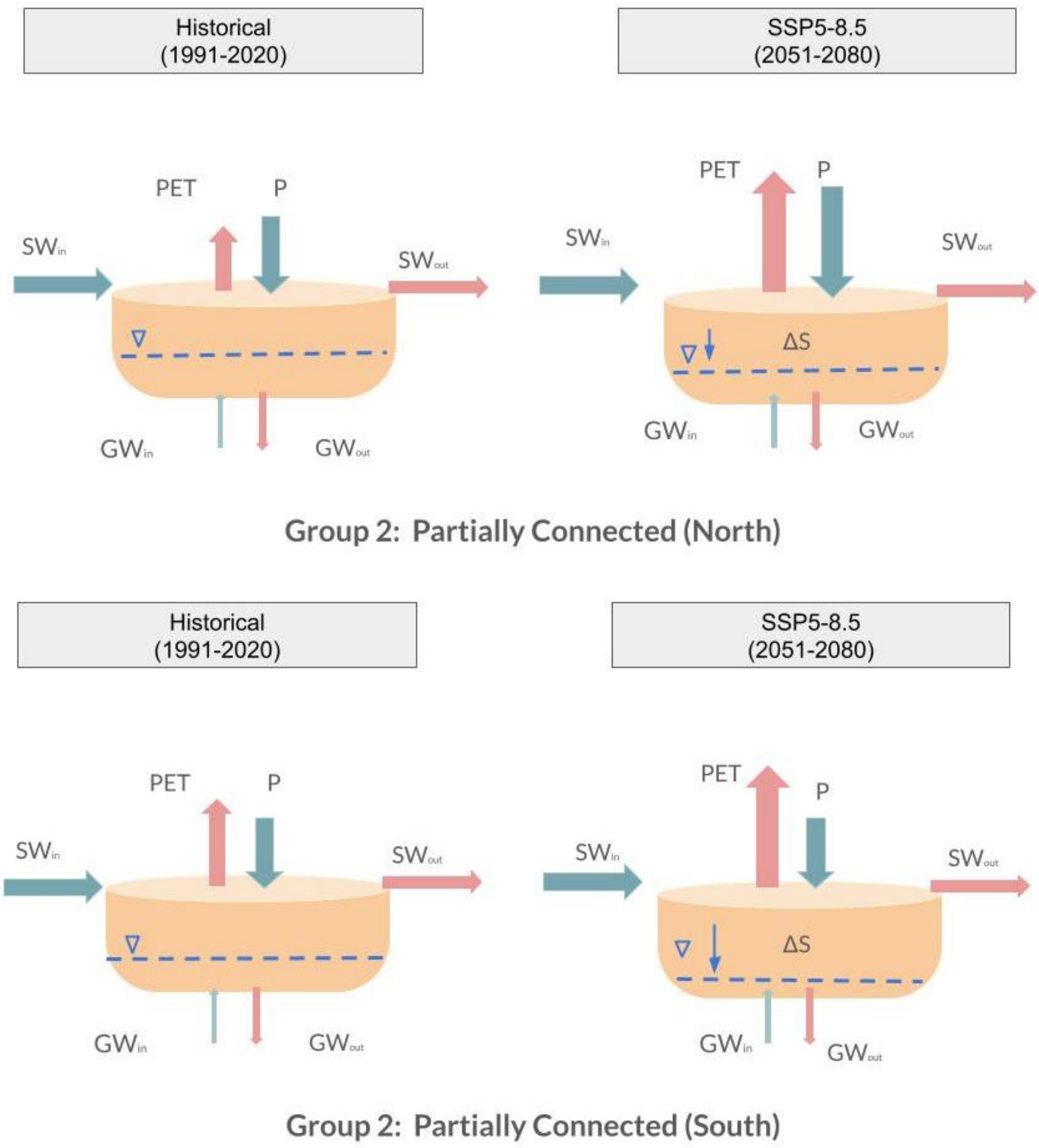
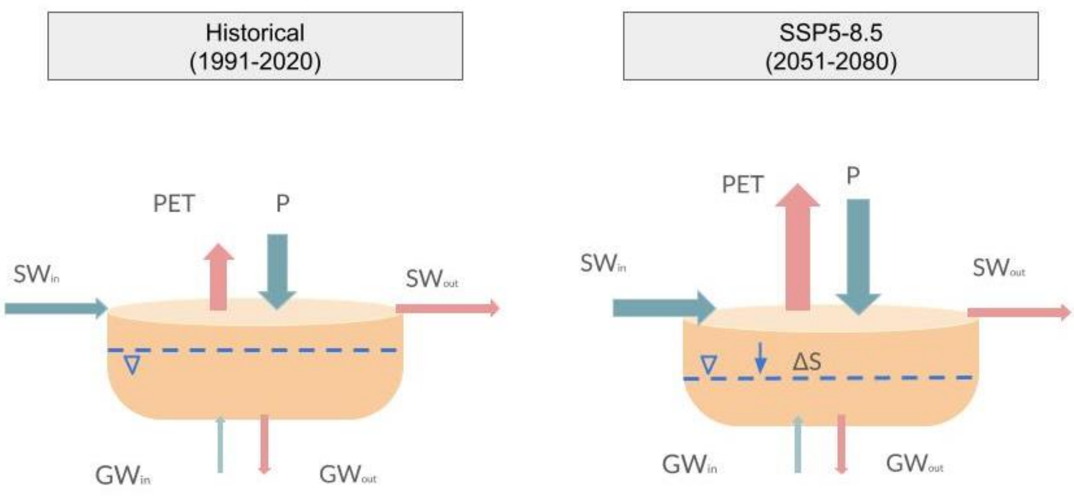



