

Wetland hydrology and the impacts of beaver dams in the Upper Columbia River floodplain wetlands

by

Catriona Leven

A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Master of Science

in

Biology

Waterloo, Ontario, Canada, 2024

© Catriona Leven, 2024

Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

The Upper Columbia River floodplain wetlands are the last remaining undammed stretch of floodplain wetlands along the Columbia River and continue to experience a natural flood pulse. This flood pulse interacts with natural levees and beaver dams across the floodplain and habitat heterogeneity results, with individual wetlands within the Columbia Wetlands having different hydrographs. I conducted research in 38 wetlands from 2020 to 2022 and aimed to determine if differing wetland hydrology allowed for wetland groups to be determined, and if those groups could be attributed to gaps in natural levees and beaver dams. Hydrograph attributes can be used to differentiate wetland groups, with three or four groups being identified depending on year. Random Forest models based on measurements of the levees, levee gaps, and beaver dams had an Out-Of-Box Error Estimate of between 36% and 53% across all groups depending on year, indicating correct classification of between 64% and 47%. Combining hydrograph attributes and levee gap and beaver dam metrics, we can describe these groups on a gradient of connectivity to the Columbia River, being Most Connected, with large open levee gaps, Partially Connected, with levees without gaps or with gaps dammed by beaver dams that are smaller, and Least Connected, with levees without gaps or gaps dammed by beaver dams that are bigger. This demonstrates the large impacts of beavers on shaping wetland systems and has implications for the differing impacts of climate change on these different wetland groups.

Acknowledgements

This research was supported by the Columbia Wetlands Stewardship Partners, Environment and Climate Change Canada, the Columbia Basin Trust, and the Columbia Valley Local Conservation Fund.

I would first like to thank my supervisor, Dr. Rebecca Rooney, for all the advice and support over the last five years, both as a lab tech and as a graduate student; thank you for offering me this opportunity and this project and for guiding me through this whole experience. I would also like to thank Dr. Suzanne Bayley, for making this project what it is, for letting me live in your basement and borrow your dog, and above all your continuing mentorship. And thank you to Dr. Roland Hall, for being on my committee and providing invaluable advice through this process.

Many thanks are also due to Annie Pankovitch, Jenn Bouwes, Spencer Cairns, Tomba Paagman, Kalista Pruden, and Jessica Holden for hours of fieldwork and literal blood, sweat, and tears to collect all these data – without you, none of this would be possible! And further thanks to Annie Pankovitch and Jessica Holden for invaluable help with GIS. Thanks also to everyone at MacDonald Hydrology Consultants – particularly Dr. Ryan MacDonald and Beth Millions – for help in the field, with data analysis, and with project direction.

I would also like to thank my parents for their ongoing support of my career, and for the many drafts of this thesis that they have read. Thank you also to my partners, for putting up with a long-distance relationship all these years and listening to my rambles about beaver dams with apparent interest.

And, finally, thank you to my Lab Rats (Matt Bolding, Megan Jordan, Hillary Quinn-Austin, Courtney Robichaud, and Marissa Zago) for your friendship and support: thank you for movie nights and the group chat, not letting me drown in any wetlands despite my best efforts, and providing commiseration and celebration in equal measures.

I could not have done this without any of you: thank you.

Table of Contents

Author's Declaration	ii
Abstract	iii
Acknowledgements	iv
List of Figures	vii
List of Tables	viii
Chapter 1 Literature Review and Introduction	1
1.1 The Columbia Wetlands	1
1.2 Climate Change and the Columbia Wetlands.....	4
1.3 Beavers and Beaver Dams	6
Chapter 2 Wetland hydrology and the impact of beaver dams in the Upper Columbia River floodplain wetlands.....	8
2.1 Introduction.....	8
2.2 Methods	14
2.2.1 Fieldwork	16
2.2.2 Numerical Analyses	17
2.3 Results	21
2.3.1 Hydrologic Characterisation of Wetland Flood Basins.....	21
2.3.2 Hydrograph Attributes Differentiate Groups.....	25
2.3.3 Levee Gap and Beaver Dam Variables Predict Wetland Groups	29
2.3.4 Hydrograph Attributes Vary Among Wetland Groups	31
2.4 Discussion.....	37
2.4.1 Wetland Hydrology and Levee Gaps and Beaver Dams Create Connectivity Gradient	38
2.4.2 Temporal variations in wetland groups.....	40
2.4.3 The importance of beaver dams in the Columbia Wetlands.....	45

2.4.4 Climate change	48
Chapter 3 Conclusion	51
References	56
Appendix A Site List.....	61
Appendix B Preliminary levee gaps identified from orthophotos, satellite imagery, LiDAR imagery, and digital elevation models.	63
Appendix C Preliminary beaver dams and lengths identified from orthophotos, satellite imagery, LiDAR imagery, and digital elevation models.	66
Appendix D Levee gap and beaver dam metrics of those features directly influencing study sites measured in the field. Appendix E explains metrics.	72
Appendix E Explanation of variables included in the levee gap and beaver dam metrics.	74
Appendix F Hydrograph attributes for all wetlands from 2020, 2021, and 2022. Appendix G and H explain these variables. Data are presented in two tables due to number of variables.	76
Appendix G Description of hydrograph attributes as defined from the hydrograph for each wetland in each year.....	89
Appendix H Diagram of hydrograph metrics; letters are explained in Appendix G.	92
Appendix I PCAs of hydrograph attributes for 2020, 2021, and 2022. 6 PCAs were retained in each year.....	93
Appendix J : Hydrograph attributes for 2020, 2021, and 2022, for each PC that contribute to more than 5% of the variance of that PC.....	95
Appendix K Representation of how wetlands changed in group between years, with each arrow representing one wetland. Arrows are coloured by the group the wetland was in in 2020.	98

List of Figures

Figure 1: Map showing location of the Columbia Wetlands (in orange; British Columbia Data Catalogue, 2013) within the Rocky Mountain trench. Inset map shows location in British Columbia, Canada.....	3
Figure 2: Schematic of predicted different levee gap and beaver dam scenarios.....	14
Figure 3: Locations of the 38 study wetlands within the Columbia Valley.	15
Figure 4: Wetland groups based on hierarchical cluster analysis of hydrograph attributes using Euclidean Distance and Ward D2 linkage; boxes indicate most parsimonious number of clusters as indicated by nbclust package, group characteristics are described in Table 2. In 2020, n = 30; 2021, n = 37; and 2022, n = 36.....	22
Figure 5: Water depth in the Columbia River at Nicholson, as collected by Environment Canada, for the three study years.....	24
Figure 6: Mean hydrographs of each wetland group in each year. Error bars are standard error; in 2020, n = 30; in 2021, n = 37; and in 2022, n = 36. In 2021, only three groups were identified so light blue represents all Intermediate wetlands.....	25
Figure 7: Hydrograph attribute differences between wetland groups in all three years, A) Amplitude of rising limb of hydrograph (m), and B) Minimum depth (m). In 2020, n = 30; 2021, n = 37, in 2022, n = 36.	28
Figure 8: Differences in beaver dams and gap volumes between wetland groups. For all three study years, A) Gap volume (m ³) and B) count of wetlands with levee gaps dammed by beavers, no levee gaps, and open levee gaps. For 2020, n = 30; 2021, n = 37; 2022, n = 36.	33
Figure 9: Differences in beaver dams and gap volumes between wetland groups based common groupings (wetlands with at least two years in same group) (n = 35), A) gap volume (m ³), B) count of wetlands that have beaver dams, that have no levee gaps, or that have open levee gaps, and C) area of wetlands that have beaver dams, that have no levee gaps, or that have open levee gaps.	35
Figure 10: The mean total gap width (blue) and dam length (brown) in the different wetland groups (if wetland was in same group for at least two years) n = 35, error bars are standard error. Lower case letters denote significance as per one-way ANOVA and Tukey’s HSD test for multiple comparisons (note: there are no significant differences between gap width in the different wetland groups).	37

List of Tables

Table 1: List of Principle Component axes and associated eigenvalues and percentage of variance explained by each axis, for each of the three study years.....	19
Table 2: Summary table of number of wetlands and area of wetlands in each group for each year and for the common groupings.....	23
Table 3: Summary of random forest models using wetland group as the response variables and levee gap and beaver dam metrics (Appendix D) as the predictor variables. Common grouping is the group in which a wetland was placed for at least two of the three study years. Note that in 2021 only 3 groups were distinguished based on the hydrograph attributes, and consequently for Random Forest Model using the common grouping, only three groups were possible.....	30
Table 4: Wetland groups and a description of their hydrograph attributes and morphological characteristics (levee gaps and beaver dams) common to the wetlands in that group.	40

Chapter 1

Literature Review and Introduction

1.1 The Columbia Wetlands

Wetlands are important ecosystems for many reasons; they are rich in biodiversity, they are of cultural importance to many people, and they provide ecosystem services including flood control, groundwater recharge, carbon storage, water storage and purification, and direct economic benefits through harvesting and recreation (Blackwell and Pilgrim, 2011; Gardner and Finlayson, 2018). They are also among some of the world's most threatened ecosystems (Dudgeon *et al.*, 2006). Wetlands worldwide are threatened by human development and climate change, and while data gaps make it hard to quantify how much natural wetland has been lost, estimates where data are available for natural wetland losses include a worldwide decline of 30% between 1970 and 2015 and a 49.8% decline since the 19th century (Davidson, 2014). Of over 19,500 wetland-dependent species assessed by the IUCN Red List, 25% are threatened by extinction, and in North America alone, 20% of all assessed wetland-dependent taxa are threatened (Gardner and Finlayson, 2018).

Floodplain wetlands are wetland systems dependent on and shaped by the river that runs through them. The flood pulse – the flow of water across the landscape during a high water period (Junk *et al.*, 1989) – is an essential driver that determines floodplain connectivity and transport of both organic and inorganic material, from organisms to sediment, but other sources of water such as local rainfall or rising groundwater also contribute to the hydrological and ecological dynamics of floodplain wetlands (Amoros and Bornette, 2002; Junk *et al.*, 1989; Tockner *et al.*, 2000). These systems are complex, with many processes operating at different temporal and spatial scales, and while many rivers and their floodplains around the world have been heavily modified by humans, the complexity of floodplain hydrological and ecological dynamics have been seen in both heavily and less modified temperate and tropical systems (Amoros and Bornette, 2002).

The Columbia River is the largest river in the Pacific Northwest, and the largest river by volume entering the Pacific Ocean from the Americas. It begins in the Rocky Mountain Trench in the British Columbian Rocky Mountains and flows for 2000 km before reaching the sea in Oregon, draining seven US states and one Canadian province along its way. As with many North American rivers it has been heavily dammed, with 14 dams on the main stem of the Columbia River, and 150 more on tributaries throughout the Columbia River basin (Weitkamp, 1994).

The Columbia Wetlands, stretching from Columbia Lake in the south to just north of Golden in the north, are floodplain wetlands along the only undammed portion of the Columbia River, and are one of the longest contiguous wetlands in North America (Zimmerman, 2004) (Figure 1). The elevation gradient of the Columbia River between Columbia Lake and Golden is very low, at about 19 cm/km, meaning that the river meanders substantially through the valley bottom, with multiple side channels and many wetlands created by erosion and deposition across the floodplain (Environmental Stewardship Division Kootenay Region, 2004). As floodplain wetlands in an undammed system, they are maintained by the natural flood pulse of water flowing over and through the natural river levees and advancing and retreating across the valley, a process that has major effects on all aspects of the wetlands (MacDonald Hydrology Consultants Ltd., 2021; Makaske *et al.*, 2009). The Columbia Wetlands show anastomosing morphology, with multiple interconnected channels enclosing flood basins, and with stable channels and frequent crevassing of the natural levees to form natural gaps in the levees (Makaske *et al.*, 2009).

The wetland system is approximately 180 km long and over 26,000 ha in area (Environment and Climate Change Canada, 2018), and provides important wildlife habitat and ecosystem services such as groundwater recharge, water for agriculture and residential use, flood mitigation, and recreational use. The wetlands are important culturally to both First Nations and settlers in the Columbia Valley, and are located on the traditional territories of the Ktunaxa Nation, Secwepemc First Nation, Shuswap First Nations Band, and Metis Nation Columbia River.

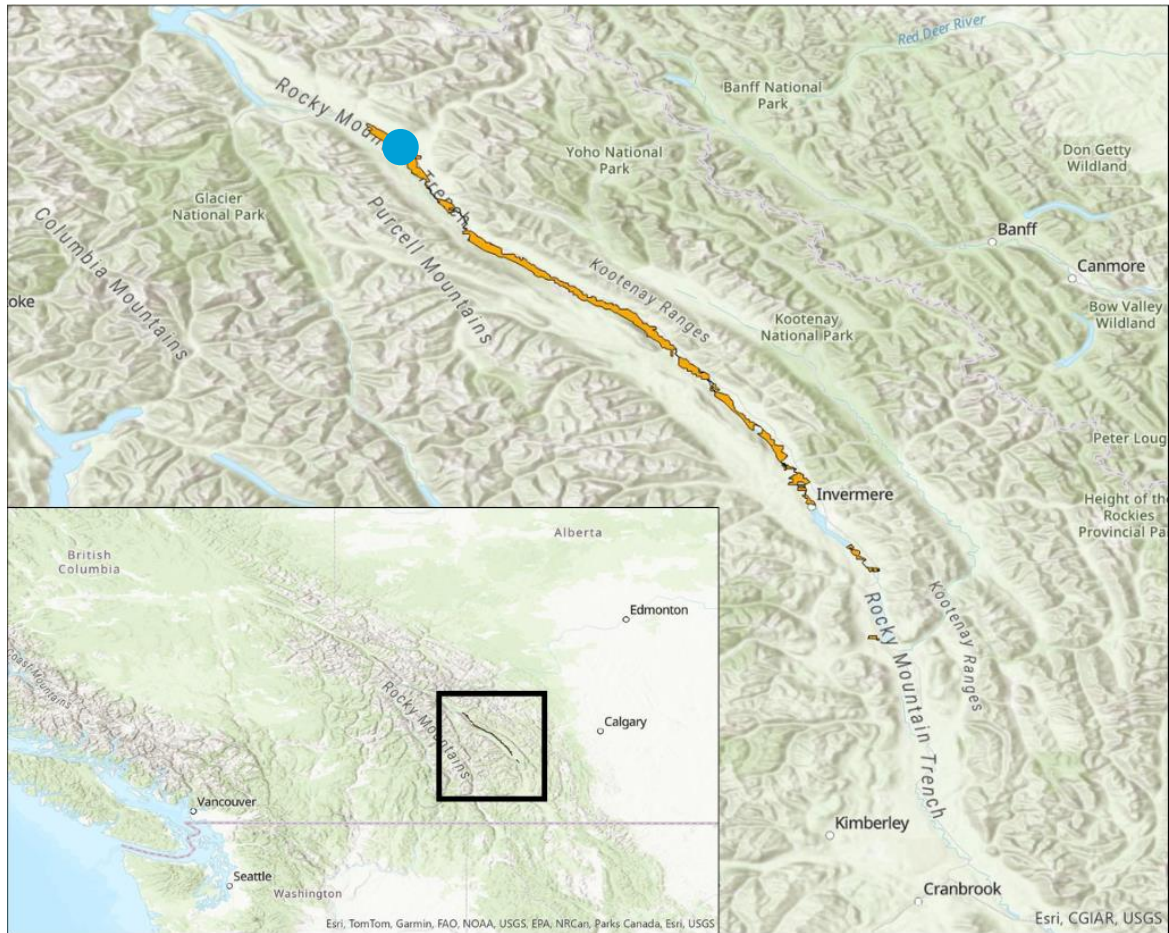


Figure 1: Map showing location of the Columbia Wetlands (in orange; British Columbia Data Catalogue, 2013) within the Rocky Mountain trench. Inset map shows location in British Columbia, Canada. Location of ECCC hydrometric station at Nicholson is indicated with the blue dot.

Among the many ecosystem services they provide, the Columbia Wetlands are habitat for a tremendous diversity of organisms. A 2004 survey found 4 species of fungi, 268 species of plants, 34 species of invertebrates, 2 species of amphibians, 1 species of reptile, 112 species of birds, and 17 species of mammals within the Columbia National Wildlife Area, which at 1,001 ha comprises just 3.9% of the entire Columbia Wetlands complex (Environment and Climate Change Canada, 2018). The Columbia Wetlands provide habitat for many wetland-dependent mammals such as North American river otter (*Lontra canadensis* (Schreber, 1777)), American beaver (*Castor canadensis* Kuhl, 1820), and muskrat (*Ondatra zibethicus* (Linnaeus, 1766)), as well as important habitat for species that use wetlands for at least part of the year such as elk (*Cervus canadensis* Erxleben, 1777) and American black bear (*Ursus*

americanus Pallas, 1780), and provide corridors to traverse the valley for upland animals such as grizzly bear (*Ursus arctos* Linnaeus, 1758).

The Columbia Wetlands are a particularly vital habitat for migrating birds. They comprise an important part of the Pacific Flyway; one of North America's four major migratory routes (Environment and Climate Change Canada, 2018). They provide a stopover site for migratory birds, including provincially listed species such as tundra swan (*Cygnus columbianus* (Ord, 1815)) which is on the BC Blue List 'of special concern' with a Provincial Conservation Status of S3N (special concern, non-breeding population). The Columbia Wetlands Waterbird Survey, which covered approximately 39% of the total Columbia Wetlands area, found that in 2019, across three dates, 41,095 birds of 90 different species were present in the wetlands, and across the five years of the survey 163 bird species were documented, with a maximum single day count of 20,822 individuals on 15th October 2016 (Darvill, 2020).

This importance is recognized provincially, federally, and globally: the Columbia Wetlands have been designated a Ramsar Wetland of International Importance since 2005, qualifying under all eight RAMSAR criteria (Zimmerman, 2004); are being proposed as an Important Bird Area (Darvill, 2020); and are protected variously as the Columbia Wetlands Wildlife Management Area under the British Columbia (BC) Wildlife Management Act, the Columbia National Wildlife Area under the Canada Wildlife Act, and as Nature Trust of Canada and Nature Conservancy of Canada properties. Given the value of these wetlands and the recognition of their importance, understanding these wetlands better will aid in developing science-based conservation and protection strategies, which are increasingly important given the amplified uncertainty and threats introduced by climate change.

1.2 Climate Change and the Columbia Wetlands

Despite these protections and recognitions, the Columbia Wetlands face many threats. Although the Columbia Wetlands remain undammed, there is nonetheless rapid residential, agricultural, and recreational growth in the Columbia Valley (Environment and Climate Change Canada, 2018) which threatens the wetlands – and the organisms living within them – from disturbances due to boat or ATV users, to water

being removed from the wetlands for agricultural irrigation or residential use. We do not have a good understanding of how these threats will affect the floodplain's wildlife and ecosystem services, particularly in combination.

One of the foremost threats facing the Columbia Wetlands, and the subject of recent research (e.g., Hopkinson *et al.*, 2020; Rodrigues *et al.*, 2024; Utzig, 2021), is climate change. The Columbia Wetlands are particularly responsive to variation in climate for several reasons. It has been suggested that mountainous regions are more sensitive to climate change because they are experiencing faster temperature increases and changes to precipitation than the global land average (Rangwala and Miller, 2012). In western North America glaciers are shrinking due to increasing temperatures, with some having retreated up to 2 km since 1900, and corresponding decreases in streamflow have also been recorded, including in the Canadian Rocky Mountains (Moore *et al.*, 2009, Rodrigues *et al.*, 2024). Across the Rocky Mountains, particularly in the Northern Rockies and Upper Columbia River, the observed late 20th century snowpack declines resulting from springtime warming are “almost unprecedented” in magnitude, with corresponding impacts on streamflow and water supply (Pederson *et al.*, 2011).

Annual temperatures in the Columbia Wetlands have already increased by almost 1°C since the 1960s and further increases of 2°C to 4°C are projected by the 2080s, depending on greenhouse gas emissions (Utzig, 2021). Changes to precipitation amounts, timing, and form are also predicted by models, with less snow and more rain falling in the valley (Utzig, 2021). As the Columbia Wetlands are dependent on the natural flood pulse, which is primarily driven by snowmelt and rainfall depending on season (Makaske *et al.*, 2009; Remmer *et al.*, 2023), the decreasing snowpack of the Canadian Rockies and changes in precipitation are a direct and urgent threat to the hydrology of the Columbia River and its floodplain wetlands. There is less water in the Columbia Wetlands today than historically (Hopkinson *et al.*, 2020; Moore *et al.*, 2020, Rodrigues *et al.*, 2024), and projections indicate that there will be increasingly less water in the future (Utzig, 2021). Over the past four decades, increasing temperature, decreasing precipitation, increasing river discharge, and an earlier and shorter peak flow period, as well as the frequency of both high-discharge and dry years increasing, indicating a shift to more extreme flow

behaviours, have all been documented (Rodrigues *et al.*, 2024). In the face of climate change, it is important to understand current functioning of the wetlands in order to be able to predict, manage for, and mitigate changes into the future.

1.3 Beavers and Beaver Dams

Beavers may provide some natural mitigation of the effects of climate change on the Columbia Wetlands by increasing wetland resilience and complexity, and specifically by increasing open water area (Hood and Bayley, 2008). Beavers are a crucial part of many wetland systems and have long been recognized as both ecosystem engineers and as animals that provide many ecosystem services. They increase the complexity of wetland habitats, and have profound ecological, hydrological, and geomorphological effects (Westbrook *et al.*, 2006; Larsen *et al.*, 2021; Thompson *et al.*, 2021) such as decreasing temperature extremes, providing carbon storage, increasing the diversity and abundance of other organisms across many taxonomic groups, and moderating extreme flow changes (Wohl, 2013; Bouwes *et al.*, 2016; Nummi *et al.*, 2019; Nummi and Holopainen, 2020; Thompson *et al.*, 2021). They provide a foundational structure to wetlands and are increasingly important parts of wetland and watercourse re-naturalization and management plans (Colleen and Gibson, 2000; Nummi and Holopainen, 2020).

Beavers in large river valleys with extensive floodplain wetlands, such as the Columbia River, have not been well studied. Most beaver research has occurred on small streams or in boreal regions, where hydrological and ecological functions are very different (e.g., Westbrook *et al.*, 2006; Hood and Bayley, 2008) compared to the Columbia Wetlands. Beavers in the Columbia Wetlands do not dam the Columbia River directly, but build dams on small side-channels and in gaps in the natural levees. Thus, while most beaver dams only hold water on their upstream side, essentially delaying or preventing waterflow downstream (e.g., Ronnquist and Westbrook, 2021), beaver dams in the Columbia Wetlands have the unusual function that they both prevent water from entering the wetlands prior to the flood pulse, and then prevent water from leaving the wetlands after the flood pulse has overtopped the dams and/or the levees. In other words, these beaver dams influence water flow in both directions, and this is not well understood.

In this thesis, I aim to classify different wetlands within the Columbia Wetlands complex based on their hydrology, and then determine the impact of beaver dams in creating these wetland hydrologic classes.

Chapter 2

Wetland hydrology and the impact of beaver dams in the Upper Columbia River floodplain wetlands

2.1 Introduction

Floodplain wetlands are wetland systems dependent on and shaped by the river that runs through them. The flood pulse – the flow of water across the landscape during a high-water period (Junk *et al.*, 1989) – is an essential driver that determines floodplain connectivity and transport of organic and inorganic material, from organisms to sediment (Junk *et al.*, 1989; Tockner *et al.*, 2000; Amoros and Bornette, 2002). The flood pulse is due to seasonal climatic changes such as rainy seasons in tropical systems and temperature and precipitation changes in temperate and subtropical systems resulting in differing amounts of water being available at different times; the larger the catchment area for a river or stream, the more predictable a flood pulse regime is, as it is less affected by local precipitation (Junk *et al.*, 1989). While overbank inundation is a key factor to understanding the flood pulse, the expansion and contraction of waterbodies across the floodplain even at less than bankfull levels is also an important factor shaping floodplain wetlands; both overbank and less than bankfull flows contribute to habitat heterogeneity and biodiversity within a floodplain wetland (Tockner *et al.*, 2000).

The flood pulse shapes the floodplain, combining with other factors such as valley slope and floodplain size to create spatial heterogeneity (Amoros and Bornette, 2002; Tockner *et al.*, 2000). Fluvial processes result in the formation of different waterbodies such as side channels, backwaters, and wetlands with different characteristics, resulting in great hydroecologic diversity across the floodplain, with waterbody size and shape, connectivity to the river, and hydrological connectivity to surface and groundwater influencing the habitat diversity (Amoros and Bornette, 2002). Other sources of water such as local rainfall or rising groundwater also contribute to the hydrological dynamics of floodplain wetlands (Remmer *et al.*, 2023). River connectivity is many factored and difficult to measure directly, with metrics such as distance from the river, the presence, size, length, and sinuosity of connections from the river,

relative elevation, and relative quantities of surface and subsurface flow, among many others, having been used to describe river connectivity (Amoros and Bornette, 2002; Neary *et al.*, 2021; Nguyen *et al.*, 2021; Park and Latrubesse, 2017; Rooney *et al.*, 2013). This is further complicated by temporal changes in river connectivity, with connectivity at the peak of the flood pulse being very different from connectivity at lower river elevation.

As with other wetland systems, many floodplain wetlands have been modified by humans, particularly due to alterations in flow regime such as by building dams (Graf, 2006). The negative effects of dams on the river systems in which they are built have been well documented with changes in peak discharge, annual amplitude, and daily discharge, and the timing of both high and low flows being altered (e.g., Graf, 2006; Poff *et al.*, 2007). This disruption to natural flows and particularly the flood pulse has corresponding impacts on biodiversity, as the shaping force of the river is removed or altered. As well as dams on rivers, floodplain wetlands are often altered by the building of railways and roads, the draining and dyking of wetlands to create agricultural land, and the channelisation of rivers through floodplains, all of which result in heavily modified systems where river connectivity, natural flood pulse, and resulting floodplain dynamics are altered or stopped (Allan, 2004; Blanton and Marcus, 2009; Hohensinner *et al.*, 2003; Kroes *et al.*, 2022). Thus, being able to study the flood pulse and hydrology of less altered systems is rare, particularly in temperate North America.

One such relatively unaltered floodplain wetland system are the floodplain wetlands along the Upper Columbia River in Canada. The Upper Columbia River is undammed for its first 180 km between its source in Columbia Lake and Kinbasket Reservoir north of Golden, and the floodplain wetlands along its length are relatively natural and still maintained by the natural flood pulse of water flowing over the natural river levees and advancing and retreating across the valley (MacDonald Hydrology Consultants Ltd., 2021; Makaske *et al.*, 2009). Due to being undammed and still driven by a natural flood pulse, the Upper Columbia River floodplain wetlands are a rare ecosystem, and they provide important habitat to

many species as well as ecosystem services such as groundwater recharge, water for agriculture and residential use, flood mitigation, and recreational use (Zimmerman, 2004).

This stretch of the Columbia River and its associated wetlands have been the source of recent study (e.g., Filgueira *et al.*, 2007; Makaske *et al.*, 2009; Carli and Bayley, 2015; Hopkinson *et al.*, 2020; MacDonald Hydrology Consultants Ltd., 2021; Utzig, 2021; Remmer *et al.*, 2023; Rodrigues *et al.*, 2024), including study of the influence of the flood pulse and wetland connectivity on submerged aquatic vegetation (Rooney *et al.*, 2013). It is increasingly important to understand the functioning of the Upper Columbia River and its floodplain wetlands due to the impacts of climate change, with climate change effects already being felt in the region and only projected to increase (e.g., Hopkinson *et al.*, 2020; Moore *et al.*, 2009; Moore *et al.*, 2020; Rodrigues *et al.*, 2023; Utzig, 2021). Observed late 20th century snowpack declines due to springtime warming were “almost unprecedented” in magnitude across the Rocky Mountains (Pederson *et al.*, 2011), and annual temperatures in the Columbia Wetlands have already increased by almost 1°C since the 1960s and further increases of 2°C to 4°C are projected by the 2080s, depending on greenhouse gas emissions (Utzig, 2021). There is already less water in the Columbia Wetlands today than historically (Hopkinson *et al.*, 2020; Moore *et al.*, 2020; Rodrigues *et al.*, 2024), with projections indicating that there will be increasingly less water in the future (Utzig, 2021). A good understanding of the heterogeneity of individual wetlands within the floodplain wetland complex has not yet been reached.

One aspect that has not been considered in the Columbia Wetlands is the potentially important activities of American beaver (*Castor canadensis*). Beavers have profound effects on wetlands and are often termed ecosystem engineers for the extensive changes they produce, providing both direct ecosystem services and economic benefits to people (Thompson *et al.*, 2021). They shape the wetland systems that they occur in by changing the hydrology and associated processes such as sediment transport and by increasing habitat complexity and biodiversity (Larsen *et al.*, 2021). Due to the large impacts that beavers have; they have been widely studied in both Europe and in North America (while American beaver (*Castor*

canadensis) and European beaver (*Castor castor*) are different species, as ecosystem engineers they function very similarly), in both river and floodplain contexts (Larsen *et al.*, 2021).

While the impacts of beavers on small floodplains have been studied (e.g., Green and Westbrook (2009) looked at the changes resulting from beaver dam removal in a floodplain 50 m to 100 m wide) beavers in a floodplain system the size of the Columbia Wetlands, which is up to 2 km wide, have not been well studied. Beavers in the Columbia Wetlands do not dam the Columbia River itself; they dam small side channels and wetlands within the floodplain, and the impacts of this type of dam-building activity are potentially different from the impacts of dam-building activity in streams or in narrower floodplains. Crucially, in stream systems the water flow is unidirectional, only flowing over the beaver dams one way, whereas in floodplain systems the water flows over beaver dams in both directions. In the spring, as the flood pulse rises, water flows over the beaver dams from the Columbia River into the wetlands; once the flood pulse has receded, the water drains out of the wetlands (either over, through, or under the dams, if they are present) back into the Columbia River. The influence of beaver dams on the morphology, hydrology, and biotic characteristics of these wetlands are likely profound.

To assess this influence, I used a combination of wetland water level measurements and natural levee and beaver dam measurements to form a wetland classification system and elucidate the impact of beaver dams on these wetlands. In my efforts to understand the role of beaver dams on the hydrology of floodplain wetlands, I focused on a limited number of variables. While there are multiple water inputs to the wetlands (the Columbia River, precipitation, groundwater, etc.), my focus was on the interaction between the Columbia River flood pulse, the morphology of the natural levees, and the beaver dams in the levee gaps and within the wetlands, and then how these physical structures impact the hydrology of the wetlands. Understanding these interactions will add to knowledge of floodplain hydrology and beaver dams in an undammed, not heavily modified floodplain system, and will allow for better informed management of the Columbia Wetlands.

River water from the Columbia River is the dominant water input to the Columbia Wetlands in the summer, while in spring and fall groundwater and precipitation play a larger role (Remmer *et al.*, 2023). The Columbia River's spring flood pulse is driven primarily by seasonal rainfall and snowmelt runoff, with some contributions from glacial melt later in the year (Makaske *et al.*, 2009). The flood pulse enters the wetlands by seeping through the natural levees, flowing through gaps in the levees, or flowing over the levees in years when the flood pulse is large enough that the river can overtop the levees. Because the levees vary in height along the length of the Columbia River, there is inter-wetland variation in terms of the flood pulse height required to overtop a given levee. I focused on differences in how the flood pulse enters and leaves a wetland will impact the wetland's hydrology.

The upper Columbia River is a dynamic, long-lived anastomosing system with evidence of anastomosis from as long ago as 2700 years BP (Makaske *et al.* 2002). It has been important in a series of studies of anastomosing river geomorphology and sedimentology and greatly contributed to our understanding of these types of systems (Makaske *et al.*, 2017). Floodplain sedimentation rate and avulsion frequency decreases downstream, indicating dominant upstream control by sediment overloading, with recent avulsion activity being linked to increased sediment supply during the Little Ice Age (Makaske *et al.*, 2017). Within the upper Columbia River floodplain, between one and five relatively stable and straight channels are bounded by well-developed levees which separate individual wetland basins (Filgueira-Rivera *et al.*, 2007), with gaps in these levees being formed through avulsion. Avulsion is where the river breaks through at a weak point in a levee and either forms a new channel into a wetland or a new river channel, depending on the individual circumstance. Makaske *et al.* (2009) determined that the main river channel is the most prone to avulsions forming gaps, since the higher flow results in more erosive power for the river. Levee gaps and new channels can persist for decades to centuries (Makaske *et al.*, 2009), and aggradation of sediment is up to four times higher on levees than in channels (Makaske *et al.*, 2002).

Gaps in the levees allow greater connectivity to the Columbia River, as water is able to flow through them even when the river's water level is too low to overtop the levees. The Columbia River does not flood

enough to overtop the levees every year. Rodrigues *et al.* (2024), found 41 normal years, 37 wet years, and 41 dry years (i.e. years where the levees are not overtopped) between 1903 and 2022, indicating that the river overtops the levees approximately 65% of the time. In dry years, the flood pulse can only enter wetlands through gaps in the levees, though some water will also seep through the natural levees. Beaver dams in these levee gaps will both hinder water entry during the flood pulse and assist in water retention after the flood, but the extent to which the dams do either of these things is not well understood.

I seek to understand how the morphology of natural levees, gaps in those levees, and beaver dams built across those gaps influence the hydrology of the wetland basins within the Upper Columbia River's floodplain. I predict that I will be able to use natural levee gaps and beaver dams as a measure of connectivity to the Columbia River, and that because of differences in that connectivity, there will be differences in hydrology among wetlands. Thus, the hydrology of wetlands in the Upper Columbia River floodplain will be greatly affected by beaver dams.

I predict that the hydrograph in a wetland connected to the main channel of the river through gaps in the natural levees will differ from the hydrograph of a wetland separated from the river by intact natural levees or one which has beaver dams spanning any levee gaps (Figure 2). In wetlands with levee gaps, the river will flood the wetlands even if the flood pulse does not overtop the levees, and when the flood pulse recedes, water levels in the wetland will drop (Scenario 1). If beaver dams are built within these gaps (Scenario 2), I predict that rising floodwater will be delayed in its entry into the wetland basin by the dam. Similarly, as the flood pulse recedes, the dam will retain water within the wetland. If the levees lack gaps (Scenario 3), I expect the wetland will not flood unless the river overtops the levees. More, that when the flood pulse recedes, the wetland will retain high water levels. However, other factors such as wetland size, catchment size, elevation, and groundwater-surface water connections may also influence a wetland's hydrograph and it is uncertain which factors will act as the primary determinants of hydrologic dynamics.

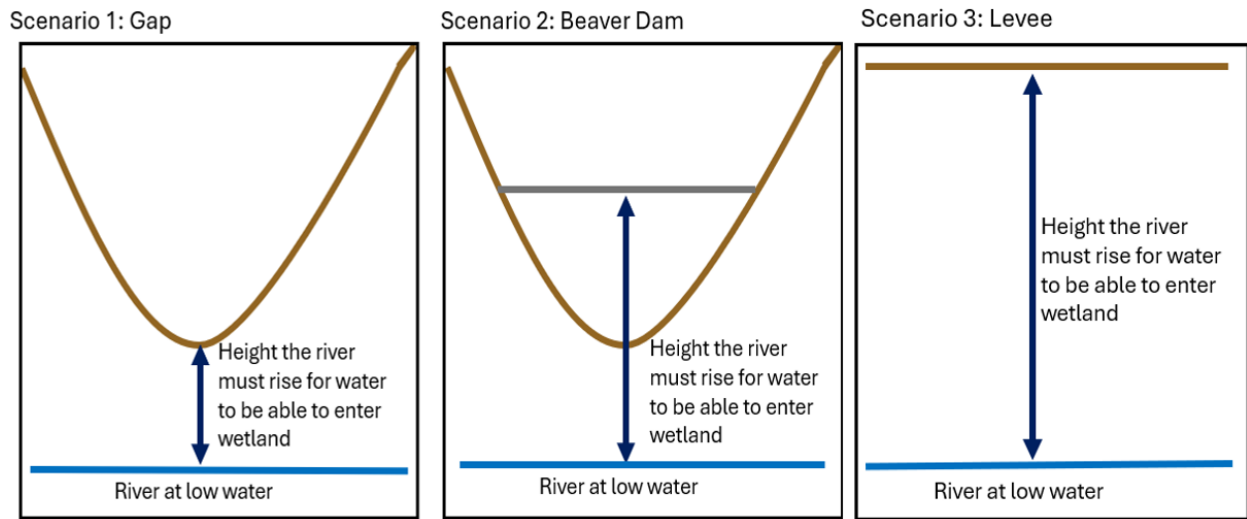


Figure 2: Schematic of predicted different levee gap and beaver dam scenarios.

2.2 Methods

I conducted research in a total of 38 wetlands (Figure 3; Appendix A), from 2020 to 2022, with the majority of fieldwork completed in 2021 and 2022. In 2020, only 30 wetlands were monitored. Eight new wetlands were picked in 2021 to better represent the different types of wetlands present in the Columbia Wetlands ecosystem. Wetlands were chosen for inclusion in this study based on local expert knowledge and previous work conducted in the Columbia Wetlands. These 38 sites are 23.32 km² in total, or just over 10% of the total area of the Columbia Wetlands, with individual wetlands ranging from 0.04 km² to 3.27 km² in size.

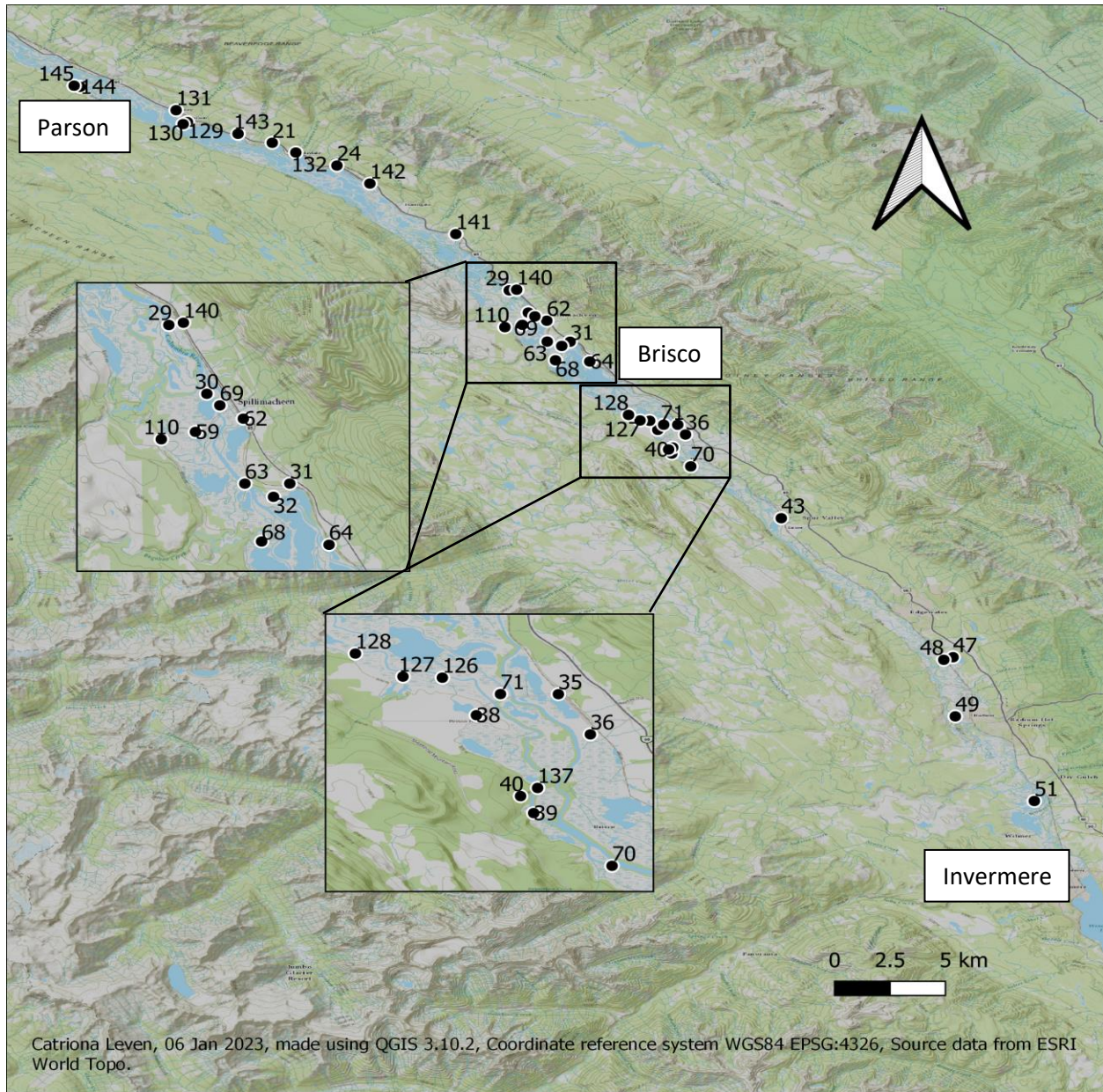


Figure 3: Locations of the 38 study wetlands within the Columbia Valley.

The three study years differed in temperature and precipitation, but were all “flood” years where the Columbia River’s flood pulse overtopped the levees. The winter of 2021/2022 had a deep snowpack in the upper Columbia region, with 140% of average snowpack recorded on January 1st, and a cool spring led to snowpack being 165% of normal on June 1st (BC Data Centre, 2022). This resulted in a later and longer flood pulse to the late and slow melting of snow, with peak depths being recorded between June 7th and June 16th. Conversely, in 2021, British Columbia was affected by a severe heat dome at the end of

June/beginning of July, with temperatures of up to 38°C recorded in alpine areas, resulting in very fast snow melt rates of 80 – 110 mm Snow Water Equivalent per day (BC Data Centre, 2022). This resulted in a high water year, presumably due to rapid melting and perhaps due to increased glacier melt. These differences in climatic factors contribute to the variability of the system.

2.2.1 Fieldwork

2.2.1.1 Wetland Hydrology

I measured water level (m) and water temperature at individual wetlands using HOBO U-20 (HOBO by Onset, Cape Cod, Massachusetts, USA) water level loggers, installed each year in May and removed in October, which recorded pressure and temperature every four hours. All measurements were extracted using HoboWare software (v3.7.26; Onset Computer Corporation, 2023) and corrected with a barometric pressure sensor located at Brisco to derive measures of water depth (m). In 2021 and 2022, there were equipment failures in some loggers, resulting in data recovered from 37 and 36 wetlands, respectively. I used a publicly available dataset from the Environment and Climate Change Canada hydrometric station on the Columbia River at Nicholson (Environment and Climate Change Canada Historical Hydrometric Data, 2024) to obtain concurrent water depth measurements from the main channel of the Columbia River.

2.2.1.2 Levee Gaps and Beaver Dams

I identified potential locations of beaver dams, beaver lodges, and levee gaps within each wetland, and within 10 m, 20 m, and 30 m wide buffers around each of the 38 study wetlands using ArcGIS Pro (v2.8.0; Environmental Systems Research Institute, 2023) and a combination of orthophotos, satellite imagery, LiDAR imagery, and digital elevation models (Airborne Imagery, 2015; Forest, Lands, and Natural Resource Operations and Rural Development, Geo BC, 2018; Appendix B and C). These buffer distances were used based on incidental observations in the field that dam(s) up to 30 m away from the wetland boundary proper were sometimes actively retaining water within the wetland. From this same imagery, I used ArcGIS Pro (v2.8.0; Environmental Systems Research Institute, 2023) tools to derive

preliminary measures of the length of beaver dams and the width of any levee gaps (m) and to inform ground truthing efforts. To characterize the wetlands proper, I also measured the perimeter length (m) and area (m²) of each wetland.

All dams and gaps were visited and measured between August 2021 and May 2022, within the same flood year. This timing was important because dams and gaps could not be measured during high water. In-person fieldwork to ground truth levee gap and beaver dam measurements was essential as the imagery ranged in date of capture and not all dams and gaps were visible from available imagery. I walked and/or kayaked the perimeter of each wetland to identify beaver dams and gaps, using the imagery derived information as a guide for where there were likely to be dams or gaps; in some instances, I located dams on the ground that were not visible through any imagery. Once at a dam or gap location, I measured the dimensions of the feature (Appendix D), took notes on building material, beaver activity (active where there were signs of fresh mud or new sticks; inactive where there were no such signs but the dam was still in good repair; and old where the dam was no longer in good repair), water flow, and its influence on the wetland, as well as drawing a rough sketch of the feature. As absolute elevation data were not available, all heights measured (e.g., of beaver dams) are relative to the levee at that point. Preliminary digital measurements were then amended based on the field-based ground-truthing.

2.2.2 Numerical Analyses

All statistical analyses, unless otherwise specified, were performed using R Statistical Software (v4.3.2; R Core Team, 2021) and plotted using the ggplot2 package (v3.5.0; Wickham, 2016). I first used hydrographs from each wetland in 2020, 2021, and 2022 to calculate 31 hydrograph attributes. I then visualised differences between wetlands in these hydrograph attributes using a Principal Component Analysis. I then used the Principal Component axes derived from this analysis to perform a Hierarchical Cluster Analysis to place wetlands into groups, thus creating hydrologically derived groups. I also used one-way ANOVAs to determine statistical differences in hydrograph attributes between these groups. I

then used Random Forest Models to determine how well levee gap and beaver dam metrics predicted these hydrologically derived groups.

2.2.2.1 Hydrograph Attributes

I first visually observed the differences in wetland patterns using hydrographs of each wetland in the three study years in Microsoft Excel (Microsoft Corporation, 2023). I then calculated 31 hydrograph attributes from the 2020, 2021, and 2022 water level data (Appendix F). I used Goodbrand and MacDonald (2022) and Neary *et.al.* (2021) as guidance for some quantitative attributes which might be suitable to characterise the hydrographs to classify the wetlands into types, and others I chose to use because they were visually distinctive in these wetland hydrographs.

2.2.2.2 Hydrographic Characterisation of Floodplain Wetland Basins

Using the hydrograph attributes, I conducted a Principal Component Analysis (PCA) to visualise hydrologic differences between wetlands using the factoextra package (v1.0.7; Kassambara, 2020) (Appendix I). PCA served as a variable reduction technique to let me control for collinearity among the many attributes of the hydrographs that I measured, (e.g., slope of flood pulse rise and length of flood pulse rise). I then assessed the importance of each Principal Component Analysis (PCA) axis and variable contributing to that axis. I followed Kaiser's Rule to determine which of the PCA axes should be retained, where all components with eigenvalues greater than 1 should be kept for statistical inference (Upton and Cook, 2014). For all three years, I retained 6 Principal Components (Table 1). In 2022, PC 6 only had an eigenvalue of 0.99; I retained six components in this year to maintain consistency over the three years. For all three years, this resulted in more than 90% of the total variance being explained. I then took the Principal Component sample scores along the first six axes and performed a Hierarchical Cluster Analysis using the base R stats package (v3.6.2; R Core Team, 2021) on these to further explore and visualise groupings among wetlands. By basing groupings on PCA scores instead of raw hydrograph attributes, I avoided issues of collinearity and unintended biases in weighting aspects of hydrographs that were represented in multiple different attributes. I specified Euclidean linkage method and Ward D2 distance measure. Group selection

from the resulting dendrogram was informed by the NbClust package (v3.1.0; Charrad, 2022), which determined the most parsimonious number of wetland groups to retain.

Table 1: List of Principle Component axes and associated eigenvalues and percentage of variance explained by each axis, for each of the three study years.

Year	Principal Component	Eigenvalue	Percentage Variance Explained	Percentage Cumulative Variance Explained
2020	PC 1	10.37	33.46	33.46
	PC 2	7.25	23.38	56.84
	PC 3	4.66	15.03	71.87
	PC 4	3.09	9.96	81.83
	PC 5	2.45	7.90	89.73
	PC 6	1.23	3.97	93.70
2021	PC 1	12.56	40.52	40.52
	PC 2	6.81	21.98	62.51
	PC 3	4.29	13.85	76.35
	PC 4	2.33	7.51	83.86
	PC 5	1.28	4.14	88.00
	PC 6	1.10	3.55	91.55
2022	PC 1	12.31	39.71	39.71
	PC 2	7.52	24.26	63.97
	PC 3	3.94	12.70	76.67
	PC 4	2.87	9.26	85.93
	PC 5	1.35	4.35	90.28
	PC 6	0.99	3.19	93.48

To determine if there were significant differences in hydrograph attributes among wetland groups, I performed one-way ANOVAs using the base R stats package (v3.6.2; R Core Team, 2021), testing whether each hydrograph attribute differed among wetland groups (e.g., did amplitude of the rising limb of the hydrograph differ among wetland groups?). I repeated this for all hydrograph attributes that explained greater than 5% of the variance of each PCA axis (Appendix J).

From the cluster analysis, I identified four groups in 2020 and 2022 and three groups in 2021. I described these groups based on their hydrograph attributes and the mean shape of the overall hydrograph: 1) Deepest Minimum Depth, 2) Largest Rising Amplitude, 3) Intermediate 1, and 4) Intermediate 2 (in 2021, I only identified one Intermediate group).

2.2.2.3 Prediction of Wetland Group Membership from Levee Gap and Beaver Dam Data

I then performed a Random Forest Analysis using my identified wetland groups and the levee gap and beaver dam data (Appendix D) to determine if these variables could predict wetland group membership in each year. I used the randomForest package (v4.7-1.1; Llaw, 2022). I standardised all the numeric input variables using Z-score standardisation:

$$\frac{(X - \mu)}{\sigma}$$

where X = data point value, μ = variable mean, and σ = variable standard deviation, to reduce dominance by variables with larger values. I then ran Random Forest models with levee gap and dam metrics as the input variables and with different numbers of variables used at each split to determine the model with the lowest estimated out-of-box error; each time I used 500 models.

To determine if there was a statistically significant difference in gap and dam metrics among the wetland groups, I also visualised all the gap and dam metrics (Appendix D) and performed one-way ANOVAs using the stats package (v3.6.2; R Core Team, 2021). Using these analyses, I then considered the combination of the hydrograph-based groups and the associated levee gap and beaver dam metrics to describe the wetland groups in terms of connectivity to the Columbia River.

2.3 Results

2.3.1 Hydrologic Characterisation of Wetland Flood Basins

While each study wetland had a unique hydrograph each year, the hierarchical cluster analysis revealed relatively consistent groups based on similarities in the attributes of their hydrographs (Figure 4). In 2020 and 2022, the wetlands were categorized into four groups, while in 2021 only three groups were identified, with the two Intermediate groups being merged (Figure 4). These groups are described based on hydrograph attributes (Figure 7) and overall shape of the hydrograph (Figure 6). As discussed in 2.2.2, I identified a common grouping for 35 wetlands, where these wetlands either did not change groups between years or were in the same group for two of three years. For consistency in identifying these common groupings I used the broader category of Intermediate, due to only one Intermediate group being distinguishable in 2021.

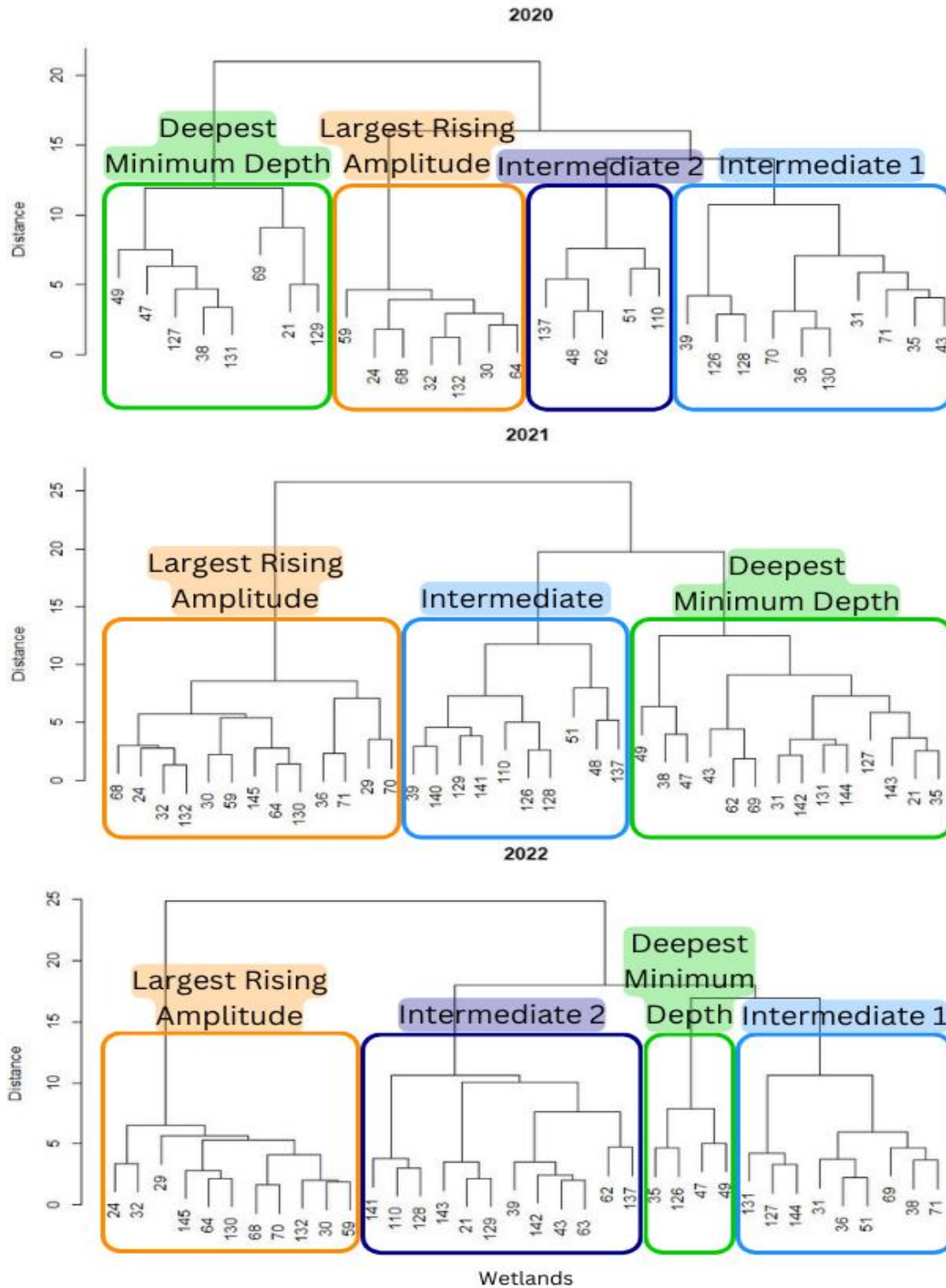


Figure 4: Wetland groups based on hierarchical cluster analysis of hydrograph attributes using Euclidean Distance and Ward D2 linkage; boxes indicate most parsimonious number of clusters as indicated by nclust package, group characteristics are described in Table 2. In 2020, $n = 30$; 2021, $n = 37$; and 2022, $n = 36$.

Group membership changed through the three years of the study, as did total number of wetlands (Table 2). The total area of wetland in each group also varied, but in both 2021 and 2022 the Largest Rising Amplitude Group had the largest area of wetlands though not necessarily the largest count of wetlands, as the Largest Rising Amplitude wetlands tend to be larger. For the common grouping (i.e., the group a wetland was in for two of three years), the Intermediate Group has the largest in number of wetlands (16) but the Largest Rising Amplitude Group is the largest in terms of area (11.92 km²) indicating that larger wetlands tend to consistently be in the Largest Rising Amplitude group (Table 2).

Table 2: Summary table of number of wetlands and area of wetlands in each group for each year and for the common groupings.