*Figure 17 Conceptual model showing partially connected wetland water balances for wetlands in the North (top) and South (bottom).*

Like more connected wetlands, northern less connected wetlands will not see a large change in water storage due to the offsetting effect of precipitation decreases and PET increases, while further south wetlands will see a greater drying effect in the summer. (Figure 18) However, the individual factors surrounding a wetland being less connected to the Columbia River need to be considered, as there are effectively two kinds of least connected wetlands. For example, 49 is a less connected wetland that, during 2024, was fully isolated, with no discernable influence from the Columbia River and no indication that the river overtopped its banks. However, there is strong groundwater influence at the site, so instead of losing water and potentially drying out, the wetland gradually gained water throughout the season. However, wetlands 62 and 137, discussed above, would be considered isolated in 2024, but the impact is vastly different. These wetlands experienced no pulse from the Columbia River and then experienced a reduction in their water storage throughout the season and showed signs of drying out. This illustrates the importance of water sources maintaining wetland form and function, and that least connected wetlands that do not receive large contributions from the Columbia River need to have an alternative inflow, such as groundwater or another stream, as precipitations contributions will not be enough to sustain wetlands in a changing climate.

It is important to note that changes in groundwater recharge are not considered in the model, but due to more precipitation in the winter falling as rain instead of snow, late season groundwater contributions to wetlands may also decrease, further reducing wetlands storage. Determining groundwater pathways is especially challenging but is an important consideration with isolated wetlands that depend on groundwater contributions.




Group 3: Least Connected (North)