Group	Count	Percent of all wetlands	Total area of wetlands of that group (km²)	% of total wetland area comprising that group
2020				
Largest Rising Amplitude	7	23.33	5.72	25.34
Intermediate 1	10	33.33	10.02	44.40
Intermediate 2	5	16.67	3.55	15.73
Deepest Minimum Depth	8	26.67	3.28	14.53
Total	30	100	22.57	100.00
2021				
Largest Rising Amplitude	13	35.14	14.21	59.58
Intermediate	10	27.03	4.16	17.44
Deepest Minimum Depth	14	37.84	5.48	22.98
Total	37	100	23.85	100.00
2022				
Largest Rising Amplitude	11	30.56	11.92	51.20
Intermediate 1	9	25.00	6.22	26.72
Intermediate 2	12	33.33	3.4	14.60
Deepest Minimum Depth	4	11.11	1.74	7.47
Total	36	100	23.28	100
Common Grouping				
Largest Rising Amplitude	11	31.43	11.92	51.11
Intermediate	16	45.71	8.28	35.51
Deepest Minimum Depth	8	22.86	3.12	13.38
Total	35	100	23.32	100

The behaviour of the Columbia River flood pulse differs between years, with variations in size and duration (Figure 5). The Columbia River overtopped the natural levees in all three study years, suggesting that these three years were all relatively wet years. Despite this consistency in the river between years, there is still variation in wetland group membership between years (Appendix K), with the Intermediate groups being particularly variable. However, in two of three years, 35 of 38 wetlands were in the same group. Between 2020 and 2021, 70% of wetlands remained in the same group. While 2022 was an unusual year hydrologically due to the prolonged flood pulse, between 2021 and 2022 64% of wetlands remained in the same group. In a direct comparison between wetland groups in 2020 and 2022, 57% of wetlands remained in the same groups (Appendix K).

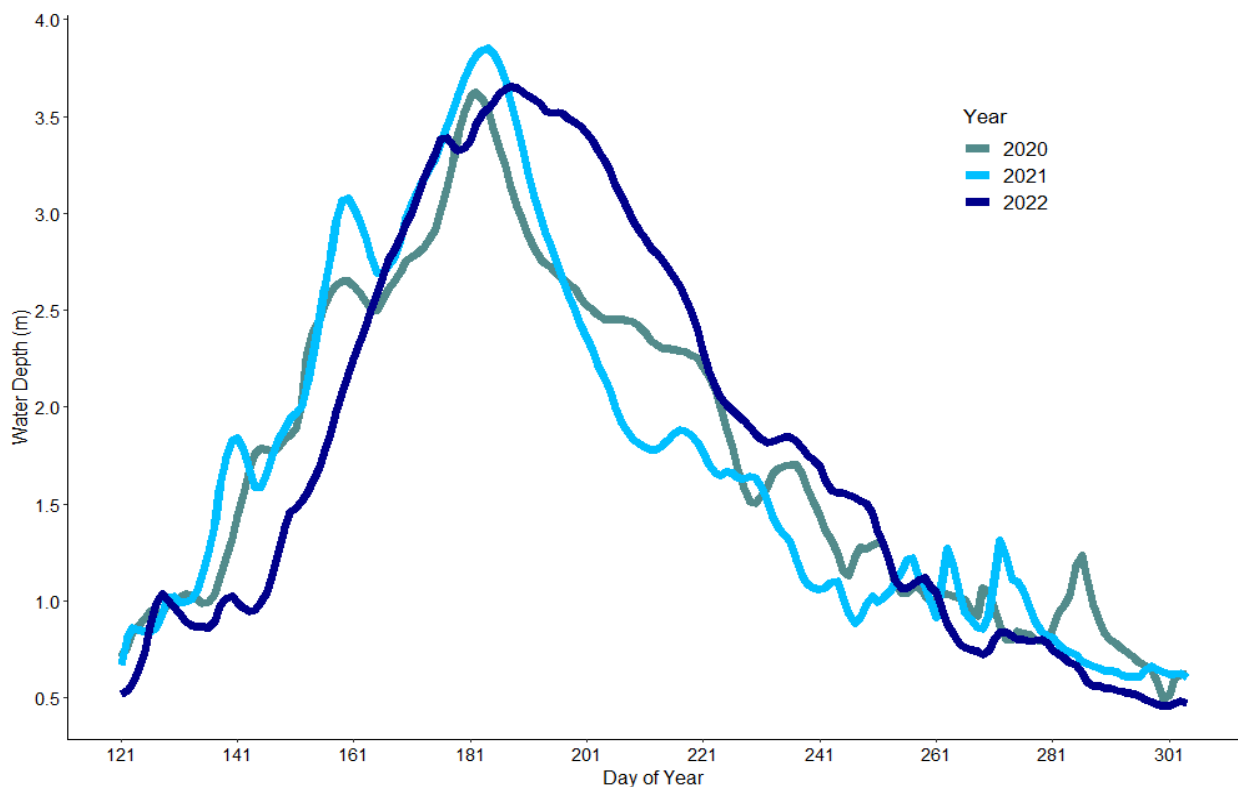


Figure 5: Water depth in the Columbia River at Nicholson, as collected by Environment Canada, for the three study years.

2.3.2 Hydrograph Attributes Differentiate Groups

When I compared the wetland groupings derived from the cluster analysis, their hydrographs showed group-level commonalities (Figure 6). The Largest Rising Amplitude wetland group began and ended with the lowest depth in all three years, showing a mean amplitude of 2 m. The Deepest Minimum Depth group had the most stable water levels in all three years, with a consistent mean depth of 1.5 m at the beginning and end of the hydrograph, and with an amplitude of only 1 m during the flood pulse. The two Intermediate groups are, as their name implies, intermediate in characteristics. The extended flood pulse of 2022 is also visible in the hydrographs, with all four groups of wetlands showing a longer period of high-water depths rather than the briefer peaks in 2020 and 2021.

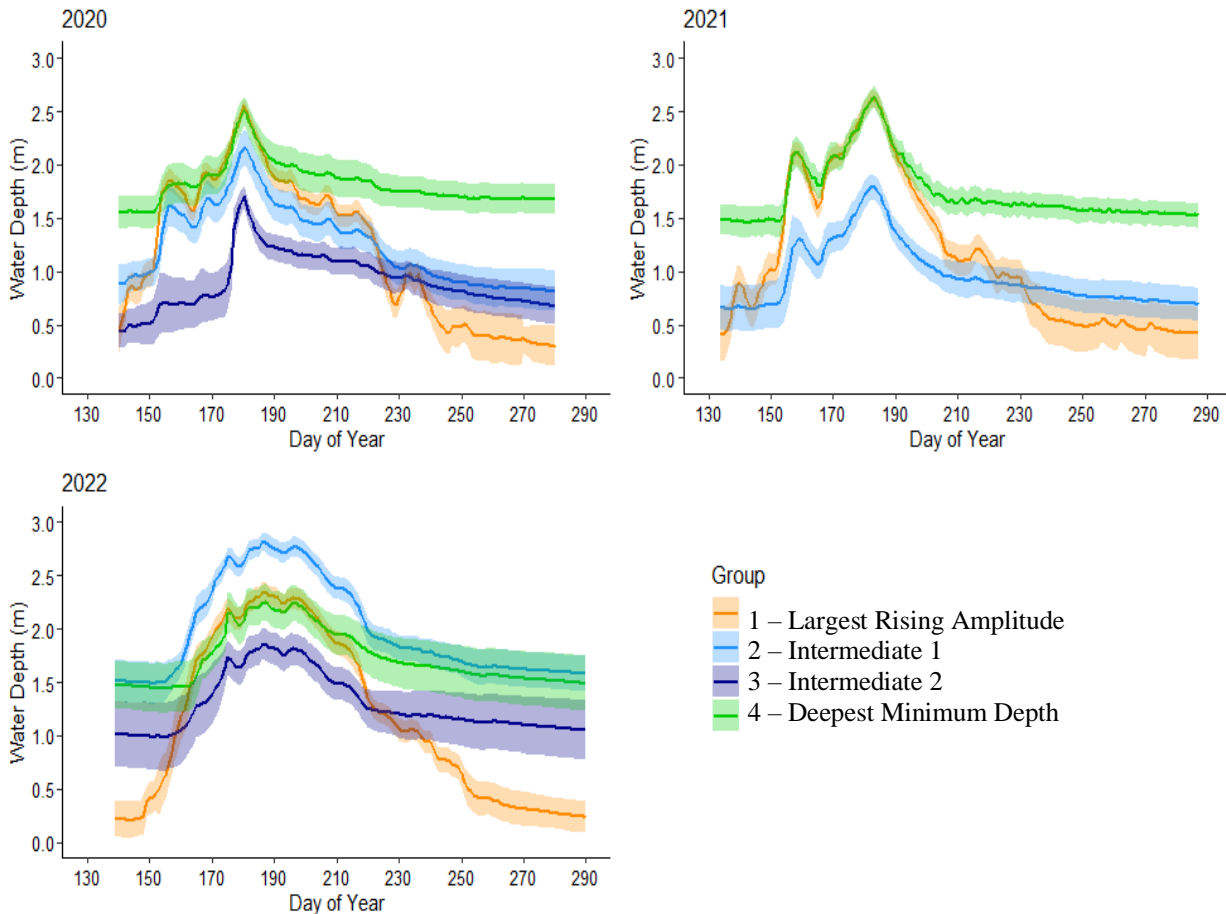


Figure 6: Mean hydrographs of each wetland group in each year. Error bars are standard error; in 2020, $n = 30$; in 2021, $n = 37$; and in 2022, $n = 36$. In 2021, only three groups were identified so light blue represents all Intermediate wetlands.

While I initially looked at all hydrograph attributes that explained more than 5% of PCA axis variance (Appendix I), I found that the three to four wetland groups differed significantly in specific hydrograph attributes, and I chose amplitude of the rising limb and deepest minimum depth to represent these groups (i.e., as representative attributes; Figure 7). I chose these attributes as representative because they differed significantly among the groups. In all three years, one-way ANOVAs revealed a statistically significant difference in amplitude of rising limb between at least two wetland groups (2020: $F_{3,26} = 5.258$, $p = 0.0057$; 2021: $F_{2,34} = 44.340$, $p < 0.0001$; 2022: $F_{3,32} = 30.640$, $p < 0.0001$). In 2020, Tukey's HSD test for multiple comparisons found that amplitude of rising limb was significantly different between the Largest Rising Amplitude group and the Intermediate 1 ($p = 0.0290$, 95% C.I. = -1.340, -0.056), Intermediate 2 ($p = 0.0630$, 95% C.I. = -1.50, -0.030), and Deepest Minimum Depth ($p = 0.0044$, 95% C.I. = -1.60, -0.25) groups; there was no significant difference between the three latter groups. In 2021, Tukey's HSD test for multiple comparisons found that the amplitude of the rising limb was statistically significantly different between the Largest Rising Amplitude group and the Intermediate ($p < 0.0001$, 95% C.I. = -1.40, -0.71) and Deepest Minimum Depth ($p < 0.0001$, 95% C.I. = -1.43, -0.79) groups. In 2022, Tukey's HSD test for multiple comparisons found a significant difference in the amplitude of the rising limb between the Largest Rising Amplitude group and the Intermediate 1 ($p < 0.0001$, 95% C.I. = -1.21, -0.41), Intermediate 2 ($p < 0.0001$, 95% C.I. = -1.57, -0.83), and Deepest Minimum Depth ($p < 0.0001$, 95% C.I. = -1.85, -0.81).

Minimum depth was similarly revealed using one-way ANOVAs to be statistically significantly different between at least two of the wetland groups in all three years (2020: $F_{3,26} = 1.520$, $p < 0.0001$; 2021: $F_{2,34} = 42.690$, $p < 0.0001$; 2022: $F_{3,32} = 21.02$, $p < 0.0001$). In 2020, using a Tukey's HSD test for multiple comparisons revealed a statistically significant difference between the Deepest Minimum Depth group and the Intermediate 2 ($p = 0.0010$, 95% C.I. = 0.35, 1.55), Intermediate 1 ($p = 0.0140$, 95% C.I. = 0.10, 1.10), and Largest Rising Amplitude ($p = 0.0002$, 95% C.I. = 0.45, 1.54) groups. In 2021, the same test revealed a statistically significant difference between minimum depth in the Deepest Minimum Depth group and the Intermediate ($p < 0.0001$, 95% C.I. = 0.53, 1.17) and Largest Rising Amplitude ($p < 0.0001$,

95% C.I. = 0.76, 1.35) groups. In 2022, the same test showed that the Largest Rising Amplitude group had a significantly different minimum depth from the Deepest Minimum Depth ($p < 0.0001$, 95% C.I. = 0.62, 1.85), Intermediate 2 ($p = 0.0022$, 95% C.I. = 0.202, 1.084), and Intermediate 1 ($p < 0.0001$, 95% C.I. = 0.81, 1.76) groups. The Intermediate 1 and Intermediate 2 were also significantly different ($p = 0.0041$, 95% C.I. = -1.10, -0.17) from each other.

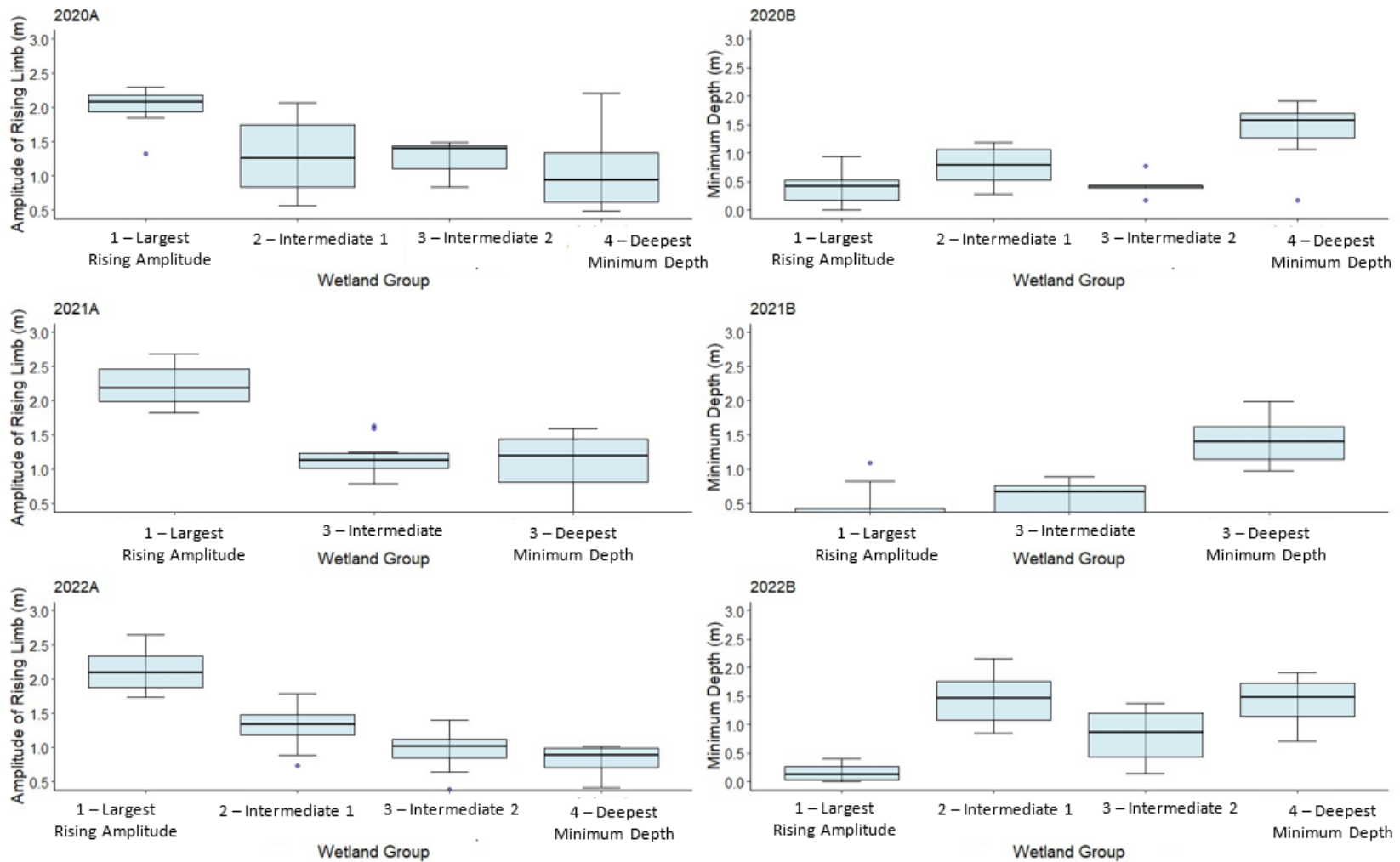


Figure 7: Hydrograph attribute differences between wetland groups in all three years, A) Amplitude of rising limb of hydrograph (m), and B) Minimum depth (m). In 2020, n = 30; 2021, n = 37, in 2022, n = 36.

2.3.3 Levee Gap and Beaver Dam Variables Predict Wetland Groups

I identified 76 levee gaps and 205 beaver dams using imagery, and I measured 45 levee gaps and 23 beaver dams in person. The Random Forest models based on measurements of the levee gaps and beaver dams (Appendix D) were able to correctly classify 40-66% of the wetlands, depending on year (Table 3) and on wetland group. The Largest Rising Amplitude group was the most consistently predicted by the models; e.g., 82% of these wetlands were correctly classified in the common grouping model. In contrast, only 25% of the Deepest Minimum Depth wetlands were correctly classified in the common grouping model (Table 3). For those models based on wetland groups in individual years, the most accurate was the 2022 model that included area and perimeter, which correctly classified 23 of 36 wetlands (64%). The least accurate model was the 2020 model, which correctly classified only 12 of 30 wetlands (40%). As group membership of individual wetlands varied slightly between years, I assigned each wetland to its common grouping, the group in which it was placed in at least two of three years. The common grouping model excluding area and perimeter was slightly more accurate than the 2022 model including area and perimeter, which correctly classified 23 of 35 wetlands (66%). Excluding 2020, at least 55% of the wetland groupings could be predicted using the levee gap and beaver dam variables, with out-of-box estimates of error rate percentage ranging from 34% to 44%.

Table 3: Summary of random forest models using wetland group as the response variables and levee gap and beaver dam metrics (Appendix D) as the predictor variables. Common grouping is the group in which a wetland was placed for at least two of the three study years. Note that in 2021 only 3 groups were distinguished based on the hydrograph attributes, and consequently for Random Forest Model using the common grouping, only three groups were possible.

Year	Number of Variables at Each Split	Out-of-Box Estimate of Error Rate Percentage	Number of Wetlands Correctly Classified	Observed wetland group membership	Assigned Group Membership By Random Forest Model				Percentage of Wetlands Correctly Classified In Each Group
					1 – Largest Rising Amplitude	2 – Intermediate 1	3 – Intermediate 2	4 – Deepest Minimum Depth	
2020	4	53.33	14 of 30	1 - Largest Rising Amplitude	6	1	0	0	86
				2 - Intermediate 1	3	4	1	2	40
				3 - Intermediate 2	0	2	0	3	0
				4 - Deepest Minimum Depth	0	2	2	4	50
2021	4	43.24	21 of 37	1 - Largest Rising Amplitude	10		2	1	77
				2 - Intermediate	1		2	7	20
				4 - Deepest Minimum Depth	1		4	9	69
2022	4	36.11	23 of 36	1 – Largest Rising Amplitude	9	1	1	0	82
				2 - Intermediate 1	0	3	6	0	33
				3 – Intermediate 2	0	2	10	0	83
				4 – Deepest Minimum Depth	0	1	2	1	25
Common Grouping	4	40.00	21 of 35	1 - Largest Rising Amplitude	9		2	0	82
				2 - Intermediate	1		10	5	63
				3 - Deepest Minimum Depth	0		6	2	25

2.3.4 Hydrograph Attributes Vary Among Wetland Groups

The contribution of individual levee gap and dam metrics to the classification vary between years (Appendix J). While I initially considered 17 metrics, I chose to focus analysis on gap volume (Figure 8A, Figure 9A), wetland gap status (Figure 8B, Figure 9B, Figure 9C), and mean gap width and dam length (Figure 10). Gap volume is the volume of a gap that is open for water to flow through (so presence of a beaver dam reduces gap volume) and is representative of how much water can enter a wetland. Wetland gap status is a qualitative metric of whether a wetland has open levee gaps, levee gaps dammed by beaver dams, or no levee gaps. Mean gap width and mean dam length are the cumulative width/length of the respective features in each individual wetland, with the mean calculated across each wetland group. I chose these metrics as they are representative of tangible differences between wetlands that can be easily understood and visualised.

Gap volume is representative of how much water can enter a wetland, and the Largest Rising Amplitude wetlands have a larger gap volume than the Intermediate and Deepest Minimum Depth groups, as well as a bigger range of volumes (Figure 8A). In 2021 and 2022, a one-way ANOVA revealed that there was a statistically significant difference in gap volume between at least two of the groups (2021: $F_{2,34} = 8.0130$, 0.0141; 2022: $F_{3,32} = 6.383$, 0.00162). Tukey's HSD Test for multiple comparisons found that in 2021, mean gap volume was significantly different between the Largest Rising Amplitude group and both the Intermediate ($p = 0.0082$, 95% C.I. = -65.62, -8.67) and the Deepest Minimum Depth ($p = 0.0025$, 95% C.I. = -64.78, -12.64) groups, while the Intermediate and Deepest Minimum Depth groups were not significantly different ($p = 0.99$). In 2022, Tukey's HSD Test for multiple comparisons found that mean gap volume was significantly different between the Largest Rising Amplitude wetlands and all three of the Intermediate 1 ($p = 0.026$, 95% C.I. = -69.97, -3.50), the Intermediate 2 ($p = 0.0016$, 95% C.I. = -77.11, -15.38), and the Deepest Minimum Depth ($p = 0.044$, 95% C.I. = -87.30, -0.95) Groups, while once again the latter three were not significantly

different. In all years, most of the wetlands grouped as Largest Rising Amplitude have open levee gaps (i.e., gaps without beaver dams in them), while the Intermediate and Deepest Minimum Depth groups are dominated by levees without gaps or levee gaps with beaver dams (Figure 8B). In 2022, there are less wetlands in the Deepest Minimum Depth group likely due to the extended flood pulse resulting in higher water levels for longer in all wetlands, regardless of group. Interestingly, the Largest Rising Amplitude group had almost no wetlands with levee gaps or gaps dammed by beavers (Figure 8B), whereas the Deepest Minimum Depth group included almost no wetlands with open levee gaps. Either these wetlands had no gaps, or the gaps were dammed. The Intermediate categories were more mixed, particularly the Intermediate 1 group from 2020 and 2022.

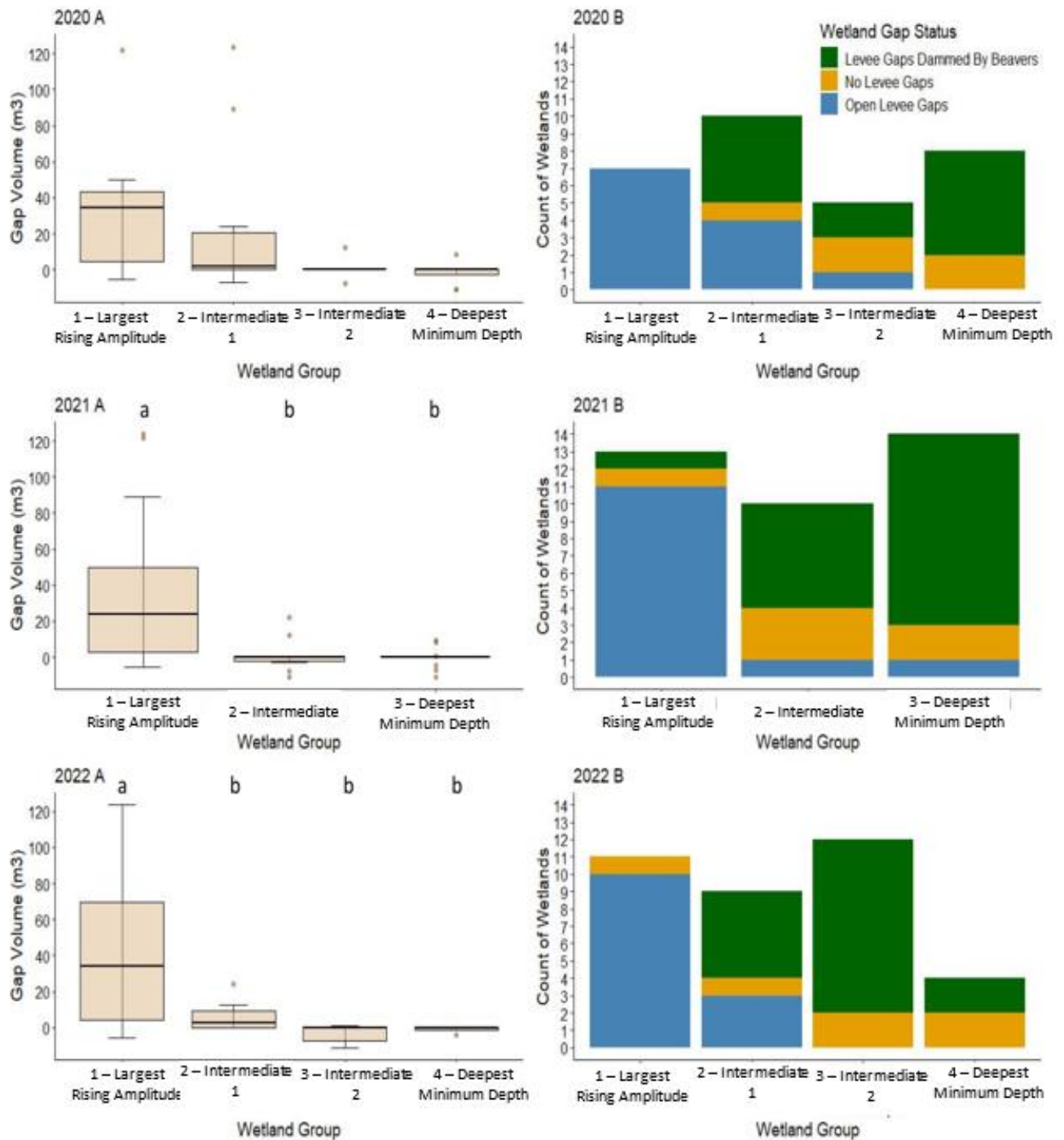


Figure 8: Differences in beaver dams and gap volumes between wetland groups. For all three study years, A) Gap volume (m3) and B) Count of wetlands with levee gaps dammed by beavers, no levee gaps, and open levee gaps. For 2020, n = 30; 2021, n = 37; 2022, n = 36.

Figure 9A provides the mean gap volume for wetlands, based on their common grouping membership across the three study years. For gap volume for the common groupings (Figure 9A), a one-way ANOVA also found statistically significant differences between at least two groups ($F_{2,32} = 5.753$, $p = 0.0073$). Tukey's HSD Test for multiple comparisons demonstrated that the Largest Rising Amplitude and Deepest Minimum Depth groups are significantly different ($p = 0.0052$, 95% C.I. = -3.86, -0.62). Figure 9B represents the distribution of wetlands among their common grouping, based on the presence of open levee gaps, gaps dammed by beavers or the absence of levee gaps. As with the individual year data (Figure 8B), the Deepest Minimum Depth group had very few wetlands with open levee gaps, whereas the Largest Rising Amplitude group had very few wetlands with levee gaps dammed by beavers.

Common Groupings

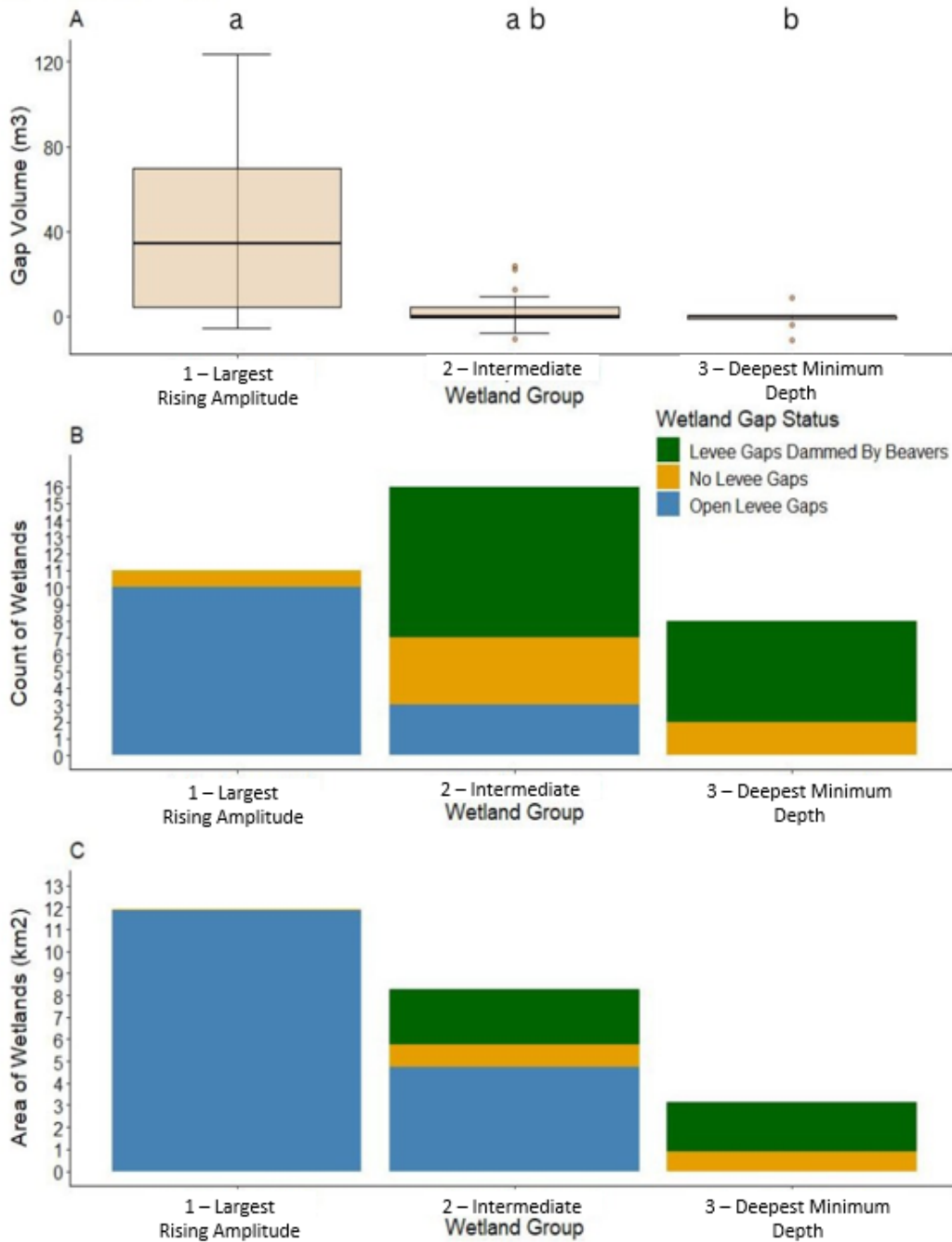


Figure 9: Differences in beaver dams and gap volumes between wetland groups based on common groupings (wetlands with at least two years in same group) (n = 35), A) gap volume (m³), B) count of wetlands that have beaver dams, that have no levee gaps, or that have open levee gaps, and C) area of wetlands that have beaver dams, that have no levee gaps, or that have open levee gaps.

The Largest Rising Amplitude wetlands have a larger mean gap width (though not significantly so) and shorter mean dam length than the Intermediate and Deepest Minimum Depth wetlands (Figure 10). The Intermediate wetlands have a shorter mean dam length than the Deepest Minimum Depth group (Figure 10). The Largest Rising Amplitude group has a mean gap width of 33.2 m and a mean dam length of 2.2 m, while the Intermediate group has a mean gap width of 12.9 m and a mean dam length of 29.6 m, and the Deepest Minimum Depth group has a mean gap width of 26.2 m and a mean dam length of 86.1 m. A one-way ANOVA found statistically significant differences between at least two groups in mean dam length ($F_{2,32} = 4.006$, $p = 0.0280$; Figure 10), though there were no statistically significant differences in mean gap width ($p = 0.124$). Tukey's HSD Test for multiple comparisons demonstrated that the Largest Rising Amplitude and Deepest Minimum Depth groups are statistically significantly different ($p = 0.022$, 95% C.I. = 10.45, 157.32).

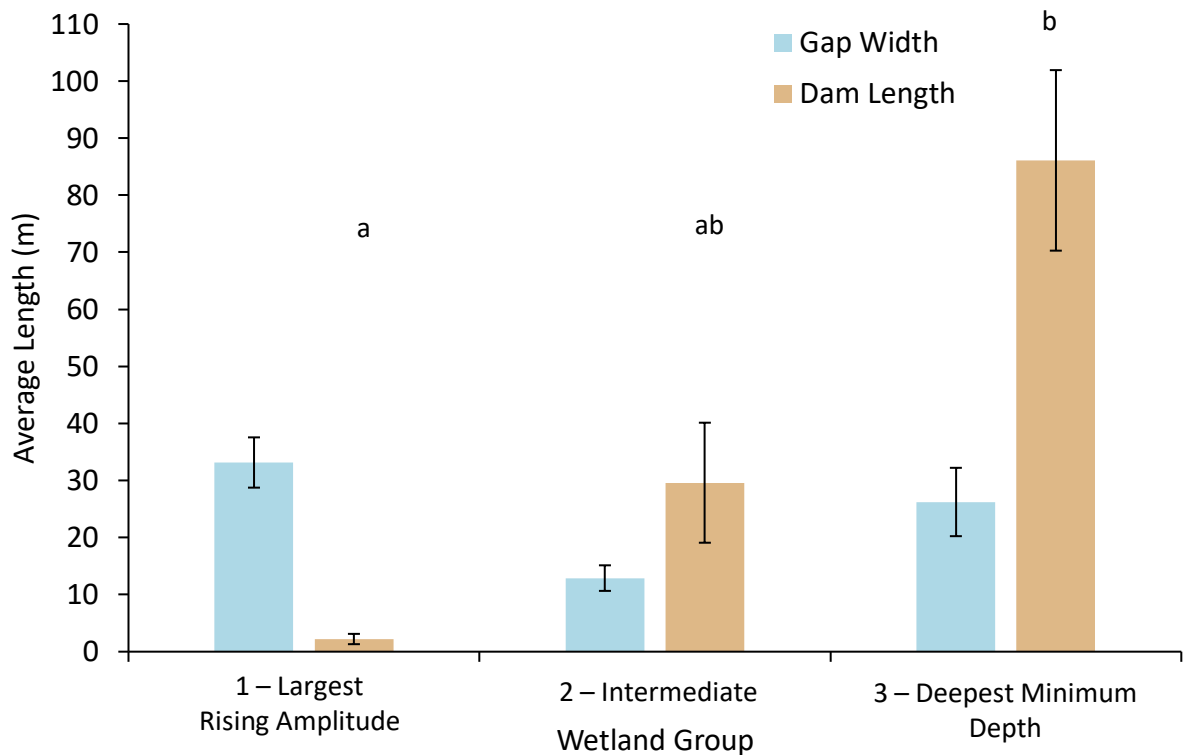


Figure 10: The mean total gap width (blue) and dam length (brown) in the different wetland groups (if wetland was in same group for at least two years) n = 35, error bars are standard error. Lower case letters denote significance as per one-way ANOVA and Tukey’s HSD test for multiple comparisons (note: there are no significant differences between gap width in the different wetland groups).

2.4 Discussion

In this study, I investigated how the morphology of natural levees, gaps in those levees, and beaver dams built across those gaps influence the hydrology of the wetland basins in the Columbia River’s floodplain. I predicted that gaps in the levee would have a large influence on wetland hydrology, and that beaver dams could modify the effect of those gaps by blocking water flow into and out of the wetland from the river. I therefore predicted that the combination of levees, gaps in the levees, and beaver dams in the gaps would result in different types of wetlands which would be distinguishable hydrologically. In a wetland connected to the main channel of the river though gaps in the natural

levees, I predicted that the hydrograph would differ from the hydrograph of a wetland separated from the river by intact natural levees or which has beaver dams spanning any levee gaps that are present. In wetlands with levee gaps, the river would flood the wetlands even if the flood pulse did not overtop the levees and when the flood pulse receded water levels in the wetland would drop. However, if beaver dams were built within these gaps, I predicted that the dam would delay the rising floodwaters' entry into the wetland basin. Similarly, as the flood pulse receded, the dam would retain water within the wetland. If the levees lacked gaps, I predicted that the wetland would not flood unless the river overtopped the levees and that when the flood pulse receded that the wetland would retain higher water levels.

I found that wetland hydrology did differ between different wetlands and that there were enough commonalities that wetland groups could be formed. I also found that levee gaps and beaver dams were more associated with some wetland groups than others. Thus, by looking at both the wetlands in the hydrological groups and the gap and dam metrics, I determined that my study wetlands exhibit a gradient of connectivity to the Columbia River, and that as with many other floodplain systems (Amoros and Bornette, 2002) connectivity is an important contributing factor to spatial heterogeneity. The presence and characteristics of levees, levee gaps, and beaver dams allow for these different levels of connectivity to the Columbia River, and thus caused the hydrograph attributes that I observed.

2.4.1 Wetland Hydrology and Levee Gaps and Beaver Dams Create Connectivity Gradient

The Largest Rising Amplitude wetland type has gaps (often large) present in the levees that are not dammed by beavers (Figure 8, Figure 9), thus resulting in the greatest amplitude, with little water present in the wetlands in spring and fall and a mean increase of 2 m with the flood pulse (Figure 6). These wetlands consistently have a significantly larger rising amplitude than the other wetlands groups

(Figure 7). These wetlands can therefore be described as the Most Connected wetland group, being the most connected to the Columbia River. Ten of eleven wetlands in this Most Connected group have open levee gaps with no beaver dams.

All wetlands within the Deepest Minimum Depth group have gaps dammed by beavers or no levee gaps (Figure 8, Figure 9), and retain the greatest amount of water all year, with the deepest minimum depth and smallest amplitude and response to the flood pulse (Figure 6, Figure 7). These wetlands are therefore the Least Connected to the Columbia River. Six of eight of the Least Connected wetlands are dammed by beavers rather than having no levee gaps, indicating the profound impact that beaver dams have on wetlands in this system.

The Intermediate group wetlands are intermediate in both hydrograph attributes (Figure 6) and gap and dam metrics (Figure 8, Figure 9). They retain more water into the fall than the Largest Rising Amplitude/Most Connected wetlands, but less than the Deepest Minimum Group/Least Connected wetlands. They are consistently significantly different from the Largest Rising Amplitude/Most Connected wetlands in amplitude of rising limb of hydrograph, and consistently significantly different from the Deepest Minimum Group/Least Connected wetlands in minimum depth (Figure 7). Of these wetlands, four have no levee gaps, nine have beaver dams, and three have open levee gaps, indicating that this group is the most variable, and that levees without gaps and beaver dammed gaps have similar effects on wetland hydrology, resulting in the observed similar hydrograph attributes. These wetlands are therefore described as Partially Connected. Hydrograph attributes and predictive morphological characteristics are summarized in table 4, which links the hydrograph derived groups with the group names describing the connectivity of each wetland to the Columbia River.

Table 4: Wetland groups and a description of their hydrograph attributes and morphological characteristics (levee gaps and beaver dams) common to the *wetlands in that group*.

Hydrological Group	Connectivity Group	Hydrograph Attributes	Morphological Characteristics
Largest Rising Amplitude	Most Connected	Shallow in May and October; large increase in water depth with flood pulse; immediate response to river rise and fall, including during early peak	Gaps in natural levee present, beaver dams not present in all gaps; often large wetlands with large gaps
Intermediate 2	<i>Bigger Gaps</i>	Less shallow in May and October; response to flood pulse less immediate and less amplitude than Most Connected	Gaps in natural levee present but beaver dams present in most gaps; beaver dams not as high as the levee; beaver dams more porous
Intermediate 1	Partially Connected	<i>Smaller Gaps</i> Less water in May and October than Bigger Gaps or Least Connected, but more than Most Connected; slower rise than Bigger Gaps group; less water in May and October than Bigger Gaps or Least Connected, but more than Most Connected	Gaps in natural levee present but beaver dams present in all gaps or no gaps in levee present; beaver dams equal to or higher than the levee; beaver dams less porous
Deepest Minimum Depth	Least Connected	Deep in May and October; smallest amplitude; delayed rise in water depth; less response to early increase in river level	No gaps in natural levee or beaver dams present in all gaps that are equal to or higher than the levee; beaver dams less porous

2.4.2 Temporal variations in wetland groups

The Columbia Wetlands are a dynamic and complex system, with both temporal and spatial variation. Each year is different due to differences in precipitation and temperature resulting in the Columbia River flood pulse being different (Rodrigues *et al.*, 2024). It is important to note that the

Columbia River overtopped the levees in all three years of my study, indicating that these were relatively wet years, although the overall amplitude, timing, and duration of the flood pulse varied between years. 2021 had a higher amplitude and a faster increase than 2020 or 2022, while 2022 had a very long period of high water (Figure 6). Thus, any conclusions I can draw are from three high water years; it would be interesting to see if the wetlands in the different groups are consistent during low water years.

In 2022, the river's flood pulse remained high for a longer period than in 2020 and 2021 (Figures 6 and 7) and the wetland groups in 2022 differ substantially from those in 2020 and 2021. In 2022, the Least Connected group was the smallest group, containing only four wetlands (11%), as compared to eight wetlands (27%) in 2020 and 14 (38%) in 2021. In 2022, fewer wetlands displayed the characteristics of Least Connected wetlands because they were more connected to the main river due to the floods overtopping the beaver dams and levees for a longer time period. This changed the hydrographic attributes statistically putting them into another wetland group. A longer duration flood pulse may also have contributed to more subsurface flow through the natural levees, although I do not have any data on this. Four wetland groups were identified in 2020 and 2022, with the Partially Connected group showing variation within it. In 2021 only one Partially Connected group was detected (Figure 4). The flood pulse varied between years with 2020 having the lowest and shortest flood pulse, and 2022 the highest and longest flood pulse; 2021 was somewhere in the middle. With only three years of data it is difficult to draw firm conclusions, it may be that the Partially Connected – Bigger Gaps and Partially Connected – Smaller Gaps Groups are distinguishable in 2020 and 2022 but not 2021 due to the slightly later flood pulse onset in 2020 and 2022 (Figure 6). Flood pulse timing has been found to be an important contributing factor to spatial heterogeneity in other floodplain wetlands (Amoros and Bornette, 2002).

Despite all three years being wet years, there was variation in wetland group membership between years (Appendix K), indicating that even fairly small changes in the flood pulse have noticeable effects on wetland hydrographs. Wetland hydrology in these floodplain wetlands is clearly sensitive. Neary *et al.* (2021) found variation between wetland patterns between years and sensitivity in lake-level measurements in the Peace-Athabasca Delta, possibly due to the potential influence of multiple processes. It is likely that multiple processes are at work in the Columbia Wetlands, and I consider only a few of them: the flood pulse as a water input, and levee gaps and beaver dams as factors affecting that. I do not consider different water inputs (e.g. precipitation, groundwater, seepage through levees) and different water outputs (e.g. evaporation, seepage through levees). There are also geomorphological factors that may contribute to observed variation, such as the absolute elevation of levees, or a detailed analysis of flow through each beaver dam.

Of the 38 study wetlands, 35 wetlands did not change groups between years or were in the same group for two of three years (Appendix K). The Most Connected wetlands are the most consistent across years, with 9 wetlands being in the Most Connected group in all years of data (out of 13 wetlands that are classified as Most Connected in at least one year); four wetlands were classified as Partially Connected in 2020, and then in 2021 and 2022 they were all within the Most Connected group. They are also the most consistently correctly classifiable group with the Random Forest Model, with at least 76% of these wetlands being correctly classified in all three years, and 81% being correctly predicted using the common grouping (Table 3). I believe this is due to the strong link between the Most Connected wetland group and the presence of undammed levee gaps. Of the 12 wetlands in the Most Connected group in two of three years, 11 of them have undammed levee gaps. This wetland group is the least sensitive to changes in the flood pulse, perhaps due to the relatively simpler process of river

water entering and then leaving the wetland through a gap, rather than the presumably more complicated process of river water interacting with levees and beaver dams.

The Random Forest Model uses the levee gap and beaver dam data to classify wetland groups and then compares these classifications to the groups derived from the hydrograph attributes. It does not consistently correctly classify Partially Connected or Least Connected wetlands, correctly classifying between 0% and 83% of the Partially Connected wetlands and 25% to 69% of the Least Connected wetlands depending on year (Table 3). I believe this could be for several reasons. Firstly, the presence of beaver dams increases variability in channel hydraulics (Majerova *et al.*, 2019), and so it is likely that in these floodplain wetlands there are variable hydraulic interactions between the flood pulse and beaver dams. Secondly, this analysis does not include the absolute elevation of levees above sea level, and how they compare to each other, as these data were not available. The available LiDAR data did not distinguish between treetops, bare ground, or depth below surface water. I believe that including absolute elevation would allow for a Random Forest Model that would correctly classify more wetlands, as it would allow for variations in overall levee elevation and not just gap depths and dam heights to be included in analyses. Filgueira-Rivera *et al.* (2007) found that of 24 surveyed levees, 10 were overtopped, and that levee heights varied from 0.9 to 2.3 m above the deepest part of the adjacent river channel; it would be interesting to know these measurements for my 38 study wetlands. However, Filgueira-Rivera *et al.* (2007) also did not have absolute levee elevation data. Thirdly, there is no statistically significant difference in gap volume, gap width, or dam length between the Partially and Least Connected groups, indicating that there is variation in these metrics within the group. However, the Least Connected group does have a larger mean dam length and a smaller mean gap volume, perhaps accounting for why these wetlands have distinct hydrographs (Figure 10). The Partially Connected groups (including the Partially Connected – Larger Gaps, Partially Connected –

Smaller Gaps, and the overall Partially Connected group) show a larger range in mean gap volume, which is perhaps why wetlands within these groups are the most variable, moving between groups across years (Sankey Diagram). This combination of different factors could be why these wetlands are the most sensitive to even small interannual variations in the flood pulse.

Some of the variation in hydrological attributes and wetland classification may also be due to other sources of water affecting the wetlands. Many of the wetlands in this study have either small creeks flowing into them or springs rising within them. Remmer *et al.* (2023) found that groundwater percentage differed greatly between wetlands in the Columbia Wetlands complex, and while Remmer *et al.* (2023) did not analyse data based on wetland group, several of the same wetlands were also included in my study. The percentage of groundwater in the wetlands in the summer (when we would expect river input to be the greatest, as this is post flood pulse) ranged from 46.7% (Site 43; Partially Connected) to 10.8% (Site 59; Most Connected) (Remmer *et al.*, 2023). Thus, clearly other sources of water are important to wetlands in this area; the Columbia River is a major driving force, but it is not the only driver of wetland dynamics.

Clearly, wetland connectivity is a continuum, and interannual variation allows for shifts along this continuum, with the behaviour of the river affecting all wetlands across the floodplain. The ‘ends’ of the continuum, represented by the Largest Riding Amplitude/Most Connected wetlands and the Deepest Minimum Depth/Least Connected wetlands that do not change between years (seven wetlands in the former group, and three wetlands in the latter group) are presumably the least sensitive to this interannual variation, while the wetlands that shift between groups are more sensitive to this interannual variation, with their relative connectivity to the Columbia River shifting depending on the size and duration of the flood pulse.

2.4.3 The importance of beaver dams in the Columbia Wetlands

Beaver dams are critically important to the Upper Columbia River floodplain wetlands, controlling or partially controlling the water levels in 39% of wetlands (Appendix J), and resulting in an increase in Partially and Least Connected wetlands, with 56% of wetlands in the former group and 75% of wetlands in the latter group having beaver dams (Figure 9). Beaver dams varied greatly across the study wetlands, with the shortest dam measuring 1.7 m and the longest 150 m; the tallest dam was 1.83 m tall and 0.65 m above the height of the levee, while the widest dam was 6.68 m wide. Some wetlands had up to 5% of their entire perimeter dammed by beavers. The interaction between beaver dams and the Columbia River flood pulse is complex, as indicated by the greater sensitivity of the wetlands with beaver dams to interannual differences in the flood pulse and the presence of beaver dams in both Partially Connected and Least Connected wetlands. Beaver dams have been found to increase habitat heterogeneity and complexity in multiple different ecosystems (Larsen *et al.*, 2021), and it is clear that they are doing so in the Columbia Wetlands as well. Even though the Columbia Wetlands are a large floodplain wetland along a major river, beavers have a profound impact.

Differences in beaver dam construction and maintenance result in different mechanisms and quantities of water flowing over, through, or under dams, and beaver dams are very dynamic, with flow states changing within a span of weeks or months (Ronnquist and Westbrook, 2021). I did not focus on the details of construction or determine detailed flow states in this study. However, I did note differences in beaver dams, for example one beaver dam in Site 49 was removed by people, resulting in the north end of that wetland draining out, though other beaver dams in the same wetland ensured that most of the wetland retained its water and thus the majority of the wetland remained as a Least Connected wetland. Similarly, in Site 141, an old beaver dam blew out between the summer of 2021 and 2022; this change did also not result in a change in wetland group, however it did result in a change in hydrograph attributes, with a mean depth of 1.10 m in 2021 prior to the dam blowing out and a mean

depth of 0.95 m in 2022 after the dam blew out (Appendix E). It is possible that less obvious changes to beaver dams such as beavers reinforcing or building higher an active dam, or an inactive dam becoming leakier over time, could account for some of the observed changes in wetland groups. A more focused study looking only at wetlands with beaver dams, could attempt to refine the understanding of beaver dams and wetland group, following the example of Ronnquist and Westbrook (2021). Such a study would also be of relevance in understanding why some levee gaps are not dammed as I consider further below.

The Most Connected group has only 31% of study wetlands within it (11 wetlands) but contains 51% (11.92 km²) of the total area of the study wetlands. The Most Connected wetlands are often larger, likely because their larger size results in larger levee gaps that have too much flow for beavers to be able to build dams. It is hard to determine the flow of water that is too much for a beaver dam to persist, due to the many factors that affect resistance to dam failure. These factors include type and age of dam building materials, the nature of the channel bed underneath the dam, and the presence and motivation of beavers to fix the dam (Ronnquist and Westbrook, 2021). Factors such as angle, velocity, and depth that contribute to water pressure against the dam also play a role. Pollock *et al.* (2014) judged that a bankfull stream power of less than 2000 W/m is favourable for building beaver dams, but that beavers will also build dams in areas with seasonally higher power conditions and repair them as they get washed out. In contrast, Andersen and Shafroth (2010) observed damage to dams with flows as low as 5m³s⁻¹. Macfarlane *et al.* (2017) considered both base flow and 2-year peak flow conditions in building their beaver dam capacity model, and considered 2 year peak flow conditions of over 2000 W/m to effectively guarantee the blowout of a dam, while 2 year peak flow conditions between 1000 and 2000 W/m provided conditions suitable for dam breaches and blowouts to occur. However, all of this work has been conducted on small to medium-sized creeks, and not in a large river floodplain system like

the Columbia Wetlands, where the flood pulse does not come down a creek in a single direction towards a dam, but spreads across the floodplain and approaches beaver dams from different directions and angles. However, it is likely that the power of the water flow is why larger wetlands and large gaps are not being dammed by beavers.

The importance of beaver dams in maintaining habitat diversity in the Columbia Wetlands is clear. Without beaver dams, fifteen of the twenty-five (63%) Partially or Least Connected wetlands would instead be in the Most Connected wetland group. The interaction between the flood pulse and beaver dams, with dams playing a role in changing connectivity to the river, results in more habitat heterogeneity than if beavers were not present building dams. While beavers are considered in the Columbia National Wildlife Area Management Plan only as a threat to cottonwoods (Environment and Climate Change Canada, 2018), they are in fact fundamental to retaining high habitat heterogeneity and thus biodiversity within the Columbia wetlands. Beavers are transitory in nature, moving on after food resources are depleted, and beaver dams are not permanent on the landscape (Larsen *et al.*, 2021). While dams can persist for many years after being abandoned they will eventually fail. Thus, wetlands that once had beaver dams and were either Partially or Least Connected will become Most Connected wetlands, more directly affected by the flood pulse. However, as these beavers move on to other areas of the wetlands, they will build dams in new wetlands and transform Most Connected wetlands to Partially or Least Connected wetlands. As long as this natural cycle of beaver activity continues, so will these different wetland groups persist. This beaver cycle as it moves spatially across the floodplain controls the ecological characteristics of the wetlands and the heterogeneity of the habitats. The increase in habitat heterogeneity caused by beaver dams has resulted in documented increases biodiversity across multiple taxonomic groups (e.g. Nummi and Holopainen, 2020; Willby *et al.*, 2018; Thompson

et al., 2021) and they likely have the same affect in the Columbia Wetlands, where the different wetland classes likely support different species.

Initially, I predicted that wetlands with no levee gaps at all, and therefore no dams, would be less connected to the Columbia River than wetlands with gaps dammed by beaver dams. However, this is not the case, as I found that beaver dams can have a similar effect on hydrology as intact levees, with wetlands with beaver dams and wetlands with intact levees both being found in both the Partially and Least Connected groups. In fact, more wetlands in the Least Connected group have beaver dams than have intact levees. Wetlands in the Least Connected group have on average smaller gaps and larger dams, though not significantly so, suggesting that this reduction in connectivity could be due to an increase in dam length. Similarly, the Partially Connected – Smaller Gaps wetlands have on average smaller gaps and larger dams, so there is a non-significant tendency towards less connected wetlands having larger dams. However, it is clear that there the interactions between beaver dams and the flood pulse, and the resulting hydrology of different wetlands, are complicated. Beaver dams have been noted to increase variability in channel hydraulics (Majerova *et al.*, 2019), and individual dams can be structurally very different and have very different hydrological effects such as in varying dynamics and amounts of pond storage (Ronnquist and Westbrook, 2021), demonstrating how complex hydrology because of beaver dams can be. This fits with my findings, where while there is clearly a link between beaver dams and Partially and Least Connected wetlands, and thus a link between beaver dams and different wetland hydrology, the details of that link are not simple.

2.4.4 Climate change

Climate is already changing the characteristics of the Columbia River and the Columbia Wetlands (e.g. Utzig, 2021; Rodrigues *et al.*, 2024). The flood pulse which is the driving force in these wetlands, has changed over the decades, with peak flow coming 11 days earlier now than between 1903

and 1928 (Rodrigues *et al.*, 2024). The duration of peak flows has also decreased from 22 days to 11 days in the same time period (Rodrigues *et al.*, 2024). Earlier and shorter flood pulses result in an overall drying of the Columbia Wetlands, with earlier flood pulses resulting in a longer summer period for evapotranspiration to remove water from the wetlands, while a shorter duration of peak flow results in less water available for the flood basin. Rodrigues *et al.* (2024) detected an increase in woody shrubs from 6% to 12% when comparing the 1984-2003 period with the 2004-2019 period. Similarly, Hopkinson *et al.* (2020) detected a decrease of 16% in the area of open water in a selected reach of the Columbia Wetlands when comparing the 1984-2003 period with the 2004-2019 period. Peak water due to glacial runoff has likely already been passed in the Columbia River headwaters (Moore *et al.*, 2020), and while the Columbia River flood pulse is mostly driven by snowmelt, with glacier contributions more important later in the year (Makaske *et al.*, 2009; Remmer *et al.*, 2023), and this is indicative of the trend of the system towards being drier. Summer flows are predicted to decrease in the future, with a corresponding increase in summer drought conditions (MacDonald Hydrology Consultants Ltd., 2024).