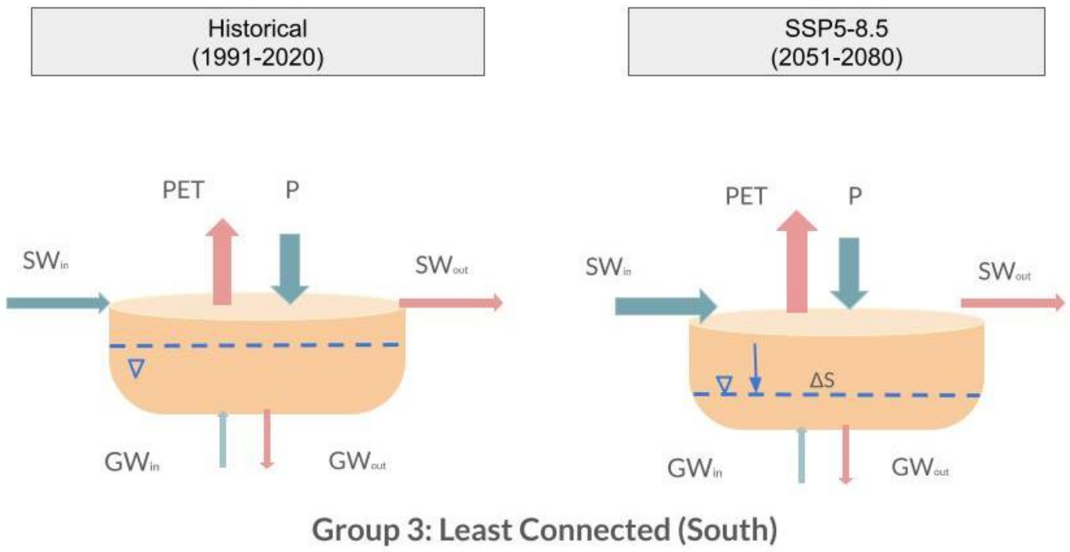



*Figure 18 Conceptual model showing partially connected wetland water balances for wetlands in the North (top) and South (bottom).*

## 6.2 Effect of Beaver Dam Analogues

Wetland restoration efforts have a discernable impact on wetland water retention, which is evident in the hydrographs of wetlands before and after beaver dam and BDA installation. These wetlands shift to being less connected to the Columbia River in that they do not lose water at the same rate as the river does following freshet. Instead, these wetlands maintain higher flows, which is evident even in extremely low flow years like 2023 and 2024. This illustrates that wetlands 38 and 71 have improved climate change resilience following restoration efforts and shows that BDAs and beaver dams can effectively improve water retention in a changing climate (Figure 19). However, efforts should be made to assess individual wetlands for potential inflows and for critical elevations to ensure that wetlands will still have an inflow source (whether it is the Columbia River, another stream, or groundwater) as partially and least connected wetlands still require a water source to withhold water into the dry season.

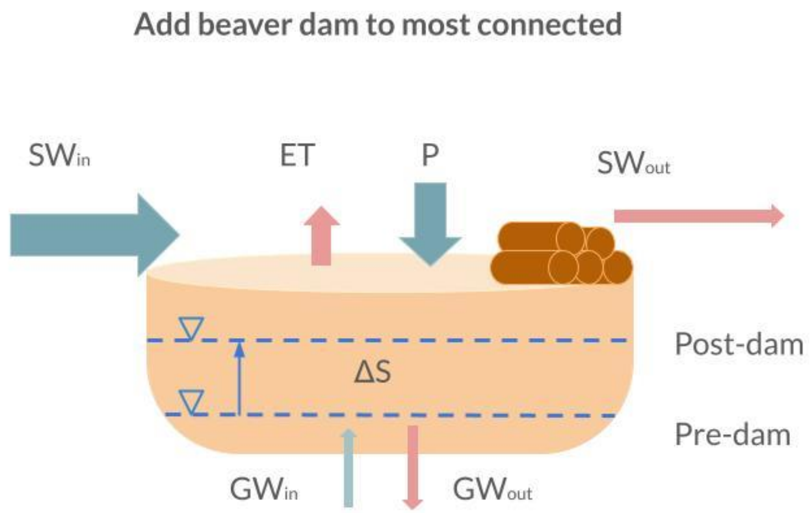



*Figure 19 Conceptual model of how the water budget changes with the introduction of a beaver dam or BDA to a wetland, increasing its water storage and reducing stream water outflow.*

## 6.3 Wetland Vulnerability

The results of this study suggest that the floodplain wetlands within the Upper Columbia River Valley are vulnerable to changes in hydrologic conditions resulting from climate change regardless of the category of wetland. However, there is a strong gradient from south to north, where southern floodplain wetlands are much more vulnerable than northern wetlands. As the floodplain wetlands are intrinsically tied to the Columbia River and receive minimal inputs after the freshet period, a longer drying period will likely result in substantial loss of wetland function later in the season under climate change.