With this drying of the Columbia Wetlands, the ability of beavers to retain surface water on the landscape, particularly between fall and spring, becomes particularly important. Hood and Bayley (2008) found that even during extreme drought, the presence of beaver was associated with a nine-fold increase in the area of open water. Green and Westbrook (2009) found a reduction of pools from 10% to 0% of the area of a small floodplain (up to 100 m wide) with the removal of beaver dams. My results are similar, with beaver dams being responsible for the retention of water in 15 of 38 study wetlands. While a reduction in open water area has been detected in the Columbia Wetlands (Hopkinson *et al.*, 2020), perhaps there would have been a greater reduction of open water without the presence of beaver dams. In the future, beaver dams may partially mitigate the impacts of climate change due to their

retention of open water on the landscape. As well as increasing open water on the landscape, beaver dams change vegetation communities, with Green and Westbrook (2009) finding a decrease in open vegetation such as sedges and grasses from 69% to less than 10%, and a corresponding increase in closed vegetation such as shrubs and trees from 21% to 90% with the removal of beaver dams. The presence of beaver dams could thus perhaps work to moderate the increase in shrubs that Rodrigues *et al.* (2024) detected across the Columbia Wetlands; without beaver dams, that increase may have been greater.

Beaver dams are crucial to the functioning of the Columbia Wetlands, and they will be only more important in the future as the impacts of climate change are increasingly felt. The impacts of an individual beaver dam can persist long after the dam has been abandoned (Laurel and Wohl, 2019), and so the mitigation of climate change impacts can continue to occur even in wetlands where beavers are no longer actively maintaining dams. The habitat complexity formed by active beaver dams, inactive beaver dams, and wetlands without beaver dams results in a resilient, healthy system that is better able to respond to the impacts of climate change.

Chapter 3

Conclusion

The Upper Columbia River floodplain wetlands are the last remaining undammed stretch of floodplain wetlands along the Columbia River and continue to experience a natural flood pulse. This flood pulse interacts with natural levees and beaver dams across the floodplain and habitat heterogeneity results, with individual wetlands within the Columbia Wetlands having different hydrographs. I conducted research in 38 wetlands from 2020 to 2022 and aimed to determine if differing wetland hydrology allowed for wetland groups to be determined, and if those groups could be attributed to gaps in natural levees and beaver dams. Hydrograph attributes can be used to differentiate wetland groups, with three or four groups being identified depending on year. Random Forest models based on measurements of the levees, levee gaps, and beaver dams were able to correctly classify 40-66% of the wetlands into these wetland groups, depending on wetland group and year. Combining hydrograph attributes and levee gap and beaver dam metrics, we can describe these groups on a gradient of connectivity to the Columbia River, being Most Connected, with large open levee gaps, Partially Connected, with levees without gaps or with gaps dammed by beaver dams that are smaller, and Least Connected, with levees without gaps or gaps dammed by beaver dams that are bigger. This demonstrates the large impacts of beavers on shaping wetland systems, and has implications for the differing impacts of climate change on these different wetland groups.

While the Columbia Wetlands have attracted some research attention, especially in recent years, to which this study contributes, there are still many unknowns about this system. The interactions of the flood pulse and other water sources across the wetlands are complex, and many questions remain about the impacts of climate change. Changes have already been documented over the past four decades, with increasing temperature, decreasing precipitation, increasing river discharge, and an

earlier and shorter peak flow period, as well as the frequency of both high-discharge and dry years increasing, indicating a shift to more extreme flow behaviours (Rodrigues *et. al*, 2024). Clearly these will have impacts on the Columbia Wetlands, as will future changes such as the predicted warming and drying (Utzig, 2021).

With decreasing water present in the Columbia Wetlands, the differences between these wetland groups may become more profound. The Most Connected wetlands are reliant on the Columbia River flood pulse to provide water and retain very little water as the flood pulse recedes due to the lack of beaver dams. If climate change results in reduced flood pulses, then these wetlands may not receive the amount of water required to maintain them in their current state. Conversely, the Partially Connected and Least Connected wetlands are less easy for the Columbia River flood pulse to flow into, and so decreased flood pulses may result in less water from the river reaching these wetlands. They may become more dependent on groundwater inflows to maintain water levels or they may become drier due to that lack of river input, and may show both hydrological and ecological changes as a result.

All three years of data analysed were relatively high flood pulse years, with the flood pulse overtopping the levee in every year; 2023 was a very low flood pulse year, so it would be interesting to analyse data from that year with this same approach, to see how the individual wetlands and the wetland groups respond to a low flood. If 2023 is an indication of what future flood pulses may be like, then this will have important implications for the future of the Columbia Wetlands complex.

There are also ecological implications of these different wetland groups, which is an area for further study now that the wetland groups have been established. Hydrologic heterogeneity results in higher habitat diversity and higher biodiversity across the entire floodplain, but we do not know in detail the relationship between wetland group and species diversity is. It is likely that Most Connected wetlands will have different species within them than Least Connected wetlands, due to the differences

in habitat created, however future research is needed in this area. Hydrological differences will lead to different ecological communities using the different wetland groups, much of which has yet to be studied. Rooney *et al.* (2013) found different submerged aquatic vegetation communities in wetlands of differing river connectivity, with communities in more connected wetlands being driven more by the direct influences of flooding than environmental variables such as water or sediment quality, however in less connected wetlands these structuring factors did play a role. Research on fish in the Upper Columbia River has mostly focused on salmonids and their use of tributaries to spawn in rather than use of the Columbia Wetlands but wetlands can function as nursery habitat for fish and provide refugia for adult fish. The Columbia Wetlands are important for both breeding and migratory birds (Darvill, 2020; Darvill and Westphal, 2020), with water levels affecting habitat available for both groups of birds. Migratory waterbirds, in particular, pass through the Columbia Wetlands in early spring – before the flood pulse – and in the fall – after the flood pulse has receded – and so the ability of Partially and Least Connected wetlands to retain water is likely crucial to their use of the wetlands. The role of beaver dams in maintaining water levels in the wetlands is clear, but their role in slowing the rise of water in the wetlands in the spring with the flood pulse may also be important. The rapid flooding of wetlands, often with large amounts of scour, as found when the flood pulse passes through levee gaps, may be a greater disturbance than a slower increase through and over a beaver dam. Ground nesting bird species may benefit from this delayed and slower rise in water within the wetland, as they have a greater chance of successfully breeding before the water rises and submerged aquatic vegetation communities have been shown to be structured by connectivity within the Columbia Wetlands (Rooney *et al.*, 2013).

Habitat heterogeneity results in higher biodiversity across the entire floodplain, but we do not know in detail the relationship between wetland group and species diversity is. It is likely that the Most

Connected wetlands will have different species within them than Least Connected wetlands, due to the differences in habitat created, however future research is needed in this area.

Understanding the behaviour of the different wetland groups and the ecological communities found in the different groups will provide important information for management and restoration of this system. Thus far, the Columbia Wetlands are a fairly intact system, with a functioning flood pulse and natural dynamics, however they will be impacted by climate change, as well as other pressures such as increasing recreation and increasing anthropogenic water use.

Given the profound impact that beaver dams have on wetland classification, there is also potential for restoration using beaver dam analogues. Beaver dam analogues are human-built structures that mimic or reinforce natural beaver dams. They try to replicate the features of natural beaver dams, and so are semiporous, temporary features, built with natural local materials including sediment, wooden posts, and branches. They are constructed either in a location where there used to be a beaver dam or in locations where it would be likely that a beaver would build a dam. They aim to mimic the effects of natural beaver dams by retaining water within a system, and thus enhancing habitat complexity, biodiversity, and habitat for species at risk and concern. Munir and Westbrook (2020) found that beaver dam analogues significantly elevated upstream water levels and resulted in a rise in the water table in the riparian area, similar to natural beaver dams.

Though population estimate data are not available, the Columbia Wetlands have many active beaver dams and thus presumably active beavers. However, particularly in the face of climate change, targeted restoration activities that will restore year-round water holding capacity to selected wetlands may help to maintain a rarer habitat type on the landscape. Beaver dam analogues have the potential to be a low-technology, relatively natural way of doing this, particularly in wetlands where there are

already inactive beaver dams, and so a beaver dam analogue would simply be restoring a natural structure already present in the wetland.

In the context of the Columbia Wetlands, beaver dam analogues could increase water retention in wetlands, essentially changing Most Connected wetlands to Partially or Least Connected wetlands, and by retaining higher water levels over the winter and spring, beaver dam analogues would diversify the habitat. This is particularly important in the face of climate change. It is also important because the Most Connected wetlands cover 51% of the wetland study area despite only being 31% of the number of the study wetlands, and thus increasing the area of these rarer habitats will be beneficial to maintain biodiversity across the floodplain wetlands.

Understanding how connectivity to the Columbia River is impacted by levee gaps and beaver dams allows for a greater understanding of the complexity of the Columbia Wetlands, and this wetland classification will be a good base for further research in this system. I also contribute to beaver dam literature by examining the impacts of beavers in a relatively understudied system, where beavers are building dams not on smaller creeks but in a large landscape with natural levees, natural gaps in the levees and multiple back channels within the floodplain of a major river. I have determined that there are between three and four wetland groups derived from hydrograph attributes, depending on year, and that 60% of the variation between these groups can be attributed to levee gap and beaver dam characteristics. I further found that beaver dams are associated with decreasing connectivity to the Columbia River, and different hydrograph attributes are found in wetlands with beaver dams.

References

- Allan, J. D. (2004). Landscapes and Riverscapes: The Influence of Land Use on Stream Ecosystems. *Annual Review of Ecology, Evolution, and Systematics*, 35, 257–284.
- Amoros, C., & Bornette, G. (2002). Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater Biology*, 47(4), 761–776. <https://doi.org/10.1046/j.1365-2427.2002.00905.x>
- Andersen, D. C., & Shafroth, P. B. (2010). Beaver dams, hydrological thresholds, and controlled floods as a management tool in a desert riverine ecosystem, Bill Williams River, Arizona. *Ecohydrology*, 3(3), 325–338. <https://doi.org/10.1002/eco.113>
- BC Data Centre. (2022). Snow Survey and Water Supply Bulletin 2022. <https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/river-forecast/2022.pdf>
- Blackwell, M. S. A., & Pilgrim, E. S. (2011). Ecosystem services delivered by small-scale wetlands. *Hydrological Sciences Journal*, 56(8), 1467–1484. <https://doi.org/10.1080/02626667.2011.630317>
- Blanton, P., & Marcus, W. A. (2009). Railroads, roads and lateral disconnection in the river landscapes of the continental United States. *Geomorphology*, 112(3–4), 212–227. <https://doi.org/10.1016/j.geomorph.2009.06.008>
- Carli CM (2011) Floodplain ecology of the Upper Columbia River. Dissertation, University of Alberta.
- Carli, C. M., & Bayley, S. E. (2015). River connectivity and road crossing effects on floodplain vegetation of the upper Columbia River, Canada. *Écoscience*, 22(2/4), 97–107.
- Collen, P., & Gibson, R. J. (2000). The general ecology of beavers (*Castor* spp.), as related to their influence on stream ecosystems and riparian habitats, and the subsequent effects on fish – a review. *Reviews in Fish Biology and Fisheries*, 10(4), 439–461. <https://doi.org/10.1023/A:1012262217012>
- Darvill, R. (2020). *Columbia Wetlands Waterbird Survey*. Prepared for: Columbia Wetland Stewardship Partners.
- Davidson, N. C. (2014). How much wetland has the world lost? Long-term and recent trends in global wetland area. *Marine and Freshwater Research*, 65(10), 934–941. <https://doi.org/10.1071/MF14173>
- Dudgeon, D., Arthington, A. H., Gessner, M. O., Kawabata, Z.-I., Knowler, D. J., Lévêque, C., Naiman, R. J., Prieur-Richard, A.-H., Soto, D., Stiassny, M. L. J., & Sullivan, C. A. (2006). Freshwater biodiversity: Importance, threats, status and conservation challenges. *Biological Reviews*, 81(2), 163–182. <https://doi.org/10.1017/S1464793105006950>
- Environment and Climate Change Canada. (2018). *Columbia National Wildlife Area Management Plan* (p. 36). Environment and Climate Change Canada, Canadian Wildlife Service, Pacific and Yukon Region.
- Environment and Climate Change Canada Historical Hydrometric Data web site (https://wateroffice.ec.gc.ca/mainmenu/historical_data_index_e.html), 2024. Nicholson Station.

- Environmental Stewardship Division Kootenay Region. (2004). *Columbia Wetlands Wildlife Area Management Plan*. Government of British Columbia: Ministry of Water, Land and Air Protection: Environmental Stewardship Division, Kootenay Region.
- Filgueira-Rivera, M., Smith, N. D., & Slingerland, R. L. (2007). Controls on natural levée development in the Columbia River, British Columbia, Canada. *Sedimentology*, 54(4), 905–919. <https://doi.org/10.1111/j.1365-3091.2007.00865.x>
- Fish and Wildlife, 2013. <https://catalogue.data.gov.bc.ca/dataset/68327529-c0d5-4fcb-b84e-f8d98a7f8612>
- Gardner, R. C., & Finlayson, C. (2018). *Global Wetland Outlook: State of the World's Wetlands and Their Services to People* (SSRN Scholarly Paper 3261606). <https://papers.ssrn.com/abstract=3261606>
- Green, K. C., & Westbrook, C. J. (2009). Changes in riparian area structure, channel hydraulics, and sediment yield following loss of beaver dams. *Journal of Ecosystems and Management*, 10(1). <https://www.proquest.com/docview/2124009327/abstract/165A0D353A124E23PQ/1>
- Hohensinner, S., Habersack, H., Jungwirth, M., & Zauner, G. (2004). Reconstruction of the characteristics of a natural alluvial river–floodplain system and hydromorphological changes following human modifications: The Danube River (1812–1991). *River Research and Applications*, 20(1), 25–41. <https://doi.org/10.1002/rra.719>
- Hood, G. A., & Bayley, S. E. (2008). Beaver (*Castor canadensis*) mitigate the effects of climate on the area of open water in boreal wetlands in western Canada. *Biological Conservation*, 141(2), 556–567. <https://doi.org/10.1016/j.biocon.2007.12.003>
- Hopkinson, C., Fuoco, B., Grant, T., Bayley, S. E., Brisco, B., & MacDonald, R. (2020). Wetland Hydroperiod Change Along the Upper Columbia River Floodplain, Canada, 1984 to 2019. *Remote Sensing*, 12(24), Article 24. <https://doi.org/10.3390/rs12244084>
- Junk, W., Bayley, P., & Sparks, R. (1989). *The Flood Pulse Concept in River-Floodplain Systems*. 106.
- Kroes, D. E., Demas, C. R., Allen, Y. A., Day, R. H., Roberts, S. W., & Varisco, J. (2022). Hydrologic modification and channel evolution degrades connectivity on the Atchafalaya River floodplain. *Earth Surface Processes and Landforms*, 47(7), 1790–1807. <https://doi.org/10.1002/esp.5347>
- Larsen, A., Larsen, J. R., & Lane, S. N. (2021). Dam builders and their works: Beaver influences on the structure and function of river corridor hydrology, geomorphology, biogeochemistry and ecosystems. *Earth-Science Reviews*, 218, 103623. <https://doi.org/10.1016/j.earscirev.2021.103623>
- MacDonald Hydrology Consultants Ltd. (2021). *Year 2 Report—Upper Columbia Wetland Vulnerability Assessment* (p. 26). Prepared for the Columbia Wetland Stewardship Partners. (March 2021).
- MacDonald Hydrology Consultants Ltd. (2024) *Vulnerability Assessment of the Columbia Floodplain Wetlands*. Prepared for the Columbia Wetlands Stewardship Partners. (March 2024).
- Macfarlane, W. W., Wheaton, J. M., Bouwes, N., Jensen, M. L., Gilbert, J. T., Hough-Snee, N., & Shivik, J. A. (2017). Modeling the capacity of riverscapes to support beaver dams. *Geomorphology*, 277, 72–99. <https://doi.org/10.1016/j.geomorph.2015.11.019>

- Majerova, M., Neilson, B. T., & Roper, B. B. (2020). Beaver dam influences on streamflow hydraulic properties and thermal regimes. *Science of The Total Environment*, 718, 134853. <https://doi.org/10.1016/j.scitotenv.2019.134853>
- Makaske, B., Smith, D. G., & Berendsen, H. J. A. (2002). Avulsions, channel evolution and floodplain sedimentation rates of the anastomosing upper Columbia River, British Columbia, Canada. *Sedimentology*, 49(5), 1049–1071. <https://doi.org/10.1046/j.1365-3091.2002.00489.x>
- Makaske, B., Smith, D. G., Berendsen, H. J. A., de Boer, A. G., van Nielen-Kiezebrink, M. F., & Locking, T. (2009). Hydraulic and sedimentary processes causing anastomosing morphology of the upper Columbia River, British Columbia, Canada. *Geomorphology*, 111(3), 194–205. <https://doi.org/10.1016/j.geomorph.2009.04.019>
- Makaske, B., Lavooi, E., de Haas, T., Kleinhans, M. G., & Smith, D. G. (2017). Upstream control of river anastomosis by sediment overloading, upper Columbia River, British Columbia, Canada. *Sedimentology*, 64(6), 1488–1510. <https://doi.org/10.1111/sed.12361>
- Microsoft Corporation. (2023). Microsoft Excel. Retrieved from <https://office.microsoft.com/excel>
- Moore, R. D., Fleming, S. W., Menounos, B., Wheate, R., Fountain, A., Stahl, K., Holm, K., & Jakob, M. (2009). Glacier change in western North America: Influences on hydrology, geomorphic hazards and water quality. *Hydrological Processes*, 23(1), 42–61. <https://doi.org/10.1002/hyp.7162>
- Moore, R. D., Pelto, B., Menounos, B., & Hutchinson, D. (2020). Detecting the Effects of Sustained Glacier Wastage on Streamflow in Variably Glacierized Catchments. *Frontiers in Earth Science*, 8. <https://doi.org/10.3389/feart.2020.00136>
- Munir, T. M., & Westbrook, C. J. (2021). Beaver dam analogue configurations influence stream and riparian water table dynamics of a degraded spring-fed creek in the Canadian Rockies. *River Research and Applications*, 37(3), 330–342. <https://doi.org/10.1002/rra.3753>
- Neary, L. K., Remmer, C. R., Krist, J., Wolfe, B. B., & Hall, R. I. (2021). A new lake classification scheme for the Peace-Athabasca Delta (Canada) characterizes hydrological processes that cause lake-level variation. *Journal of Hydrology: Regional Studies*, 38, 100948. <https://doi.org/10.1016/j.ejrh.2021.100948>
- Nguyen, C., Daly, E., & Pauwels, V. R. N. (2021). A dynamic connectivity metric for complex river wetlands. *Journal of Hydrology*, 603, 127163. <https://doi.org/10.1016/j.jhydrol.2021.127163>
- Nummi, P., & Holopainen, S. (2020). Restoring wetland biodiversity using research: Whole-community facilitation by beaver as framework. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 30(9), 1798–1802. <https://doi.org/10.1002/aqc.3341>
- Nummi, P., Liao, W., Huet, O., Scarpulla, E., & Sundell, J. (2019). The beaver facilitates species richness and abundance of terrestrial and semi-aquatic mammals. *Global Ecology and Conservation*, 20, 10. <https://doi.org/10.1016/j.gecco.2019.e00701>
- Park, E., & Latrubesse, E. M. (2017). The hydro-geomorphologic complexity of the lower Amazon River floodplain and hydrological connectivity assessed by remote sensing and field control. *Remote Sensing of Environment*, 198, 321–332. <https://doi.org/10.1016/j.rse.2017.06.021>
- Pederson, G. T., Gray, S. T., Woodhouse, C. A., Betancourt, J. L., Fagre, D. B., Littell, J. S., Watson, E., Luckman, B. H., & Graumlich, L. J. (2011). The Unusual Nature of Recent Snowpack

- Declines in the North American Cordillera. *Science*, 333(6040), 332–335.
<https://doi.org/10.1126/science.1201570>
- Poff, N. L., Olden, J. D., Merritt, D. M., & Pepin, D. M. (2007). Homogenization of Regional River Dynamics by Dams and Global Biodiversity Implications. *Proceedings of the National Academy of Sciences of the United States of America*, 104(14), 5732–5737.
- Pollock, M., Heim, M., & Werner, D. (2003). Hydrologic and Geomorphic Effects of Beaver Dams and Their Influence on Influence on Fishes. In *American Fisheries Society Symposium* (Vol. 2003).
- Rangwala, I., & Miller, J. R. (2012). Climate change in mountains: A review of elevation-dependent warming and its possible causes. *Climatic Change*, 114(3–4), 527–547.
<http://dx.doi.org/10.1007/s10584-012-0419-3>
- Remmer, C. R., Rooney, R., Bayley, S., & Leven, C. (2023). The importance of groundwater to the upper Columbia River floodplain wetlands. *Canadian Water Resources Journal / Revue Canadienne Des Ressources Hydriques*, 0(0), 1–15.
<https://doi.org/10.1080/07011784.2023.2234869>
- Rodrigues, I. S., Hopkinson, C., Chasmer, L., MacDonald, R. J., Bayley, S. E., & Brisco, B. (2024). Multi-decadal floodplain classification and trend analysis in the Upper Columbia River valley, British Columbia. *Hydrology and Earth System Sciences*, 28(10), 2203–2221.
<https://doi.org/10.5194/hess-28-2203-2024>
- Ronnquist, A. L., & Westbrook, C. J. (2021). Beaver dams: How structure, flow state, and landscape setting regulate water storage and release. *Science of The Total Environment*, 785, 12.
<https://doi.org/10.1016/j.scitotenv.2021.147333>
- Rooney, R. C., Carli, C., & Bayley, S. E. (2013). River Connectivity Affects Submerged and Floating Aquatic Vegetation in Floodplain Wetlands. *Wetlands*, 33(6), 1165–1177.
<https://doi.org/10.1007/s13157-013-0471-4>
- Thompson, S., Vehkaoja, M., Pellikka, J., & Nummi, P. (2021). Ecosystem services provided by beavers *Castor* spp. *Mammal Review*, 51(1), 25–39. <https://doi.org/10.1111/mam.12220>
- Tockner, K., Malard, F., & Ward, J. V. (2000). An extension of the flood pulse concept. *Hydrological Processes*, 14(16–17), 2861–2883. [https://doi.org/10.1002/1099-1085\(200011/12\)14:16/17<2861::AID-HYP124>3.0.CO;2-F](https://doi.org/10.1002/1099-1085(200011/12)14:16/17<2861::AID-HYP124>3.0.CO;2-F)
- Upton, G., & Cook, I. (2014). principal components analysis. In *A Dictionary of Statistics*. : Oxford University Press. Retrieved 17 Jul. 2024, from <https://www-oxfordreference-com.proxy.lib.uwaterloo.ca/view/10.1093/acref/9780199679188.001.0001/acref-9780199679188-e-1289>.
- Utzig, G. (2021). *The Columbia Wetlands and Climate Disruption: A Preliminary Assessment* (p. 13).
- Weitkamp, L. A. (1994). *A review of the effects of dams on the Columbia River Estuarine environment, with special reference to salmonids* (p. 157) [Report funded by U.S. Department of Energy and Coastal Zone and Northwest Fisheries Science Center].
- Westbrook, C. J., Cooper, D. J., & Baker, B. W. (2006). Beaver dams and overbank floods influence groundwater–surface water interactions of a Rocky Mountain riparian area. *Water Resources Research*, 42(6). <https://doi.org/10.1029/2005WR004560>

Willby, N. J., Law, A., Levanoni, O., Foster, G., & Ecke, F. (2018). Rewilding wetlands: Beaver as agents of within-habitat heterogeneity and the responses of contrasting biota. *Philosophical Transactions: Biological Sciences*, 373(1761), 1–8.

Wohl, E. (2013). Landscape-scale carbon storage associated with beaver dams. *Geophysical Research Letters*, 40(14), 3631–3636. <https://doi.org/10.1002/grl.50710>

Zimmerman, E. (2004). *Columbia Wetlands Ramsar Information Sheet* (p. 19). The East Kootenay Environmental Society.

Appendix A

Site List

List of sites, with easting and northing, wetland area, wetland perimeter, and wetland group in all three study years as well as Dominant Group (the group a wetland was placed in for 2 of 3 years).

Site	Easting	Northing	Wetland Area (km ²)	Wetland Perimeter (m)	2020 Wetland Group	2021 Wetland Group	2022 Wetland Group	Dominant Group
21	532535	5652873	0.49	3734	4 - Least Connected	3 - Least Connected	3 - Partially Connected - Smaller Gaps	Least Connected
24	535422	5651111	0.46	4721	1 - Most Connected	1 - Most Connected	1 - Most Connected	1 - Most Connected
29	543167	5641399	0.08	2054	ND	1 - Most Connected	1 - Most Connected	1 - Most Connected
30	544030	5639666	1.11	5653	1 - Most Connected	1 - Most Connected	1 - Most Connected	1 - Most Connected
31	545913	5637403	0.4	4021	2 - Partially Connected - Bigger Gaps	3 - Least Connected	2 - Partially Connected - Bigger Gaps	Partially Connected
32	545543	5637069	1.35	7600	1 - Most Connected	1 - Most Connected	1 - Most Connected	1 - Most Connected
35	550776	5630949	0.16	2030	2 - Partially Connected - Bigger Gaps	3 - Least Connected	4 - Least Connected	Least Connected
36	551130	5630189	2.07	10029	2 - Partially Connected - Bigger Gaps	1 - Most Connected	2 - Partially Connected - Bigger Gaps	Partially Connected
38	549892	5630542	0.54	4225	4 - Least Connected	3 - Least Connected	2 - Partially Connected - Bigger Gaps	Least Connected
39	550531	5628689	0.12	2302	2 - Partially Connected - Bigger Gaps	Partially Connected	3 - Partially Connected - Smaller Gaps	Partially Connected
43	555476	5623684	0.75	6081	2 - Partially Connected - Bigger Gaps	3 - Least Connected	3 - Partially Connected - Smaller Gaps	Partially Connected
47	563287	5612893	0.78	4933	4 - Least Connected	3 - Least Connected	4 - Least Connected	Least Connected
48	562874	5612685	0.53	4950	3 - Partially Connected - Smaller Gaps	Partially Connected	ND	Partially Connected

Site	Easting	Northing	Wetland Area (km ²)	Wetland Perimeter (m)	2020 Wetland Group	2021 Wetland Group	2022 Wetland Group	Dominant Group
49	563443	5608264	0.61	4358	4 - Least Connected	3 - Least Connected	4 - Least Connected	Least Connected
51	567072	5601686	2.26	10167	3 - Partially Connected - Smaller Gaps	Partially Connected	2 - Partially Connected - Bigger Gaps	Partially Connected
59	543772	5638706	0.56	3547	1 - Most Connected	1 - Most Connected	1 - Most Connected	1 - Most Connected
62	544859	5639039	0.55	4075	3 - Partially Connected - Smaller Gaps	3 - Least Connected	3 - Partially Connected - Smaller Gaps	Partially Connected
64	546804	5635861	0.13	1654	1 - Most Connected	1 - Most Connected	1 - Most Connected	1 - Most Connected
68	545273	5635944	0.14	2431	1 - Most Connected	1 - Most Connected	1 - Most Connected	1 - Most Connected
69	544325	5639373	1.35	6495	4 - Least Connected	3 - Least Connected	2 - Partially Connected - Bigger Gaps	Least Connected
70	551389	5627697	0.12	1655	2 - Partially Connected - Bigger Gaps	1 - Most Connected	1 - Most Connected	1 - Most Connected
71	550149	5630945	3.27	11962	2 - Partially Connected - Bigger Gaps	1 - Most Connected	2 - Partially Connected - Bigger Gaps	Partially Connected
110	542996	5638520	0.22	2446	3 - Partially Connected - Smaller Gaps	Partially Connected	3 - Partially Connected - Smaller Gaps	Partially Connected
126	549517	5631250	0.04	1157	2 - Partially Connected - Bigger Gaps	Partially Connected	4 - Least Connected	Partially Connected
127	549090	5631267	0.19	2721	4 - Least Connected	3 - Least Connected	2 - Partially Connected - Bigger Gaps	Least Connected
128	548571	5631699	0.13	2589	2 - Partially Connected - Bigger Gaps	Partially Connected	3 - Partially Connected - Smaller Gaps	Partially Connected
129	528755	5654469	0.12	1767	4 - Least Connected	Partially Connected	3 - Partially Connected - Smaller Gaps	Partially Connected

Site	Easting	Northing	Wetland Area (km ²)	Wetland Perimeter (m)	2020 Wetland Group	2021 Wetland Group	2022 Wetland Group	Dominant Group
130	528565	5654310	0.32	4429	2 - Partially Connected - Bigger Gaps	1 - Most Connected	1 - Most Connected	1 - Most Connected
131	528247	5655396	2.72	12695	4 - Least Connected	3 - Least Connected	2 - Partially Connected - Bigger Gaps	Least Connected
132	533588	5652117	0.29	2903	1 - Most Connected	1 - Most Connected	1 - Most Connected	1 - Most Connected
137	550568	5629167	0.75	4883	3 - Partially Connected - Smaller Gaps	Partially Connected	3 - Partially Connected - Smaller Gaps	Partially Connected
140	543498	5641456	0.17	1698	ND	Partially Connected	ND	NA
141	540750	5645785	0.17	2257	ND	Partially Connected	3 - Partially Connected - Smaller Gaps	Partially Connected
142	536898	5649710	0.24	3479	ND	3 - Least Connected	3 - Partially Connected - Smaller Gaps	NA
143	531008	5653564	0.13	1911	ND	3 - Least Connected	3 - Partially Connected - Smaller Gaps	NA
144	523973	5657202	0.49	3734	ND	3 - Least Connected	2 - Partially Connected - Bigger Gaps	NA
145	523706	5657294	0.46	4721	ND	1 - Most Connected	1 - Most Connected	1 - Most Connected

Appendix B

Preliminary levee gaps identified from orthophotos, satellite imagery, LiDAR imagery, and digital elevation models.

Site	Length (m)	Easting	Northing	Flow Type	Wetland	Flow
71	6.141517	533161.2565	5652049.257	Creek	21	Partial
15	24.893359	534921.5953	5651029.603	River	24	Yes
16	25.458515	535083.1347	5650985.545	River	24	Yes
17	6.376966	536163.5906	5650166.597	River	24	Yes
24	6.901693	535748.6244	5650446.176	River	24	Yes
25	9.590938	535778.3825	5650426.466	River	24	Yes
26	7.612752	535843.7784	5650368.078	River	24	Yes
27	2.548828	536219.5641	5650128.851	River	24	Yes
60	35.005776	536553.798	5649934.089	Between	24	Partial
29	5.92368	543007.8592	5639809.519	Creek	30	Partial

Site	Length (m)	Easting	Northing	Flow Type	Wetland	Flow
55	25.460025	544233.2534	5639644.455	River	30	Yes
31	6.712468	545243.1177	5637345.398	River	31	Yes
30	22.286735	545364.125	5637022.36	River	32	Yes
65	90.932422	546563.0816	5634839.68	Between	32	Yes
66	11.090475	545807.7941	5636503.909	Between	32	Yes
67	10.915157	545886.1436	5636462.485	Between	32	Yes
53	13.81519	550362.9299	5631117.131	Between	35	Partial
40	6.372885	550496.387	5628803.98	River	36	Partial
44	9.932595	552486.9529	5627571.369	River	36	Partial
45	13.764772	552882.7755	5627313.8	River	36	Partial
46	9.175271	550792.1145	5629304.904	River	36	No
68	3.448838	550938.0983	5629906.766	River	36	Yes
38	6.180095	550328.1779	5630502.364	River	38	Partial
39	5.682428	550426.4626	5629776.155	River	38	Partial
43	10.395809	550941.2605	5630123.205	River	43	Yes
47	8.422075	555290.5646	5623790.791	Between	43	Partial
74	12.408544	555846.0435	5622058.364	River	43	Yes
48	5.038287	564090.6818	5609438.731	River	49	Partial
49	15.135733	566874.8332	5603116.979	River	51	Yes
50	11.169073	567431.2574	5601792.353	River	51	Yes
51	9.42228	566951.0646	5601236.576	Between	51	Partial
52	17.65629	566628.6165	5601069.848	Between	51	Partial
56	14.508731	544030.7112	5638909.891	River	59	Yes
61	18.565673	543815.6679	5638138.925	Between	59	No
62	9.017384	543940.6325	5638161.662	Between	59	No
57	9.321968	544283.8698	5638429.969	River	62	No
63	19.773274	544647.267	5639259.107	River	62	No
64	25.447703	544727.0034	5637161.61	Between	63	Partial
34	4.95868	546774.903	5635830.832	River	64	Partial
32	32.859154	545496.9046	5636754.946	River	68	Yes
33	24.892575	545622.712	5634678.128	Between	68	Partial
73	30.805878	545434.7426	5636060.411	River	68	Yes
22	8.435164	544508.4034	5639453.13	River	69	No
41	13.579639	551086.4541	5628003.038	River	70	Yes
42	15.196324	553932.9556	5624641.712	Between	70	Partial
36	3.19426	550147.9652	5631070.201	River	71	Yes
37	1.699973	550166.2158	5631075.159	Partial	71	Partial
35	4.966876	549376.9647	5631479.321	River	127	Partial
70	66.068981	528665.9996	5654545.691	Creek	129	Yes

Site	Length (m)	Easting	Northing	Flow Type	Wetland	Flow
2	10.272638	527262.3422	5655875.896	River	130	Yes
3	3.195472	527616.9515	5655757.668	River	130	Partial
4	4.431353	527674.8569	5655710.678	River	130	Partial
5	11.556243	527814.753	5655586.71	River	130	Partial
8	10.122296	531115.3832	5652772.752	River	130	Partial
9	12.429047	529844.7854	5653178.558	River	130	Partial
10	26.648345	529539.1244	5653655.251	River	130	Yes
23	10.111973	529186.4756	5653585.359	River	130	Yes
69	14.077658	528631.501	5654545.482	Creek	130	Yes
7	9.093137	528604.1391	5654472.792	Between	130	Partial
11	8.191307	528703.558	5654367.217	Between	130	Partial
6	2.510863	528325.2174	5654688.984	Between	130	Partial
59	6.942217	528473.9195	5654653.568	Between	130	Partial
12	9.707181	531033.2481	5653404.33	Between	130	Partial
58	18.746356	527837.3383	5655567.668	River	131	Partial
13	24.523959	533369.6824	5651651.661	River	132	Yes
14	8.567115	533162.634	5652045.141	Creek	132	Partial
54	3.363489	533069.5823	5651968.738	River	132	Yes
20	13.946944	543150.5186	5641657.533	River	140	Partial
21	14.440718	543647.7704	5640911.673	River	140	Partial
28	6.947139	543589.7137	5640935.59	River	140	No
19	10.277599	540555.085	5645966.617	River	141	Partial
72	16.271294	541065.888	5644627.837	River	141	Partial
18	23.926546	536517.5835	5649725.708	River	142	Partial
0	10.579563	523410.1608	5657727.71	None	145	No
1	10.782324	523617.572	5657580.718	River	145	Yes

Appendix C

Preliminary beaver dams and lengths identified from orthophotos, satellite imagery, LiDAR imagery, and digital elevation models.

Dam Number	Dam Length (m)	Easting	Northing	Associated Site
20	20.8219584	531883.763	5652677.912	21
21	11.39934415	531978.9127	5652660.135	21
22	20.31248109	532851.3925	5652160.366	21
27	33.19528593	536501.8172	5649965.472	24
174	33.66709333	536554.0442	5649934.658	24
176	17.02980097	543189.4583	5641619.852	29
178	14.92235967	543196.4549	5641518.565	29
180	9.276479187	543287.2168	5641269.487	29
48	11.15434956	543873.456	5639170.111	30
49	10.40400206	543690.7206	5639187.546	30
50	16.81915898	543164.106	5639339.055	30
51	8.015539931	543074.206	5639329.597	30
52	5.89055246	543217.3644	5639535.729	30
53	13.00617205	543243.6689	5639551.691	30
54	9.107756952	543266.6029	5639551.674	30
61	12.14082268	543667.3552	5639023.156	30
62	11.03226342	543525.3371	5638998.476	30
63	6.86692438	543442.8365	5639017.687	30
64	10.42536672	543366.6392	5639014.366	30
116	5.686822136	543773.9585	5639012.369	30
121	8.512432109	543199.7454	5638928.689	30
77	4.81703026	550898.9843	5629291.457	36
78	54.51498142	551344.1479	5629675.399	36
102	65.77696483	551281.9703	5628600.907	36
103	43.67775788	551259.5096	5628663.639	36
104	19.41177395	551281.0703	5628651.242	36
141	6.6073602	551082.6947	5630128.154	36
142	5.993427486	551020.0212	5630143	36
75	7.924097346	550321.1071	5630444.188	38
76	7.417059888	550382.5851	5629757.37	38
86	36.78732812	555312.0122	5623770.693	43
87	14.54871336	555362.2538	5623790.679	43
88	16.71290972	555447.464	5623861.632	43
89	11.64297555	554923.2589	5623014.049	43
90	11.33253435	555557.9768	5622395.689	43
91	7.848812175	555639.9451	5622188.972	43
92	8.529403068	555684.0803	5622196.326	43

Dam Number	Dam Length (m)	Easting	Northing	Associated Site
93	9.358097658	555694.3948	5622159.458	43
94	15.88105345	567469.8721	5602066.744	51
95	11.09950639	567407.2258	5602415.197	51
96	2.894392402	567127.1647	5603019.04	51
97	4.098537607	567116.4702	5603032.042	51
98	6.414713671	567105.6035	5603039.289	51
99	3.468287799	567079.4919	5603049.383	51
100	3.183615736	567053.3735	5603043.13	51
101	2.413332695	567038.4292	5603035.78	51
60	23.63264852	544045.1273	5638933.77	59
65	5.989028575	543244.3873	5638768.674	59
66	57.51260437	543219.1668	5638345.196	59
68	40.1929364	543434.6751	5638342.349	59
69	44.4268921	543990.5852	5638152.667	59
114	14.21757911	543966.5013	5638575.959	59
115	10.76350855	544029.4582	5638661.38	59
117	15.28150443	544030.4311	5638683.173	59
118	12.48353632	544033.6107	5638712.062	59
119	12.71246471	544037.2764	5638737.524	59
120	16.70067332	544060.2815	5638853.157	59
122	8.512432109	543199.7454	5638928.689	59
153	15.86880136	543214.4561	5638358.738	59
154	3.678419304	543925.4048	5638181.04	59
155	21.75688029	543832.4946	5638157.112	59
184	57.51260437	543219.1668	5638345.196	59
188	228.0726982	543119.9831	5638566.982	59
204	15.86880136	543214.4561	5638358.738	59
182	17.21511562	544648.1146	5639260.023	62
190	27.24707926	544687.3913	5639144.577	62
192	10.747736	544355.0377	5638693.968	62
194	11.59548056	544631.993	5639044.945	62
196	6.19959464	544657.8396	5639068.016	62
70	24.87238694	544728.1912	5637160.225	63
71	5.289120051	544702.1047	5636965.053	63
72	6.894809305	544885.8892	5636806.865	63
124	14.0621532	544594.2665	5637403.192	63
125	8.787594013	544542.9251	5637385.145	63
126	46.71025985	544375.4659	5637396.877	63
127	38.01554249	544384.0746	5637349.99	63
128	53.48549909	544379.8144	5637282.288	63
129	26.60420881	544227.0492	5637125.653	63

Dam Number	Dam Length (m)	Easting	Northing	Associated Site
130	15.61112965	544099.6712	5637044.168	63
131	34.0255288	544508.612	5636869.505	63
132	38.50734726	544552.9115	5636899.399	63
133	11.26289945	544578.4121	5636968.023	63
134	10.08308518	544592.924	5636914.852	63
135	22.12927304	544589.1667	5637036.304	63
136	38.18154177	544599.1273	5637259.571	63
137	24.98998627	544414.9181	5637468.998	63
138	14.57267652	544570.2991	5637539.647	63
139	14.24518645	544583.5215	5637546.482	63
140	4.473474703	546779.6422	5635830.403	64
73	6.340880715	544909.851	5635599.701	68
55	16.97718033	544519.2008	5639457.443	69
56	10.90865858	544499.9303	5639445.723	69
57	12.20493873	544560.4434	5639394.434	69
58	12.95008525	544568.8819	5639380.114	69
59	14.14523678	544606.6882	5639315.849	69
123	7.832788083	544282.0306	5638428.913	69
183	17.21511562	544648.1146	5639260.023	69
191	27.24707926	544687.3913	5639144.577	69
193	10.747736	544355.0377	5638693.968	69
195	11.59548056	544631.993	5639044.945	69
197	6.19959464	544657.8396	5639068.016	69
79	13.99893496	551584.4135	5627175.14	70
80	22.48690522	552638.8535	5626629.738	70
81	53.95107034	552539.646	5626463.067	70
82	11.47830653	553316.3602	5625483.918	70
83	12.48836419	553782.5229	5624999.733	70
84	13.54537929	553926.9103	5624745.101	70
85	15.74406838	553934.473	5624698.005	70
74	3.330902528	550146.6603	5631065.013	71
67	57.51260437	543219.1668	5638345.196	110
109	20.47997569	543152.4891	5638343.28	110
110	17.56620542	543122.8712	5638370.972	110
111	228.0726982	543119.9831	5638566.982	110
185	57.51260437	543219.1668	5638345.196	110
189	228.0726982	543119.9831	5638566.982	110
205	15.86880136	543214.4561	5638358.738	110
112	24.87036762	548769.4795	5631059.356	127
168	12.83011272	529487.6035	5654136.267	129
198	43.78199591	528884.9565	5654251.95	129

Dam Number	Dam Length (m)	Easting	Northing	Associated Site
200	8.738730114	528702.7816	5654348.923	129
5	10.10116967	527884.3246	5654915.972	130
9	28.65643836	528666.2969	5654121.042	130
14	23.57765208	529766.6774	5653296.042	130
15	15.7996017	529789.3579	5653245.808	130
16	26.28240642	529807.5457	5653215.552	130
17	4.572128889	529855.9868	5653182.994	130
18	15.33885402	529847.8522	5653153.562	130
143	8.738730114	528702.7816	5654348.923	130
158	15.90090027	527741.5506	5655680.16	130
160	18.67018682	527781.3418	5655648.374	130
162	18.74633477	527837.3383	5655567.668	130
164	251.3677277	527912.9961	5655487.06	130
166	21.1253051	528267.4843	5654710.863	130
169	12.83011272	529487.6035	5654136.267	130
170	9.150838712	530389.5757	5653779.563	130
172	23.7791923	530992.0868	5653454.664	130
186	12.00875519	530479.7264	5653715.657	130
199	43.78199591	528884.9565	5654251.95	130
201	8.738730114	528702.7816	5654348.923	130
202	6.586676318	527724.1915	5655697.445	130
4	251.3677277	527912.9961	5655487.06	131
6	14.9139232	528440.1466	5654698.844	131
7	20.32910335	528468.0097	5654676.731	131
8	4.818749721	528568.8012	5654610.742	131
159	15.90090027	527741.5506	5655680.16	131
161	18.67018682	527781.3418	5655648.374	131
163	18.74633477	527837.3383	5655567.668	131
165	251.3677277	527912.9961	5655487.06	131
167	21.1253051	528267.4843	5654710.863	131
203	6.586676318	527724.1915	5655697.445	131
23	5.313056809	533125.585	5652019.866	132
24	17.13777724	533274.031	5651746.406	132
25	24.01796335	533354.626	5651649.852	132
26	28.16099841	533449.8432	5651388.251	132
106	215.6242279	533946.5331	5651342.992	132
107	175.773267	533995.5524	5651297.784	132
145	57.35882699	533945.8429	5651443.138	132
146	17.19993713	533206.9348	5651792.798	132
147	49.5387546	533360.7547	5651627.191	132
148	33.28321147	533493.9661	5651330.871	132

Dam Number	Dam Length (m)	Easting	Northing	Associated Site
43	12.70015057	543034.1416	5641994.525	140
44	17.02980097	543189.4583	5641619.852	140
45	14.92235967	543196.4549	5641518.565	140
46	9.276479187	543287.2168	5641269.487	140
47	16.65995123	543625.8396	5641015.326	140
177	17.02980097	543189.4583	5641619.852	140
179	14.92235967	543196.4549	5641518.565	140
181	9.276479187	543287.2168	5641269.487	140
33	16.31483538	540533.3744	5645922.75	141
34	3.39630924	540601.6183	5645961.002	141
35	2.0494965	540639.7599	5645933.78	141
36	27.55144629	540577.2071	5645591.607	141
37	16.69144489	540594.1131	5645549.42	141
38	10.16396624	540769.9248	5644896.073	141
39	26.79618316	540819.0963	5644890.378	141
40	97.34567222	540846.2159	5644812.51	141
41	40.70090355	540987.2972	5644724.055	141
42	42.43482589	541085.2463	5644652.003	141
108	3.425558988	540949.4942	5644698.483	141
113	24.60953576	541186.1162	5644590.285	141
151	3.583882357	541073.2268	5644645.278	141
152	8.236681881	540555.1939	5645967.634	141
28	12.64490827	536694.6906	5649848.495	142
29	15.96209287	536730.5913	5649820.146	142
30	7.311350338	536625.7875	5649711.798	142
31	14.61444303	536705.5768	5649668.956	142
32	19.31345963	536787.3652	5649665.789	142
149	8.683565062	536963.1865	5649259.246	142
150	1.828127316	536940.5027	5649246.233	142
175	33.66709333	536554.0442	5649934.658	142
10	9.150838712	530389.5757	5653779.563	143
11	17.9190107	530518.4906	5653638.865	143
12	48.75530072	530858.7329	5653628.088	143
13	23.7791923	530992.0868	5653454.664	143
19	15.75591314	531736.763	5652778.99	143
105	12.00875519	530479.7264	5653715.657	143
144	10.51319622	531411.3112	5652956.871	143
171	9.150838712	530389.5757	5653779.563	143
173	23.7791923	530992.0868	5653454.664	143
187	12.00875519	530479.7264	5653715.657	143
156	33.92988671	523785.8263	5657232.937	144

Dam Number	Dam Length (m)	Easting	Northing	Associated Site
1	63.44243087	523415.3662	5657702.465	145
2	6.224595358	523599.3211	5657564.161	145
3	45.85672316	523270.1802	5657780.721	145
157	33.92988671	523785.8263	5657232.937	145

Appendix D Levee gap and beaver dam metrics of those features directly influencing study sites measured in the field. Appendix E explains metrics.

Wetland	Perimeter	Area	NoGap	GapW	GapD	PerGap	NoDam	DamL	PerDam	GapDepth	PerGap PerDam	GapStat	DamStat	DamHW	Levee	Water	GapV
43	6080.64	0.75	1	10.8	0.7	0.18	1	64.13	1.05	-0.65	-0.88	Dammed	Active	Yes	796.94	797.59	-7.02
21	3733.51	0.49	1	17.2	0.85	0.46	1	211.18	5.66	-0.65	-5.20	Dammed	Active	Yes	798.98	799.63	-11.18
129	4428.91	0.32	2	22.45	1.14	0.51	2	257.25	5.81	-0.49	-5.30	Dammed	Active	Yes	799.55	800.04	-11.00
110	1157.18	0.04	1	31.6	1.03	2.73	1	41.50	3.59	-0.25	-0.86	Dammed	Active	Yes	799.40	799.65	-7.90
132	4882.55	0.75	2	25.3	1.2	0.52	1	2.15	0.04	-0.22	0.47	Open	Old	Partly	798.20	798.42	-5.57
35	2030.47	0.16	1	23.5	0.57	1.16	1	19.00	0.94	-0.18	0.22	Dammed	Active	Yes	797.21	797.39	-4.23
141	3478.63	0.24	3	18.18	1.29	0.52	3	23.24	0.67	-0.16	-0.15	Dammed	Active	Partly	798.54	798.70	-2.85
126	2721.2	0.19	0	0	0	0.00	0	0.00	0.00	0.00	0.00	None	Levee	Levee	797.10	797.10	0.00
48	4950.26	0.53	0	0	0	0.00	0	0.00	0.00	0.00	0.00	None	Levee	Levee	796.00	796.00	0.00
137	1698.16	0.17	0	0	0	0.00	0	0.00	0.00	0.00	0.00	None	Levee	Levee	796.71	796.71	0.00
47	4932.59	0.78	0	0	0	0.00	0	0.00	0.00	0.00	0.00	None	Levee	Levee	796.97	796.97	0.00
127	2589.05	0.13	0	0	0	0.00	0	0.00	0.00	0.00	0.00	None	Levee	Levee	797.02	797.02	0.00
29	2053.61	0.08	0	0	0	0.00	0	0.00	0.00	0.00	0.00	None	Levee	Levee	797.75	797.75	0.00
63	1653.56	0.13	0	0	0	0.00	0	0.00	0.00	0.00	0.00	None	Levee	Levee	797.40	797.40	0.00
69	1655.1	0.12	2	29.5	1.035	1.78	2	54.30	3.28	0.00	-1.50	Dammed	Active	Yes	797.49	797.49	0.00
144	2352.94	0.19	1	57.3	0.92	2.44	1	57.30	2.44	0.00	0.00	Dammed	Old	Yes	798.87	798.87	0.00
143	2220.6	0.08	0	0	0	0.00	0	111.00	5.00	0.00	-5.00	Dammed	Active	Yes	799.50	799.50	0.00
131	2902.72	0.29	1	18.65	0.91	0.64	1	166.24	5.73	0.00	-5.08	Dammed	Active	Yes	799.31	799.31	0.00
49	4357.68	0.61	1	116	1.37	2.66	1	232.00	5.32	0.00	-2.66	Dammed	Active	Yes	796.28	796.28	0.00
62	4074.77	0.55	1	36.84	1.51	0.90	1	36.84	0.90	0.01	0.00	Dammed	Active	Yes	797.78	797.77	0.37
128	1767.28	0.12	1	1.1	0.74	0.06	1	2.10	0.12	0.03	-0.06	Dammed	Active	Partly	797.11	797.08	0.03
142	3619.67	0.39	2	5.95	0.64	0.16	2	4.23	0.12	0.14	0.05	Dammed	Old	Yes	798.03	797.89	0.83
39	2302.09	0.12	1	2.8	1	0.12	1	1.70	0.07	0.20	0.05	Dammed	Active	Yes	797.02	796.82	0.56
24	4720.58	0.46	2	17.9	2.68	0.38	1	3.50	0.07	0.33	0.31	Open	Old	Partly	797.78	797.45	5.91

71	2445.7	0.22	1	5.6	1.1	0.23	1	1.70	0.07	0.47	0.16	Dammed	Active	Partly	796.99	796.52	2.63
140	2256.5	0.17	2	39.59	1.475	1.75	2	45.29	2.01	0.56	-0.25	Dammed	Active	Yes	798.31	797.75	22.17
32	7600.45	1.35	2	50	1	0.66	0	0.00	0.00	1.00	0.66	Open	None	No	797.38	796.38	50.00
59	3546.51	0.56	2	31.4	1.09	0.89	1	18.70	0.53	1.09	0.36	Open	Old	Partly	798.61	797.52	34.23
36	10029.26	2.07	3	19.94	1.2	0.20	0	0.00	0.00	1.20	0.20	Open	None	No	797.15	795.95	23.93
51	10166.99	2.26	1	10.31	1.2	0.10	0	0.00	0.00	1.20	0.10	Open	None	No	797.77	796.57	12.37
30	5652.57	1.11	1	28.5	1.3	0.50	0	0.00	0.00	1.30	0.50	Open	None	No	797.60	796.30	37.05
31	4021.09	0.4	1	7.04	1.35	0.18	0	0.00	0.00	1.35	0.18	Open	Old	No	797.37	796.02	9.50
145	1910.78	0.13	1	10.5	1.35	0.55	0	0.00	0.00	1.35	0.55	Open	None	No	798.96	797.61	14.18
64	2431.48	0.14	1	2.2	1.4	0.09	0	0.00	0.00	1.40	0.09	Open	None	No	797.26	795.86	3.08
130	12695.03	2.72	4	88.33	1.4	0.70	0	0.00	0.00	1.40	0.70	Open	None	No	798.01	796.61	123.66
38	4225.03	0.54	1	5	2.8	0.12	1	6.10	0.14	1.70	-0.03	Dammed	Active	Yes	797.36	795.66	8.50
68	6495.4	1.35	3	66.98	1.82	1.03	0	0.00	0.00	1.82	1.03	Open	None	No	797.29	795.47	121.90
70	11961.62	3.27	2	43.55	2.05	0.36	0	0.00	0.00	2.05	0.36	Open	None	No	796.85	794.80	89.28

Appendix E

Explanation of variables included in the levee gap and beaver dam metrics.

Variable Name	Spreadsheet Abbreviation	Description	Units
Wetland Perimeter	Perimeter	Total length of wetland perimeter	m
Wetland Area	Area	Total wetland area	Km ²
Number of Gaps	NoGap	Count of number of gaps in the levees	Count
Total Gap Width	GapW	Total width of all gaps (including those with beaver dams across them) in the levees	m
Mean Gap Depth	GapD	Mean depth of open gaps (i.e. not gaps that have beaver dams across them)	m
Gap Percentage	PerGap	Percentage of wetland perimeter that is gap (i.e. (gap length / wetland perimeter)*100)	%
Number of Dams	NoDam	Count of number of dams in the levees	Count
Total Dam Length	DamL	Total length of all dams in the wetland	m
Dam Percentage	PerDam	Percentage of wetland perimeter that is dam (i.e. (dam width / wetland perimeter)*100)	m
Gap Depth Including Dams	GapDepth	Mean depth of all gaps within wetland, including those that have dams in them (i.e. gaps with dams will be less deep than gaps without dams; in this case gap depth would be the distance from the top of the levee to the top of the dam)	%
Difference Between Gap Percentage and Dam Percentage	PerGapPerDam	Percentage of wetland perimeter that is gap minus percentage of wetland perimeter that is dam (i.e. Gap percentage – dam percentage)	%
Gap Status	GapStat	Assessment of whether the wetlands gaps are Open (gaps present, no dams), Dammed (gaps are present but beaver dams have been built), or None (no gaps are present). If a wetland had one open gap and one dammed gap it was characterized as Open.	Categorical
Dam Status	DamStat	Assessment of dam status and activity, whether dams were Active (signs of beaver activity such as fresh mud or sticks observed), Old (no such signs were seen), None (no dams present), or Levee (no gaps present).	Categorical
Are Dams Holding Water?	DamHW	Yes, No, or Partly	Categorical
Levee Elevation	Levee	Estimated lowest levee elevation along the wetland perimeter	m above sea level

Elevation At Which Water Enters Wetland	Water	Estimated elevation at which water can enter the wetland, i.e. the levee elevation for wetlands without gaps, and the levee elevation minus Gap Depth Including Dams for wetlands with gaps	m above sea level
Gap volume	GapV	Gap Depth Including Dams multiplied by Gap Width to give an estimate of gap volume, i.e. how much water can enter the wetland through the gaps. For wetlands without gaps, this is 0.	m ³

Appendix F

Hydrograph attributes for all wetlands from 2020, 2021, and 2022. Appendix G and H explain these variables. Data are presented in two tables due to number of variables.