Given that there are limited water inputs in the later part of summer, 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. 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 et al., 2003) and could affect the geographic distribution of species (Lake, 2008). Further, the encroachment of woody/shrub cover may result from drier conditions (Liu et al., 2022; Rodrigues et al., 2023). This suggests a fundamental ecosystem shift could occur under future climates and efforts should be made to increase storage at the individual wetland scale.

# 7 Recommendations

The results of this study demonstrate the importance of streamflow in driving wetland hydroperiod. This suggests all wetland types are vulnerable to climate change, independent of grouping. We also suggest increasing storage on the landscape through BDAs is an important adaptive measure to help with increasing resilience to climate change. We recommend allocating resources to increase the number of BDA installations across the Columbia Wetlands and developing additional communication tools to further promote the importance of their ecological function. Additional hydrological analysis would refine our understanding of individual wetlands; however, it is not likely that our understanding of overall vulnerability will improve.

# 8 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 likely 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 can improve climate change resilience in floodplain wetlands in the Upper Columbia Valley.

MacHydro prepared this document for the account of the Columbia Wetland Stewardship Partners. The material in it reflects the judgment of the MacHydro considering the information available to the MacHydro at the time of document preparation. Any use which a third party makes of this document or any reliance on decisions to be based on it is the responsibility of such third parties. MacHydro accepts no responsibility for damages, if any, suffered by any third party because of decisions made or actions based on this document.

As a mutual protection to the Columbia Wetland Stewardship Partners, the public, and ourselves, all documents are submitted for confidential information of our client for a specific project. Authorization for any use and/or publication of this document or any data, statements, conclusions, or abstracts from or regarding our documents and drawings, through any form of print or electronic media, including without limitation, posting or reproduction of same on any website, is reserved pending MacHydro's written approval. A signed and sealed copy of this document is on file at MacHydro. That copy takes precedence over any other copy or reproduction of this document.

We trust the above satisfies your requirements. Please contact us should you have any questions or comments.

# 9 References


Ajami, H., Meixner, T., Dominguez, F., Hogan, J., and Maddock, T. (2012). Seasonalizing mountain system recharge in semi-arid basins – climate change impacts. Groundwater, 50, 585-597.

Barnett, T.P., Adam, J.C., and Lettenmaier, D.P. (2005). Potential Impacts of a Warming Climate on Water Availability in Snow Dominated Regions. Nature, 438(7066), 303-309.

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

BC Ministry of Environment (1990). Soils of the East Kootenay Area. https://sis.agr.gc.ca/cansis/publications/surveys/bc/bc20/bc20_report.pdf

Brahney, J., Weber, F., Foord, V., Janmaat, J., and Curtis, P.J. (2017). Evidence for a Climate-Driven Hydrologic Regime Shift in the Canadian Columbia Basin. Canadian Water Resources Journal/Revue Canadienne Des Ressources Hydriques, 42 (2): 179–192.

Brandt, W.T., Haleakala, K., Hatchett B.J., and Pan M. (2022). A Review of the Hydrologic Response Mechanisms During Mountain Rain-on-Snow. Frontiers in Earth Science, 10, https://doi.org/10.3389/feart.2022.791760.

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.

Carver, M. (2017). Water Monitoring and Climate Change in the Upper Columbia Basin: Summary of Current Status and Opportunities; Columbia Basin Trust: Castlegar, BC, Canada.

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., Turetsky, M.R., Stewart, R.E., Hayashi, M., van der Kamp, G., Marshall, S., Campbell, E., Marsh, P., Carey, S.K., Quinton, W.L., Li, Y., Razavi, S., Berg, A., McDonnell, J.J., Spence, C., Helgason, W.D., Ireson, A.M., Black, T.A., Elshamy, M., Yassin, F., Davison, B., Howard, A., Thériault, J.M., Shook, K., Demuth, M.N., and Pietroniro, A. (2021). 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.

Dierauer, J., Allen, D., and Whitfield, P. (2021). Climate change impacts on snow and streamflow drought regimes in four ecoregions of British Columbia. Canadian Water Resources Journal/Revue Canadienne Des Ressources Hydriques, 46 (4): 168-193.