Site	Year	Mean Depth (m)	Initial Depth (m)	Final Depth (m)	Max Depth (m)	Min Depth (m)	Change (m)	Early Peak Depth (m)	Day deepest	Day shallowest	Depth 2 weeks after deepest date	Depth 4 weeks after deepest date	Day 2 weeks	Day 4 weeks
21	2020	1.62	1.64	1.59	2.13	1.52	0.61	1.65	180	243	1.63	1.58	194.00	208.00
24	2020	1.37	0.53	0.12	2.82	0.11	2.72	2.09	180	278	2.17	2.01	194.00	208.00
30	2020	1.11	0.41	0.25	2.48	0.24	2.24	1.67	180	280	1.77	1.57	194.00	208.00
31	2020	1.51	1.19	1.21	2.59	1.18	1.41	1.79	180	141	1.82	1.65	194.00	208.00
32	2020	1.41	0.70	0.49	2.77	0.49	2.28	2.01	180	280	2.02	1.87	194.00	208.00
35	2020	1.52	1.50	1.12	2.30	1.12	1.18	1.81	181	280	1.80	1.69	195.00	209.00
36	2020	1.41	0.80	0.79	2.57	0.77	1.80	1.89	181	267	1.88	1.76	195.00	209.00
38	2020	2.24	1.66	1.84	3.17	1.65	1.52	2.66	181	149	2.64	2.58	195.00	209.00
39	2020	0.92	0.68	0.64	1.69	0.64	1.05	1.12	181	280	1.11	1.02	195.00	209.00
43	2020	1.37	1.00	1.12	2.13	0.98	1.15	1.54	181	151	1.54	1.43	195.00	209.00
47	2020	2.15	1.65	2.02	2.91	1.62	1.30	1.85	180	151	2.45	2.37	194.00	208.00
48	2020	1.02	0.41	0.94	1.79	0.39	1.40	0.53	180	151	1.39	1.31	194.00	208.00
49	2020	2.01	1.82	1.95	2.38	1.81	0.57	1.97	180	140	2.07	2.07	194.00	208.00
51	2020	0.96	0.42	0.44	1.93	0.42	1.51	1.31	179	141	1.32	1.27	193.00	207.00
59	2020	0.80	0.00	0.00	2.28	0.00	2.28	1.34	180	270	1.43	1.23	194.00	208.00
62	2020	1.20	0.80	1.05	1.90	0.78	1.13	0.91	180	141	1.41	1.38	194.00	208.00
64	2020	1.14	0.43	0.42	2.28	0.42	1.87	1.68	180	280	1.68	1.59	194.00	208.00
69	2020	1.40	0.97	1.27	2.27	0.94	1.33	1.15	180	151	1.60	1.52	194.00	208.00
68	2020	1.23	0.36	0.18	2.57	0.17	2.39	1.84	180	280	1.88	1.73	194.00	208.00
70	2020	1.18	0.30	0.28	2.36	0.27	2.09	1.76	181	280	1.76	1.61	195.00	209.00
71	2020	1.76	1.10	1.17	2.76	1.10	1.66	2.20	181	141	2.22	2.10	195.00	209.00

Site	Year	Mean Depth (m)	Initial Depth (m)	Final Depth (m)	Max Depth (m)	Min Depth (m)	Change (m)	Early Peak Depth (m)	Day deepest	Day shallowest	Depth 2 weeks after deepest date	Depth 4 weeks after deepest date	Day 2 weeks	Day 4 weeks
110	2020	0.64	0.44	0.46	1.27	0.41	0.86	0.53	180	150	0.80	0.72	194.00	208.00
126	2020	1.07	0.96	0.81	1.71	0.81	0.90	1.15	181	280	1.27	1.16	195.00	209.00
127	2020	2.19	2.14	2.00	2.78	1.92	0.86	2.28	181	263	2.40	2.26	195.00	209.00
128	2020	0.75	0.70	0.53	1.26	0.47	0.79	0.86	181	255	0.98	0.85	195.00	209.00
129	2020	1.21	1.22	1.07	1.89	1.06	0.83	1.23	181	261	1.27	1.16	195.00	209.00
130	2020	1.13	0.55	0.51	2.33	0.49	1.83	1.63	181	253	1.72	1.55	195.00	209.00
131	2020	1.79	1.35	1.65	2.64	1.34	1.30	1.95	181	140	2.03	1.87	195.00	209.00
132	2020	1.41	0.64	0.69	2.67	0.57	2.11	2.00	180	261	2.06	1.95	194.00	208.00
137	2020	0.72	0.19	0.50	1.67	0.17	1.50	0.26	181	151	1.11	1.02	195.00	209.00
Briver	2020	1.95	1.11	0.94	3.13	0.86	2.27	2.58	181	273	2.57	2.40	195.00	209.00
21	2021	1.76	1.75	1.70	2.40	1.59	0.82	1.94	183	207	1.64	1.61	197.00	211.00
24	2021	1.21	0.25	0.15	2.95	0.13	2.82	2.50	183	207	1.96	1.18	197.00	211.00
29	2021	0.97	0.24	0.19	2.29	0.18	2.11	1.76	182	285	1.43	1.19	196.00	210.00
30	2021	1.01	0.02	0.25	2.62	0.01	2.60	2.02	183	135	1.56	0.98	197.00	211.00
31	2021	1.53	1.22	1.24	2.76	1.20	1.56	2.17	183	143	1.69	1.33	197.00	211.00
32	2021	1.32	0.70	0.69	2.88	0.69	2.19	2.33	183	236	1.85	1.23	197.00	211.00
35	2021	1.72	1.57	1.42	2.67	1.41	1.26	2.30	183	278	1.99	1.63	197.00	211.00
36	2021	1.42	0.87	0.90	2.77	0.83	1.94	2.34	183	137	1.91	1.37	197.00	211.00
38	2021	2.10	1.68	1.69	3.24	1.64	1.60	2.90	182	152	2.59	2.03	196.00	210.00
39	2021	1.02	0.76	0.78	1.89	0.71	1.18	1.60	182	154	1.18	0.95	196.00	210.00
43	2021	1.47	1.03	1.26	2.29	0.99	1.30	2.06	183	153	1.56	1.43	197.00	211.00
47	2021	2.18	1.89	1.96	2.96	1.80	1.16	2.59	181	154	2.44	2.23	195.00	209.00
48	2021	1.26	0.78	1.03	1.97	0.70	1.26	1.68	181	154	1.54	1.34	195.00	209.00
49	2021	2.03	1.89	1.94	2.43	1.87	0.56	2.16	181	137	2.07	2.03	195.00	209.00

Site	Year	Mean Depth (m)	Initial Depth (m)	Final Depth (m)	Max Depth (m)	Min Depth (m)	Change (m)	Early Peak Depth (m)	Day deepest	Day shallowest	Depth 2 weeks after deepest date	Depth 4 weeks after deepest date	Day 2 weeks	Day 4 weeks
51	2021	1.26	0.81	0.87	2.41	0.78	1.63	1.99	181	137	1.66	1.28	195.00	209.00
59	2021	0.77	0.04	0.04	2.49	0.03	2.46	1.78	183	135	1.24	0.69	197.00	211.00
62	2021	1.45	1.06	1.29	2.31	1.02	1.29	1.27	183	142	1.64	1.57	197.00	211.00
64	2021	0.98	0.34	0.33	2.38	0.31	2.07	1.93	183	282	1.54	0.95	197.00	211.00
68	2021	1.22	0.29	0.23	2.81	0.23	2.58	2.27	183	287	1.83	1.23	197.00	211.00
69	2021	1.62	1.09	1.43	2.56	1.02	1.54	1.86	183	153	1.66	1.65	197.00	211.00
70	2021	1.20	0.30	0.47	2.51	0.29	2.22	2.25	182	134	1.88	1.24	196.00	210.00
71	2021	1.75	1.12	1.25	2.94	1.10	1.84	2.59	183	137	2.23	1.74	197.00	211.00
110	2021	0.73	0.31	0.56	1.48	0.28	1.20	0.59	183	141	0.90	0.83	197.00	211.00
126	2021	0.77	0.58	0.56	1.53	0.52	1.01	1.10	183	155	0.94	0.75	197.00	211.00
127	2021	2.24	2.09	2.00	3.00	1.99	1.01	2.65	183	287	2.39	2.19	197.00	211.00
128	2021	0.48	0.28	0.24	1.33	0.19	1.14	1.04	183	268	0.77	0.32	197.00	211.00
129	2021	1.06	0.97	0.92	1.90	0.89	1.01	1.42	183	252	1.02	0.93	197.00	211.00
130	2021	1.02	0.47	0.44	2.50	0.42	2.08	2.01	183	285	1.60	0.81	197.00	211.00
131	2021	1.59	1.43	1.40	2.55	1.39	1.17	2.09	183	278	1.65	1.42	197.00	211.00
132	2021	1.25	0.39	0.38	2.86	0.37	2.49	2.38	183	283	1.95	1.19	197.00	211.00
137	2021	0.84	0.22	0.52	1.77	0.16	1.61	1.09	182	156	1.17	1.03	196.00	210.00
140	2021	1.01	0.96	0.87	1.69	0.84	0.85	1.18	182	278	1.07	0.97	196.00	210.00
141	2021	1.10	1.02	0.64	2.08	0.64	1.44	1.76	183	286	1.33	0.94	197.00	211.00
142	2021	1.72	1.45	1.36	2.87	1.35	1.52	2.42	183	287	1.94	1.56	197.00	211.00
143	2021	1.54	1.51	1.51	2.00	1.46	0.54	1.61	183	202	1.49	1.49	197.00	211.00
144	2021	1.46	1.29	1.14	2.64	1.13	1.52	2.04	183	278	1.82	1.24	197.00	211.00
145	2021	0.71	0.18	0.14	2.16	0.12	2.04	1.55	183	247	1.28	0.64	197.00	211.00
21	2022	1.57	1.52	1.48	1.98	1.37	0.61	1.56	187	219	1.83	1.56	201.00	215.00

Site	Year	Mean Depth (m)	Initial Depth (m)	Final Depth (m)	Max Depth (m)	Min Depth (m)	Change (m)	Early Peak Depth (m)	Day deepest	Day shallowest	Depth 2 weeks after deepest date	Depth 4 weeks after deepest date	Day 2 weeks	Day 4 weeks
24	2022	1.36	0.23	0.08	2.80	0.07	2.74	1.50	187	286	2.64	2.21	201.00	215.00
29	2022	1.01	0.00	0.42	1.88	0.00	1.88	0.20	186	152	1.71	1.32	200.00	214.00
30	2022	1.14	0.00	0.21	2.43	0.00	2.43	1.21	186	148	2.28	1.81	200.00	214.00
31	2022	1.91	1.50	1.53	2.85	1.47	1.38	1.52	187	149	2.71	2.15	201.00	215.00
32	2022	1.48	0.69	0.39	2.76	0.39	2.37	1.46	187	290	2.62	2.08	201.00	215.00
35	2022	1.72	1.44	1.32	2.42	1.30	1.12	1.43	197	288	2.11	1.67	211.00	225.00
36	2022	1.59	0.88	1.01	2.66	0.85	1.82	1.31	188	151	2.50	2.03	202.00	216.00
38	2022	2.41	1.81	1.99	3.27	1.76	1.51	1.79	188	155	3.17	2.80	202.00	216.00
39	2022	1.15	0.82	0.83	1.80	0.75	1.05	0.78	188	155	1.69	1.24	202.00	216.00
43	2022	1.60	1.17	1.33	2.23	1.09	1.15	1.12	188	153	2.13	1.67	202.00	216.00
47	2022	2.11	1.77	1.89	2.74	1.67	1.06	1.71	196	155	2.34	2.18	210.00	224.00
49	2022	2.08	1.93	2.02	2.38	1.91	0.48	1.97	196	146	2.13	2.10	210.00	224.00
51	2022	1.61	1.02	1.11	2.50	0.98	1.52	1.44	186	146	2.32	1.86	200.00	214.00
59	2022	0.93	0.00	0.09	2.30	0.00	2.30	0.94	186	148	2.14	1.53	200.00	214.00
62	2022	1.08	0.70	0.87	1.66	0.64	1.03	0.67	186	155	1.48	1.25	200.00	214.00
63	2022	1.66	1.31	1.36	2.32	1.21	1.11	1.36	187	155	2.14	1.80	201.00	215.00
64	2022	1.12	0.34	0.36	2.20	0.31	1.89	0.97	187	148	2.08	1.67	201.00	215.00
68	2022	1.22	0.07	0.14	2.48	0.07	2.42	1.22	187	139	2.34	1.86	201.00	215.00
69	2022	1.95	1.46	1.77	2.65	1.37	1.28	1.40	186	161	2.48	2.07	200.00	214.00
70	2022	1.22	0.28	0.34	2.33	0.24	2.10	0.95	188	148	2.24	1.88	202.00	216.00
71	2022	1.86	1.14	1.25	2.84	1.08	1.76	1.30	188	151	2.70	2.36	202.00	216.00
110	2022	0.64	0.39	0.38	1.22	0.29	0.93	0.33	186	155	1.06	0.80	200.00	214.00
126	2022	1.00	0.81	0.73	1.57	0.71	0.86	0.76	197	290	1.24	0.96	211.00	225.00
127	2022	2.47	2.34	2.17	3.04	2.15	0.89	2.32	188	290	2.95	2.65	202.00	216.00

Site	Year	Mean Depth (m)	Initial Depth (m)	Final Depth (m)	Max Depth (m)	Min Depth (m)	Change (m)	Early Peak Depth (m)	Day deepest	Day shallowest	Depth 2 weeks after deepest date	Depth 4 weeks after deepest date	Day 2 weeks	Day 4 weeks
128	2022	0.51	0.22	0.17	1.15	0.15	1.00	0.21	187	278	1.10	0.89	201.00	215.00
129	2022	1.38	1.27	1.21	1.94	1.19	0.74	1.29	187	288	1.79	1.38	201.00	215.00
130	2022	1.15	0.46	0.43	2.29	0.41	1.88	0.99	187	289	2.16	1.75	201.00	215.00
131	2022	1.79	1.56	1.56	2.47	1.54	0.93	1.58	187	289	2.33	1.93	201.00	215.00
132	2022	1.25	0.26	0.28	2.55	0.21	2.34	1.34	187	144	2.37	2.00	201.00	215.00
137	2022	0.86	0.24	0.54	1.62	0.15	1.47	0.18	188	161	1.50	1.21	202.00	216.00
142	2022	1.46	1.06	1.03	2.33	1.00	1.34	1.02	187	155	2.19	1.74	201.00	215.00
143	2022	1.45	1.42	1.42	1.67	1.38	0.30	1.43	187	212	1.57	1.41	201.00	215.00
144	2022	2.28	2.02	1.84	3.18	1.83	1.35	2.00	187	288	3.05	2.57	201.00	215.00
145	2022	0.82	0.21	0.15	1.92	0.13	1.79	0.56	188	265	1.76	1.32	202.00	216.00
Briver	2022	2.59	1.58	1.46	3.74	1.44	2.30	2.58	188	288	3.64	3.28	NA	NA
141	2022	0.95	0.57	0.51	1.73	0.49	1.25	0.80	187	271	1.61	1.31	201.00	215.00

Site	Year	2 week slope	4 week slope	Slope of rise	Slope of fall	Max Depth - Early Peak	Fall end depth - lowest depth	Final depth - Initial depth	Fall End Depth - Rise Start Depth
21	2020	0.04	0.02	0.06	0.03	0.48	0.03	-0.06	-0.57
24	2020	0.05	0.03	0.06	0.03	0.74	0.08	-0.41	-2.54
30	2020	0.05	0.03	0.05	0.03	0.81	0.08	-0.16	-2.12
31	2020	0.06	0.03	0.05	0.03	0.80	0.10	0.02	-1.30
32	2020	0.05	0.03	0.05	0.03	0.76	0.20	-0.21	-2.06
35	2020	0.04	0.02	0.03	0.02	0.49	0.05	-0.38	-1.10
36	2020	0.05	0.03	0.04	0.03	0.68	0.08	-0.01	-1.68
38	2020	0.04	0.02	0.05	0.03	0.51	0.30	0.18	-1.17
39	2020	0.04	0.02	0.03	0.02	0.57	0.23	-0.04	-0.79

43	2020	0.04	0.02	0.04	0.01	0.58	0.14	0.13	-0.99
47	2020	0.03	0.02	0.04	0.01	1.06	0.39	0.37	-0.88
48	2020	0.03	0.02	0.05	0.01	1.26	0.53	0.53	-0.84
49	2020	0.02	0.01	0.02	0.05	0.41	0.25	0.13	-0.29
51	2020	0.04	0.02	0.04	0.02	0.62	0.07	0.02	-1.37
59	2020	0.06	0.04	0.06	0.03	0.94	0.02	0.00	-2.22
62	2020	0.04	0.02	0.03	0.01	1.00	0.26	0.26	-0.82
64	2020	0.04	0.02	0.05	0.02	0.61	0.06	-0.01	-1.76
69	2020	0.05	0.03	0.05	0.08	1.12	0.68	0.31	-0.61
68	2020	0.05	0.03	0.06	0.02	0.73	0.00	-0.19	-2.38
70	2020	0.04	0.03	0.05	0.02	0.60	0.00	-0.02	-2.05
71	2020	0.04	0.02	0.04	0.02	0.55	0.07	0.07	-1.54
110	2020	0.03	0.02	0.03	0.02	0.74	0.29	0.02	-0.54
126	2020	0.03	0.02	0.03	0.01	0.56	0.00	-0.15	-0.87
127	2020	0.03	0.02	0.02	0.01	0.50	0.26	-0.14	-0.56
128	2020	0.02	0.01	0.02	0.01	0.40	0.04	-0.18	-0.73
129	2020	0.04	0.03	0.07	0.05	0.67	0.18	-0.15	-0.60
130	2020	0.04	0.03	0.04	0.03	0.70	0.07	-0.04	-1.71
131	2020	0.04	0.03	0.04	0.02	0.69	0.25	0.30	-1.02
132	2020	0.04	0.03	0.05	0.03	0.68	0.04	0.05	-2.03
137	2020	0.04	0.02	0.06	0.01	1.41	0.32	0.30	-1.15
Briver	2020	0.04	0.03	0.05	0.03	0.55	0.11	-0.17	-2.13
21	2021	0.05	0.03	0.04	0.05	0.46	0.02	-0.06	-0.73
24	2021	0.07	0.06	0.05	0.04	0.44	0.01	-0.11	-2.77
29	2021	0.06	0.04	0.05	0.02	0.53	0.01	-0.05	-2.06
30	2021	0.08	0.06	0.06	0.04	0.59	0.30	0.23	-2.27
31	2021	0.08	0.05	0.05	0.06	0.59	0.12	0.02	-1.40
32	2021	0.07	0.06	0.05	0.04	0.55	0.00	-0.01	-2.15

35	2021	0.05	0.04	0.04	0.04	0.37	0.23	-0.14	-0.99
36	2021	0.06	0.05	0.04	0.03	0.43	0.14	0.03	-1.77
38	2021	0.05	0.04	0.05	0.03	0.34	0.23	0.01	-1.35
39	2021	0.05	0.03	0.04	0.05	0.29	0.28	0.02	-0.87
43	2021	0.05	0.03	0.04	0.03	0.23	0.42	0.23	-0.87
47	2021	0.04	0.03	0.04	0.03	0.37	0.43	0.07	-0.68
48	2021	0.03	0.02	0.05	0.02	0.29	0.63	0.25	-0.60
49	2021	0.03	0.01	0.05	0.06	0.27	0.21	0.04	-0.30
51	2021	0.05	0.04	0.04	0.02	0.42	0.11	0.06	-1.50
59	2021	0.09	0.06	0.05	0.04	0.71	0.06	0.00	-2.34
62	2021	0.05	0.03	0.05	0.07	1.04	0.64	0.23	-0.63
64	2021	0.06	0.05	0.04	0.03	0.45	0.06	-0.01	-1.99
68	2021	0.07	0.06	0.05	0.02	0.54	0.02	-0.06	-2.54
69	2021	0.06	0.03	0.05	0.07	0.70	0.64	0.34	-0.85
70	2021	0.04	0.05	0.05	0.02	0.25	0.25	0.17	-1.92
71	2021	0.05	0.04	0.04	0.02	0.35	0.23	0.13	-1.58
110	2021	0.04	0.02	0.03	0.02	0.89	0.51	0.26	-0.67
126	2021	0.02	0.03	0.04	0.03	0.43	0.22	-0.02	-0.77
127	2021	0.04	0.03	0.04	0.04	0.35	0.31	-0.09	-0.66
128	2021	0.04	0.04	0.04	0.04	0.28	0.14	-0.05	-0.96
129	2021	0.06	0.03	0.05	0.06	0.48	0.06	-0.05	-0.94
130	2021	0.06	0.06	0.05	0.04	0.49	0.01	-0.03	-2.01
131	2021	0.06	0.04	0.06	0.06	0.46	0.05	-0.03	-1.08
132	2021	0.07	0.06	0.05	0.04	0.48	0.11	-0.01	-2.32
137	2021	0.04	0.03	0.06	0.01	0.68	0.35	0.30	-1.23
140	2021	0.04	0.03	0.03	0.03	0.51	0.10	-0.09	-0.73
141	2021	0.05	0.04	0.04	0.04	0.33	0.27	-0.38	-1.14
142	2021	0.07	0.05	0.05	0.05	0.45	0.23	-0.10	-1.25

143	2021	0.04	0.02	0.03	0.05	0.39	0.03	-0.01	-0.48
144	2021	0.03	0.05	0.05	0.06	0.61	0.12	-0.15	-1.36
145	2021	0.06	0.05	0.04	0.04	0.61	0.02	-0.04	-1.98
21	2022	0.01	0.02	0.02	0.02	0.43	0.00	-0.04	-0.48
24	2022	0.01	0.02	0.06	0.04	1.30	0.06	-0.15	-2.55
29	2022	0.01	0.02	0.06	0.02	1.68	0.41	0.42	-1.35
30	2022	0.01	0.02	0.06	0.03	1.22	0.34	0.21	-1.94
31	2022	0.01	0.03	0.04	0.04	1.33	0.10	0.03	-1.19
32	2022	0.01	0.02	0.06	0.04	1.30	0.37	-0.30	-1.91
35	2022	0.02	0.03	0.03	0.02	0.99	0.11	-0.13	-0.97
36	2022	0.01	0.02	0.05	0.03	1.36	0.14	0.12	-1.63
38	2022	0.01	0.02	0.05	0.02	1.48	0.27	0.18	-1.21
39	2022	0.01	0.02	0.04	0.03	1.02	0.34	0.01	-0.67
43	2022	0.01	0.02	0.04	0.03	1.11	0.44	0.16	-0.68
47	2022	0.03	0.02	0.03	0.00	1.03	0.44	0.12	-0.52
49	2022	0.02	0.01	0.01	0.02	0.42	0.20	0.09	-0.21
51	2022	0.01	0.02	0.05	0.02	1.06	0.23	0.09	-1.21
59	2022	0.01	0.03	0.06	0.04	1.36	0.10	0.09	-2.07
62	2022	0.01	0.01	0.05	0.01	1.00	0.51	0.18	-0.37
63	2022	0.01	0.02	0.04	0.02	0.96	0.39	0.05	-0.60
64	2022	0.01	0.02	0.05	0.03	1.22	0.13	0.03	-1.69
68	2022	0.01	0.02	0.06	0.03	1.27	0.08	0.08	-2.28
69	2022	0.01	0.02	0.05	0.03	1.25	0.57	0.31	-0.53
70	2022	0.01	0.02	0.05	0.02	1.38	0.09	0.06	-1.97
71	2022	0.01	0.02	0.05	0.02	1.53	0.35	0.12	-1.32
110	2022	0.01	0.01	0.03	0.01	0.89	0.37	-0.01	-0.44
126	2022	0.02	0.02	0.03	0.02	0.82	0.18	-0.08	-0.64
127	2022	0.01	0.01	0.03	0.03	0.73	0.24	-0.17	-0.58

128	2022	0.00	0.01	0.03	0.02	0.94	0.02	-0.05	-0.95
129	2022	0.01	0.02	0.03	0.03	0.65	0.04	-0.06	-0.58
130	2022	0.01	0.02	0.05	0.03	1.30	0.05	-0.04	-1.74
131	2022	0.01	0.02	0.04	0.04	0.90	0.02	-0.01	-0.77
132	2022	0.01	0.02	0.06	0.04	1.21	0.15	0.02	-2.05
137	2022	0.01	0.01	0.07	0.03	1.44	1.04	0.30	-0.38
142	2022	0.01	0.02	0.05	0.04	1.31	0.32	-0.03	-0.92
143	2022	0.01	0.01	0.01	0.02	0.25	0.02	-0.01	-0.19
144	2022	0.01	0.02	0.04	0.04	1.18	0.12	-0.18	-1.10
145	2022	0.01	0.02	0.05	0.03	1.37	0.02	-0.06	-1.65
Briver	2022	NA	NA	NA	NA	NA	NA	NA	NA
141	2022	0.01	0.02	0.04	0.02	0.93	0.05	-0.06	-1.10

Site	Year	Length of fall	Amplitude of rise	Amplitude of fall	Day rise started	Day fall started	Day fall ended	Depth rise started	Depth fall started	Depth fall ended	Length of rise
21	2020	19.00	0.48	0.57	172	181	200	1.64	2.12	1.55	8.00
24	2020	86.00	2.29	2.54	140	182	268	0.53	2.73	0.19	40.00
30	2020	65.00	2.07	2.12	140	181	246	0.41	2.44	0.32	40.00
31	2020	47.00	1.39	1.30	152	181	228	1.20	2.58	1.28	28.00
32	2020	64.00	2.08	2.06	141	181	245	0.69	2.75	0.69	39.00
35	2020	71.00	0.77	1.10	152	181	252	1.53	2.27	1.17	29.00
36	2020	67.00	1.78	1.68	141	182	249	0.79	2.52	0.85	40.00
38	2020	44.00	1.47	1.17	152	182	226	1.70	3.12	1.95	29.00
39	2020	39.00	1.01	0.79	152	182	221	0.68	1.66	0.87	29.00
43	2020	99.00	1.13	0.99	152	181	280	1.00	2.10	1.12	29.00
47	2020	99.00	1.30	0.88	151	181	280	1.62	2.89	2.01	29.00

Site	Year	Length of fall	Amplitude of rise	Amplitude of fall	Day rise started	Day fall started	Day fall ended	Depth rise started	Depth fall started	Depth fall ended	Length of rise
48	2020	99.00	1.40	0.84	151	181	280	0.39	1.76	0.92	29.00
49	2020	6.00	0.52	0.29	152	180	186	1.86	2.34	2.06	28.00
51	2020	75.00	1.49	1.37	142	180	255	0.44	1.86	0.49	37.00
59	2020	73.00	2.28	2.22	140	181	254	0.00	2.24	0.02	40.00
62	2020	99.00	1.10	0.82	143	181	280	0.80	1.87	1.04	37.00
64	2020	74.00	1.84	1.76	141	181	255	0.44	2.23	0.48	39.00
69	2020	8.00	1.32	0.61	152	181	189	0.95	2.23	1.62	28.00
68	2020	99.00	2.20	2.38	140	181	280	0.36	2.55	0.17	40.00
70	2020	99.00	2.06	2.05	140	181	280	0.30	2.33	0.27	41.00
71	2020	98.00	1.65	1.54	140	182	280	1.10	2.71	1.17	41.00
110	2020	27.00	0.84	0.54	152	181	208	0.43	1.24	0.71	28.00
126	2020	98.00	0.77	0.87	152	182	280	0.94	1.68	0.81	29.00
127	2020	39.00	0.65	0.56	152	182	221	2.13	2.73	2.18	29.00
128	2020	65.00	0.56	0.73	152	182	247	0.70	1.24	0.51	29.00
129	2020	12.00	0.65	0.60	172	182	194	1.24	1.84	1.24	9.00
130	2020	49.00	1.78	1.71	140	182	231	0.55	2.27	0.56	41.00
131	2020	41.00	1.21	1.02	152	181	222	1.43	2.62	1.60	29.00
132	2020	63.00	2.04	2.03	140	181	244	0.64	2.64	0.61	40.00
137	2020	99.00	1.44	1.15	157	181	280	0.22	1.64	0.49	24.00
Briver	2020	85.00	2.00	2.13	140	182	267	1.14	3.10	0.97	41.00
21	2021	14.00	0.68	0.73	167	184	198	1.73	2.34	1.61	16.00
24	2021	64.00	2.69	2.77	167	184	198	0.26	2.91	0.14	49.00
29	2021	103.00	2.04	2.06	138	184	287	0.25	2.25	0.20	44.00
30	2021	55.00	2.60	2.27	136	184	239	0.02	2.58	0.31	47.00
31	2021	24.00	1.52	1.40	153	184	208	1.24	2.72	1.33	30.00