Earman, S., Campbell, A. R., Phillips, F. M., and Newman, B. D. (2006). Isotopic exchange between snow and atmospheric water vapor: estimation of the snowmelt component of groundwater recharge in the southwestern United States. Journal of Geophysical Research Atmosphere, 111(D9), D09302.

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

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(10), 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.

Filguira-Rivera, M., Smith, N., and Slingerland, R. (2007). Controls on natural levee development in the Columbia River, British Columbia, Canada. Sedimentology. 54. 905 - 919.

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.

Golden, H.E., Lane, C.R., Rajib, A., and Wu, Q. (2021). Improving global flood and drought predictions: integrating non-floodplain wetlands into watershed hydrologicmodels. Environment Research Letters, 16, (091002).

Hatchett, B. J., Cao, Q., Dawson, P. B., Ellis, C. J., Hecht, C. W., Kawzenuk, B., Lancaster, J.T., Osborne, T.C., Wilson, A.M., Anderson, M.L., Dettinger, M.D., Kalansky, J.F., Kaplan, M.L., Lettenmaier, D.P., Oakley, N.S., Ralph, F.M., Reynolds, D.W., White, A.B., Sierks, M., Sumargo, E. (2020). Observations of an Extreme Atmospheric River Storm with a Diverse Sensor Network. Earth and Space Science, 7 (8), e2020EA001129. doi:10.1029/2020EA001129

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.

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.

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

Leven, C. (2024). Wetland hydrology and the impacts of beaver dams in the Upper Columbia River floodplain wetlands. [Master's Thesis; University of Waterloo].

Leven, C., Bayley, S., and Holden, J. (2024). Hydrology and Beavers: Columbia Wetlands Floodplain Hydrology and the Role of Beaver Dams. March 31, 2024. Final Report: Year 5

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., Smith, D.G., Berendsen, H.J.A., de Boe, A.G., van Nielen-Kiezebrink, M.F., and Locking, T. (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 .

Meng, B., Liu, J., Bao, K., and Sun, B. (2020). Methodologies and Management Framework for Restoration of Wetland Hydrologic Connectivity: A Synthesis. Integrated Environmental Assessment and Management.

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

Phillips, J. (2017). Wetland buffers and runoff hydrology. In Wetlands. Pp 207-220.

Remmer, C., Rooney, R., Bayley, S., and Leven, C. (2023). The importance of groundwater to the upper Columbia River floodplain wetlands. Canadian Water Resources Journal / Revue canadienne des ressources hydriques. 49. 1-15.

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, Hydrology Earth Systems Science, *https://doi.org/10.5194/hess-2023-211*.

Rood, S.B., Foster, S.G., Hillman, E.J., Luek, A., and Zanewich, K.P. (2016). Flood Moderation: Declining Peak Flows along Some Rocky Mountain Rivers and the Underlying Mechanism. Journal of Hydrology, 536, 174 – 182. *https://doi.org/10.1016/j.jhydrolo.2016.02.043*

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.

Stewart, I., Cayan, D., and Dettinger, M. (2004). Changes in snowmelt runoff timing in western North America under abusiness as usual'climate change scenario. Climatic Change, 62, 217-232.

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

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. (2007)., Climate change impacts in the Elbow River watershed. Canadian Water Resources Journal, 32(4), 285-302.

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.

Winograd, I.J., Riggs, A.C., and Coplen, T.B. (1998). The relative contributions of summer and cool-season precipitation to groundwater recharge, Spring Mountains, Nevada, USA, Hydrogeol. J., 6(1), 77-93.

Winter, T. (2007). The vulnerability of wetlands to climate change: a hydrologic landscape perspective. Journal of the American Water Resources Association. JAWRA Journal of the American Water Resources Association. 36, 305 – 311.

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.

Xu, D., Bisht, G., Tan, Z., Eva Sinha, E., Di Vittorio, A.V., Zhou, T., Ivanov, V.Y., and Leung, R.L. (2024). Climate change will reduce North American inland wetland areas and disrupt their seasonal regimes. *Nature Communications,* 15, 2438. https://doi.org/10.1038/s41467-024-45286-z

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*.