Site	Year	Length of fall	Amplitude of rise	Amplitude of fall	Day rise started	Day fall started	Day fall ended	Depth rise started	Depth fall started	Depth fall ended	Length of rise
32	2021	53.00	2.19	2.15	137	184	237	0.69	2.84	0.69	46.00
35	2021	24.00	1.11	0.99	155	184	208	1.56	2.63	1.65	28.00
36	2021	55.00	1.91	1.77	138	184	239	0.86	2.73	0.97	45.00
38	2021	47.00	1.60	1.35	152	184	231	1.64	3.21	1.87	30.00
39	2021	16.00	1.16	0.87	155	184	200	0.73	1.86	0.99	27.00
43	2021	28.00	1.29	0.87	154	184	212	1.00	2.27	1.40	29.00
47	2021	22.00	1.11	0.68	156	184	206	1.84	2.91	2.23	25.00
48	2021	26.00	1.25	0.60	155	184	210	0.71	1.93	1.33	26.00
49	2021	5.00	0.35	0.30	174	184	189	2.08	2.38	2.08	7.00
51	2021	73.00	1.63	1.50	137	182	255	0.78	2.39	0.89	44.00
59	2021	55.00	2.45	2.34	136	184	239	0.04	2.44	0.09	47.00
62	2021	9.00	1.28	0.63	156	184	193	1.04	2.29	1.66	27.00
64	2021	57.00	2.05	1.99	137	184	241	0.34	2.36	0.37	46.00
68	2021	100.00	2.52	2.50	134	184	284	0.30	2.79	0.25	49.00
69	2021	13.00	1.54	0.85	153	184	197	1.02	2.51	1.66	30.00
70	2021	85.00	2.21	1.92	135	185	270	0.30	2.46	0.54	47.00
71	2021	68.00	1.83	1.58	139	184	252	1.11	2.91	1.33	44.00
110	2021	29.00	1.19	0.67	143	184	213	0.29	1.46	0.79	40.00
126	2021	28.00	0.99	0.77	156	184	212	0.54	1.51	0.74	27.00
127	2021	15.00	0.75	0.66	166	185	200	2.26	2.95	2.30	17.00
128	2021	25.00	1.10	0.96	153	184	209	0.23	1.29	0.33	30.00
129	2021	17.00	0.87	0.94	167	184	201	1.03	1.89	0.95	16.00
130	2021	55.00	1.97	2.01	145	184	239	0.53	2.45	0.44	38.00
131	2021	17.00	1.03	1.08	166	184	201	1.52	2.52	1.44	17.00
132	2021	56.00	2.47	2.32	135	184	240	0.40	2.80	0.48	48.00
137	2021	103.00	1.60	1.23	157	184	287	0.17	1.74	0.51	25.00

Site	Year	Length of fall	Amplitude of rise	Amplitude of fall	Day rise started	Day fall started	Day fall ended	Depth rise started	Depth fall started	Depth fall ended	Length of rise
140	2021	29.00	0.79	0.73	154	184	213	0.90	1.67	0.94	28.00
141	2021	29.00	1.11	1.14	152	184	213	0.97	2.05	0.91	31.00
142	2021	23.00	1.46	1.25	153	184	207	1.41	2.83	1.59	30.00
143	2021	10.00	0.49	0.48	167	184	194	1.51	1.97	1.49	16.00
144	2021	22.00	1.39	1.36	154	185	207	1.25	2.60	1.24	29.00
145	2021	52.00	1.99	1.98	137	185	237	0.17	2.12	0.14	46.00
21	2022	20.00	0.39	0.48	169	200	220	1.59	1.85	1.37	18.00
24	2022	70.00	2.65	2.55	144	200	270	0.15	2.67	0.12	43.00
29	2022	62.00	1.88	1.35	153	198	260	0.01	1.75	0.41	33.00
30	2022	56.00	2.43	1.94	148	200	256	0.00	2.28	0.34	38.00
31	2022	33.00	1.34	1.19	157	198	231	1.51	2.76	1.57	30.00
32	2022	54.00	2.05	1.91	151	198	252	0.71	2.68	0.76	36.00
35	2022	54.00	0.98	0.97	163	198	252	1.44	2.37	1.40	34.00
36	2022	57.00	1.79	1.63	153	198	255	0.87	2.62	0.99	35.00
38	2022	56.00	1.47	1.21	160	198	254	1.81	3.23	2.03	28.00
39	2022	22.00	1.03	0.67	163	197	219	0.77	1.77	1.09	25.00
43	2022	22.00	1.11	0.68	162	197	219	1.13	2.21	1.53	26.00
47	2022	39.00	1.02	0.52	164	200	239	1.72	2.64	2.11	32.00
49	2022	9.00	0.41	0.21	161	197	206	1.97	2.33	2.11	35.00
51	2022	57.00	1.48	1.21	154	196	253	1.02	2.42	1.21	32.00
59	2022	57.00	2.30	2.07	148	199	256	0.00	2.17	0.10	38.00
62	2022	36.00	1.00	0.37	164	199	235	0.67	1.52	1.15	22.00
63	2022	26.00	1.09	0.60	157	199	225	1.23	2.20	1.60	30.00
64	2022	63.00	1.88	1.69	149	199	262	0.32	2.13	0.44	38.00
68	2022	91.00	2.37	2.28	148	199	290	0.12	2.42	0.14	39.00
69	2022	21.00	1.27	0.53	162	200	221	1.38	2.47	1.93	24.00

Site	Year	Length of fall	Amplitude of rise	Amplitude of fall	Day rise started	Day fall started	Day fall ended	Depth rise started	Depth fall started	Depth fall ended	Length of rise
70	2022	92.00	2.10	1.97	148	198	290	0.24	2.29	0.33	40.00
71	2022	55.00	1.75	1.32	155	200	255	1.09	2.74	1.43	33.00
110	2022	36.00	0.92	0.44	156	199	235	0.30	1.10	0.66	30.00
126	2022	41.00	0.81	0.64	165	198	239	0.76	1.53	0.89	32.00
127	2022	20.00	0.73	0.58	163	201	221	2.31	2.97	2.39	25.00
128	2022	54.00	0.93	0.95	160	200	254	0.22	1.12	0.17	27.00
129	2022	19.00	0.65	0.58	164	200	219	1.29	1.81	1.23	23.00
130	2022	56.00	1.73	1.74	155	199	255	0.56	2.20	0.46	32.00
131	2022	19.00	0.89	0.77	162	201	220	1.58	2.33	1.56	25.00
132	2022	57.00	2.31	2.05	147	199	256	0.24	2.41	0.36	40.00
137	2022	11.00	1.40	0.38	169	199	210	0.22	1.58	1.20	19.00
142	2022	24.00	1.30	0.92	160	199	223	1.04	2.24	1.32	27.00
143	2022	11.00	0.24	0.19	170	199	210	1.43	1.58	1.40	17.00
144	2022	31.00	1.18	1.10	160	201	232	2.00	3.05	1.94	27.00
145	2022	52.00	1.75	1.65	152	200	252	0.17	1.80	0.15	36.00
Briver	2022	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
141	2022	57.00	1.15	1.10	156	200	257	0.59	1.64	0.54	31.00

Appendix G
Description of hydrograph attributes as defined from the hydrograph for each wetland in each year

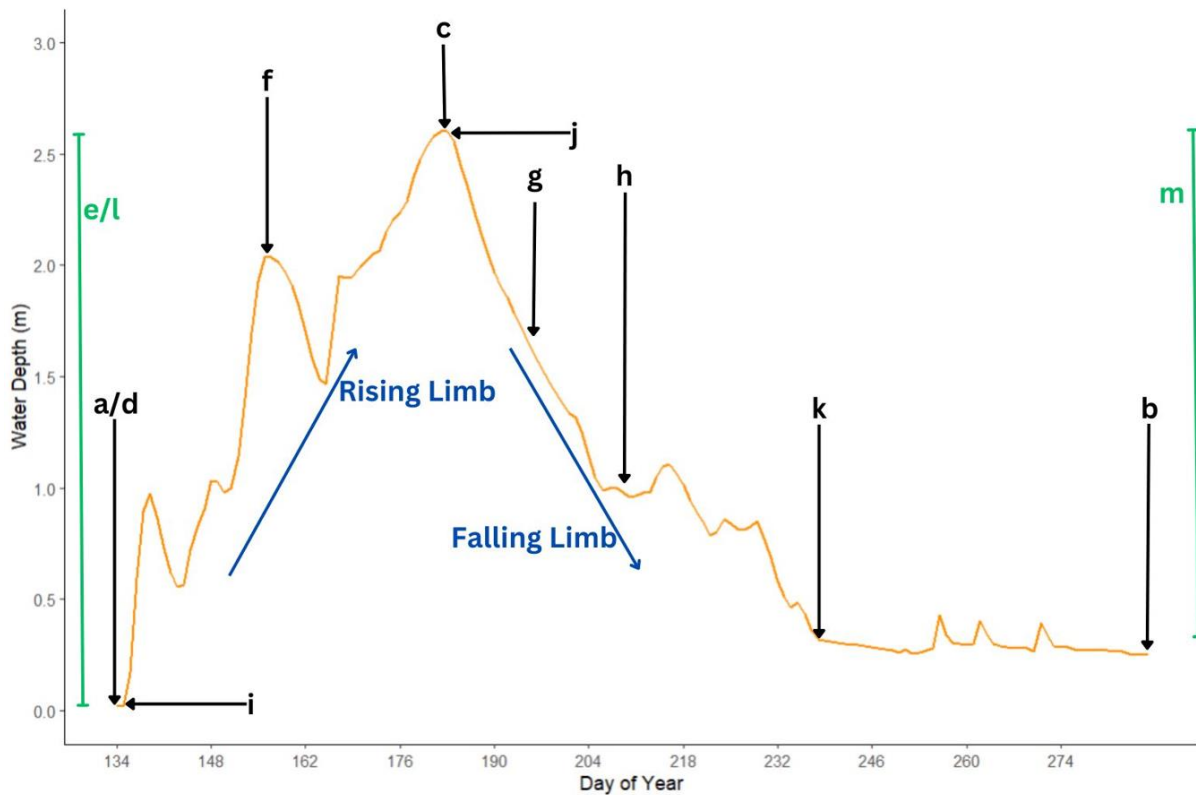
Variable	Spreadsheet Abbreviation	Description
Wetland	Wetland	Wetland ID number
Year	Year	Year of data collection
Mean Depth (m)	Mean Depth (m)	Mean depth calculated from all water depth data points from May to October
Initial Depth (m)	Initial Depth (m)	Depth when water logger was installed in wetland and data collection started (in May for all three years); a in Appendix Figure 1
Final Depth (m)	Final Depth (m)	Depth when water logger was removed from wetland and data collection ended (in October for all three years); b in Appendix Figure 1
Maximum Depth (m)	Maximum Depth (m)	Maximum depth during the data collection period; c in Appendix Figure 1
Minimum Depth (m)	Minimum Depth (m)	Minimum depth during the data collection period; d in Appendix Figure 1
Change in Depth (m)	Change (m)	The difference between the maximum and minimum depths (maximum depth minus minimum depth); e in Appendix Figure 1
Early Peak Depth (m)	Early Peak Depth (m)	In many years the river has a two-part flood pulse with a small increase in water earlier in the season before the main flood-pulse. In 2020 this was June 7 th and in 2021 it was Jun 8 th ; there was no such early peak in 2022, but for comparative purposes I used the depth on June 7 th . f in Appendix Figure 1
Day of Maximum Depth	Day Deepest	The Day of Year/Julian Day on which the Maximum Depth was recorded; this was the variable used for analysis instead of date.
Day of Minimum Depth	Day Shallowest	The Day of Year/Julian Day on which the Minimum Depth was recorded; this was the variable used for analysis instead of date.
Depth 2 Weeks After Maximum Depth	Depth 2 Weeks After Deepest Date	The depth recorded two weeks (14 days) after the Maximum Depth was recorded, as a measure of the falling limb of the hydrograph; g in Appendix Figure 1
Depth 4 Weeks After Maximum Depth	Depth 4 Weeks After Deepest Date	The depth recorded four weeks (28 days) after the Maximum Depth was recorded, as a measure of the falling limb of the hydrograph; h in Appendix Figure 1

Day 2 Weeks After Maximum Depth	Day 2 Weeks	The Day of Year/Julian Day two weeks (14 days) after the Maximum Depth was recorded
Day 4 Weeks After Maximum Depth	Day 4 Weeks	The Day of Year/Julian Day four weeks (28 days) after the Maximum Depth was recorded
Beginning Depth of Rising Limb of Hydrograph	Day Rise Started	The depth at which the rising limb of the hydrograph began; i in Appendix Figure 1
Beginning Depth of Falling Limb of Hydrograph	Day Fall Started	The depth at which the falling limb of the hydrograph began; j in Appendix Figure 1
End Depth of Falling Limb of Hydrograph	Day Fall Ended	The depth at which the falling limb of the hydrograph ended; k in Appendix Figure 1
Day Rise Started	Depth Rise Started	The Day of Year/Julian Day on which the rising limb of the hydrograph began; the date on which the Beginning Depth of Rising Limb of Hydrograph was recorded
Day Fall Started	Depth Fall Started	The Day of Year/Julian Day on which the falling limb of the hydrograph began; the date on which the Beginning Depth of Falling Limb of Hydrograph was recorded
Day Fall Ended	Depth Fall Ended	The Day of Year/Julian Day on which the falling limb of the hydrograph ended; the date on which the End Depth of Falling Limb of Hydrograph was recorded
Length of Rise	Length Of Rise	The number of days between the Day Rise Started and the Day of Maximum Depth
Length of Fall	Length Of Fall	The number of days between the Day Fall Started and the Day Fall Ended
Amplitude of Rising Limb	Amplitude Of Rise	The difference between the Beginning Depth of Rising Limb and the Maximum Depth; the amplitude of the rising limb of the hydrograph; i in Appendix Figure 1. In Appendix Figure 1 this is the same as Change in Depth (e) but this is not always the case (e.g. some wetlands have their shallowest depth in October not May).
Amplitude of Falling Limb	Amplitude Of Fall	The difference between the Maximum Depth and the End Depth of Falling Limb; the amplitude of the falling limb of the hydrograph; m in Appendix Figure 1
2-week Slope	2 Week Sqdwfelo	The slope of the falling limb between Maximum Depth and Depth Two Weeks After Maximum Depth; $(\text{Maximum Depth} - \text{Depth Two Weeks After Maximum Depth}) \div (\text{Two Weeks})$

4-week Slope	4 Week Slope	The slope of the falling limb between Maximum Depth and Depth Four Weeks After Maximum Depth; $(\text{Maximum Depth} - \text{Depth Four Weeks After Maximum Depth}) \div (\text{Four Weeks})$
Slope of Rise	Slope Of Rise	The slope of the rising limb between Beginning Depth of Rising Limb and Maximum Depth; $(\text{Beginning Depth of Rising Limb} - \text{Maximum Depth}) \div (\text{Beginning Depth of Rising Limb} - \text{Day of Maximum Depth})$
Slope of Fall	Slope Of Fall	The slope of the falling limb between Maximum Depth and Depth Fall Ended; $(\text{Maximum Depth} - \text{Depth Fall Ended}) \div (\text{Day of Maximum Depth} - \text{Day Fall Ended})$
Max Depth - Early Peak	Max Depth - Early Peak	Maximum Depth minus Early Peak Depth
Fall end depth - Minimum Depth	Fall End Depth - Lowest Depth	End Depth of Falling Limb minus Minimum Depth
Final depth - Initial depth	Final Depth - Initial Depth	Final Depth minus Initial Depth
Fall End Depth - Rise Start Depth	Fall End Depth - Rise Start Depth	End Depth of Falling Limb minus Beginning Depth of Rising Limb

Appendix H

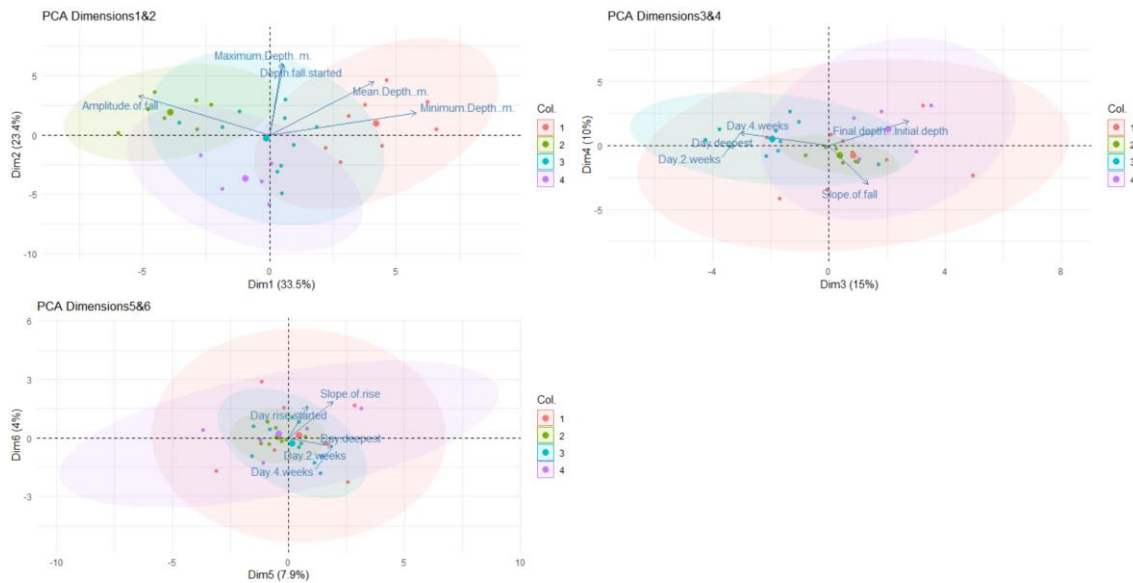
Diagram of hydrograph metrics; letters are explained in Appendix G.



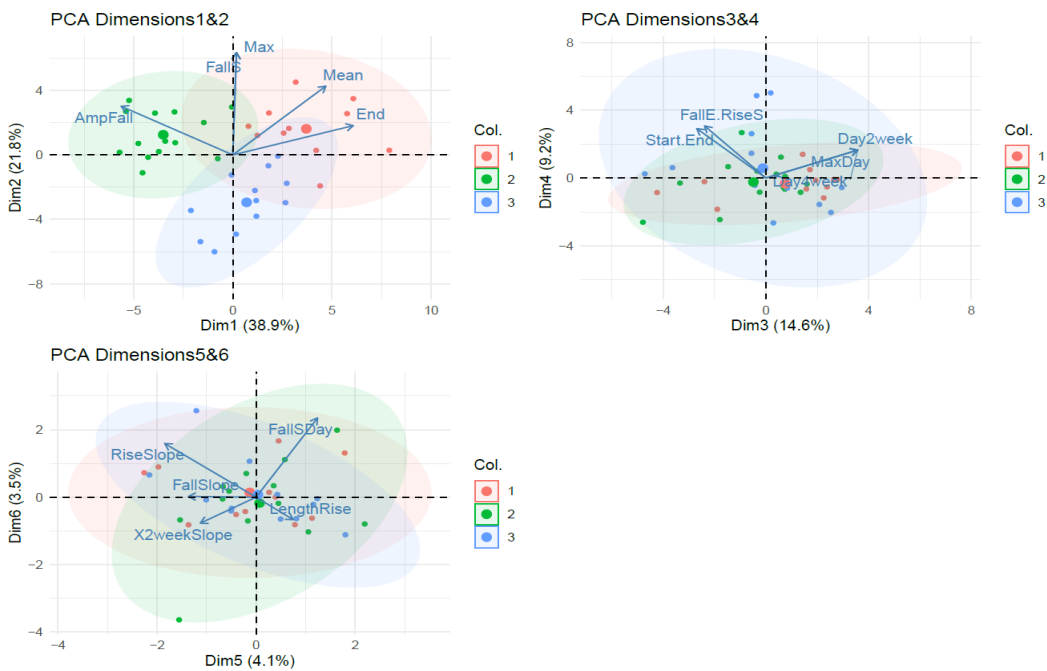
Appendix I

PCAs of hydrograph attributes for 2020, 2021, and 2022. 6 PCAs were retained in each year.

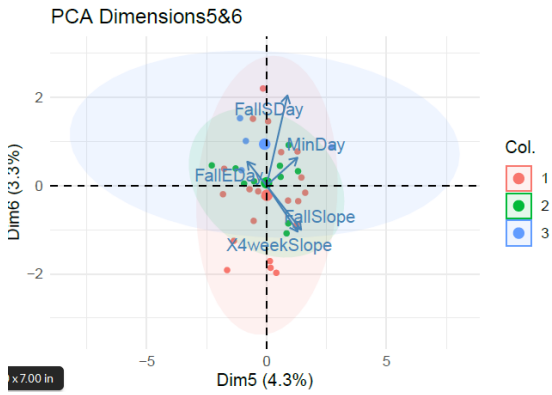
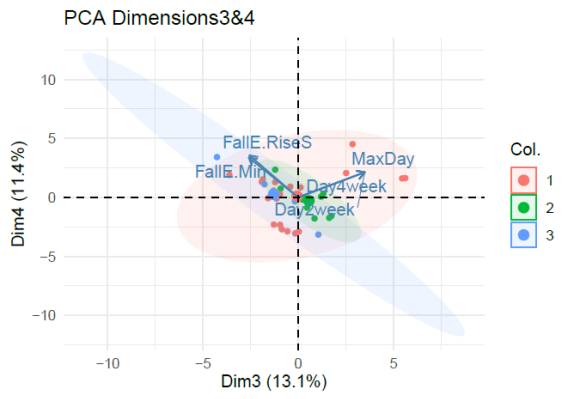
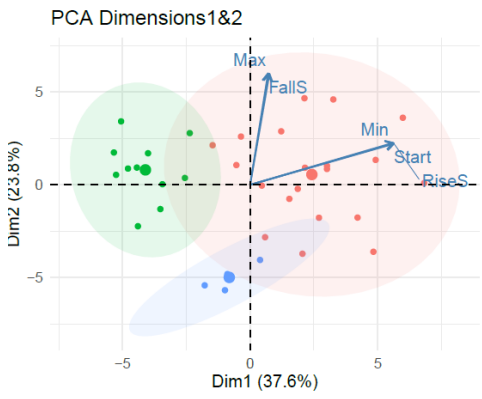
2020



2021



2022



Appendix J: Hydrograph attributes for 2020, 2021, and 2022, for each PC that contribute to more than 5% of the variance of that PC.

2020		2021		2022	
PC1		PC1		PC1	
Variable	Contribution	Variable	Contribution	Variable	Contribution
Depth.fall.ended	8.75155956	Depth.fall.ended	7.024421	Amplitude.of.rise	6.72936
Final.Depth..m.	8.56860101	Final.Depth..m.	6.920862	Change..m.	6.56744
Minimum.Depth..m.	8.49217134	Initial.Depth..m.	6.601499	Minimum.Depth..m.	6.43330
Depth.rise.started	8.11127143	Minimum.Depth..m.	6.555714	Initial.Depth..m.	6.42896
Initial.Depth..m.	8.10071362	Depth.rise.started	6.499186	Depth.rise.started	6.39670
Amplitude.of.fall	6.76078428	Fall.End.Depth...Rise.Start.Depth	6.259551	Depth.fall.ended	6.37738
Change..m.	6.38971234	Amplitude.of.fall	6.258916	Final.Depth..m.	6.35200
Amplitude.of.rise	6.34674592	Length.of.rise	6.207278	Amplitude.of.fall	6.23194
		Amplitude.of.rise	6.154330	Fall.End.Depth...Rise.Start.Depth	6.22928
		Change..m.	6.077200	Day.rise.started	6.03340
				Day.fall.ended	5.22707
				Length.of.fall	5.21952
				Slope.of.rise	5.01971
PC2		PC2		PC2	
Variable	Contribution	Variable	Contribution	Variable	Contribution
Maximum.Depth..m.	13.26298622	Maximum.Depth..m.	14.470764	Maximum.Depth..m.	13.16026
Depth.fall.started	13.19483754	Depth.fall.started	14.462041	Depth.fall.started	13.12112
Early.Peak.Depth..m.	12.36963291	Early.Peak.Depth..m.	13.582243	Depth.2.weeks.after.deepest.date	12.94433
Depth.2.weeks.after.deepest.date	12.12011691	Depth.2.weeks.after.deepest.date	12.007586	Depth.4.weeks.after.deepest.date	12.26597
Depth.4.weeks.after.deepest.date	11.33365875	Mean.Depth..m.	6.936671	Early.Peak.Depth..m.	8.49700

Mean.Depth..m.	7.26176839	Depth.4.weeks.after.deepest.date	5.846576	Mean.Depth..m.	8.17769
PC3		PC3		PC3	
Variable	Contribution	Variable	Contribution	Variable	Contribution
Day.deepest	11.66986387	Day.deepest	17.137230	Day.deepest	18.32105
Day.2.weeks	11.66986387	Day.2.weeks	17.137230	Day.2.weeks	18.32105
Day.4.weeks	11.66986387	Day.4.weeks	17.137230	Day.4.weeks	18.32105
Fall.End.Depth...Rise.Start.Depth	10.67759391	Slope.of.fall	9.528707	X2.week.slope	15.74652
Final.depth...Initial.depth	9.444993078	Day.shallowest	6.662524	Length.of.rise	6.78616
Day.fall.started	9.364241931	Final.depth...Initial.depth	5.770730	Slope.of.fall	5.06041
Fall.end.depth...lowest.depth	8.58481169	Day.fall.ended	5.403738		
Max.Depth...Early.Peak	8.579987406				
Day.shallowest	8.041156236				
PC4		PC4		PC4	
Variable	Contribution	Variable	Contribution	Variable	Contribution
Day.fall.ended	18.76818949	Final.depth...Initial.depth	25.053947	Final.depth...Initial.depth	23.72453
Length.of.fall	18.72490118	Fall.end.depth...lowest.depth	18.396148	Fall.end.depth...lowest.depth	22.29387
Slope.of.fall	17.59839067	Max.Depth...Early.Peak	18.044533	Day.shallowest	20.41263
Final.depth...Initial.depth	6.984431614	Day.shallowest	13.982002	Day.fall.started	7.46349
		Slope.of.rise	5.020148	Max.Depth...Early.Peak	6.52282
PC5		PC5		PC5	
Variable	Contribution	Variable	Contribution	Variable	Contribution
Day.deepest	11.31585647	Slope.of.rise	26.807667	Slope.of.fall	22.80019
Day.2.weeks	11.31585647	Slope.of.fall	14.129612	X4.week.slope	18.98289
Day.4.weeks	11.31585647	Day.rise.started	9.512975	Day.shallowest	11.12020
Slope.of.rise	11.22513775	Day.fall.started	8.140363	Length.of.fall	8.54396

Max.Depth...Early.Peak	8.743600119	X2.week.slope	6.971057	Day.fall.ended	8.22313
Day.fall.started	8.340444041	Day.deepest	5.444248	Fall.end.depth...lowest.depth	5.70962
Fall.end.depth...lowest.depth	5.953392331	Day.2.weeks	5.444248		
Fall.End.Depth...Rise.Start.Depth	5.862263085	Day.4.weeks	5.444248		
X4.week.slope	5.679282451				
X2.week.slope	5.103086674				
PC6		PC6		PC6	
Variable	Contribution	Variable	Contribution	Variable	Contribution
Slope.of.rise	21.12084448	Day.fall.started	55.256178	Day.fall.started	54.22853
Length.of.rise	17.44160697	Slope.of.rise	17.635814	Slope.of.fall	9.63031
Day.rise.started	16.42746912	X2.week.slope	7.635649	Day.shallowest	6.88269
Slope.of.fall	9.099669185			X4.week.slope	6.35657
Length.of.fall	7.622361265			Fall.end.depth...lowest.depth	5.35886
Day.fall.ended	7.504167208				
Fall.End.Depth...Rise.Start.Depth	5.437380367				

Appendix K

Representation of how wetlands changed in group between years, with each arrow representing one wetland. Arrows are coloured by the group the wetland was in in 2020.

